A Textbook of

Physics

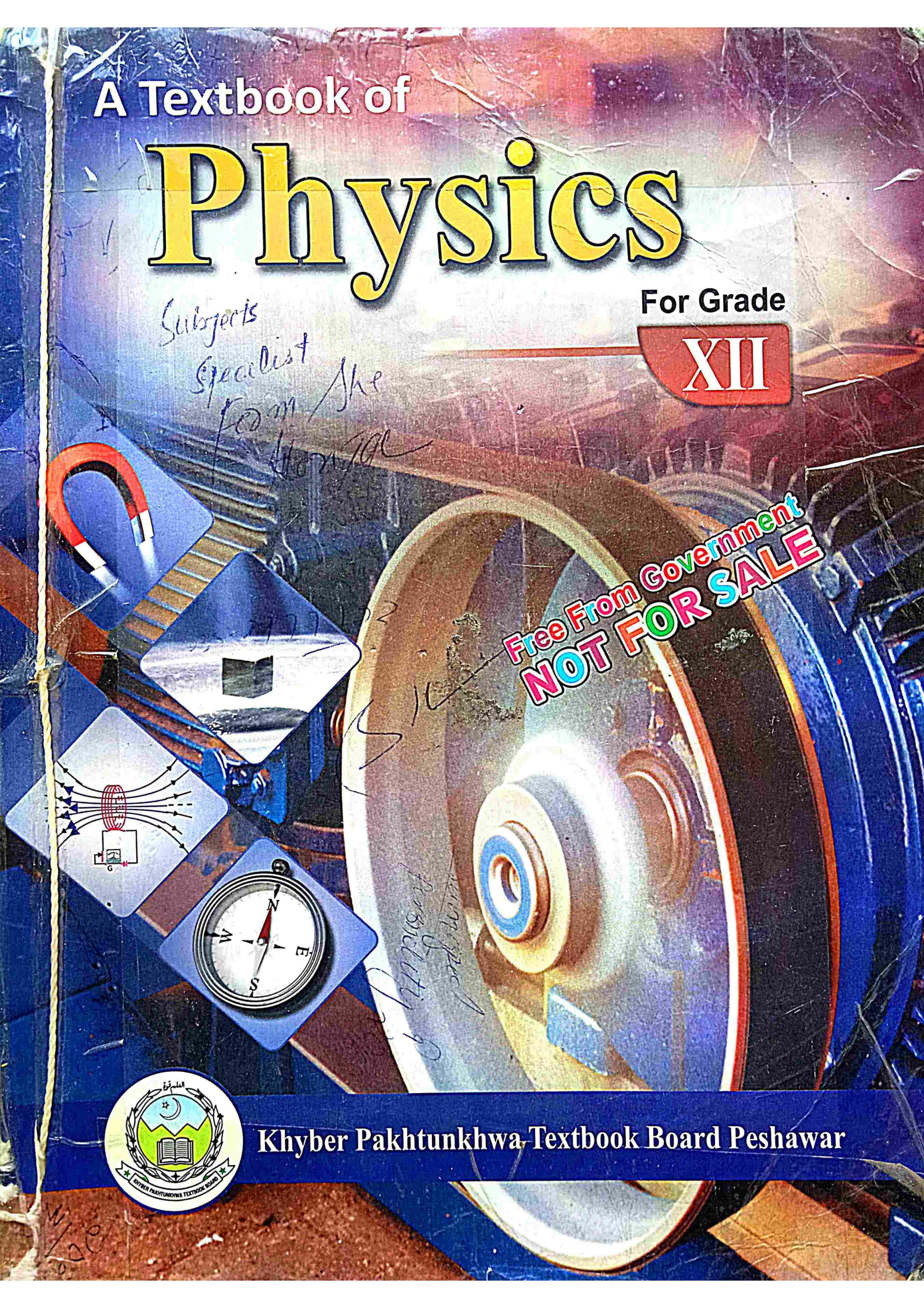
For Grade

XII

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Khyber Pakhtunkhwa Textbook Board Peshawar

A Textbook of Physics Grade-XII

Khyber Pakhtunkhwa Textbook Board,
Peshawar

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Authors:

Prof. Shaukat Ali Taran
Government Post Graduate College Timergara
Shadab Gul Assistant Prof.
Government Post Graduate College, Lakki Marwat
Dr. Naeem Khalid
Dean of Sciences, Islamia College, Peshawer

Prof. Abdul Baseer
Edwardes College, Peshawer
Abdul Rehman, Lecturer
Akram Khan Durrani College Bannu
Aamir Ullah Khan
Director, Pakistan Virtual College, Hayatabad Peshawar
Hafiz Mehar Elahi
Peshawar Model Degree College, Peshawer

Review Supervision:

Gohar Ali Khan, Director, Curriculum and Teachers Education, Abbottabad.

Focal Person:

Zulfiqar Khan, Additional Director (Curriculum and Textbook Review) DCTE, Abbottabad.

Re-reviewers:

Fazli Maula
Associate Prof. G.P.G College Mandian, Abbottabad
Ahsan Saleem
(Subject Specialist) GHSS Bandi Dhundan, Abbottabad
Muhammad Arshid
(Subject Specialist) GHSS Lassan Thakral, Mansehra
Dr. Shafqat Hussain
(Subject Specialist) Desk Officer, DCTE, Abbottabad
Nasir Kamal (Assistant Subject Specialist)
Khyber Pakhtunkhwa Textbook Board, Peshawar

Editor:

Nasir Kamal, Assistant Subject Specialist (Physics)
Khyber Pakhtunkhwa Textbook Board, Peshawar.

Printing Supervision:

Rashid khan Paindakhel (Chairman)
Saeedur Rehman (Member E&P)
Khyber Pakhtunkhwa Textbook Board, Peshawar

Academic Year 2021-22
Email: membertbb@yahoo.com
Website: www.kptbb.gov.pk
Phone: 091-9217159-60

PREFACE

This book is based on national curriculum 2006. In this edition some topics, diagrams, numerical questions, have been improved, and some brainstorming questions, assignments, projects are added to enhance the learning capacity of students.

Throughout the book an attempt has been made to present the mathematical symbols in italic for its easy understanding.
In case of any errors we request the readers to point out these errors so that they are eliminated in the next edition. I hope that the teachers students, and experts will keep us informed about the textbook, so that we may be able to improve the textbook, because there is always room for improvement. For feedback and comment mail us at: nasirkamal2@yahoo.com

Editor

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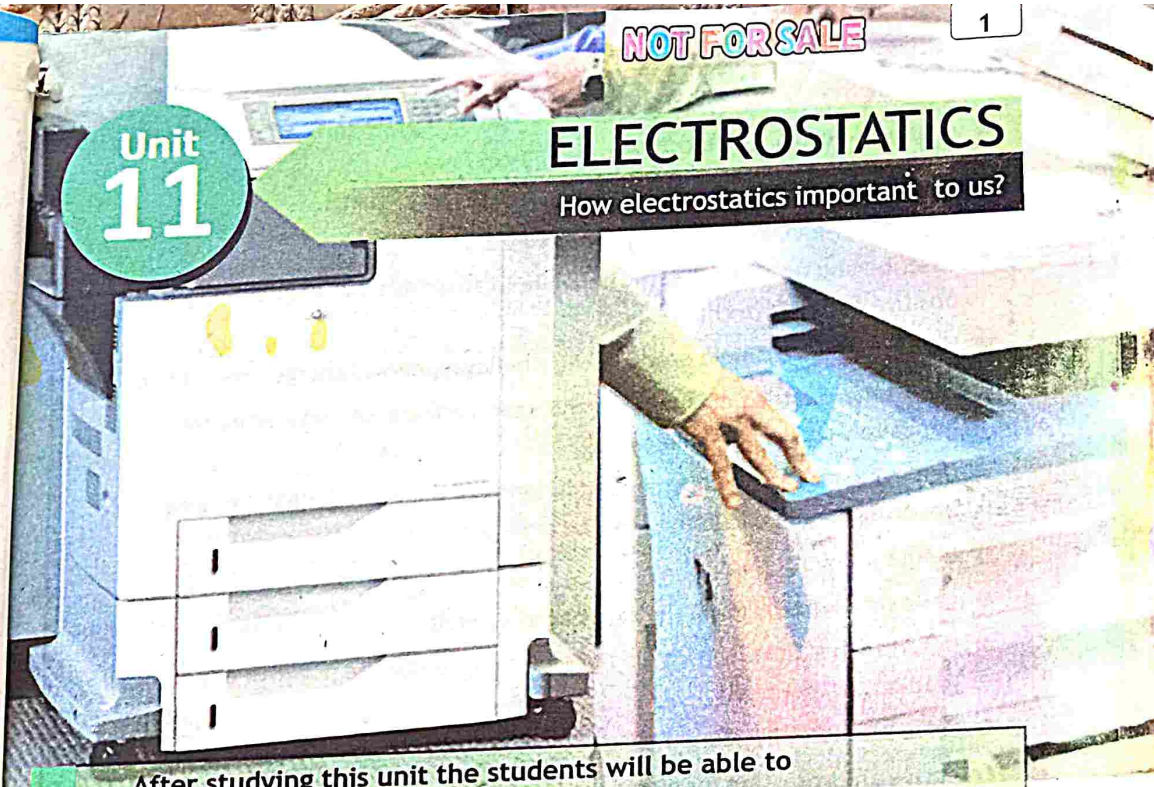
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Unit 11

ELECTROSTATICS

How electrostatics important to us?



LEARNING OUTCOMES

After studying this unit the students will be able to

- state Coulomb's law and explain that force between two point charges is reduced in a medium other than free space using Coulomb's law.
- derive the expression $E = 1/4\pi\varepsilon_o\, q/r^2$ for the magnitude of the electric field at a distance 'r' from a point charge 'q'.
- describe the concept of an electric field as an example of a field of force.
- define electric field strength as force per unit positive charge.
- solve problems and analyse information using $E = F/q$.
- solve problems involving the use of the expression $E = 1/4\pi\varepsilon_o\, q/r^2$.
- calculate the magnitude and direction of the electric field at a point due to two charges with the same or opposite signs.
- sketch the electric field lines for two point charges of equal magnitude with same or opposite signs.

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LEARNING OUTCOMES

- describe the concept of electric dipole.
- define and explain electric flux.
- describe electric flux through a surface enclosing a charge.
- state and explain Gauss's law.
- describe and draw the electric field due to an infinite size conducting plate of positive or negative charge.
- sketch the electric field produced by a hollow spherical charged conductor.
- sketch the electric field between and near the edges of two infinite size oppositely charged parallel plates.
- define electric potential at a point in terms of the work done in bringing unit positive charge from infinity to that point.
- define the unit of potential.
- solve problems by using the expression $V = W/q$.
- describe that the electric field at a point is given by the negative of potential gradient at that point.
- solve problems by using the expression $E = V/d$.
- derive an expression for electric potential at a point due to a point charge.
- calculate the potential in the field of a point charge using the equation $V = 1/4\pi\varepsilon_o q/r$.
- define and become familiar with the use of electron volt.
- define capacitance and the farad and solve problems by using $C=Q/V$.
- describe the functions of capacitors in simple circuits.
- solve problems using formula for capacitors in series and in parallel.
- explain polarization of dielectric of a capacitor.
- demonstrate charging and discharging of a capacitor through a resistance.
- prove that energy stored in a capacitor is $W=1/2\ QV$ and hence $W=1/2\ CV^2$.

In this unit two fundamental processes of electrostatics are introduced: Coulomb's law for force between stationary charges and the principle of superposition for electric field configurations.

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Electrostatics is the studies of electric charges which are at rest or static. The electric force between static charged particles is known as the electrostatic force.

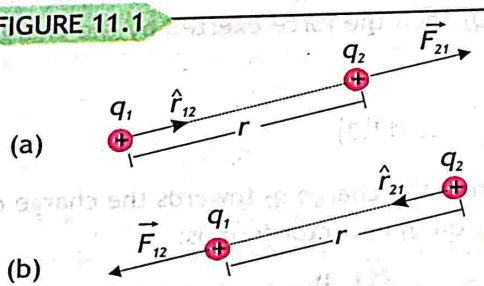
The electrostatic force is attractive or repulsive force between particles that are caused due to their electric charges. It is also referred to as Coulomb's force. In SI units, charge is measured in coulombs (symbol C). The charge q is quantized and it is an integral multiple of elementary charge e, i.e., $q=ne$
Another quantity being discussed that plays an important role in electrical circuits is capacitance and its dependence on the dielectrics.

11.1 COULOMB'S LAW

The quantitative measurement of the force between two electric charges was first made by Coulomb. He carried out series of experiments to measure the force between electric charges using an apparatus known as torsion balance. Coulomb expresses his experimental data in the form of a statement which is known as Coulomb's law.

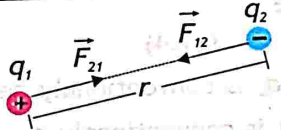
It states "the magnitude of the force between two point charges is directly proportional to the product of the magnitudes of the charges and inversely proportional to the square of the distance between them."

FIGURE 11.1



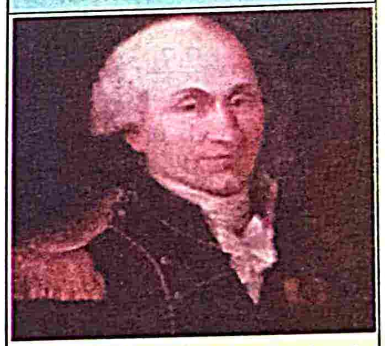
Coulomb force between similar charges

FIGURE 11.2



Coulomb force between opposite charges.

(1736-1805).



Charles-Augustin de Coulomb was an eminent French physicist who formulated the law known Coulomb's law

The magnitude of the force $\vec{F}$ between two electric charges q_1 and q_2 separated by distance r can be expressed as

$$F \propto q_1 q_2 \qquad \ldots(A)$$

$$F \propto \frac{1}{r^2} \qquad \ldots(B)$$

combining Eq(A) & Eq(B)

$$F \propto \frac{q_1 q_2}{r^2} \qquad \ldots(11.1)$$

$$F = k\frac{q_1 q_2}{r^2}$$

Where, k is a constant of proportionality and its value depends upon the system of the units used and the medium between the charges. The electric charges q_1 and q_2 are assumed to be point or localized charges, provided that the size of the bodies carrying the charges is very small as compared to the distance between them.

In order to show the direction of the force we use unit vector along the line joining the two charges as shown in Fig:11.1.(a). If $\hat{r}_{12}$ is unit vector, pointing from the charge q_1 towards the charge q_2, then the force exerted by the charge q_1 on q_2 in vector form is:

$$\vec{F}_{21} = k\frac{q_1 q_2}{r^2}\hat{r}_{12} \qquad \ldots(11.2)$$

Similarly if $\hat{r}_{21}$ is unit vector, pointing from the charge q_2 towards the charge q_1, then the force exerted by the charge q_2 on q_1 in vector form is:

$$\vec{F}_{12} = k\frac{q_1 q_2}{r^2}\hat{r}_{21} \qquad \ldots(11.3)$$

Since $\hat{r}_{12} = -\hat{r}_{21}$

So from Eq: (11.2) and 11.3 we can write

$$\vec{F}_{21} = -\vec{F}_{12} \qquad \ldots(11.4)$$

The force exerted by the charge q_1 on q_2 is conventionaly denoted by $\vec{F}_{21}$ and the force exerted by the charge q_2 on q_1 is conventionaly denoted by $\vec{F}_{12}$. The

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force F_{12} exerted by q_2 on q_1 is equal in magnitude to the force F_{21} exerted by q_1 on q_2 and in the opposite direction as illustrated in Fig 11.2 (o) This proves that Coulomb's law fits into Newton's third law.

The constant k can be generally expressed in terms of permittivity of the free space ε_o i.e., $k = \frac{1}{4\pi\varepsilon_o}$

Experimentally measured value of

$$\varepsilon_o = 8.85\times10^{-12}\ C^2\ N^{-1}\ m^{-2}$$

so $k = \frac{1}{4\pi\varepsilon_o} = 9.0 \times 10^9\ N\ m^2\ C^{-2}$

COULOMB'S LAW IN MATERIAL MEDIA

Eq:(11.2) gives the force between two charges when there is air or vacuum between them. But it is experimentally observed that when an insulator is placed between the electric charges, it reduces the force. Permittivity is the property of a medium which affects the magnitude of force between two point charges.

The coulomb's force can now be written as

$$F_{med} = \frac{1}{4\pi\varepsilon}\frac{q_1 q_2}{r^2} \qquad \ldots(11.5)$$

The quantity ε is called the permittivity of the medium. For a particular insulator the permittivity of a material medium compared with the permittivity of vacuum is called relative permittivity or dielectric constant ε_r. Its ratio is given by

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_o} \qquad \ldots(11.6)$$

Obviously the ε_r is dimensionless constant and its value is always greater than unity for various dielectrics. The values of relative permittivity for various dielectrics are given in table 11.1.

Table 11.1 :The relative permittivity of various dielectrics

Material	ε_r
Vacuum	1
Air	1.0006
Benzene	2.284
Germinium	16
Water	78.5
Glass	4.8-10
Mica	3-7.5
Paraffine paper	2
Rubber	2.94
Ammonia(liquid)	22-25

The force in a medium of relative permittivity ε_r, is given by

$$\vec{F}_{med} = \frac{1}{4\pi\varepsilon_o \varepsilon_r}\frac{q_1 q_2}{r^2}\hat{r} \quad \ldots (11.7)$$

$$\vec{F}_{med} = \frac{\vec{F}_{vac}}{\varepsilon_r} \quad \ldots (11.8)$$

EXAMPLE 11.1

Three charges q_1 = -5 μC, q_2 = +10 μC and q_3 = -12 μC are placed in a line as shown in figure. Calculate the net electrostatic force on charge q_2 due to the other two charges.

GIVEN

Charge (q_1) = -5 μC = -5 x 10^{-6} C

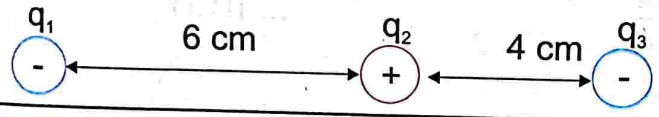
Charge (q_2) = +10 μC = +10 x 10^{-6} C

Charge (q_3) = -12 μC = -12 x 10^{-6} C

k = 9 x 10^9 Nm^2C^{-2}

The distance between charge q_1 and q_2 (r_{12}) = 6 cm = 0.06 m = 6 x 10^{-2} m

The distance between charge q_2 and q_3 (r_{23}) = 4 cm = 0.04 m = 4 x 10^{-2} m



REQUIRED

The magnitude of net electrostatic force on charge q_2=F_{net}=?
The direction of electrostatic force=?

SOLUTION

Electrostatic force on charge q_2 due to charge q_1= $F_{21} = k\frac{q_1 q_2}{r_{12}^2}$

$$= 9.0 \times 10^9 \text{ N m}^2 \text{ C}^{-2} \frac{(5\times10^{-6}\,C)(10\times10^{-6}\,C)}{(6\times10^{-2}\text{ m})^2}$$

$$= 9.0 \times 10^9 \text{ N m}^2 \text{ C}^{-2} \frac{(50\times10^{-12}\,C^2)}{(36\times10^{-4}\text{ m}^2)}$$

$$= 125\text{N}$$

Electrostatic force on charge q_2 due to q_3=

$$F_{23} = 9.0 \times 10^9 \text{ N m}^2 \text{ C}^{-2} \frac{(10\times10^{-6}\,C)(12\times10^{-6}\,C)}{(4\times10^{-2}\text{ m})}$$

$$= 9.0 \times 10^9 \text{ Nm}^2\text{C}^{-2} \frac{(120\times10^{-12}\,C^2)}{(16\times10^{-4}\text{ m}^2)}$$

$$\frac{(1080\times10^{-3})\text{N}}{(16\times10^{-4})} = 675\text{N}$$

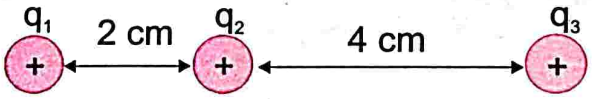
The net electrostatic force on charge q_2=F_2 = F_{21} - F_{23}

= 675 N - 125 N = 550 N.

The direction of the net electrostatic force on charge q_2 points towards charge q_3 (points to the right).

ASSIGNMENT 11.1

Three charges +q_1 = 5 μC , +q_2 = 10 μC and q_3 are placed as shown in the figure . What is the electrostatic charge on q_3 if the net electrostatic force on charges q_2 is zero. (20×10^{-6}C)



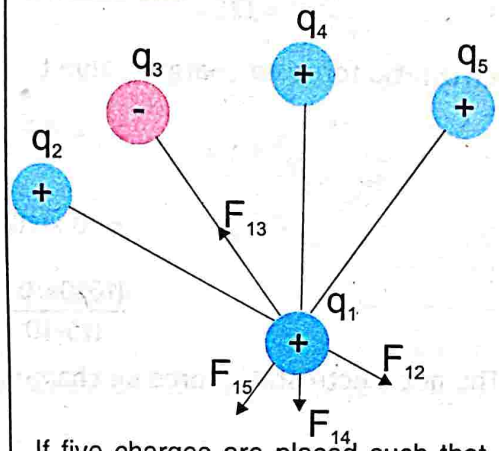
11.2 ELECTRIC FIELD AND ITS INTENSITY

The concept of electric field was first proposed by Michael Faraday, in the 19th century. He stated that the electric field around a charge is like a sphere with in which other charges are influenced by it.

An electric field is defined as *any region around a charge in which an electric test charge would experience an electric force.*

Electric field is characterized by strength and direction at every point in space. The strength and direction of electric field can be determined by placing a unit positive test charge in that field. The direction in which this unit positive test charge move or tends to move is the direction of electric field. The test charge is so small that it does not distort the original field due to the primary source.

TIP



If five charges are placed such that, as shown in figure, then the resultant force exerted by charges q_2 , q_3 , q_4 , and q_5 on charges q_1 is

$F_1 = F_{12} + F_{13} + F_{14} + F_{15}$

A single vector quantity containing information about the field strength and its direction at that point is denoted by $\vec{E}$ and is known as electric field intensity. If unit positive test charge q_o experience a force F due to the electric field of charge q.Then

the intensity of an electric field at any point is the force per unit positive test charge placed at that point.

The electric field intensity $\vec{E} = \dfrac{\vec{F}}{q_o}$

Or $\vec{F} = q_o \vec{E}$ ... (11.9)

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The SI unit of electric field intensity is newton per coulomb (NC^{-1}) or volt per metre (Vm^{-1}).

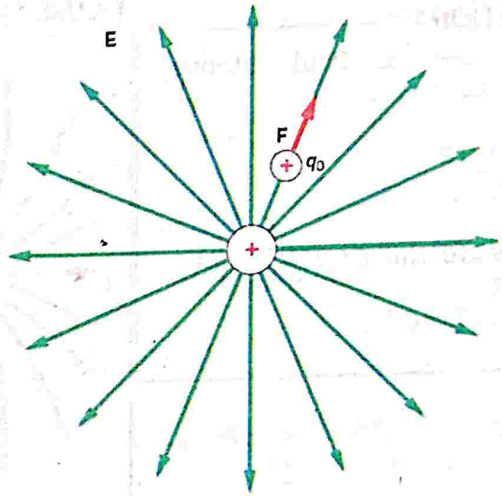
Coulomb's law enables the electric field to be calculated for any point in space around a fixed static charge q. The magnitude of electric field is given by:

$$F = \frac{kqq_o}{r^2}$$

As $\hat{r}$ is the unit vector directed from charge q to q_o so in vector form

$$\vec{F} = \frac{kqq_o}{r^2}\hat{r}$$

FIGURE 11.3



Electric field intensity due to a point charge.

So the field intensity is given by

$$\vec{E} = \frac{\vec{F}}{q_o} = k\frac{\frac{qq_o}{r^2}}{q_o}\hat{r}$$

$$\vec{E} = k\frac{q}{r^2}\hat{r} \qquad \text{...(11.10)}$$

The strength of the field is proportional to the magnitude of the charge. Its strength decreases as the test charge moves away (unit charge) from source charge q.

EXAMPLE 11.2

Find electric field at a distance of 30cm from a 3 μ C point charge.

GIVEN

radius r = 30 cm = 30×10^{-2} m= 0.3 m

charge $q = 3\mu C = 3 \times 10^{-6}$ C

REQUIRED

electric field $=E=?$

SOLUTION

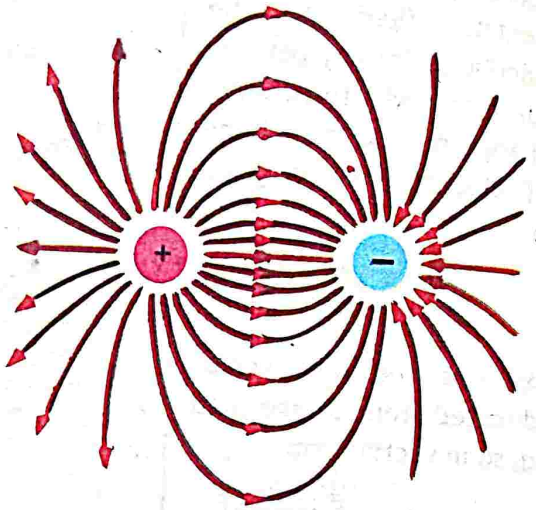
Using electric field intensity formulae

$$E=\frac{1}{4\pi\varepsilon_o}\frac{q}{r^2}$$

$$=(9\times10^9\,Nm^2C^{-2})(\frac{3\times10^{-6}\,C}{(0.3m)^2})$$

$$=3\times10^5\,NC^{-1}$$

FIGURE 11.4



Two equal and opposite charges

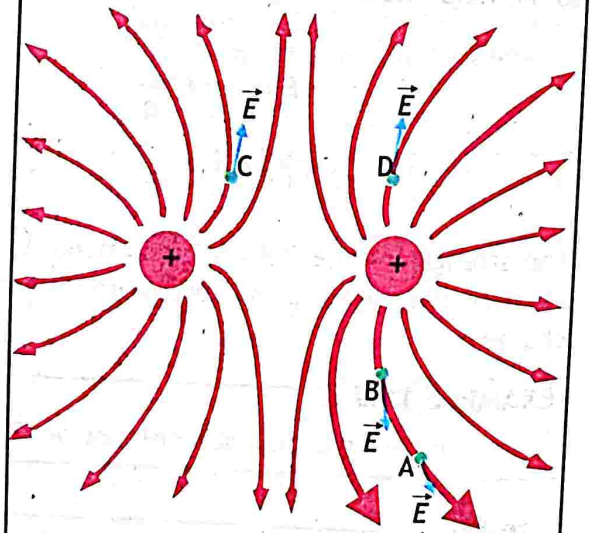
11.2.1 REPRESENTATION OF ELECTRIC FIELD BY LINES

In the previous section, the vector nature of the electric field strength was discussed. An electric field can be used in the pictorial form to describe the overall intensity of the field around it. This pictorial representation is called the electric field lines.

An electric field line is an imaginary line or curve drawn through a region of empty space. The direction of the electric field at point A, B, C and D is tangent to the field line through that point.

The electric field lines, point in

FIGURE 11.5



Two equal and positive charges placed at certain distance

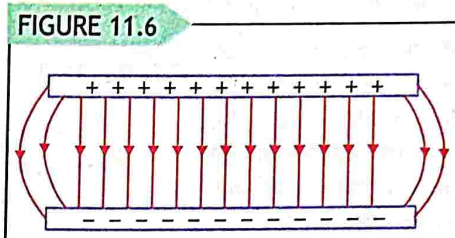
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the direction that a positive test charge would accelerate if placed upon the line. The arrows indicate the electric field at different points. The direction of these arrows is outward for positive charge and is inward for negative charge as shown in Fig: 11.4

The field lines starts from positive charge and terminate at negative charge as shown in Fig. (11.5)

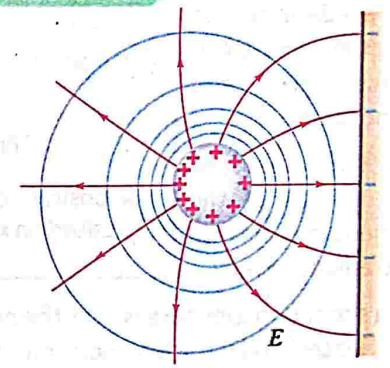
Fig: 11.6 show two infinitely large parallel plates separated by a very small distance. The upper plate has a uniform positive charge distribution while the lower plate has a negative one. If the plates are not of infinite length, the field lines at the ends of plates will be a little bulging out, showing that field is not uniform at the ends. The field such as at the ends of plates is called "fringing field".

FIGURE 11.6



Uniform electric field between charged plates.

FIGURE 11.7



Electric lines of force on the surface of metal plate

Another interesting property of field lines can be explained with the help of Fig. 11.7 Suppose that a charge $+q$ is placed near a metal plate. The positive charge will attract the negative charges (electrons) in the metal plate, resulting in the motion of these charges until some of them reach that surface of the metal which is near to $+q$ charge where they will be at rest. The electric lines of force cannot pass through a conductor. Therefore electric field is zero inside a conductor.

APPLICATIONS OF ELECTROSTATICS

PHOTOCOPIERS: The copying process of photocopier is called xerography. It consists of a drum which is made up of aluminum and is coated with selenium.

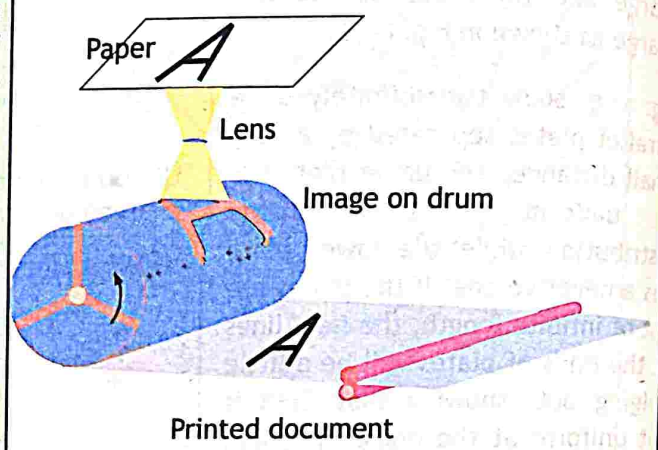
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Selenium is an insulator in the dark and become conductor when expose to light thus it is a photoconductor. The drum, charged with static electricity, can attract the toner particles.

When the paper to be copied is laid on the glass plate, then the dark and light areas of the document produce same image on the drum as shown in figure 11.8. The dark areas retain their positive charge but light areas become conducting, lose their, positive charge and become neutral.

Thus the positive charge image of the document remains on the selenium surface.

FIGURE. 11.8



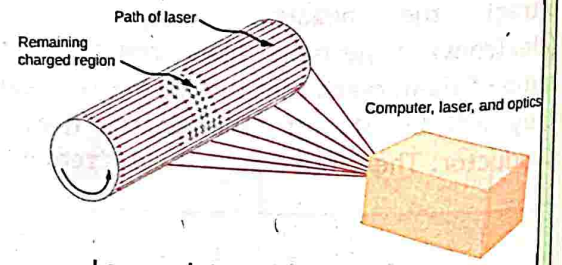
A positive-charge image of the letter "A" is created on xerographic drum.

When a sheet of paper passes over the drum, the particles of toner are attached to it. Heated rollers then melt the toner into the paper to produce the permanent impression of the document.

B) LASER PRINTER

Laser printers use a laser to produce an image on the photoconducting drum as shown in Figure 11.9 In a laser printer, a laser beam is scanned across a photoconducting drum, leaving a positive charge image.

FIGURE 11.9



Laser printer with a static laser scanning unit.

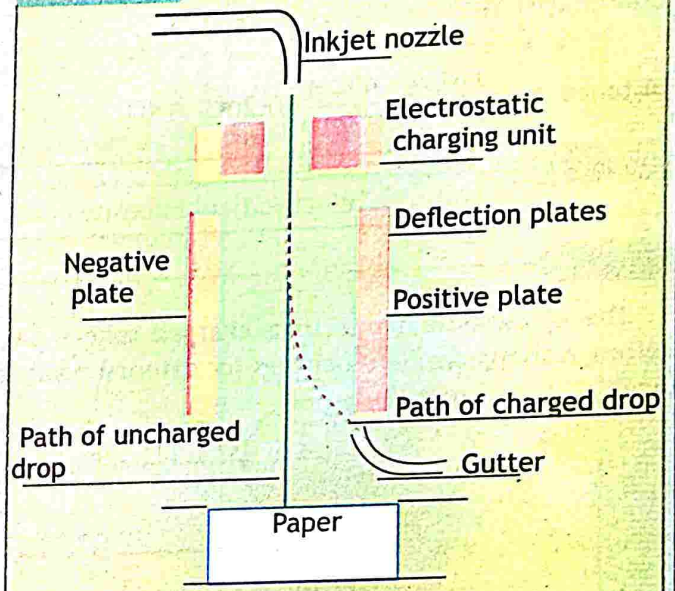
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The other steps for charging the drum and transferring the image to paper are the same as in xerography. Laser light can be very precisely controlled, enabling laser printers to produce high-quality images.

C) INKJET PRINTERS

An inkjet printer is another type of printer that uses electric charges in its operation. In an inject printer tiny drops of ink are forced out of a fine nozzle, charged electrostatically and then passed between two oppositely charged plates; a negatively charged drop will be attracted towards a positive plate causing it to be deflected as shown in Figure:11.10.

FIGURE 11.10



Charging of ink droplets between two oppositely charged plates.

Whenever ink is to be placed on the paper, the charging control, responding to instructions from the computer, turns off the electric field. The uncharged droplets fly straight through the deflection plates and strike the paper.

Quiz?

What are the basic differences between laser printer and photocopier?

EXAMPLE 11.3

A metallic sphere of diameter 40 cm carries a charge of 600 μ C. Find the electric field intensity (a) at a distance of 60cm from the centre of the sphere and (b) at the surface of sphere.

GIVEN

Distance of a charge from the sphere $r = OB = 60\,cm = 60\times10^{-2}\,m$;

Charge on sphere $q = 600\mu C = 600\times10^{-6}\,C$

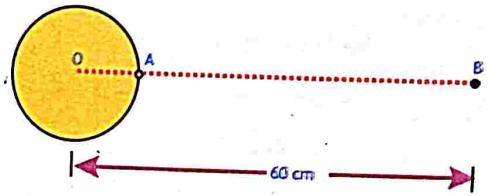
Distance $r = \frac{d}{2} = \frac{OA}{2} = \frac{40cm}{2} = 0.2m$

REQUIRED

electric field intensity= E=?

SOLUTION

The electric field due to a charged sphere has spherical symmetry. Therefore, a charged sphere behaves for external points as if the whole charge is placed at its centre.



Field intensity due to a charged sphere

(a) Electric field intensity from the centre of the sphere $E = k\frac{q}{r^2}$

$$= 9\times10^9 \times \frac{600\times10^{-6}}{(60\times10^{-2})^2} = 1.5\times10^9\,N/C$$

(b) electric field intensity from the surface of a sphere $E = k\frac{q}{r^2}$

$$= 9\times10^9 \times \frac{600\times10^{-6}}{(0.2)^2}$$

$$= 13.5\times10^7\,N/C$$

11.4 ELECTRIC FLUX

The concept of **flux** describes how much of something goes through a given area. You may conceptualize the flux of an electric field as a measure of the number of electric field lines passing through an area. For discussing the flux of a vector field, it is helpful to introduce an area vector $\vec{A}$. The area vector of a flat surface has magnitude equal to area (A) and its direction is along the normal to the surface ($\hat{n}$) as shown in figure 11.11.

The electric flux is denoted by Φ_E. For uniform field $\vec{E}$ and area $\vec{A}$ electric flux is defined as the measure of number of lines of force that pass through the area placed in the electric field. Flux Φ_E is the scalar product of the electric field E and plane surface area A.

$$\Phi_E = \vec{E}.\vec{A}$$

$$= EA\cos\theta \qquad \ldots(11.11)$$

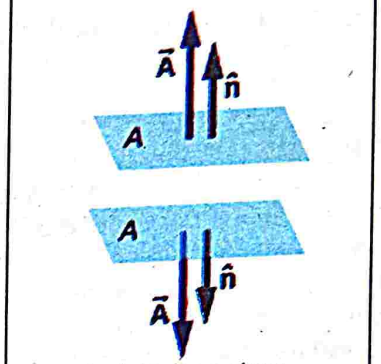
The electric flux Φ_E depends upon:

i. surface area
ii. electric field intensity
iii. the orientation of surface area A with respect to the field lines E.

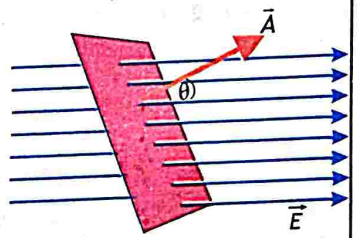
FLUX AT ANY ANGLE (θ) : if the area $\vec{A}$ is tilted such that it is making an angle θ with the electric field lines as shown in figure(11.11 b) in this case the electric flux is

$$\Phi_E = E.A = EA\cos\theta$$

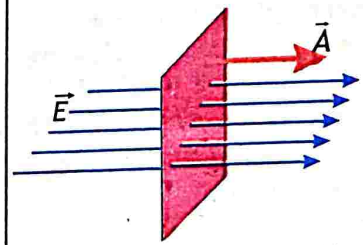
FIGURE 11.11



(a) Unit vectors



(b) Electric flux at any angle θ



(c) Electric flux(maximum flux)

The number of lines passing through the area will be E ($A\cos\theta$) depending upon angle θ.

MAXIMUM FLUX: if the surface is placed perpendicular to the electric field such that surface area $\vec{A}$ is parallel to electric field $\vec{E}$ then maximum electric lines of force will pass through the surface as shown in figure 11.11c.

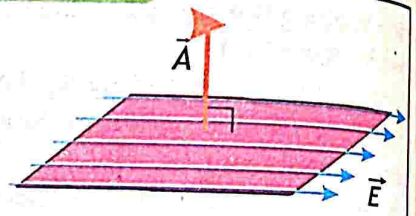
Consequently maximum electric lines will pass through the surface.

The electric flux is $\Phi_E = EA\cos 0 = EA$

Therefore large number of lines passes through the area.

ZERO FLUX : if the surface is placed parallel to the electric field such that surface area $\vec{A}$ is normal to electric field $\vec{E}$ then no electric lines of force will pass through the surface as shown in Figure 11.11d. Consequently no electric flux will pass through the surface.

FIGURE 11.11



(d) : Electric flux(zero flux)

Then flux is $\Phi_E = EA\cos 90 = 0$

ELECTRIC FLUX THROUGH CLOSE SURFACE

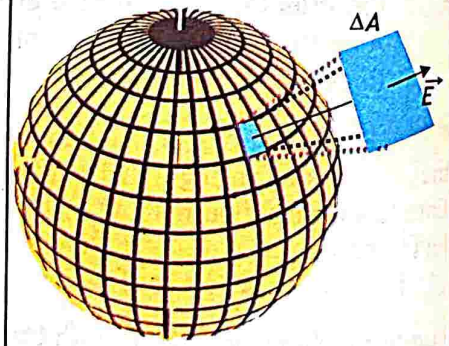
If the case is such that either field is non-uniform or the surface is curved, then we divide the surfaces into very small patches of area ΔA called differential area and assume that these are approximately flat and they are so small that electric field E is almost uniform over it. For one of these small patches of area as shown in Fig.11.12 . The electric flux is defined by the relation. (Differential form),

$$\Phi_E = E.\Delta A$$

To calculate total flux through the whole surface we add flux from each patch such that

$$\Phi_E = \Sigma \vec{E}.\Delta\vec{A}$$

FIGURE 11.12

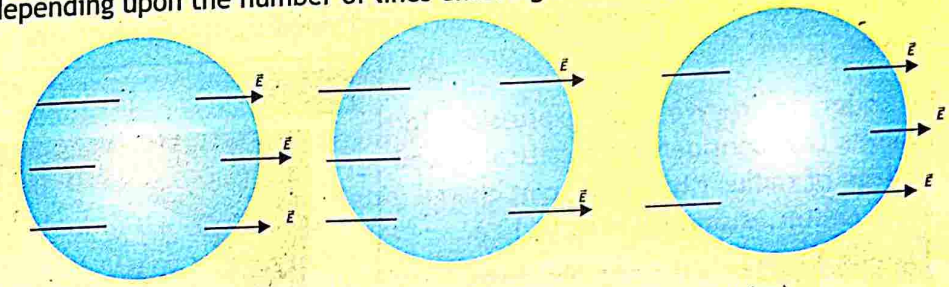


Electric flux through a close surface

NOT FOR SALE

DO YOU KNOW?

In case of closed surface the electric flux may be positive negative or zero depending upon the number of lines entering or leaving the surface:



Positive, negative and zero flux through a close surface

(i) The electric flux is zero if numbers of field lines entering are equal to field line leaving the surface or no field line intercepting the surface as shown in fig (a).

(ii) The electric flux is negative if net numbers of electric field lines are entering the closed surface or more field lines are entering than leaving the surface as shown in fig (b).

(iii) The electric flux is positive if net numbers of electric field lines are leaving the surface as shown in fig (c).

11.5 GAUSS'S LAW

The electric field of a given charge distribution can be calculated using Coulomb's law. But sometimes the actual calculations can become quite complicated.

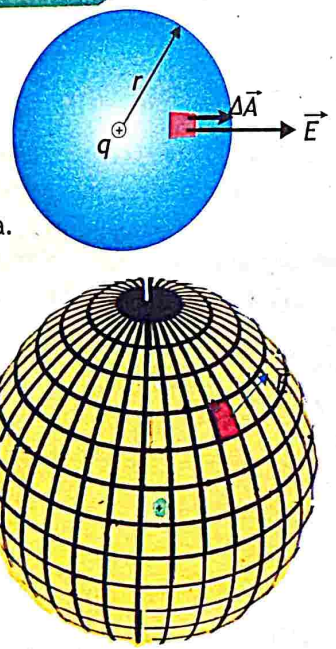
An alternative method to calculate the electric field of a given charge distribution relies on a theorem called Gauss' law. Gauss' law provides a

relationship between the net electrical flux Φ through a closed surface and t net charge q enclosed by that surface.

Gauss' law states that the net electric flux through a closed surface is equal the total charge q enclosed by the surface divided by the permittivity of fr space.

In order to derive the expression for Gauss's Law consider the spherical closed surface of radius r having a point charge q at its center as shown in Fig.11.13 a.

FIGURE 11.13



Flux through a close surface

Carl Friedrich Gauss (1777 - 1855)



Gauss was a German mathematician and scientist who contributed significantly to many fields, including number theory, statistics, analysis, differential geometry, geophysics, electrostatics, astronomy and optics.

To calculate the electric flux through the whole surface, it is divided int n-number of small patches having area ΔA_1, $\Delta A_2, \Delta A_3, \Delta A_4 \ldots\ldots, \Delta A_n$. Th intensity of electric field is same at every point as they are at equidistant fro the charge.

The electric flux through the small elements ΔA_1 is

$$\Phi_1 = \vec{E}_1 . \Delta\vec{A}_1 = E_1 \Delta A_1 \cos 0 = E_1 \Delta A_1$$

The electric flux through the other small element ΔA_2 is

$$\Phi_2 = \vec{E}_2 . \Delta\vec{A}_2 = E_2 \Delta A_2 \cos 0 = E_2 \Delta A_2$$

Similarly the electric flux through ΔA_n is

$$\Phi_n = \vec{E}_n . \Delta\vec{A}_n = E_n \Delta A_n \cos 0 = E_n \Delta A_n$$

The total flux through the entire surface is

$$\Phi_E = \Phi_1 + \Phi_2 + \Phi_3 + \Phi_4 + \ldots\ldots\ldots + \Phi_n$$

$$\Phi_E = \Sigma_{surface}\, E\Delta A \qquad \ldots(11.12)$$

But as electric field intensity E is constant over the surface of sphere

Therefore,

$$\Phi_E = E\, \Sigma_{surface}\, \Delta A$$

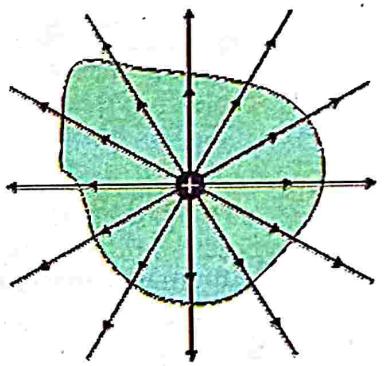
Since, $$E = \frac{q}{4\pi\varepsilon_o}\frac{1}{r^2}$$

Thus the above equation can be written as

$$\Phi_E = \frac{q}{4\pi\varepsilon_o}\frac{1}{r^2}\Sigma_{surface}\Delta A$$

$\Sigma_{surface}\, \Delta A$= total area enclosed by spherical surface=$4\pi r^2$

FIGURE 11.14



Flux through an irregular close surface

$$\Phi_E = \frac{q}{4\pi\varepsilon_o}\frac{1}{r^2}(4\pi r^2)$$

$$\Phi_E = \frac{q}{\varepsilon_o} \quad \ldots(11.13)$$

The above equation shows that electric flux does not depend upon the shape or geometry of a closed surface. But it depends upon the medium and the charge enclosed by that surface.

In order to calculate the electric flux through irregular close surface S, enclosing point charges $q_1, q_2, q_3 \ldots\ldots q_n$ as shown in Fig 11.15 a. Then the total electric flux through that closed surface is

$$\Phi_E = \frac{q_1}{\varepsilon_o} + \frac{q_2}{\varepsilon_o} + \frac{q_3}{\varepsilon_o} \ldots\ldots\ldots \frac{q_n}{\varepsilon_o}$$

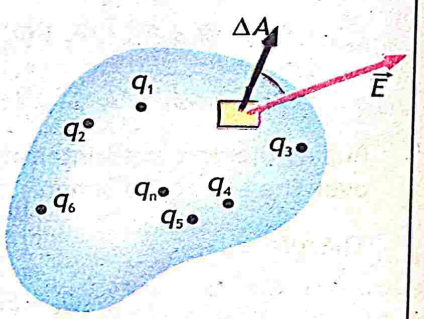
$$= \frac{1}{\varepsilon_o}(q_1 + q_2 + q_3 + \ldots\ldots\ldots q_n)$$

$$\Phi_E = \frac{1}{\varepsilon_o}\sum_{i=1}^{n} q_i$$

$$= \frac{1}{\varepsilon_o} \text{ (total charge enclosed by a surface)}$$

$$= \frac{Q}{\varepsilon_o}$$

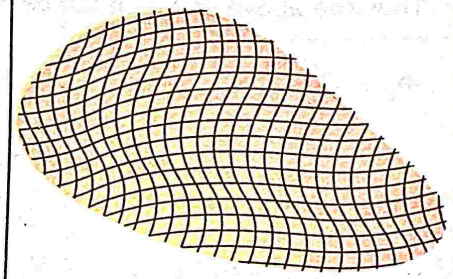
FIGURE 11.15



(a) Number of charges in a closed surface

Thus Gauss's law shows that the electric flux through any closed surface is $1/\varepsilon_o$ times the total charge enclosed in it.

FIGURE 11.15



(b) Flux through an irregular close surface having number of patches

11.5.1 APPLICATIONS OF GAUSS'S LAW

Gauss's law provides a convenient method to calculate *E* in the case of charge distribution.

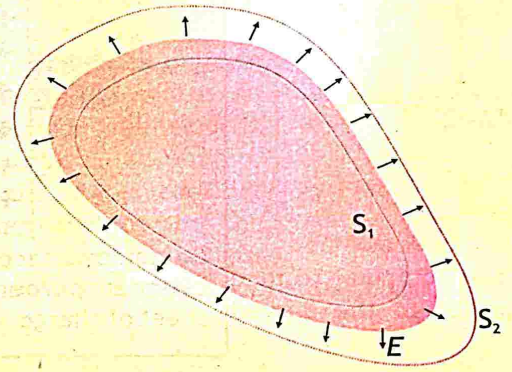
A conductor is a material with neutral atoms rather than a volume distribution of charge. Fig shows an imaginary Gaussian surface S_1, lies just below the actual surface of the conductor; consequently, there is no net charge inside the conductor.

Therefore, there is no excess charge inside a conductor.
According to Gauss's law $\Phi_E = \Sigma \vec{E} . \Delta \vec{A} = 0$ as Q = 0.

Hence E= 0 inside a conductor.

If a conductor possesses excess charge, then the electric field is still zero. Thus E= 0 inside a conductor. Consequently any excess charge must lie on its surface. Another imaginary Gaussian surface S_2 is shown by dotted line outside a conductor. At the surface of a charged conductor, the electric field is normal to the surface at every point. All the charge is deposited on the outer surface of the conductor. Thus the excess charge is not inside a conductor but it resides on the conductor's surface.

Electric field *E* is shown by arrows, dotted pink line shows Gaussian surface S_2 outside and dotted blue line shows Gaussian surface S_1 inside



11.5.1.3 ELECTRIC FIELD INTENSITY DUE TO AN INFINITE SHEET OF CHAR

Consider an infinite plane sheet of charge with surface charge density σ. Let S_1 be the point at a distance r from the sheet and E be the electric field at this point. Gaussian surface is in the form of a cylinder of cross-sectional area A perpendicular to the sheet of charge as shown in Fig11.16. By symmetry, the electric field is at right angles to the end caps and away from the plane. Its magnitude is the same at points S_1 and S_2.

The charge enclosed by the surface will be σA. Since we know by Gauss's law

$$\text{Total electric flux} = \frac{1}{\varepsilon_0} \times (Q)$$

Q = charge enclosed by the surface

$$\Phi_E = \frac{1}{\varepsilon_0} \times (Q)$$

Since $\delta = Q/A$ or, $\delta A = Q$

$$\Phi_E = \frac{\delta A}{\varepsilon_0} \qquad \ldots(11.14)$$

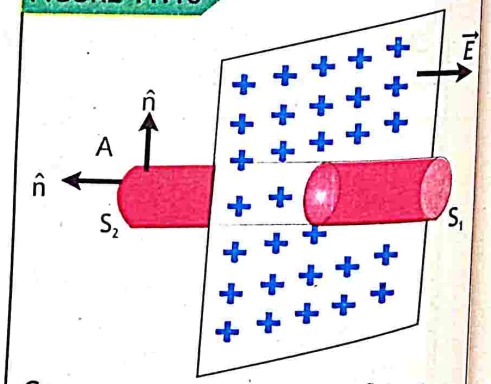
The direction of E is perpendicular to face containing A and parallel to the curved surface.

FOR YOUR INFORMATION



Airlines Airbus A380 flew through a storm when 500 peoples were on the board but none of them were injured. As there is no electric field, no potential difference inside a metal shell, so one of the safest way to be inside a metal shell during thunderstorm.

FIGURE 11.16



Gaussian surface in the form of a cylinder perpendicular to the sheet of charge.

The electric flux through the end faces is $E\Delta A$, while flux through the curved surface is zero. Thus

$$\Phi_E = \vec{E}.\Delta\vec{A} + \vec{E}.\Delta\vec{A} + 0$$

Hence, $2EA = \frac{\delta A}{\varepsilon_0}$

or
$$E = \frac{\delta}{2\varepsilon_0} \qquad \ldots(11.15)$$

and
$$\vec{E} = \frac{\delta}{2\varepsilon_0}\hat{r} \qquad \ldots(11.16)$$

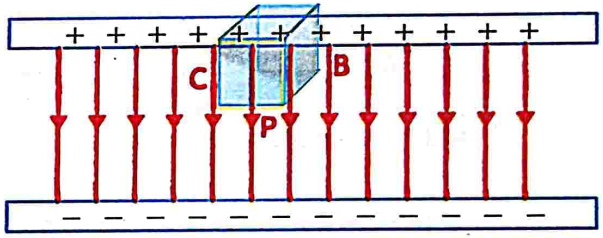
Where $\hat{r}$ is the unit vector normal to the sheet and directed away from it.

11.5.1.3 ELECTRIC FIELD INTENSITY BETWEEN TWO OPPOSITELY CHARGED PARALLEL PLATES.

Consider two oppositely charged parallel metal plates. The charge densities of these metal plates are +σ and - σ.

These plates are assumed to be of infinite length in order to avoid fringing field at end. Under these conditions, the field intensity will be uniform and normal to the plates. In order to find the electric field intensity E, at point P between the plates consider a Gaussian surface in the form of a box of cross sectional area A with its upper surface lies within the plate as shown in figure (11.17).

FIGURE 11.17



Gaussian surface in the form of a cubical box between the plates

Therefore by Gauss's Law electric flux is

$$\Sigma \vec{E}.\Delta\vec{A} = \frac{Q}{\varepsilon_o}$$

As the box sides are parallel to electric field E so the flux through sides will be zero, while the electric field intensity E is normal to the lower surface of Gaussian box.

Net electric flux= Φ_E

Electric flux through the side B + electric flux through the side C + electric flux through the lower surface= $\delta A/\varepsilon_o$

$$\vec{E}.\Delta\vec{A} + \vec{E}.\Delta\vec{A} + \vec{E}.\Delta\vec{A} = \frac{\sigma A}{\varepsilon_o}$$

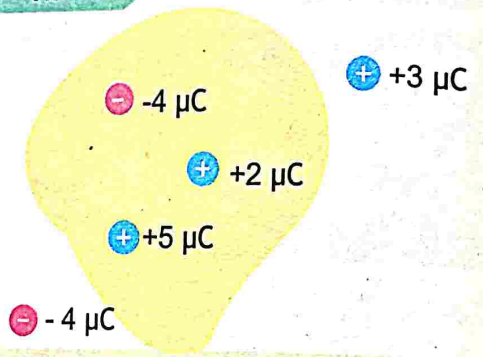
$$0 + 0 + \vec{E}\,\vec{A} = \frac{\sigma A}{\varepsilon_o}$$

$$E = \frac{\sigma}{\varepsilon_o} \qquad \ldots(11.17)$$

and in vector form $\vec{E} = \frac{\sigma}{\varepsilon_o}\hat{r}$

This gives the electric field between oppositely charged parallel plates. We see that the resulting electric field between the plates is uniform, perpendicular to the plates, and independent of the distance from the plates.

TIP



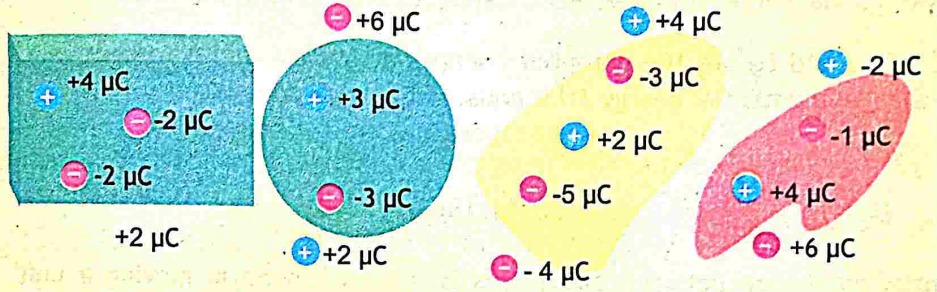
The electric flux through arbitrary Gaussian surface can be calculated as

$$\Phi_E = \frac{-4\mu C + 2\mu C + 5\mu C}{\varepsilon_0} = \frac{3\times10^{-6}\,C}{8.85\times10^{-12}\,C^2.N^{-1}.m^{-2}}$$

$$= 3.4\times10^5\ N.m^2.C^{-1}$$

Project

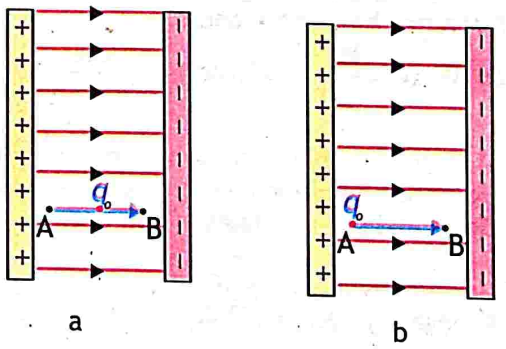
Calculate the electric flux through each Gaussian surface shown in Figure



11.6 ELECTRIC POTENTIAL

Previously we studied the electric field due to two parallel plates with a space between them. To explain electric potential consider two oppositely charged parallel plates as shown in Fig (11.18 a). If a positive charge $+q_o$ is placed in between these plates and allowed to move freely in an electric field it will move towards the negative plate, pulled by the electric force and will gain an equivalent amount of kinetic energy.

FIGURE 11.18



Potential difference between point A & B in electric field.

The energy is required to move the charge towards the left plate. Let W_{BA} be the work done by the force $F=q_oE$ in carrying a positive charge q_o from point B to point A without producing any acceleration as shown in Fig.11.18 b. This work done will be stored as electrical potential energy in the charge.

If U_A and U_B are the potential energies at point A and B respectively, then change in potential energy ΔU is equal to the work done W_{BA}.

$$\Delta U = W_{BA}$$

$$U_A - U_B = W_{BA} \qquad \ldots (11.18)$$

Potential difference between two points is the work done in moving a unit positive charge from one point to another keeping the charge in electrostatic equilibrium.

To get equations for potential difference ΔV divide Eq (11.18) by q_o we get

$$\frac{W_{BA}}{q_o} = \frac{\Delta U}{q_o} = V_A - V_B = \Delta V \qquad \ldots (11.19)$$

where V_A and V_B are the electric potentials at point A and B, respectively.

Eq (11.19) can be written as

$$\Delta U = q_o \Delta V = W_{BA} \qquad \ldots (11.20)$$

$$U_A = q_o V_A, \; U_B = q_o V_B$$

From Eq (11.19) it is clear that potential difference between two points is the difference of potential energy per unit charge.

Where ΔV is potential difference between A and B.

Eq (11.20) can be written as $\Delta V = \frac{W_{BA}}{q_o}$ or 1volt=$\frac{\text{1Joule}}{\text{1Coulomb}}$

One volt is the potential difference between two points in an electric field if one joule of work is done in moving one coulomb of charge from the one point to the other. Other multiples and sub-multiples of volt are

1 milli volt (mV) = 10^{-3} V, 1 micro volt (μV) = 10^{-6} V
1 kilo volt (kV) = 10^{3} V, 1 mega volt (MV) = 10^{6} V
1 giga volt (GV) = 10^{9} V

In order to give concept of electric potential at a point in an electric field a reference point is required where electric potential is zero and this point is taken at infinity. If point B is at infinity where electric potential is $V_B = 0$, while at point A electric potential is $V_A = W_{\infty A}/q_o$.

On dropping the subscripts $V = \frac{W}{q_o}$

Thus the electric potential at any point is equal to the work done in bringing a unit positive charge from infinity to that point without producing any acceleration.

11.8 FIELD AND POTENTIAL GRADIENT

Let us consider a uniform field, for which the lines of force are parallel and equidistance from each other. Let A and B be two points which are very close to each other so that the electric field intensity is almost constant as shown in Fig 11.18.The exact relationship can easily be derived for the field of a point charge if a test charge q_o is moved a small distance Δr from point B to A then

work done on test charge = force × distance moved

$$\Delta W = F \, \Delta r$$

In an electric field, the force acting is equal to the charge times the field strength

$$F = q_o E$$

work done = $\Delta W = E \, q_o \Delta r$

Using Eq 11.20 we have

$$\therefore \Delta W = -q_o \Delta V$$

The negetive sign is applied because the work done on q_o is against field force q_oE, so

$$q_o \Delta V = -E \, q_o \Delta r$$

$$E = -\frac{\Delta V}{\Delta r} \qquad \ldots (11.21)$$

The strength of the field is equal to the potential gradient.

The rate of change of electric potential ΔV with respect to displacement Δr is known as potential gradient.

The negative sign indicates that the direction of the field is opposite to the direction in which the potential is increasing. This relationship between field strength and potential gradient is analogous to gravitational field.

EQUIPOTENTIAL SURFACES

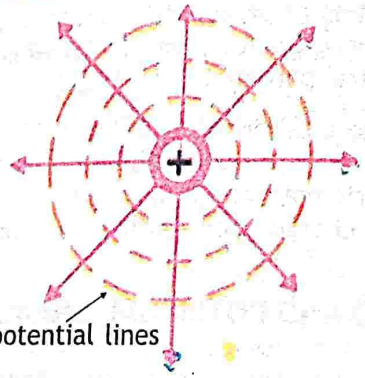
In pervious section electric field which was peresented by imaginary lines around a source similarly we can represent electric potentials pictorially by drawing imaginary lines known as equipotential lines.

The surfaces which have equal electrostatic potential at each point are known as Equipotential Surfaces.

These are imaginary surfaces surrounding a charge distribution. An equipotential line connects points in space where the potential of an electric field is the same. The work done to move any charge from one place to other place on an equipotential surface is zero as all the points have same potential.

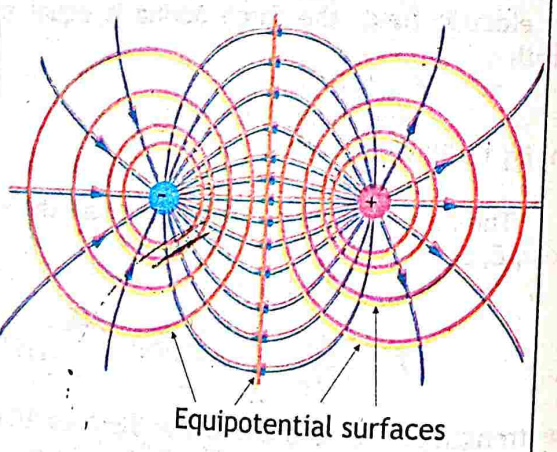
In Fig11.19 (a) electric field around a point charge is represented by pink arrows while equipotential surfaces are represented by orange dashed lines. If there are two or more charges present, then the potential at any point is the sum of the potentials due to each charge. Potential is a scalar quantity. However; potential can be either positive or negative, depending upon the sign of the charge.

FIGURE 11.19



(a)

Equipotential lines/surfaces around positive charge



(b)

Equipotential lines due to two opposite charges

EXAMPLE 11.5

You have a 12.0-V motorcycle battery that can move 5000 C of charge, and a 12.0-V car battery that can move 60,000 C of charge. How much energy does each deliver?

GIVEN

For the motorcycle battery, q=5000C and ΔV=12.0V

For the car battery, q=60,000C and ΔV=12.0V

REQUIRED

ΔU_{cycle} =? ΔU_{car}=?

SOLUTION

$$\Delta U_{cycle} = (5000C)(12.0V)=(5000C)(12.0J/C)=6.00\times10^{4}J.$$

$$\Delta U_{car}= (60,000C)(12.0V)=7.20\times10^{5}J.$$

ASSIGNMENT 11.2

When a 12.0 V car battery powers a single 30.0-W headlight, how many electrons pass through it each second? Answer (1.56×10^{19} electrons)

11.7 ELECTRIC POTENTIAL ENERGY AND POTENTIAL DUE TO A POINT CHARGE

Like earth's gravitational field every charge has electric field which theoretically expands upto infinity. Consider an isolated charge +Q fixed in space as shown in Fig11.20. The electric field intensity E is given by equation

$$\vec{E}=\frac{1}{4\pi\varepsilon_o}\frac{Q}{r^2}\hat{r}$$

As the test charge q is at infinity which is moved towards charge +Q a force of repulsion acts on it. Since external work is required to be done to bring charge from infinity to point A therefore negative sign is inserted in equation. The work done is

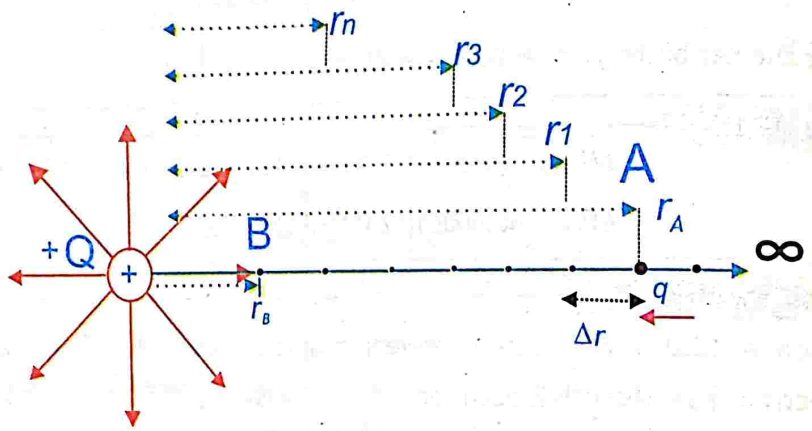
$$\Delta W = -q\vec{E}.\Delta\vec{r}=qE\Delta r\cos180^{\circ}$$

$$\Delta W = qE\Delta r \quad \ldots(11.22)$$

Now putting the value of E in Eq (11.22) we have

$$\Delta W = \frac{1}{4\pi\varepsilon_o}\frac{Qq}{r^2}\Delta r$$

FIGURE 11.20



Work done on a test charge q in moving it towards source charge $+Q$

Let the test charge is at a large distance r_A from charge Q. Electric fiel does not remain constant but varies as the square of the distance from th charge.

We divide the distance between r_A and r_B into infinitesimally small displacement so that the field intensity over each displacement remains constant.

Work done between point r_A and r_1 is

$$\Delta W_{r_A \to r_1} = \frac{Qq}{4\pi\varepsilon_o}\left(\frac{r_A - r_1}{r_A r_1}\right)$$

At the beginning of the first displacement E varies as $1/r_A^2$ and at the end E varies as $1/r_1^2$ since the average $1/r^2$ over each small displacement is

$$\frac{1}{\langle r^2 \rangle} = \frac{1}{\langle rr \rangle}$$

Therefore one r is replaced by r_A and another by r_1.

$$\frac{1}{\langle r^2 \rangle} = \frac{1}{r r_1}$$

Replacing $1/r^2 = 1/r_A r_1$ and $\Delta r = r_A - r_1$ in above equation we get:

By division

$$\therefore \left(\frac{r_A}{r_A r_1} - \frac{r_1}{r_A r_1}\right) = \left(\frac{1}{r_1} - \frac{1}{r_A}\right)$$

$$\Delta W_{r_A \to r_1} = \frac{Qq}{4\pi\varepsilon_o}\left(\frac{1}{r_1} - \frac{1}{r_A}\right) \quad \ldots (11.23)$$

Similarly for second small displacement $\Delta r = r_1 - r_2$. Work done is

$$\Delta W_{r_1 \to r_2} = \frac{Qq}{4\pi\varepsilon_o}\left(\frac{1}{r_2} - \frac{1}{r_1}\right)$$

And

$$\Delta W_{r_n \to r_B} = \frac{Qq}{4\pi\varepsilon_o}\left(\frac{1}{r_B} - \frac{1}{r_n}\right) \quad \ldots (11.24)$$

The total work done in moving a charge q from r_A to r_B can be calculated by taking its sum.

$$\Delta W_{r_A \to r_B} = \frac{Qq}{4\pi\varepsilon_o}\left(-\frac{1}{r_A} + \frac{1}{r_1} - \frac{1}{r_1} + \frac{1}{r_2} - \frac{1}{r_2} + \ldots\ldots\ldots + \frac{1}{r_B}\right)$$

$$\Delta W_{r_A \to r_B} = \frac{Qq}{4\pi\varepsilon_o}\left(\frac{1}{r_B} - \frac{1}{r_A}\right) \quad \ldots (11.25)$$

The work done to move a test charge q from infnity to a distance r from Q is

$$W_{r_A \to r_B} = \frac{Qq}{4\pi\varepsilon_o}\left(\frac{1}{r_B} - \frac{1}{\infty}\right)$$

$$W_{r_A \to r_B} = \frac{Qq}{4\pi\varepsilon_o}\left(\frac{1}{r_B}\right) \quad \ldots (11.26)$$

The electric potential energy at distance r from Q is

$$U = \frac{Qq}{4\pi\varepsilon_o}\left(\frac{1}{r}\right) \quad \ldots (11.27)$$

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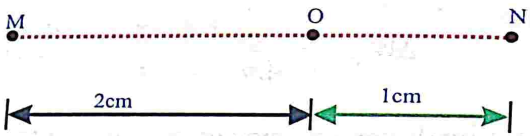
The electric potential at a point in an electric field may be defined as the amou of work done in moving a unit positive charge from infinity to that point wit uniform velocity.

The electric potential at distance r from Q is

$$V = \frac{W}{q} = \frac{1}{4\pi\varepsilon_o}\frac{Q}{r} \qquad \ldots (11.28)$$

EXAMPLE 11.6

A point charge of 3μC is placed at point O between M and N, 3cm apa Point M is 2cm from the charge and N is 1cm from the charge. What is t potential difference $V_M - V_N$?



Potential due to a point charge

GIVEN

charge q= 3μC , distance r_1 =2cm, distance r_2 = 1cm

REQUIRED

the potential difference $V_M - V_N$ =?

SOLUTION

Potential at M due to the charge is

$$V_M = k\frac{q}{r_1}$$

$$V_M = 9\times10^9 \times \frac{3\times10^{-6}}{2\times10^{-2}} = 13.5\times10^5 \text{ V}$$

Potential at N due to the charge is

$$V_N = k\frac{q}{r_2} = 9\times10^9 \times \frac{3\times10^{-6}}{1\times10^{-2}} = 27\times10^5 \text{ V}$$

$$\therefore \quad V_M - V_N = 13.5\times10^5 - 27\times10^5 = -13.5\times10^5 \text{ V}$$

ASSIGNMENT 11.3

Two charges 5 x 10^{-8} C and -3 x 10^{-8} C are located 16 cm apart. At what point(s) on the line joining the two charges is the electric potential zero? Take the potential at infinity to be zero. Ans(10 cm)

THE ELECTRON VOLT (eV)

The electron-volt is a unit of energy *or* work which is defined as the amount of energy acquired or lost by an electron when it is displaced across two points between which potential difference is one volt.

Since the magnitude of the charge of an electron is about 1.602×10^{-19} C, it follows that an electron-volt is about 1.602×10^{-19} J.

By definition

Δ(KE) = l eV, when q = e = 1.602 × $l0^{-19}$ C and ΔV= 1V.

thus

l eV = 1.602 × $l0^{-19}$ C × 1 V
= 1.602 × $l0^{-19}$ J

This is the smaller unit of energy. Its bigger units are multiples of 1 eV that are in frequent use are given below.

l Million electron volt = l Mev = $l0^6$ eV
l Giga electron volt = l GeV = $l0^9$ eV

EXAMPLE 11.6

A particle carrying a charge (3e) falls through a potential difference of 5V. Calculate the energy acquired by the particle.

GIVEN

Charge =q =3e, potential difference ΔV= 5V

REQUIRED

Energy: K.E=?

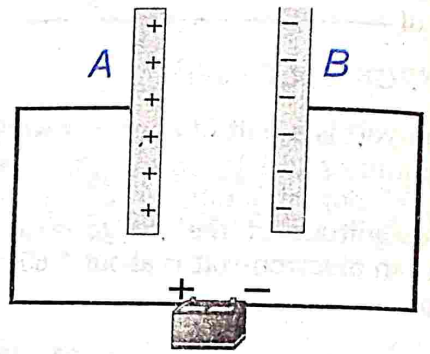
SOLUTION

The energy acquired by the charged particle is
Δ(KE) = $q\Delta V$=(3e) (5 V) =15eV
= 15×1.602 × $l0^{-19}$ J= 2.4 × $l0^{-18}$ J

11.10 CAPACITOR

A device which is used for storing electric charges is called capacitor. The most common capacitor consists of two parallel metal plates, separated by small distance. The medium between the two plates is air or a sheet of some insulator. This medium is known as dielectric. Figure 11.21 shows a parallel plate capacitor.

FIGURE 11. 21



Parallel plates of a capacitor

The capacitor is commonly charged by connecting its plates for a while to the opposite terminals of a battery. In this way some electrons are transferred through the battery from the positive plate to the negative plate. When a charge is transferred to one of the plate say (A) due to electrostatic induction it would induce charge Q on the inner surface of the other plate B. Charge $+Q$ and $-Q$ appear on the plates. Mutual attraction between the charges keeps them bound on the inner surface of two plates and thus the charge remains stored in the capacitor even after removal of the battery.

FIGURE 11.22



Capacitors use in different electronic devices.

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11.10.1 CAPACITANCE OF A CAPACITOR AND ITS UNIT

The capability of a capacitor to store charges is called it capacitance. When a charge Q is transferred on one of the plate of a capacitor it causes the potential difference V between the plates. In other words, the charge 'Q' on the plate of a capacitor is directly proportional to the potential difference V between them i.e. $Q \propto C$

$$Q = CV \qquad \ldots(11.29)$$

OR $$\Rightarrow C = \frac{Q}{V}$$

Where, C is the capacitance of a capacitor.

The capacitance is thus defined as *the ratio of magnitude of charge on either plate to the potential difference produced between the plates.*

The SI unit of capacitance is called farad.

Farad (F) is defined as *"the capacity of that capacitor which stores a charge of 1 coulomb having the potential difference of 1 volt between the plates".*

Convenient sub-multiples of farad are:

$$1\mu F\,(\text{micro Farad}) = 10^{-6}\ F \;\&\; 1pF\,(\text{Pico Farad}) = 10^{-12}\ F$$

11.10.2 CAPACITANCE OF A PARALLEL PLATE CAPACITOR

Let us consider a parallel plate capacitor connected to a voltage source V. The charges on the capacitor plates increases till the potential difference V across the plates build. Let the charges on the plates are $+Q$ and $-Q$ when the potential difference is V. If the positive plate is at potential V_1 and negative plate is at potential V_2, then the electric field strength between the plates is

$$E = \frac{-\Delta V}{\Delta r} = \frac{-(V_2 - V_1)}{d} = \frac{V_1 - V_2}{d} = \frac{V}{d} \qquad \text{(A)}$$

Where, $V = V_1 - V_2$ is the potential difference and d is the separation between the plates. The strength of the electric field also depends on the number of charges on the plates. The charge density is the total charge per unit area of the plate. i.e.,

$$\sigma = \frac{Q}{A}$$

By using Gauss's law the electric field intensity E between the plates is

$$E = \frac{\sigma}{\varepsilon_o} = \frac{Q}{\varepsilon_o A} \qquad (B)$$

From Eq (A) & (B) we have

$$E = \frac{V}{d} = \frac{Q}{\varepsilon_o A}$$

Or

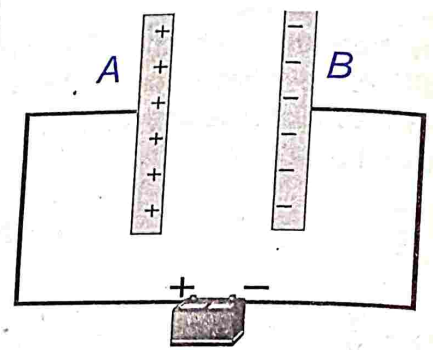
$$Q = \frac{\varepsilon_o A V}{d} \qquad \ldots (11.30)$$

By using $C_{vac} = \frac{Q}{V}$ Eq(11.30) becomes

$$C_{vac} = \frac{Q}{V} = \frac{\varepsilon_o A}{d} \qquad \ldots (11.31)$$

When a dielectric is inserted between the plates of a capacitor, then it is seen that the charge storing capacity of a capacitor is enhanced by the dielectric which permits it to store ε_r times more charge for the same potential

FIGURE:11.23



Plates of a capacitor separated by a distance d

NOT FOR SALE

difference. In case of a parallel plate capacitor completely filled with a dielectric the capacitance is

$$C_{med} = \frac{\varepsilon_o \varepsilon_r A}{d} \qquad \ldots (11.32)$$

Eq11.32: shows the dependence of capacitance upon the area of the plates, the separation between the plates and the medium between them.
From Eq(11.31) and Eq(11.32) we have

$$\varepsilon_r = \frac{C_{med}}{C_{vac}} \qquad \ldots (11.33)$$

This relation provides us with the definition of relative permittivity or dielectric constant or specific inductive capacity:
The ratio of the capacitance of a capacitor with a given material filling the space between the plates to the capacitance of the same capacitor when the space is evacuated is the relative permittivity ε_r of the material.

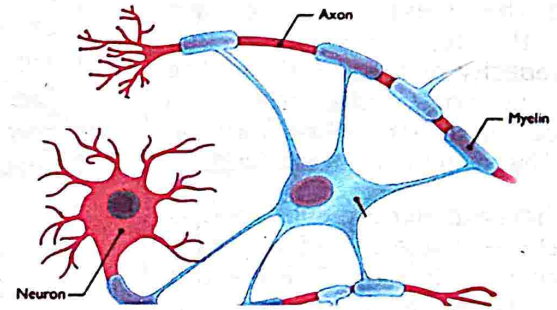
11.10.3 COMBINATIONS OF CAPACITORS

We know that the capacitors can be connected either in series or in parallel. We want to find out an equivalent capacitor that has the same capacitance as that of the combination of capacitors

SERIES COMBINATION OF CAPACITORS

When the capacitors are connected plate to plate i.e. the right plate of one capacitor is connected to the left plate of the next capacitor so on as shown in Fig:11.24 then it called series

FOR YOUR INFORMATION



An axon membrane acts as a capacitor. Axon of a resting human nerve cell has a potential difference of 65mV.Current enters the axon (or dendrite) through ion channels (e.g. Na+ channels) in a region of membrane, depolarizing that region. The intracellular positive charge is attracted to adjacent negatively charged regions of membrane.

combination. A battery of voltage V is connected between points A and B. In this type of combination the equivalent capacitance is given by

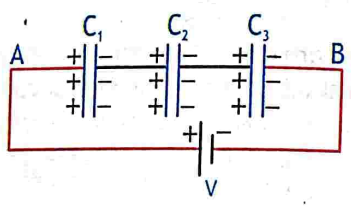
$$\frac{1}{C_e}=\frac{1}{C_1}+\frac{1}{C_2}+\frac{1}{C_3} \qquad \ldots (11.34)$$

PARALLEL COMBINATION OF CAPACITORS

When the battery is connected to the parallel plates of a capacitor as shown in Figure 11.25. The equivalent capacitance C_e of this combination is given by

$$C_e = C_1 + C_2 + C_3 \qquad \ldots (11.35)$$

FIGURE 11.24



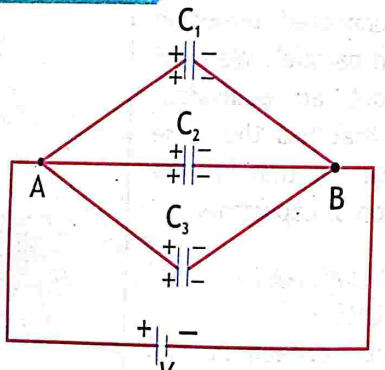
Series combination of capacitors

11.11 ELECTRIC POLARIZATION

In the previous section we explored the dependence of charge storing capacity of a capacitor on the dielectric material. A ***dielectric*** is an electrical insulator that can be polarized by an applied electric field.

When a dielectric substance is placed between two parallel plates with an applied electric field. The electric field distorts the negatively charged particles towards the positive plate and the positive charge particles towards the negative plate as shown in figure 11.26. The slight separation of charge makes one side of the atom somewhat positive and the opposite side somewhat negative. This phenomenon is known as electric polarization.

FIGURE 11.25



Parallel combination of capacitors

ELECTRIC DIPOLE

We know that dielectric materials are made up of the two types of molecules ;polar and non polar molecules. A polar molecule like water behaves as a permanent dipole; although electrically neutral as a whole.

On the other hand, a non-polar molecule like nitrogen has no electric dipole moment in the absence of an external field. In the presence of electric field negative charges in non-polar substance displaces to the opposite of electric field E as shown in Fig11.26.Dipole moments occur when there is a separation of charge. Under the action of external field the centres of negative and positive charges shift and form dipoles. The dipole moment is a measure of the polarity of the molecule.

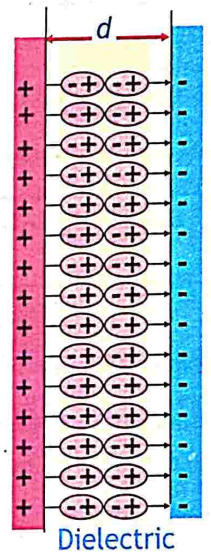
The system in which two charges of equal magnitude but of opposite sign separated by the distance d, are present is termed as a dipole.

Electric dipole moment is represented by P, which is equal to the product of the charge Q present in the dipole and the distance d between the two charges of the dipole.

$$P = |Qd| \qquad \ldots (11.36)$$

Where P is a vector quantity.

FIGURE 11.26



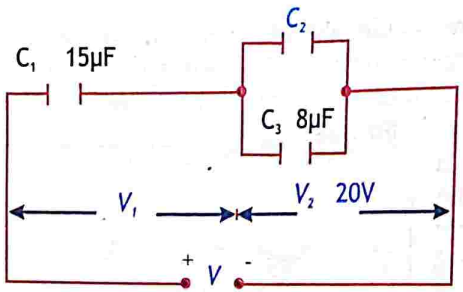
Polarization of a dielectric in an electric field gives rise to thin layers of bound charges on the surfaces, creating positive and negative surface charge densities.

EXAMPLE 11.7

Figure shows a different combination of capacitors, if the total charge is 600μC. Then determine the values of V_1 and C_2.

GIVEN

total charge Q= 600μC; capacitance C_1=15 μF, capacitance C_3= 8μF, Potential V_2= 20V



Capacitors C_1, C_2, & C_3 connected to potential V

REQUIRED

capacitance C_2=?, Potential V_1=?

SOLUTION

P.D. across capacitor C_1: $V_1 = \frac{Q}{C_1} = \frac{600\times10^{-6}}{15\times10^{-6}} = 40V$

Total P.D.: $V = V_1 + V_2 = 40 + 20 = 60V$

Charge on capacitor C_3 is: $Q_3 = C_3 \times V_2$

$= (8\times10^{-6})\times20$

$= 160\times10^{-6} C = 160\mu C$

∴ Charge on capacitor C_2 is: $Q_2 = 600 - 160 = 440\mu C$

∴ Capacitance of capacitor $C_2 = \frac{440\times10^{-6}}{20}$

$= 22\times10^{-6} F = 22\mu F$

EXAMPLE 11.8

A 6μF capacitor is charged to a P.D. of 200V and then connected in parallel with an un-charged 3μF capacitor. Calculate the P.D. across the parallel plate capacitors.

GIVEN

Capacitance of charged capacitor C_1 = 6μF

Capacitance of un-charged capacitor C_2= 3μF,

P.D. of capacitor C_1 is: V= 200V

REQUIRED

P.D. across the parallel plate capacitors V=?.

SOLUTION

Charge on capacitor, C_1 is: $Q = C_1V = (6\times10^{-6}) \times 200 = 0.0012C$

The equivalent capacitance of parallel combination of capacitors is

$C_{eq} = C_1 + C_2 = 6 + 3 = 9\mu F$.

The charge 0.0012 C is distributed between the two capacitors to have a common P.D.

∴ P.D. across Parallel plate capacitors: $V = \frac{Q}{C_T} = \frac{0.0012}{9\times10^{-6}} = 133.3V$

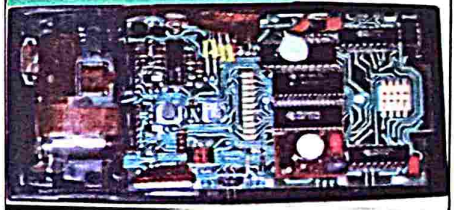
11.12 ENERGY STORED IN A CAPACITOR

Initially, the capacitor is uncharged when voltage is zero. When it is connected to source of potential difference V it is charged. Finally when charges +Q and -Q are deposited on the plates, the potential difference between the plates becomes V. The average voltage on the capacitor is V / 2. Thus the energy stored in a capacitor is

$$\text{Energy} = U = \frac{QV}{2} \quad \ldots (11.37)$$

From $Q = CV$

For your Information



Energy stored in the large capacitor is used to preserve the memory of an electronic calculator when its battery is charged.

$$U = \frac{QV}{2} = \frac{CV^2}{2} \qquad \ldots (11.38)$$

$$U = \frac{Q^2}{2C}$$

It is also possible to regard the energy as being stored in the electric fi between the plates rather than the potential energy of the charges on t plates. Such a view point is useful when the Electric field between the plates considered rather than the charges on the plates causing the field is to considered .We know that

$$V = E\,d$$

and

$$C = \frac{A\varepsilon_r\varepsilon_o}{d}$$

Substituting these values in Eq.(11.38). We get

$$U = \frac{1}{2} \times \frac{A\varepsilon_r\varepsilon_o}{d} \times (Ed)^2$$

$$U = \frac{1}{2}\varepsilon_r\,\varepsilon_o\,E^2 \times (Ad) \qquad \ldots (11.39)$$

The product (Ad) is volume between the plates. Let u denote the ener density that is, the energy contained in a unit volume of the field. Then

$$u = \frac{\text{Energy}}{\text{Volume}} = \frac{U}{Ad}$$

$$u = \frac{1}{2}\varepsilon_r\varepsilon_o E^2 \qquad \ldots (11.40)$$

11.13 CHARGING AND DISCHARGING OF A CAPACITOR THROUGH A RESISTOR

Consider a circuit having a capacitance *C* and a resistance *R* which are joined i series with a battery of voltage *V* through a key *K* as shown in the figure 11.2 Let us assume that the capacitor, *C* has no charge when the key (k) is full open. These are the initial conditions of the circuit, then $t = 0$, $i = 0$ and $q = 0$.

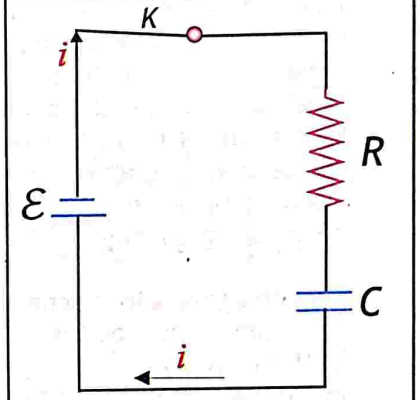
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When the key is pressed, the capacitor begins to store charge. If at any time during charging, *I* is the current through the circuit and *Q* is the charge on the capacitor. It can be shown that after time t, as charge builds up on the plates, it repels more charge than is arriving, and the current drops as the charge on the plates increases.

The graph between time t and charge q is shown in Figure 11.28. At time t = 0 charge q=0 and at certain time t charge q reaches its maximum value q_o.

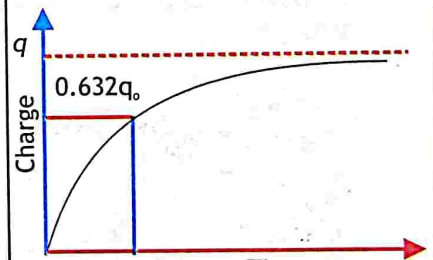
The graph also shows that the charge reaches its maximum value sooner when the time constant is small. As the capacitor charges up, the potential difference across its plates begins to increase with the actual time taken for the charge on the capacitor to reach 63% of its maximum possible fully charged voltage.

FIGURE 11.27



RC circuit

FIGURE 11.28



Charging Of a Capacitor

TIME CONSTANT

The time taken to charge a capacitor in a given circuit is determined by the time constant of the circuit.

The factor RC is called 'time constant. The time constant is the duration of time for the capacitor in which 63.2 % of its maximum value charge is deposited on the plates which is illustrated in curve Figure 11.28 .

Maximum charge on capacitor = capacitance × e.m.f. of battery

Figure 11.29 shows a resistor capacitor circuit called *RC* circuit.

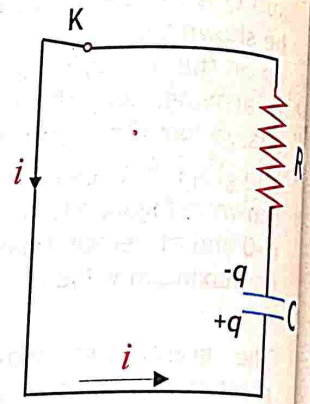
When the battery is removed and key (k) is first closed, the capacitor starts to discharge as shown in Fig.11.30.

FOR YOUR INFORMATION

In principle, a capacitor can never charge up fully, because the rate of charging decreases as the charge increases. In practice, after a finite time the charging current becomes too small to measure, and the capacitor is effectively fully charged.

The capacitor will discharge itself through resistance R. When $t = RC$, the magnitude of charge remaining on each plate is, $q = q_o$ (0.368). Time constant of RC circuit is thus also the time during which the charge on the capacitor falls from its maximum value to 36.8%. The corresponding graph in Fig. 11.30 shows that discharging begins at $t = 0$ when $q = q_o$, and decreases gradually.

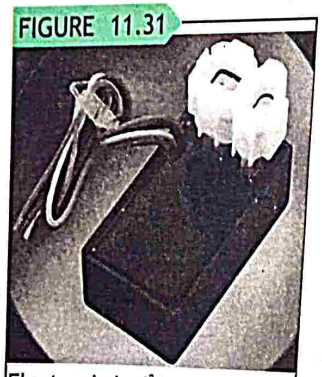
FIGURE 11.29



Discharging a capacitor

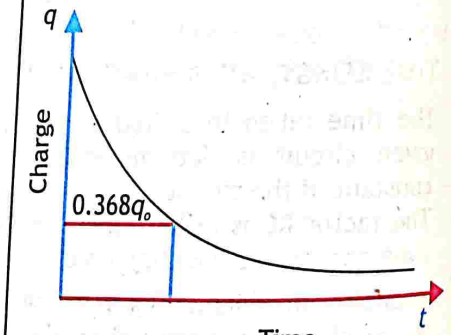
The charging and discharging of a capacitor has many applications. Capacitor discharge ignition (CDI) is a type of automotive electronic ignition system which is widely used in motorcycles, lawn mowers, chain saws, small engines, turbine powered aircraft, and some cars. It can enhance the capability of power supply and make the spark much stronger.

FIGURE 11.31



Electronic Ignition CDI

FIGURE 11.30



Discharging of a capacitor

Tip

Electronic flashguns for cameras have to be left for a short period of time between flashes. There is a capacitor inside that stores energy, it needs to be charged up again by the battery in the flashgun.

KEY POINTS

Coulomb's Law: the magnitude of the force between two point charges is directly proportional to the product of the magnitudes of the charges and inversely proportional to the square of the distance between them.

Electric potential at any point: it is equal to the work done in bringing a unit positive charge from infinity to that point without producing any acceleration.

Electric field: the region around a charge in which an electric test charge would experience an electric force.

The electric flux Φ: the number of lines of force that pass through the area placed in the electric field. $\Phi = E.A = EA\cos\theta$
When area A is normal to the electric field E then electric flux is maximum. When area A is parallel to the electric field E then electric flux is minimum.

Gauss's law: The electric flux through any closed surface is $1/\varepsilon_o$ times the total charge enclosed in it.

Capacitor : A device which is used for storing electric charges.

Electron volt (eV): the unit of energy and is related to joule as
$1eV = 1.602 \times 10^{-19}$ J

Dipole : the system in which two charges of equal magnitude but of opposite sign separated by the distance d .

EXERCISE

MULTIPLE CHOICE QUESTIONS

Choose the best possible answer

1. A charge Q is divided into two parts q and $Q-q$ and separated by a distance R. The force of repulsion between them will be maximum when:

   A. $q = Q/4$ B. $q = Q/3$

   C. $q = Q/2$ D. $q = Q$

2. Three objects are brought close to each other, two at a time. When objects A and B are brought together, they attract. When objects B and C are brought together, they repel. From this, we conclude that

   A. objects A and C possess charges of the same sign.

   B. objects A and C possess charges of opposite sign.

   C. all three of the objects possess charges of the same sign.

   D. one of the objects is neutral

3. Object A has a charge of +2 μC, and object B has a charge of +6 μC. Which statement is true about the electric forces on the objects?

   A. $F_{AB} = -3F_{BA}$ B. $F_{AB} = -F_{BA}$

   C. $3F_{AB} = -F_{BA}$ D. $F_{AB} = 3F_{BA}$

4. Some charge is being given to a conductor. Then its potential

   A. Is maximum at surface

   B. Is maximum at centre

   C. Is remain same throughout the conductor

   D. Is maximum somewhere between surface and centre

5. The unit of Electric field intensity is :

   A. Volt/metre B. newton/Coulomb

   C. Joule/ Coulomb.metre D. Volt.metre

6. A proton is about 1840 time heavier than an electron. When it is accelerated by a potential difference if 1 kV, its kinetic energy will be:

   A. 1840 keV B. 1/1840 keV

   C. 1 keV D. 920 keV

NOT FOR SALE

9. An electron with an initial speed of $29\times10^5 ms^{-1}$ is fired in the same direction as a uniform electric field with a magnitude of 80 NC^{-1}. How far does the electron travel before being brought to rest momentarily and turned back?

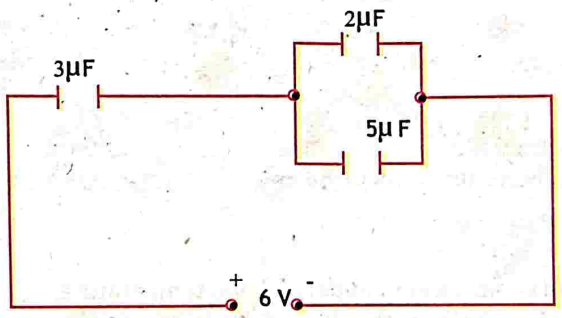
   (Answer 0.299m)

10. Three capacitors of capacitance 4μF, 6μF and 8μF respectively are connected in series to a 250V d.c. supply. Find (i) the total capacitance (ii) charge on each capacitor and (iii) P.D. across each capacitor.

    (Answer 1.84μF, 460×10^{-6} C, 115 V, 76.6V and 57.7 V)

11. Find the charge on 5μF capacitor in the circuit shown in Fig. .

    (Answer 9 μF)



12. A 6μF capacitor is charged to a P.D. of 120V and then connected to an un-charged 4 μF capacitor. Calculate the P.D. across the capacitors.

    (Answer 72 V)

NOT FOR SALE



Unit 12

CURRENT ELECTRICITY

How does an electric eel catch its prey?

LEARNING OUTCOMES

After studying this unit the students will be able to

- describe the concept of steady current.
- state Ohm's law.
- define resistivity and explain its dependence upon temperature.
- define conductance and conductivity of conductor.
- state the characteristics of a thermistor and its use to measure low temperatures.
- distinguish between e.m.f and p.d. using the energy considerations.
- explain the internal resistance of sources and its consequences for external circuits.
- describe some sources of e.m.f.
- describe the conditions for maximum power transfer.
- describe thermocouple and its function.
- explain variation of thermoelectric e.m.f. with temperature.
- apply Kirchhoff's first law as conservation of charge to solve problem.
- apply Kirchhoff's second law as conservation of energy to solve problem.

NOT FOR SALE

- describe the working of rheostat in the potential divider circuit.
- describe what is a Wheatstone bridge and how it is used to find unknown resistance?
- describe the function of potentiometer to measure and compare potentials without drawing any current from the circuit.

Current electricity is the study of charges in motion. This unit explores the concept of electric current, the flow of electric charges in a metallic conductor. Simple electrical circuits can be solved by applying Ohm's law. For other circuits, Kirchhoff rules are applied.
We all enjoy the comforts and benefits of using electricity. Electricity authorities use high-voltage transmission lines and transformers to distribute electricity to homes and industries in a town.

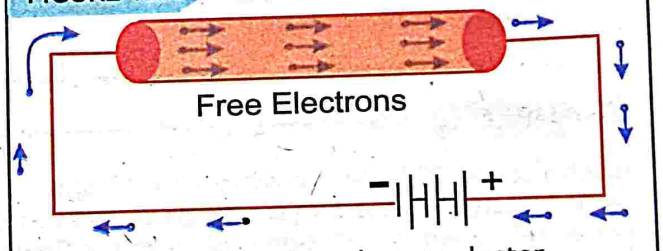
In this unit we shall discuss briefly the various features associated with the moving charges.

12.1 STEADY CURRENT

The continuous flow of free electrons is called steady current. The flow of electronic current can be easily explained by referring Figure 12.1. The conductor has a large number of free electrons when electric field or voltage is applied, then free electrons, being negatively charged, will start moving towards the positives terminal around the circuit.

This directed flow of electrons is called electric current.

FIGURE 12.1



Flow of free electrons in a conductor

Following are the main points:

1. The actual direction of current is from negative terminal to the positive terminal through out that part of the circuit external to the cell. However, prior to electron theory, it was assumed that current flows from positive terminal to the negative terminal of the cell via the circuit. This convention is so firmly established that it is still in use. This assumed direction is now called conventional current.

2. Those substances which have larger number of free electrons will permit current flow easily. Such substances are called conductors, for example Copper, Zinc, Silver, Aluminum etc.

In different current carrying materials the charges on the moving particles may be positive or negative. In metals the moving charges are always electrons (negative charges). While in gases the moving charges are negative and positive ions. We define the current through the cross-section area A to be *the net charge flowing through the area per unit time.*

Thus if a net charge 'Q' flows through an area in a time t, the current I is

$$I = \frac{Q}{t} \qquad (12.1)$$

The charge Q is measured in coulombs and time t in seconds. Therefore the unit of electric current will be coulombs/sec or ampere (A). *One ampere is the current when one coulomb of charge flows across any cross section of a conductor in one second.* The submultiples of ampere are:

1 milliampere = 1 mA = 1×10^{-3} A

1 microampere = 1 μA = 1×10^{-6} A

Tip

Current is a scalar quantity as it does not follow vector law of addition.

Do you know?

Now if electrons drift so slowly, how room light turns on quickly when switch is closed? The answer is that propagation of electric field takes place with the speed of light.

EXAMPLE 12.1

Each second 10^{18} electrons flow from right to left across a cross-section of a wire attached to the two terminals of a battery. (a) Calculate the current in the wire, (b) in which direction the current is flowing.

GIVEN

Here $n = 10^{18}$;
Charge on single electron: $e = 1.6 \times 10^{-19}$ C,
$t = 1$ s

REQUIRED

(a) Electric current I =? , (b) direction of current flow=?

SOLUTION

Electric current $I = \frac{Q}{t} = \frac{ne}{t}$

$$I = \frac{10^{18} \times 1.6 \times 10^{-19}}{1} = 1.6 \times 10^{-1}\,\text{A} = 160\,\text{mA}$$

The current is flowing from left to right i.e. in opposite direction of electron flow.

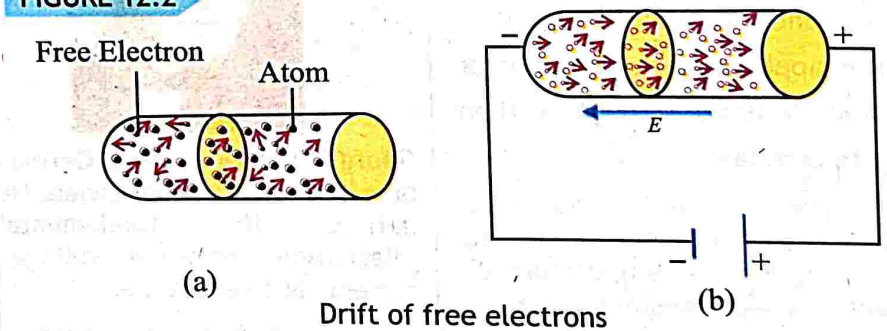
DRIFT VELOCITY IN CONDUCTOR

Every conductor is made up of atoms which are in turn composed of electrons. These electrons move in random directions within the atom. Due to their random motion, the net velocity of negatively charged electrons in a conductor is zero.

But when a potential difference is applied to the ends of a conductor, an electric field $\vec{E}$ is set up at every point within the wire. As a result of this force electrons in the conductor acquire a certain amount of velocity which causes a net flow in one direction. This velocity that causes the electrons to move in a certain direction is known as Drift Velocity.

The net velocity with which free electrons get drifted in a conductor under the influence of electric field is called drift velocity ($\vec{V}_d$).

FIGURE 12.2



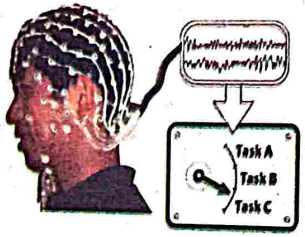
Drift of free electrons

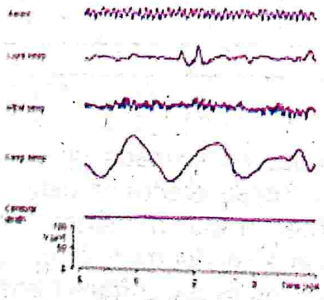
FOR YOUR INFORMATION

Electroencephalogram

An electroencephalogram (EEG) is a test that uses metal discs (called electrodes) to evaluate the electrical activity in the brain. The brain constantly generates minute electrical currents even during sleep and in deep coma. The electrodes with thin wires are attached to your scalp which detects tiny electrical charges that result from the activity of your brain cells.

The computer records your brains electrical activity on the screen or on a paper as wavy line. These lines allow neurologists to quickly assess whether there are abnormal patterns. An EEG is one of the main diagnostic tests for epilepsy, Brain tumors, Stroke etc.





12.2 OHM'S LAW

This law was presented by German scientist George Simon Ohm in (1826). It relates the three fundamental electrical quantities: voltage (V), the current (I) and resistance (R). If a voltage V is applied across a conductor and current (I) flows through it then according to ohm law

The magnitude of the current in a conductor is proportional to the applied voltage as long as the temperature of the conductor is kept constant.

Georg Simon OHM (1787-1854)



Georg Simon Ohm was a German physicist and mathematician. He defines the fundamental relationship between voltage, current, and resistance.

Mathematically $I \propto V$ or $I = \frac{V}{R}$

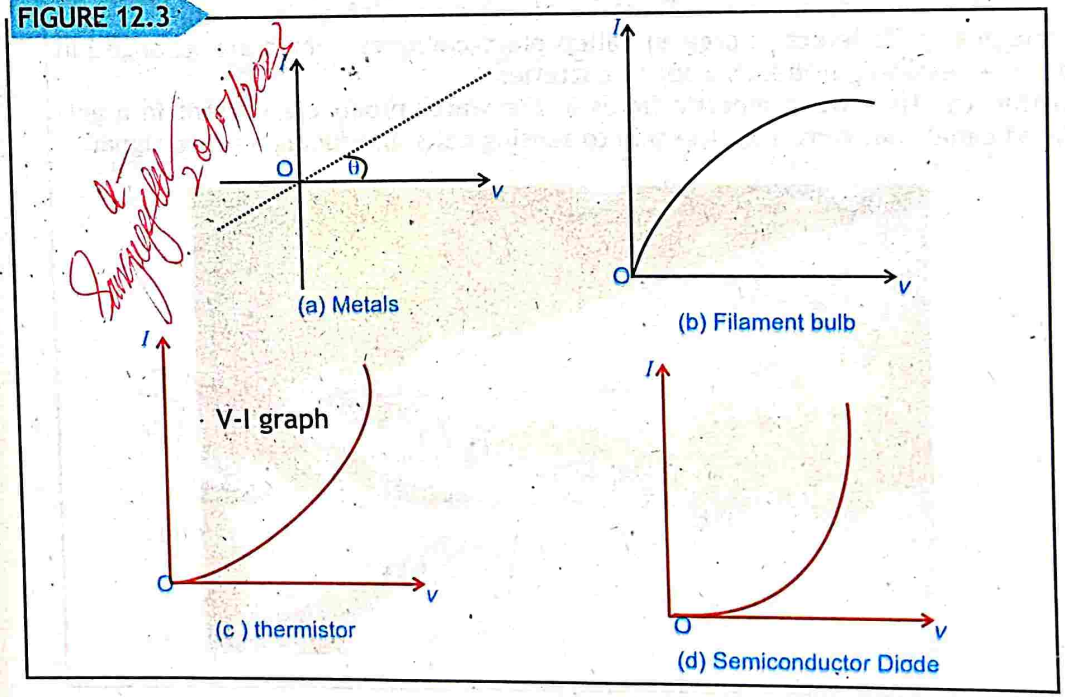
or $$V = IR \qquad (12.2)$$

Where R is constant, which is known as the resistance of the conducting material. Resistance depends upon the nature, dimension and physical state of the conductor. For a conductor that obeys Ohm's law, a graph of current I as a function of voltage 'V' is a straight line passing through the origin Figure. (12.3(a).

The slope of the line is $\tan\theta = \frac{I}{V} = \frac{1}{R}$

As R is constant the slope is constant for ohmic conductors. The Ohm's law is not valid for all conducting material. Those materials for which the slope of I verses V graph is not constant are called non-Ohmic materials. For examples Fig 12.3 (b, c &d) illustrates the non-Ohmic characteristics of the filament of an electric bulb, a thermistor and of a semiconductor diode respectively. The I-V graph for non-Ohmic materials is non linear (curved).

FIGURE 12.3



EXAMPLE 12.2

The high voltage in a TV receiver is 17 kV. The maximum allowable current is 150μA. What is the least permissible value of load resistance?

GIVEN

voltage V= 17 kV, current I = 150μA

REQUIRED

load resistance R=?

SOLUTION

$$V = 17KV = 17\times10^{3}\ V$$

$$I = 150\mu A = 150\times10^{-6}\ A$$

$$R = \frac{V}{I} = \frac{17\times10^{3}}{150\times10^{-6}} = 113.3\times10^{6}\Omega$$

Do you know?

A number of animals both produce and detect electrical signals. Fish, sharks, platypuses, and echidnas (spiny anteaters) all detect electric fields generated by nerve activity in prey. Electric eels produce their own emf through biological cells (electric organs) called electroplaques, which are arranged in both series and parallel as a set of batteries.
Within the fish, weak electric fields in the water produce a current in a gel-filled canal that runs from the skin to sensing cells, producing a nerve signal.



12.3 ELECTRICAL RESISTANCE

Resistance is the opposition offered by the substance to the flow of free electrons. This opposition occurs because atoms and molecules of the substance obstruct the flow of these electrons. Certain substances (metals such as silver, copper, aluminium) offer very little opposition to the flow of electric current. The moving electrons collide with atoms or molecules of the substance, each collision resulting in the liberation of minute quantity of heat. The SI unit of resistance is the ohm and is represented by the symbol Ω (omega).

It is defined as, the resistance of wire is to be 1 ohm if a potential difference of one volt across its ends causes 1 ampere current to flow through it.

$$1\Omega = \frac{1V}{1A}$$

12.3.1 FACTORS UPON WHICH RESISTANCE DEPENDS

It is observed experimentally that there are four factors which affects the resistance of a wire

1) It is directly proportional to its length i.e.

$$R \propto L$$

2) It is inversely proportional to its area of cross-section i.e.

$$R \propto \frac{1}{A}$$

3) It depends upon the nature of material

4) It is directly proportional to the temperature.

From the first three points (keeping the temperature constant), the resistance of a conductor is,

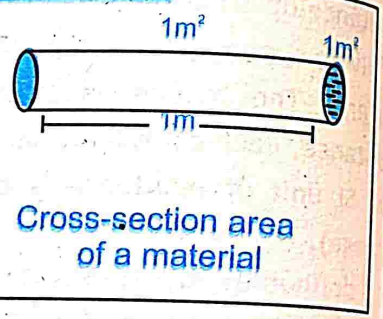
$$R \propto \frac{L}{A}$$

$$\text{or} \quad R=\rho\frac{L}{A} \qquad (12.3)$$

Where ρ (Greek LETTER 'Rho') is a constant and is known as resistivity or specific resistance of the material.

The specific resistance of a material is the resistance offered by 1m length of wire of a material having an area of cross-section of $1m^2$. A wire of 1 metre length is shown in figure 12.4. The unit of resistivity is ohm-meter (Ω.m). The resistivity of a substance varies over a wide range. To give an idea to the reader, the following table may be referred.

FIGURE 12.4.



The resistivity of metals and alloys is very small. Therefore, these materials are good conductors of electric current. On the other hand, resistivity of insulators is extremely large. As a result, these materials hardly conduct any current. There is also an intermediate class of material known as semiconductors. The resistivity of these substances lies between conductors and insulators.

Table 12.1

The resistivity's of some metals.

Metals	Resistivity(μΩm)
Copper (hard drawn)	0.0178
Aluminium	0.0285
Tin	0.114
Silver	0.0163
Brass	0.06-0.09
Iron	0.1
Lead	0.219

CONDUCTANCE: The Reciprocal of resistance of a conductor is called conductance (G). If a conductor has resistance R, then its conductance G is given by

$$G=\frac{1}{R} \qquad \ldots(12.4)$$

The SI unit of conductance is mho (i.e. ohm spelled back ward) these days, it is a usual practice to use Siemen as the unit of conductance. It is denoted by symbol S.

CONDUCTIVITY: The reciprocal of resistivity of a conductor is called its conductivity. It is denoted by the symbol σ. If a conductor has resistivity ρ, then its conductivity is given by

$$\sigma=\frac{1}{\rho}=\frac{L}{RA} \qquad (12.5)$$

The unit of conductivity is mho m^{-1} or siemen $meter^{-1}$ $(S.m^{-1})$

12.4 EFFECT OF TEMPERATURE ON RESISTANCE

The resistance of a material changes with the change in temperature. The effect of temperature upon resistance varies according to the type of material.

i) Thus resistance of a conductor (e.g. copper, aluminum) increases with the increase of temperature. The change in resistance is fairly regular for normal range of temperatures.

ii) The resistance of electrolytes, insulators (e.g. glass, mica, rubber etc.) and semiconductors (e.g. germanium, silicon etc.) decreases with the increase in temperature.

12.4.1 TEMPERATURE CO-EFFICIENT OF RESISTANCE/RESISTIVITY

Consider a conductor having resistance R_o at 0°C and R_T at T °C. It has been found that in the normal range of temperatures, the increase in resistance $(R_T - R_o)$ is

i) Directly proportional to the initial resistance i.e.

$$R_T-R_o \propto R_o$$

ii) Directly proportional to the rise in temperature i.e.

$$R_T-R_o \propto T$$

Combining the above two relations, we get

$$R_T-R_o \propto R_oT$$

$$R_T-R_o=\alpha R_oT \qquad (12.6)$$

Where α is the constant and is called temperature co-efficient of resistance. Its value depends upon the nature of material and temperature. Rearranging equation (12.6) we get:

$$R_T = R_o(1+\alpha T) \qquad (12.7)$$

From equation (12.6) we get:

$$\alpha = \frac{R_T - R_o}{R_o T} \qquad (12.8)$$

Temperature co-efficient of resistance α may be defined as *increase in resistance per ohm original resistance per degree rise in temperature.*

The unit of α as derived from the definition is K^{-1}. Since the resistance of metals increases with the rise in temperature, they have positive temperature co-efficient of resistance, while co-efficient α is negative for semiconductor because they show decrease in resistance as the temperature raises. The resistivity or specific resistance of most materials increases linearly with increasing temperature. The equation,(12.8) also apply to ρ. At temperature 'T' the resistivity 'ρ_T' of a material is given by

$$\rho_T = \rho_o(1+\alpha T) \qquad ...(12.9)$$

$$\alpha = \frac{\rho_T - \rho_o}{\rho_o T} \qquad ...(12.10)$$

EXAMPLE 12.3

A transmission line made of copper has a resistance of 100 Ω at 0C°. Calculate the change in resistance between summer and winter, knowing that temperature varies from +35C° to -30C°. Assume the temperature co-efficient of copper to be 0.00427/C° at 0C°.

GIVEN

temperature T_1= +35C°, temperature T_2 =-30C°, resistance R_o= 100 Ω
temperature co-efficient of copper α= 0.00427/C°,

REQUIRED

change in resistance R=?

SOLUTION

$$R_T = R_o(1+\alpha T)$$
$$\Rightarrow R_{-30} = 100(1+0.00427(-30)$$
$$\Rightarrow R_{-30} = 87.2\,\Omega$$
similarly $R_{+35} = 100(1+0.00427(35)]$
$$R_{+35} = 115\,\Omega$$
Change in resistance = 115 - 87.2 = 27.8 Ω

EXAMPLE 12.4

Calculate the resistance of copper conductor having a length of 2 km and a cross-section of 22 mm². Assume the resistivity is $18 \times 10^{-9}\,\Omega$.m.

GIVEN

Length L = 2 km = 2000m
Cross-section A = 22mm² = 22×10^{-6} m²
Resistivity $\rho = 18 \times 10^{-9}\,\Omega$-m

REQUIRED

Resistance of copper R= ?

SOLUTION

The resistance of copper wire of length L, cross-sectional area A and resistivity ρ is given by

$$R = \frac{\rho L}{A}$$

Thus resistance of copper conductor is

$$R = 18\times10^{-9} \times \frac{2000}{22\times10^{-6}} \qquad R = 1.64\,\Omega$$

ASSIGNMENT 12.1

(a) Calculate the resistance per unit length of a 22 nichrome wire of radius 0.321mm. (b) If a potential difference of 10V is maintained across 1m length of nichrome wire, what is the current in the wire? $\rho_{nichromes} = 1.5\times10^{-6}\Omega$.m. answer(4.6 Ω/m, 2.2 A)

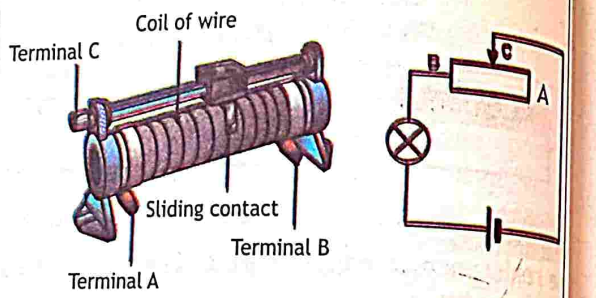
12.5 WIRE-WOUND VARIABLE RESISTORS

High stability and high accuracy resistors are always wire-wound. It is then enclosed in an insulating cover.
Generally, nickel chromium is used because of its very small temperature co-efficient of resistance. Wire wound resistors can safely operate at higher temperatures than carbon type resistors. Wire wound variable resistor can be used in two ways.
i) Rheostats ii) Potential divider

i) RHEOSTATS

To use the variable resistor as a current control device one of the two fixed terminals say A and the sliding terminal C are inserted in the circuit as shown in figure12.5. In this way the resistance of the wire between A and the sliding contact C is used. If the sliding contact is shifted away from the terminal, A the length and hence the resistance included in the circuit increase.
If the sliding contact is moved towards A, the resistance decreases. Adjusting the resistance in the circuit controls the current in a circuit.

FIGURE 12.5



Rheostats

ii) POTENTIAL DIVIDER

A potential divider provides a convenient way of getting a variable potential difference from a fixed potential difference. With the help of the battery, a potential difference V is applied across the ends A and B of the resistor (figure 12.6). Let R be the resistance of wire AB. The current I passing through it is

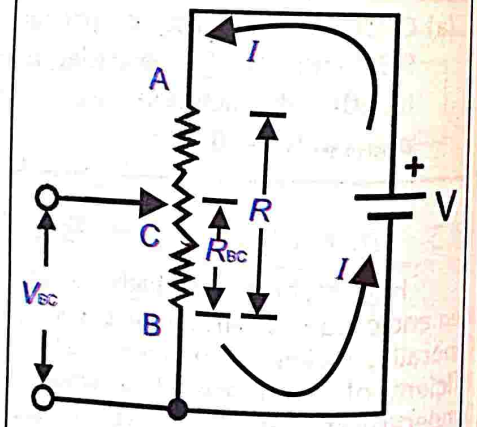
$$I = V/R$$

If R_{BC} is the resistance of the portion of the wire BC and the current passing through BC is I. The PD between the points B and C is given by

$$V_{BC} = IR_{BC}$$

$$\Rightarrow \quad V_{BC} = \frac{V}{R}R_{BC} = \frac{R_{BC}}{R}V$$

FIGURE 12.6



Potential divider

NOT FOR SALE

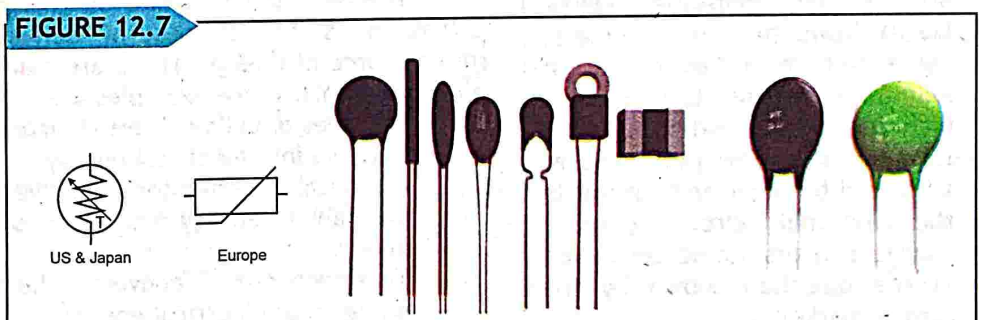
Depending on the position of the sliding contact C, the value of the fraction R_{BC}/R can be varied from 0 to 1. When the contact C, moving towards B, the length and hence the resistance R_{BC} of the portion of the wire decreases. Thus V_{BC} decreases. On the other hand if the sliding contact C is moved towards the end A, the length and the resistance R_{BC} of the wire increases and hence the voltage V_{BC} increases.

12.6 THERMISTOR

Thermistor is temperature sensing device or resistance thermometer whose prime function is to exhibit change in electrical resistance when subjected to a corresponding change in body temperature. It is made of metallic oxides, pressed into a bead, disk, or cylindrical shape and then encapsulated with an impermeable material such as epoxy or glass. The two main types of the thermistors are NTC (Negative Temperature Coefficient) and PTC (Positive Temperature Coefficient).

NEGATIVE TEMPERATURE COEFFICIENT (NTC) THERMISTOR: These types of thermistor are most commonly used. The resistance of an NTC thermistor decreases with increasing temperature. Conversely, its resistance increases with decreasing temperature. A small changes in temperature can cause significant changes in their electrical resistance. This makes them ideal for accurate temperature measurement and control. Some appliances, such as washing machines, clothes dryers, refrigerators and freezers, as well as small appliances like hair dryers, ovens, toasters, thermostats, air conditioners and fire alarms also have NTCs for temperature control. Figure 12.7 shows some Types of thermistor.

FIGURE 12.7



(a) Thermistor Symbol

(b) Types of thermistor

POSITIVE TEMPERATURE COEFFICIENT (PTC) THERMISTOR: This type of thermistor is generally used for fuse purpose. The resistance of PTC thermistor increases with increase in temperature and when temperature decreases, its resistance decreases. One of the properties of PTC thermistors is that when an excessively large current flows, they generate heat by themselves and become highly resistive. With this property, they are used as overcurrent protection devices. They are used as timing devices in televisions. They are also used as heater in automotive industry to provide additional heat inside cabin with diesel engine or to heat diesel in cold climatic conditions before engine injection.

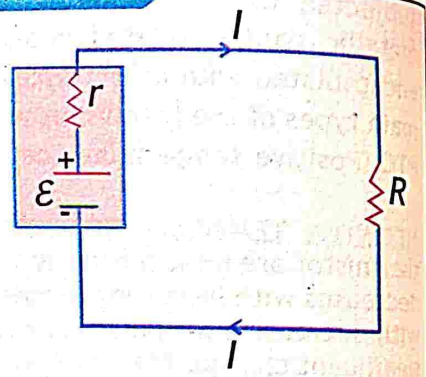
12.7 ELECTROMOTIVE FORCE

An external energy source is required by most electrical circuits to move charge through the circuit. The circuit therefore must include a device that maintains a potential difference between two points in the circuit, just as a circulating fluid requires as analogous device (pump).

Such a device which converts non-electrical energy into electrical energy is called a source of electromotive force (emf).

This reminds us a pump, which can cause water to move from a place of low gravitational potential to a place of high potential. Figure (12.8) shows the e.m.f. source $\mathcal{E}$, connected to a resistor R. It maintains its upper terminal at a high potential and its lower terminal at a low potential, as indicated by the + and - signs. In the external circuit positive charge carriers would be driven in the direction shown by the arrows marked I.

FIGURE 12.8



emf of a battery

SOURCES OF e.m.f

The work done by emf on charge carriers in its interior must be derived from a source of energy. There are many sources of e.m.f. A few examples are

1. Batteries or cells convert chemical energy into electrical energy.
2. Electrical generators convert mechanical energy into electrical energy.
3. Thermocouples convert heat energy into electrical energy.
4. Radiant (a solar cell) converts sunlight directly into electrical energy.

We define e.m.f. $\mathcal{E}$ of a source equal to the work done in carrying 1 coulomb of charge through the source.

Suppose q coulombs require an amount of work W joule to be transported through the source then $\mathcal{E}$ in volts is given by

$$\mathcal{E} = \frac{W}{q} \qquad \ldots(12.11)$$

The potential at the ends of a terminal of a battery when circuit is open is also called e.m.f.

The unit of e.m.f. is the joule/coulomb, which is the volt (abbreviation V):

1 volt = 1 joule/coulomb

12.8 INTERNAL RESISTANCE OF A SUPPLY

All supplies (e.g. a cell) must have some internal resistance, however small. When the cell is delivering no current i.e. no load, the potential difference across the terminals will be equal to e.m.f ($\mathcal{E}$) of the cell. When some load resistance 'R' is connected across the terminals of the cell, the current I starts flowing in the circuit Figure (12.9). This current causes a voltage drop across internal resistance r of the cell so that terminal voltage V available will be less than $\mathcal{E}$. The relationship between $\mathcal{E}$ and V can be easily established.

FOR YOUR INFORMATION



Just as a water fountain requires a pump, an electric circuit requires a source of electromotive force to sustain a steady current. In an electronic circuit there must be a device somewhere in the loop that acts like the water pump in a water fountain. In this device a charge travels uphill's from lower to higher potential energy even though the electrostatic force is trying to push it from higher to lower potential energy. The direction of current in such a device is from lower to higher potential, just the opposite of what happens in an ordinary conductor. The influence that makes current flow from lower to higher potential is called electromotive force.

$$I=\frac{\mathcal{E}}{R+r} \quad \Rightarrow \quad IR=\mathcal{E}-Ir$$

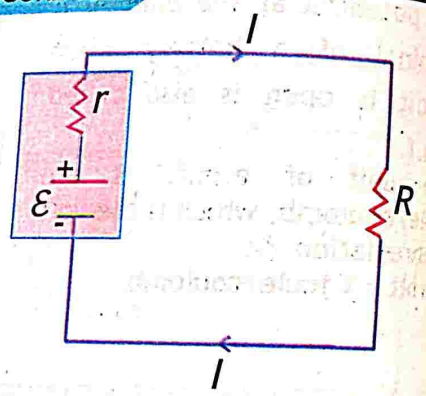
But $IR=V$, the terminal voltage of the cell

$$V=\mathcal{E}-Ir$$

Now, if $r=0$ (Open Circuit); $I=0$ then $V=\mathcal{E}$

But, when the circuit is closed, the current move through it experiences an associated drop in potential equal to Ir. Thus when a current is flowing through a source, the Potential difference V between the terminals of the source is $V=\mathcal{E}-Ir$. The Potential V called the terminal voltage, is less than the e.m.f.($\mathcal{E}$) because of the term Ir representing the Potential drop across the internal resistance r.

FIGURE 12.9



Internal resistance of a battery

12.9 ELECTRIC POWER

When voltage V is applied to a circuit, it causes current I to flow through the resistance R in time t. (Figure 12.10)

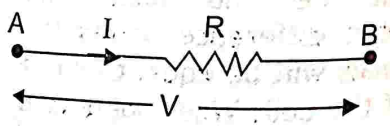
The total charge Q flows in t second is $Q=I\times t$ and $V=\frac{W}{Q}$

$W=QV=VIt$

Clearly work is being done in moving the charges in the circuit.

This work done in moving the charges in a unit time is called the electric power or the rate at which work is done in an electric circuit is called electric power.

FIGURE 12.10



Work done on a charge

$$\text{Electric Power}=\frac{\text{Work done in electric circuit}}{\text{Time}}$$

$$\text{Electric power } =P=\frac{W}{t}=\frac{VIt}{t}$$

$$P=VI \qquad \ldots(12.12)$$

using Eq $V=IR$ we get

$$P=I^2R \qquad \ldots(12.13)$$

or

$$P=\frac{V^2}{R} \qquad \ldots(12.14)$$

The above three formulas are equally valid for calculation of electric power in a D.C. circuit. Which one is to be used depends simply on the known quantities.

UNIT OF ELECTRIC POWER: The SI unit of power is watt. A power of 1 watt is said to be consumed in a circuit if a potential difference of 1 volt causes a current of 1 ampere to flow through it.

1 Watt $=1\text{V}\times1\text{A}$

The bigger units of power are kilowatt (kW) and mega watt (MW)

1 kW $=1000$ watts $=10^3$ watts

1 MW $=10^6$ watts

KILOWATT-HOURS: Electric energy is commonly consumed in very large quantity for the measurement of which Joule is a very small unit. Hence a large unit of energy is required which is called kilowatt-hour. One kilowatt-hour is commonly termed as one commercial unit of electrical energy. It is the amount of energy obtained by a power of 1 kilowatt in one hour.

$$1\text{ kWh} = 1000\text{ W}\times3600\text{ s}=3.6\times10^6\text{ Ws}$$

$$1\text{ kWh} = 3.6\times10^6\text{ J} \quad \therefore 1\text{J}=1\text{W}\times1\text{s}$$

EXAMPLE 12.5

A heating coil has a resistance of 20 Ω. It is designed to operate on 220 V. What electric energy in joules is supplied to the heater in 10 s?

GIVEN

$R=20\ \Omega$, $V=220$ V and $t=10$ s

REQUIRED

electric energy W=?

SOLUTION

From Ohm's law $V = IR$ or $I = \frac{V}{R}$

$$I = \frac{220\ V}{20\ \Omega} = 11A$$

Now applying the formula

$$W = I^2 Rt$$

$$W = (11\ A)^2 (20\Omega)(10\ s)$$

$$W = 24200\ J$$

EXAMPLE 12.6

The following are the details of load and a circuit connected through a supply meter.

(i) Six lamps of 40 watts each working for 4 hours per day.

(ii) Two fluorescent tubes 125 watts each working for 2 hours per day.

(iii) 1000 watts heater working for 3 hours per day.

Find the cost of electrical energy consumed in 30 days of a month when the rate of electricity is 7.0 Rs per unit.

SOLUTION

Total watts for lamps = $40 \times 6 = 240$ watts

Total watts for tubes = $125 \times 2 = 250$ watts

Heater = 1000 watts

Energy consumed per day =

$= (250 \times 4) + (250 \times 2) + (1000 \times 3)$

= 4460 watt hours

= 4.46 Kwh

Total energy consumed in the month of June

$= 4.46 \times 30 = 133.8 kwh$

Bill for the month of June = 7×133.8

= 936.6 Rs

ASSIGNMENT 12.2

A heating coil is rated at 100W,220V. The coil is cut in half and two pieces are joined in parallel to the same source. Now what is the energy liberated per second?

Answer (4×10^2 J)

12.10 MAXIMUM POWER OUTPUT

In many electronic circuits and systems it is important to have maximum transfer of power from the source to the load. For example, in radio or TV transmitting systems, it is desired to transfer the maximum power possible from the transmitting medium to the antenna systems. We want maximum power transfer from amplifier to speaker system. This is accomplished by proper matching of load resistance R and source resistance r.

If the load resistance is less or greater than the source resistance, then the power delivered to the load will be minimum.

Consider the circuit of figure 12.11, as the current I flows through the load resistance R the charges flow from a point of higher potential to a point of lower potential. In this process, they lose potential energy. If V is the potential difference across R, the loss of potential energy per second is known as power delivered to R by the current I.

From electrical power

$$P_{out} = IV$$

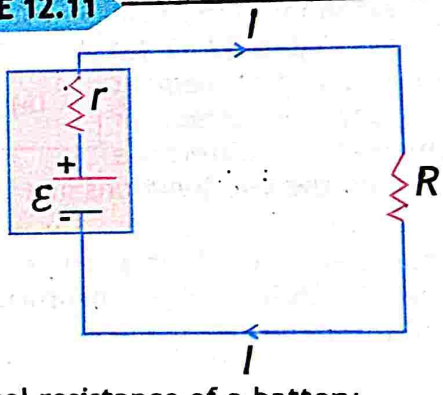
$$P_{out} = I^2 R$$

$$P_{out} = \frac{\varepsilon^2 R}{(R+r)^2}$$

$$P_{out} = \frac{\varepsilon^2 R}{(R-r)^2 + 4Rr}$$

When $R = r$, the denominator of the expression for P_{out} is minimum and so P_{out} is maximum.

FIGURE 12.11



Internal resistance of a battery

Thus it can be concluded that *maximum power is delivered to a load R when the internal resistance of the source of emf is equal to the load resistance*, also called maximum power transfer theorem.

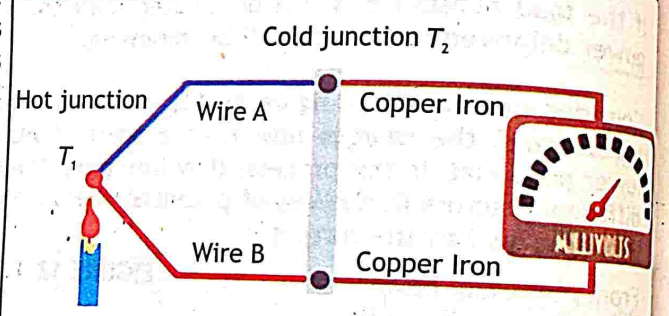
The value of the maximum output power is

$$(P_{out})_{max} = \frac{\varepsilon^2}{4r} = \frac{\varepsilon^2}{4R} \qquad \ldots(12.15)$$

12.11 THERMOCOUPLES

In early 1821, Thomas Seebeck searched experimentally for a relation betwee electricity and heat. A thermocouple consists of two dissimilar wires A and that are joined at one end T_1 (the "hot" junction). The other end T_2 (th "cold" junction) is maintained at a constant reference temperature (usuall the melting point of ice). The device connected at their ends shows a deflection. This is known as Seebeck Effect. The e.m.f. generated in the circuit is called thermoelectric e.m.f. In this process energy is directly converted into electrical energy. Figure 12.12 (a) shows an arrangement to study the effect of temperature difference between the two junctions in a Cu-Fe thermocouple.

FIGURE 12.12



(a) Variation of thermo emf with temperature

Thus thermocouple is a temperature measuring device. In other words, it is a type of sensor used for measuring the temperature in the form of an electric current or the EMF.

The wire pairs can be composed of noble metals (such as platinum, iridium, silver, osmium, gold, and rhodium) or base metals, (such as copper, iron or nickel-copper alloy, lead and zinc). Thus it remains true for any pair of metals. Thermocouples are the most widely used temperature sensors in industry due to their low cost, simplicity, size and useable temperature range. The electromotive force ε is a function of the temperature gradient. The thermo- e.m.f. produced is very small, of the order of mV per every degree of temperature difference. The Seebeck effect is reversible, i.e., if the hot and cold junctions are interchanged, the direction of e.m.f. (and hence current) reverses.

The greater the separation of the metals forming the thermocouple in the series, greater is the thermo e.m.f. produced.

Its temperature dependence is given by

$$\varepsilon = \alpha T + \frac{1}{2}\beta T^2 \qquad \ldots(12.16)$$

Where α and β are constants (called thermoelectric coefficients) which depends on the nature of the metals.

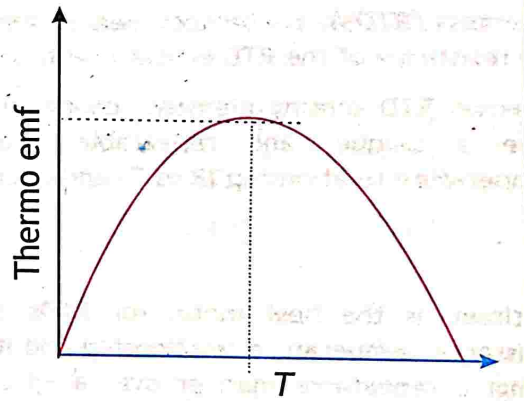
12.12 VARIATION IN THERMOELECTRIC e.m.f. WITH TEMPERATURE

Keeping the junction B at 0°C, the temperature of junction A is increased. When both the junctions are at the same temperature, there is no thermo e.m.f. when the temperature at one junction is cold while at other end is increased the thermo e.m.f. also increases with temperature and reaches a maximum value at a certain temperature, called the neutral temperature T.

The value of the neutral temperature is constant for a thermocouple, depends on the nature of materials and is independent of the temperature of the cold junction. As the temperature of the hot junction is increased, the thermo e.m.f. starts decreasing instead of increasing.

The particular temperature at which, the thermo e.m.f. becomes zero is called the inversion temperature Figure 12.12 (b). The graph shows the variation of the thermo e.m.f. with the temperature of hot junction, with the cold junction.

FIGURE 12.12

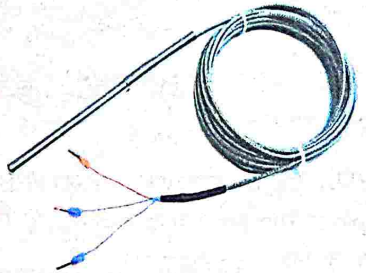


(b) Variation of thermo emf with temperature T for copper-iron thermocouple

NOT FOR SALE

Resistance thermometers

Accurate temperature measurement is essential for food producers, hospitals, refineries, chemical plants, in research labs, and pharmaceutical manufacturers. That's why a great many lab and industrial applications today pick reliable, accurate resistance temperature detectors (RTDs) as the temperature measurement instrument of choice.



Resistance thermometers, also called resistance temperature detectors (*RTD*'s), are sensors used to measure temperature by correlating the resistance of the RTD element with temperature.

Common RTD sensing elements constructed of platinum, copper or nickel have a unique, and repeatable and predictable resistance versus temperature relationship (R vs T) and operating temperature range.

The R vs T relationship is defined as *the amount of resistance change of the sensor per degree of temperature change.*

Platinum is the best metal for RTDs because it follows a very linear resistance-temperature relationship and it follows the R vs T relationship in a highly repeatable manner over a wide temperature range. The unique properties of platinum make it the material of choice for temperature standards over the range of -272.5 °C to 961.78 °C. They are slowly replacing the use of thermocouples in many industrial applications below 600 °C, due to higher accuracy and repeatability.

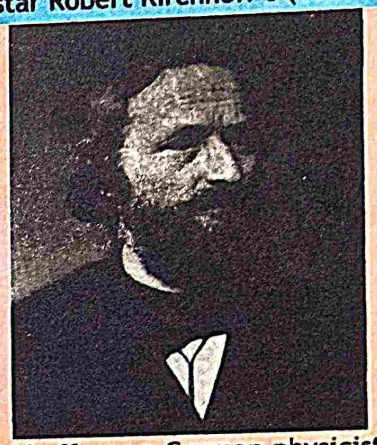
NOT FOR SALE

12.13 KIRCHOFF'S LAW

Many complex circuits, where simplification by series and parallel combinations is impossible due to combination of more than one batteries in a circuit. Ohm's law cannot be applied to solve such circuits. Circuits like this are known as multi-loop circuits.

In order to find the current in all branches of a multi-loop circuit (or the emf of a battery or the value of a resistor) Robert Kirchhoff's gave two laws, known as Kirchhoff's laws. These laws also apply to very simple circuits.

Gustar Robert Kirchhoff's (1824-1887)



Kirchhoff was a German physicist who made significant contributions to the fundamental understanding of black-body radiation emitted by heated objects, spectroscopy, and electrical circuits.

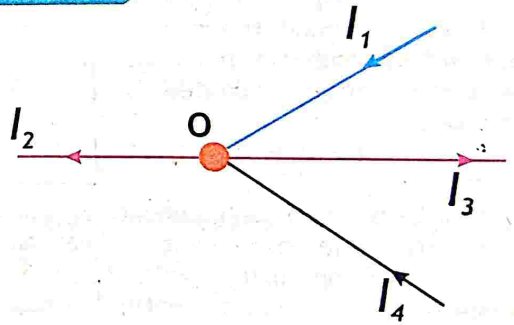
KIRCHOFF'S CURRENT LAW (KCL)

Kirchhoff's current rule (the *junction rule*) is manifestation of the conservation of charge to a junction; it is illustrated in Figure 12.13. Current is the flow of charge, and charge is conserved. This law is related to the currents at the junctions of an electric circuit and may be stated as under:

The algebraic sum of all the currents meeting at a junction in an electrical circuit is zero. $\sum I = 0$

A junction is a point in a circuit where two or more components are connected. As algebraic sum is one in which the sign of the quantity is taken into account. For example, consider four conductors carrying currents I_1, I_2, I_3 and I_4.

FIGURE 12.13



Junction at O with four branches.

If we take the signs of currents flowing towards point O as positive, then currents flowing away from point O will be assigned negative sign. Thus applying Kirchhoff's current laws to the junction

$$(I_1)+(I_4)+(-I_2)+(-I_3)=0$$

Or $$I_1+I_4=I_2+I_3 \qquad \ldots(12.17)$$

i.e. sum of incoming currents = sum of outgoing current.

Hence, Kirchhoff's current law may also be stated as *the algebraic sum of currents flowing towards the junction in an electrical circuit is equal to the algebraic sum of currents flowing away from that junction.*

KIRCHOFF'S VOLTAGE LAW (KVL)

This law refers to e.m.f and voltage drops in a closed circuit or closed loop and may be stated as under:

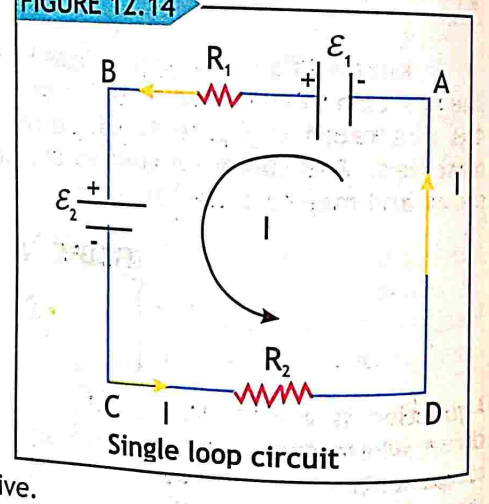
In any closed electrical circuit, the algebraic sum of all the electromotive force, (e.m.f) and voltage drops in resistor is equal to zero i.e.

Algebraic sum of emf + algebraic sum of voltage drops = 0.

The validity of Kirchoff's voltage law can be easily established by referring to the closed loop ABCDA shown in Figure 12.14. Starting from any point (say point A) in this closed circuit after going around the circuit and go back to this point (i.e. point A). The following convention is adopted to solve the circuit.

i) A rise in potential is taken positive.
ii) A drop in potential is taken negative.
iii) For batteries, the positive end is always at higher potential.
iv) Current flows from high potential to the low potential.
v) Assume the direction of current either clock wise or counter clockwise.

FIGURE 12.14



Single loop circuit

PROCEDURES OF APPLYING KIRCHHOFF'S LAWS FOR PROBLEM SOLUTION

Moving along the direction of current flow



The fall in potential is $-IR_1$

Moving along the direction of current flow



The fall in potential is $-IR_2$

Moving from the negative terminal to the positive terminal



For rise in potential $+\mathcal{E}_1$

Moving from the positive terminal to the negative terminal



For fall in potential $-\mathcal{E}_2$

Thus applying Kirchhoffs law, on figure 12.14 we get

$$\mathcal{E}_1 - IR_1 - \mathcal{E}_2 - IR_2 = 0$$

$$\Rightarrow \quad \mathcal{E}_1 - \mathcal{E}_2 = IR_1 + IR_2$$

$$\Rightarrow \quad \mathcal{E}_1 - \mathcal{E}_2 = IR_1 + IR_2 \qquad \text{Or} \qquad \Sigma\mathcal{E} = \Sigma IR \qquad \ldots(12.18)$$

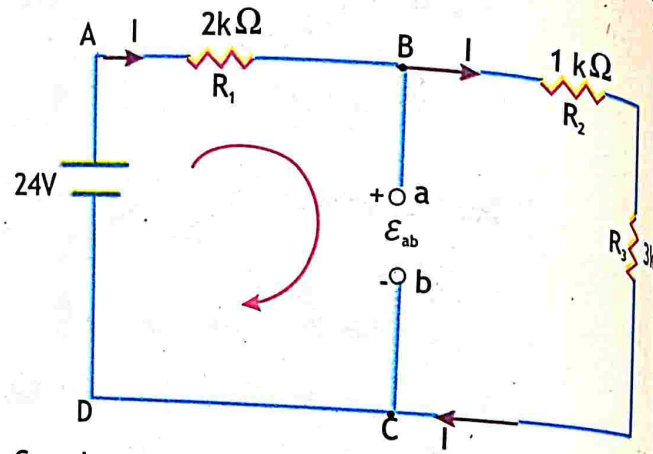
The sum of all the emf $\mathcal{E}$ in a loop in a circuit is equal to the sum of all the IR voltage drops in that loop. KVL is in fact, a statement of the law of conservation of energy.

Tips

1. The choice of loops is quite arbitrary, but it should be such that each resistance is included at least once in the selected loop. Kirchhoff's voltage law can be applied to these closed loops to get the desired equations.
2. The direction in which currents are assumed to flow is not important, since if wrong direction is chosen, it will be indicated by a negative sign in the result.

EXAMPLE 12.7

Figure shows three resistors and two voltage sources. Use Kirchhoff's voltage law to find the emf $\mathcal{E}_{ab}$.



Complex circuit solution through Kirchhoff's rule

GIVEN

$\mathcal{E}_1$=24V,
R_1= 2kΩ , R_2= 1kΩ and
R_3= 3kΩ

REQUIRED

e.m.f. $\mathcal{E}_{ab}$ = ?

SOLUTION

Total circuit resistance, $R_T = 2 + 1 + 3 = 6k\Omega$

Circuit current, $I = \frac{\mathcal{E}}{R_T} = \frac{24V}{6k\Omega} = 4mA$

Applying Kirchhoff's voltage law to loop *ABCDA*, we have

$\mathcal{E}_1 - IR - \mathcal{E}_{ab} = 0$

$24 - 4\ mA \times 2k\Omega - \mathcal{E}_{ab} = 0$

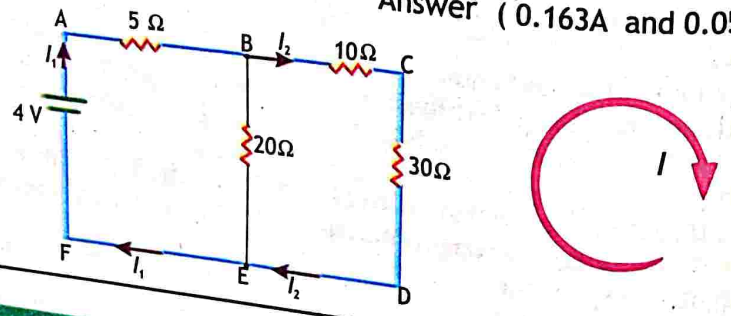
$24 - 8 - \mathcal{E}_{ab} = 0$

$\Rightarrow \mathcal{E}_{ab} = 24 - 8 = 16V$

ASSIGNMENT 12.3

Circuit ABCDEF is shown in Figure . Calculate the current in each branch of the circuit using Kirchhoff's voltage law.

Answer (0.163A and 0.05454 A)

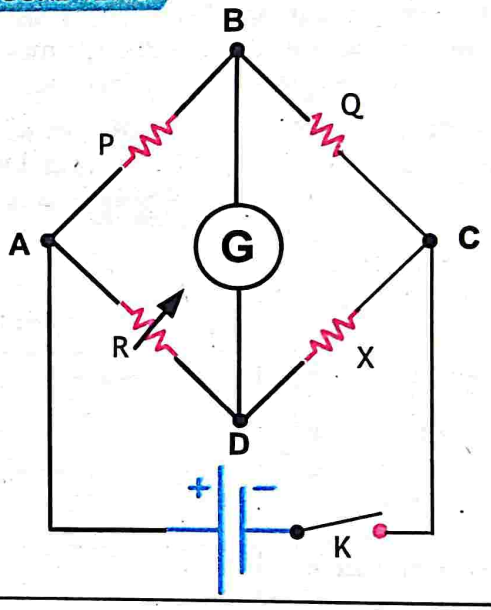


NOT FOR SALE

12.14 WHEATSTONE BRIDGE

This bridge was first proposed by Wheatstone an English telegraph engineer for measuring accurately the value of an unknown resistance. It consist of four resistors (two fixed resistances *P* and *Q* which are known one variable resistance R which is also known and one unknown resistance *X* whose value is to be found) as shown in figure 12.15. Across one pair of opposite junctions (A and C) battery is connected and across the other opposite pair of junctions (B and D), a galvanometer is connected.
The value of P and Q are properly fixed. When the key is switched on, the current *I* divide unequally between the two branches and the galvanometer shows current.

FIGURE 12.15



The value of resistance *R* is varied until the galvanometer shows zero current. Under such conditions, the bridge is said to be balance. The point at which the bridge is balanced is called null point.

Let I_1 and I_2 be the currents through *P* and *R* respectively when the bridge is balanced.

Since there is no current through Galvanometer, the current in *Q* and *X* are also I_1 and I_2 respectively. As the Galvanometer reads zero, points B and D are at the same potential. This means that voltage drops from A to B and A to D must be equal.

Also voltage drops from B to C and D to C must be equal. Hence
For balanced bridge the potential drop across AB= the potential drop across AD

$$I_1P = I_2R \qquad (i)$$

similarly the potential drop across BC= the potential drop across DC

and $I_1Q = I_2X \qquad (ii)$

Dividing Eq: (i) by Eq: (ii), we get

$$\frac{P}{Q} = \frac{R}{X}$$

$$PX = RQ$$

$$X = \frac{RQ}{P} \qquad \ldots(12.19)$$

ence, if three resistances on the right side of equation12.19 are known, th ourth resistance X can be calculated. This is the principle of determinin nknown resistance by Wheatstone bridge.

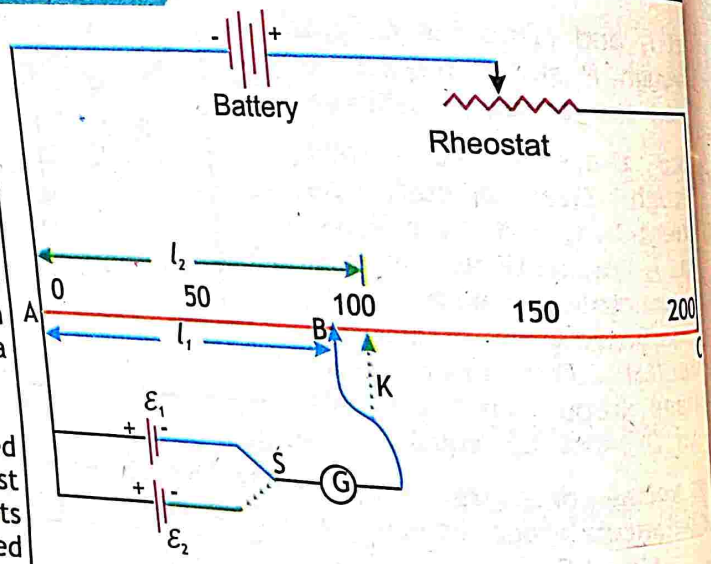
12.15 POTENTIOMETER

A potentiometer is a null type resistance network device for measurin potential differences.

For the accurate measurement of potential difference, current and resistance the potentiometer is most useful instrument. Its principle of action is that a unknown emf or potential difference is measured by balancing it, wholly or i part, against a known potential difference.

A simplest potentiometer consists of wire AC of uniform cross-section stretche alongside a scale and connected across battery of potential V as shown i Figure 12.16. The battery through the rheostat and slide wire supply the working current. The working current may vary by changing the setting of the rheostat. A standard cell of known emf $\mathcal{E}_1$ is connected between A and terminal 1 of a two way switch S.

FIGURE 12.16



Simplest potentiometer circuit

Slider B is pressed momentarily against wire AC and its position is adjusted until the galvanometer deflection is zero when B is making contact with AC. Let l_1 be the corresponding distance between A and B. The fall of potential over length l_1 of the wire is then the same as the emf $\mathcal{E}_1$. Then move the switch to 2, thereby replacing the standard cell by another cell, the e.m.f $\mathcal{E}_2$ of which is to be measured.

Adjust the slider B again to give zero deflection on G. If l_2 be the new distance between A and B,

then $$\frac{\mathcal{E}_2}{\mathcal{E}_1} = \frac{l_2}{l_1} \qquad \ldots(12.20)$$

$$\mathcal{E}_2 = \frac{l_2}{l_1} \times \mathcal{E}_1$$

Applications of potentiometer: following are the applications of potentiometer.

1. Measurement of small e.m.f (upto 2V) and high e.m.f(say 250 V).
2. Comparison of e.m.f of two cells.
3. Measurement of resistance and current.
4. Calibration of ammeter and voltmeter.

EXAMPLE 12.8

Using a Weston cadium cell of 1.0183 V and a standard resistance of 0.1Ω a potentiometer was adjusted so that 1.0183 m was equivalent to the e.m.f of the cell: when a certain direct current was flowing through the standard resistance, the voltage across it corresponds to 150 cm. What was the value of current?

GIVEN

Emf of the cell, $\mathcal{E}_1$=1.0183 V L_1=1.0183 m,
L_2=150 cm = 1.5 m, Resistance R= 0.1Ω

REQUIRED

current I_2 = ?

SOLUTION

$$\frac{\mathcal{E}_2}{\mathcal{E}_1} = \frac{\ell_2}{\ell_1}$$

$$\mathcal{E}_2 = \frac{\ell_2}{\ell_1} \times \mathcal{E}_1 = \frac{1.5}{1.0183} \times 1.0183 = 1.5\,V$$

current flowing through the standard resistance, $I_2 = \frac{\mathcal{E}_2}{R}$

$$= \frac{1.5}{0.1} = 15A$$

ASSIGNMENT 12.4

A potentiometer wire of length 1 m is connected to a driver cell of emf 3V. When a cell of 1.5V emf is in secondary circuit the balance point is found to be at 60 cm. On replacing this cell and using a cell of unknown emf the balance point shifts to 80 cm. Calculate unknown emf of the cell.

Answer (2V)

NOT FOR SALE

KEY POINTS

Steady current : the continuous flow of free electrons

Electric current : *the net charge flowing through the cross-section area A per unit time.* $I = Q/t$

Ohm law : *the magnitude of the current in metals is proportional to the applied voltage as long as the temperature of the conductor is kept constant.* $V = IR$

Resistance : *the opposition offered by the substance to the flow of free electrons.*

Conductance (G): the reciprocal of resistance of a conductor.

Temperature co-efficient of resistance: *increase in resistance per ohm original resistance per degree rise in temperature.*

Thermistor : a heat sensitive device usually made of a semiconductor material whose resistance changes very rapidly with change of temperature.

Source of electromotive force: *a device which converts non-electrical energy into electrical energy .*

Electric power: *the rate at which work is done in an electric circuit.*

Kirchoff's law: *the algebraic sum of the currents meeting at a junction in an electrical circuit is zero.*

NOT FOR SALE

EXERCISE

MULTIPLE CHOICE QUESTIONS

Choose the best possible answer

1. Three resistors of resistance R each are combined in various ways. Which of the following cannot be obtained?

   A. $3R\ \Omega$ B. $\frac{2R}{4}\Omega$ C. $\frac{R}{3}\Omega$ D. $\frac{2R}{3}\Omega$

2. When n resistances each of value r are connected in parallel, then resultant resistance is x. When these n resistances are connected in series, total resistance is

   A. nx B. rnx C. x / n D. $n^2 x$.

3. Two bulbs marked 200 watt-250 volts and 100 watt-250 volts are joined in series to 250 volts supply. Power consumed in circuit is

   A. 33 watt B. 67 watt C. 100 watt D. 300 watt.

4. Resistance of a wire is r ohms. The wire is stretched to double its length, then its resistance in ohms is

   A. $r / 2$ B. $4r$ C. $2r$ D. $r / 4$.

5. 10^6 electrons are moving through a wire per second, the current developed is

   A. 1.6×10^{-19} A B. 1 A C. 1.6×10^{-13} A D. 10^6 A

6. When a wire is stretched and its radius becomes $r/2$, then its resistance will be

   A. $16R$ B. $4R$ C. $2R$ D. 0

resistance of the fourth arm ? Answer (75 Ω)

MULTIPLE CHOICE QUESTIONS

9 The resistivity of two wires is ρ_1 and ρ_2 which are connected in series. there dimensions are same then the equivalent resistivity of t combination will be

A. $(\rho_1 + \rho_2)$ B. $\frac{1}{\rho_1} + \frac{1}{\rho_2}$

C. $\frac{\rho_1 + \rho_2}{2}$ D. $\frac{\rho_1}{\rho_2}$

10 The powers of two electric bulbs are 100w and 200 w. Which a connected to power supply of 220 V. The ratio of resistance of the filament will be,

A. 1:2 B. 2:1 C. 1:3 D. 4:3

11 Thermocouple is an arrangement of two different metals

a) To convert heat energy into electrical energy
b) To produce more heat
c) To convert heat energy into chemical energy
d) To convert electric energy into heat energy

12 In order to achieve high accuracy, the slide wire of a potentiomete should be

A. As long as possible B. As short as possible
C. Very thin D. Very thick

13 When a potentiometer is used for measurement of voltage of an unknow source, the power consumed in the circuit of the unknown source under null condition is

A. high. B. small. C. ideally zero. D. very high.

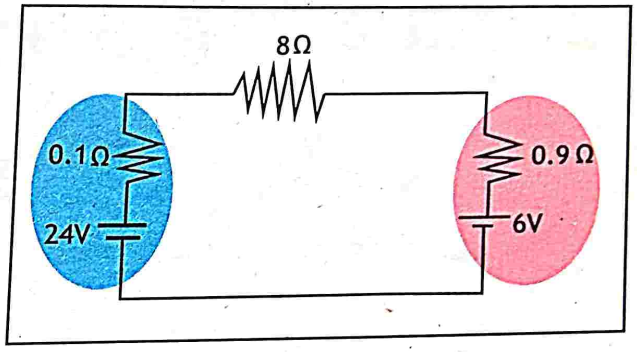
14 In a Wheatstone bridge method, the bridge is said to be balanced, when the current through the galvanometer is

A. 1 A B. 0 A C. Maximum D. Half of the maximum value

Kirchoff's law: the algebraic sum of the currents meeting at a junction in an electrical circuit is zero.

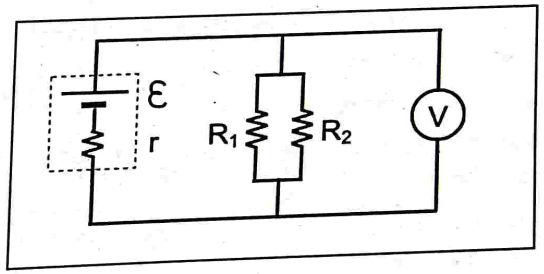
9 Find the terminal potential difference of each cell in circuit of figure.

Answer (23.8 V, 7.8 V)



10 The voltmeter in the circuit at the right may be considered to be ideal. Values are, $\mathcal{E}$= 15.0 V; internal resistance, r = 5.00 Ω; R_1= 100 Ω; R_2= 300 Ω. Calculate the current in R_1.

Answer (0.01406A)



11 Three arms of a wheatstone bridge are of 75 Ω each. What is the resistance of the fourth arm ?

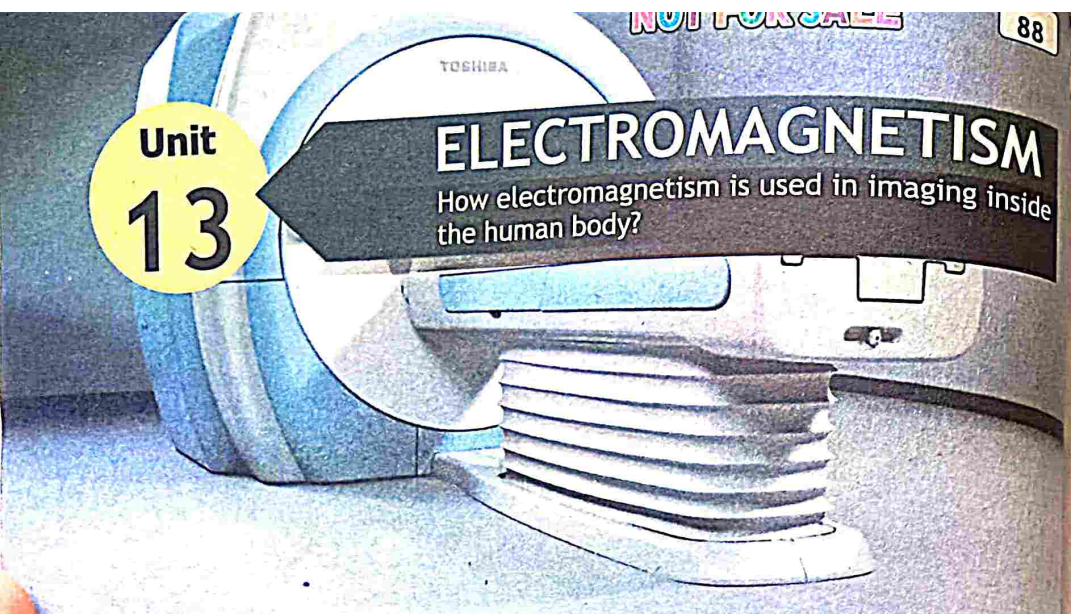
Answer (75 Ω)

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Unit 13

ELECTROMAGNETISM

How electromagnetism is used in imaging inside the human body?



LEARNING OUTCOMES

After studying this unit the students will be able to

- explain that magnetic field is an example of a field of force produced either by current-carrying conductors or by permanent magnets.
- describe magnetic effect of current.
- describe and sketch field lines pattern due to a long straight wire.
- explain that a force might act on a current-carrying conductor placed in a magnetic field.
- Investigate the factors affecting the force on a current carrying conductor in a magnetic field.
- solve problems involving the use of $F = BIL \sin\theta$.
- define magnetic flux density and its units.
- describe the concept of magnetic flux (Φ) as scalar product of magnetic field (B) and area (A) using the relation $\Phi_B = B_\perp A = B \bullet A$.
- state Ampere's law.
- apply Ampere's law to find magnetic flux density around a wire and inside a solenoid.

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- describe quantitatively the path followed by a charged particle shot into a magnetic field in a direction perpendicular to the field.
- explain that a force may act on a charged particle in a uniform magnetic field.
- describe a method to measure the e/m of an electron by applying magnetic field and electric field on a beam of electrons.
- predict the turning effect on a current carrying coil in a magnetic field and use this principle to understand the construction and working of a galvanometer.
- explain how a given galvanometer can be converted into a voltmeter or ammeter of a specified range.
- describe the use of avometer / multimeter (analogue and digital).

A magnet (from Greek 'Magnesian stone') is a material or object that produces a magnetic field. This magnetic field is invisible but is responsible for the most notable property of a magnet: a force that pulls on other ferromagnetic materials, such as iron, and attracts or repels other magnets. A permanent magnet is an object made from a material that is magnetized and creates its own persistent magnetic field. An everyday example is a refrigerator magnet used to hold notes on a refrigerator door.

For your information — Recording media and swipe cards

Magnetic recording media: VHS (Video Home System) tapes contain a reel of magnetic tape. The information that makes up the video and sound is encoded on the magnetic coating on the tape. Common audio cassettes also rely on magnetic tape. Similarly, in computers, floppy disks and hard disks record data on a thin magnetic coating.

Credit, debit, and ATM cards: All of these cards have a magnetic strip on one side. This strip encodes the information to contact an individual's financial institution and connect with their account(s).



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13.1 MAGNETIC FIELD

A magnetic field surrounds a magnetic substance making up a permanent magnet. In addition to containing an electric field, the region of space surrounding any moving electric charge also contains a magnetic field. When charges are not moving no such effect is seen. Magnetic field is represented by magnetic induction vector B. We can define a magnetic field 'B' at some point in space in terms of the magnetic force 'F_B' that the field exerts on a test object, for which we use a charged particle moving with a velocity 'v'.

The relationship between magnetism and electricity was discovered in 1819. During a lecture demonstration, Hans Christian Oersted found that electric current in a wire deflected a nearby compass needle. Thus a steady current through a conducting wire creates a magnetic field, as shown in figure 13.1.

To demonstrate the magnetic field produced by the current in a wire, we can perform simple experiments.

FIGURE 13.1



Using an apparatus similar to the one shown, Oersted was able to demonstrate a connection between magnetism and electricity by applying current to the wire.

OERSTED(1777-1851)

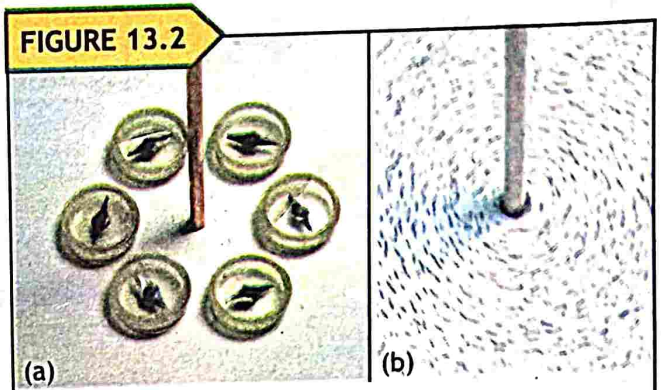


In 1806 Hans Christian Oersted became a professor at the University of Copenhagen, where his first physical researches dealt with electric currents and acoustics. In 1932 the name oersted was adopted for the physical unit of magnetic field strength.

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When current is passed through a long wire with compass needles placed around it in a circle, compass needles lineup with the magnetic field. Similar observations can be made through a cardboard on which iron fillings are sprinkled. These iron fillings form concentric circles around the wire, as shown in figure 13.2.

FIGURE 13.2



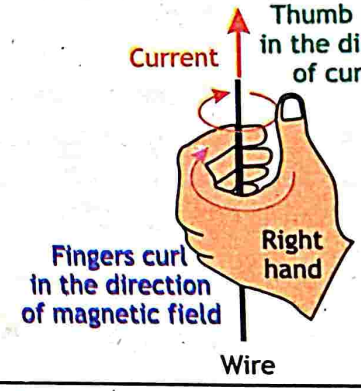
(a) A current carrying wire with compass needles lining up with magnetic field in circular pattern (b) A current carrying wire through a cardboard shows concentric circles of iron fillings around the wire.

These experiment shows the orientation of a magnetic field, which is in the form of circle around the wire. The direction of magnetic field can be determined by Right Hand Rule I as shown in figure 13.3.

FIGURE 13.3

RIGHT-HAND RULE I FOR THE MAGNETIC FIELD FROM A CURRENT CARRYING WIRE:

Put your thumb in the direction of current and curl your fingers around the wire, the curled fingers will show the direction of magnetic field. This rule is for direction of conventional current or flow of positive charges. For electronic current flow the same rule is applied but with left hand.



13.2 FORCE ON A CURRENT CARRYING CONDUCTOR

When a current carrying wire is placed in a uniform magnetic field, the magnetic field of the wire and external uniform field interact, resulting in a force on the wire as shown in figure 13.4. This force 'F_B' depends on the magnetic field 'B' applied, current 'I' in the wire, and the length 'L' of the wire that lies in the field, and the sine of angle 'θ' that the current carrying wire makes with the field.

Mathematically $F_B \propto ILB\sin\theta$

$$F_B = kILB\sin\theta$$

Here the constant of proportionality is k, which in SI units has the numeric value exactly equal to 1, therefore

$$F_B = ILB\sin\theta \quad \text{13.1}$$

Or in vector form $\vec{F}_B = ILB\sin\theta\,\hat{n}$

or $\vec{F}_B = I(\vec{L}\times\vec{B})$

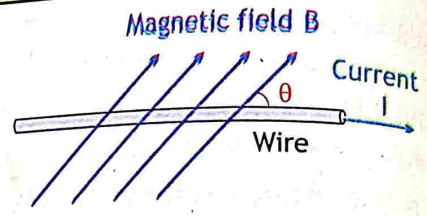
This magnetic force 'F_B' is minimum when θ is 0° (as sin 0° =0), if we keep B, *I* and *L* constant, the magnetic force 'F_B' is maximum when θ is 90° (as sin 90° =1).

$$F_{B(max)} = ILB\sin 90° \quad \text{as} \quad \sin 90° = 1$$

$$F_{B(max)} = ILB \quad \text{13.2}$$

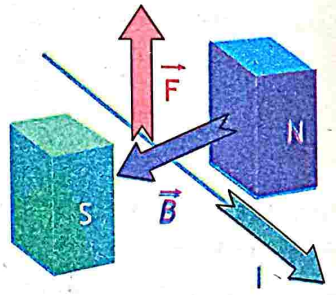
As force is a vector quantity so its direction should also be determined.

FIGURE 13.4



Conductor in a magnetic field

FIGURE 13.5



Conductor in a magnetic field

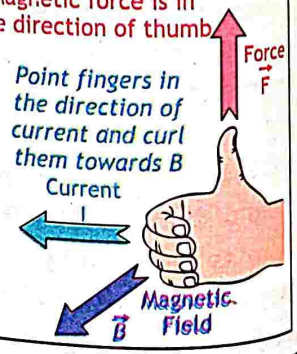
The direction of magnetic force F_B on a wire can be determined by right hand rule II and Fleming's left hand rule as shown in figure 13.6 and 13.7 respectively. The magnetic induction B will be one tesla if 1 m long wire carrying a current of 1 A are placed perpendicular to each other and the force between them is 1N. In SI $B=1T=NA^{-1}m^{-1}$. In CGS $1G=10^{-4}$ Tesla.

$$1T = 1\frac{N}{Am}$$

FIGURE 13.6

RIGHT-HAND RULE II FOR THE FORCE ON A CURRENT CARRYING CONDUCTOR:

Outstretch the fingers of right hand in the direction of current then bend the fingers in the direction of magnetic field (through the shorter angle between them) then the extended thumb will give the direction of force on the current carrying wire. This rule is for direction of conventional current or flow of positive charges. For electronic current flow the same rule is applied but with left hand.

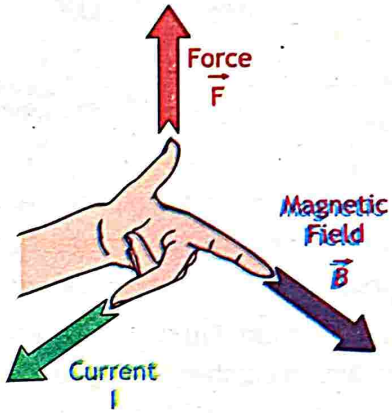


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FIGURE 13.7

FLEMING'S LEFT HAND RULE FOR THE FORCE ON A CURRENT CARRYING CONDUCTOR:

Set the thumb and the first two fingers of the left hand at right angles to each other as shown. With the first finger pointing in the direction of the field and second finger pointing in the direction of current, the thumb will give the direction of the force.



EXAMPLE 13.1 — **MAGNETIC FORCE ON WIRE**

A wire carrying 2 A current and has length of 10 cm between the poles of a magnet is kept at an angle of 30° to the uniform field of 0.6 T. Find the force acting on the wire?

GIVEN

Current 'I' = 2A

Length 'L' = 10 cm = 0.01 m

Magnetic field 'B' = 0.6 T

Angle 'θ' = 30°

REQUIRED

Magnetic Force 'F_B' = ?

SOLUTION

The force on a current carrying wire in magnetic field is given by

$$F_B = ILB\sin\theta$$

Putting values

$$F_B = 2\,A\times 0.1\,m\times 0.6\,\frac{N}{Am}\times\sin 30°$$

therefore $F_B = 0.06\,N$ — **Answer**

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13.3 MAGNETIC FLUX

The scalar product of magnetic induction $\vec{B}$ and the area $\vec{A}$, is called magnetic flux Φ_B.

$$\Phi_B = \vec{B} \bullet \vec{A} = BA\cos\theta$$

Magnetic induction tells us how close together magnetic field lines are, as it tells us the strength of the magnetic field. The number of magnetic field lines passing through a surface placed perpendicular to it is called magnetic flux.

A. Maximum Flux: If area vector A is parallel to the magnetic field B, then maximum number of magnetic field lines will pass through the surface. Therefore magnetic flux will be maximum,

$\Phi_B = BA\cos 0^\circ$ since $\cos 0^\circ = 1$ therefore $\Phi_B = BA$ ——— (1)

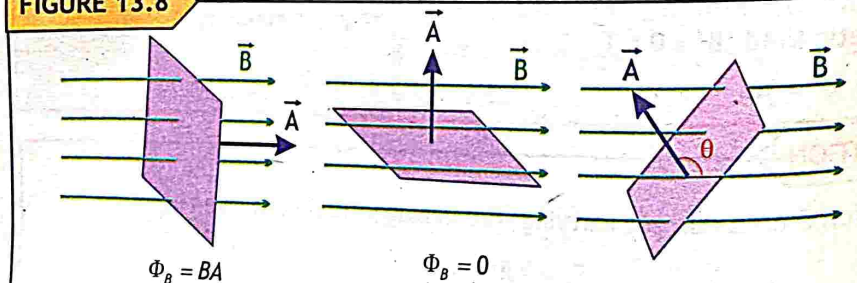
B. Minimum Flux: If area vector A is perpendicular to the magnetic field B, then no magnetic field lines will pass through the surface. Therefore magnetic flux will be zero or minimum,

$\Phi_B = BA\cos 90^\circ$ since $\cos 90^\circ = 0$ therefore $\Phi_B = 0$ ——— (2)

C. Flux at any Angle: If area vector A is making any angle with magnetic field B, then magnetic flux will depend upon the angle θ between them,

$$\Phi_B = BA\cos\theta \text{ ——— (3)}$$

FIGURE 13.8



Magnetic flux

MAGNETIC FLUX THROUGH CURVED OR NON-UNIFORM MAGNETIC FIELD

If the magnetic field is non-uniform or the area is curved. Then we divide the whole curved path into small patches each of area ΔA, such that they are approximately flat and magnetic field is almost uniform over it as shown in figure 13.9.

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or one of these small patches the magnetic flux is

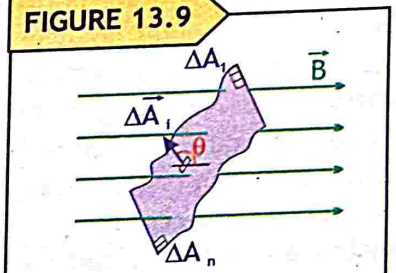
$$\Phi_B = \vec{B} \bullet \Delta\vec{A}_i = B\Delta A_i \cos\theta$$

To calculate the flux through whole surface, we add the flux from each patch, such that

$$\Phi_B = \sum_{i=1}^{n} \Delta\Phi_B = \sum_{i\ 1\ =}^{n} \vec{B}_i \bullet \Delta\vec{A}_i = \sum_{i=1}^{n} B_i \Delta A_i \cos\theta_i$$

$$\Phi_B = B\cos\theta \sum \Delta A = BA\cos\theta \quad \text{13.3}$$

FIGURE 13.9



$$\Phi_B = \sum_{i=0}^{n} B_i \Delta A_i \cos\theta$$

UNIT OF MAGNETIC FLUX AND FLUX DENSITY

The SI unit of magnetic flux is equal to the unit of magnetic field (1 T) times the unit of area (m^2), $1\ Wb = 1\ T \times m^2$. This unit is called the weber (1 Wb), in honor of the German physicist Wilhelm Weber.

$$1\ Wb = 1\ T \times m^2 \quad (1T = 1\ N/A\ m)$$

$$So\ 1\ Wb = 1\ N\ m/A$$

The unit of magnetic induction can be written as $T = Wb\ m^{-2}$

13.4: AMPERE CIRCUITAL LAW

Ampere's circuital law, given by Andre Marie Peter Ampere in 1826, relates the integrated magnetic field in a loop around a current carrying wire to the current passing through the wire.

Ampère's circuital law states that, for any closed loop, the sum of the length elements multiplied by the component of magnetic field parallel to each element is proportional to the current enclosed by the path.

$$\sum B.\Delta l = \mu_0 I$$

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Ampere law is the relation between magnetic field and current near a current carrying conductor. When no current is present in the wire, all compass needles point in the same direction (toward the Earth's north pole). When the wire carries a strong current, the compass needles deflect in a direction tangent to the circle, which is the direction of the magnetic field created by the current. Now consider a test point P located at distance r from the current carrying conductor, where we want to find the magnitude of magnetic induction B as shown in figure 13.10. At point 'P', the magnetic induction is directly proportional to the current 'I' flowing through the conductor and inversely proportional to the distance 'r' from the wire.

$$B \propto \frac{I}{r} \quad \text{or} \quad B = \frac{\mu_o}{2\pi} \times \frac{I}{r} \qquad \text{——} (1)$$

Where $\mu_o/2\pi$ is the constant of proportionality, and 'μ_o' is the permeability of a vacuum and its value is $4\pi \times 10^{-7}$ Tm/A or $4\pi \times 10^{-7}$ Wb/A m. Since, the sum of all the length elements Δl gives the circumference of circle $2\pi r$,

$$\sum \Delta l = 2\pi r \qquad \text{——} (2)$$

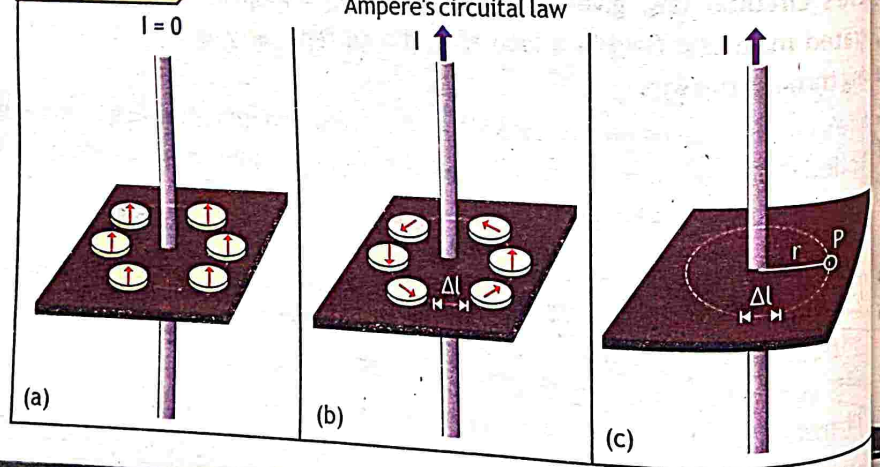
AMPERE (1775- 1836)



Ampère, a Frenchman, is credited with the discovery of electromagnetism – the relationship between electric currents and magnetic fields.

FIGURE 13.10

Ampere's circuital law



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PERMEABILITY (μ)

The permeability of a vacuum (μ_o) is $4\pi \times 10^{-7}$ Wb/At.m (webers/ampere-turn' meter) and is used as a reference. The relative permeability (μ_r) of a material is the ratio of its absolute permeability to the permeability of a vacuum.

$$\mu_r = \frac{\mu}{\mu_o}$$

Because it is a ratio of permeabilities, μ_r is dimensionless. Typical magnetic materials, such as iron, have a relative permeability of a few hundred.

from equation 1 and equation 2 the dot product of B for any closed path Δl we can write

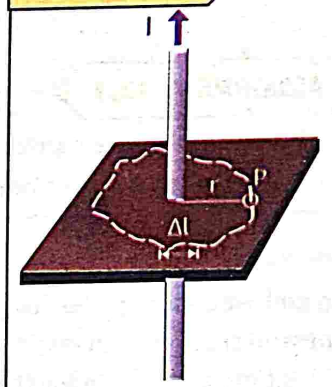
$$\sum B \bullet \Delta l = B \sum \Delta l = \frac{\mu_o I}{2\pi r} \times \sum \Delta l$$

$$\text{or} \quad \sum B \bullet \Delta l = \frac{\mu_o I}{2\pi r} \times 2\pi r$$

$$\text{hence} \quad \boxed{\sum B \bullet \Delta l = \mu_o I} \qquad 13.4$$

Equation 13.4 is Ampere's law. The closed path is called Amperian path. In general this law can be applied to any closed path around a current carrying conductor as shown in figure 13.11. For any other medium apart from vacuum or air the permeability μ of that material is used in the equation for Ampere's law.

FIGURE 13.11



Amperian path

EXAMPLE 13.2 — **MAGNETIC FIELD BETWEEN CURRENT CARRYING WIRES**

Two long parallel wires 6 cm apart carry current of 8 A and 2 A in the same direction. What is magnitude of magnetic field midway between them?.

GIVEN

current due to wire 1 = I_1 = 8 A , current due to wire 2 = I_2 = 2 A

At midway between wires '$r_1 = r_2$' = 6 cm/2 = 0.03 m

REQUIRED

Net magnetic field B_{net} = ?

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SOLUTION

The net magnetic field is $B_{net} = B_1 + B_2$

as fields are opposite in the middle, therefore $B_{net} = B_1 - B_2$

Applying Ampere Circuital Law $B_{net} = \mu_o \frac{I_1}{2\pi r_1} - \mu_o \frac{I_2}{2\pi r_2}$

putting values $B_{net} = 4\pi \times 10^{-7} \frac{T\,m}{A} \frac{8A}{2\pi 0.03m} - 4\pi \times 10^{-7} \frac{T\,m}{A} \frac{2A}{2\pi 0.03m}$

therefore $B_{net} = 4 \times 10^{-5} T$ **Answer**

ASSIGNMENT 13.1 **MAGNETIC FIELD OF A LONG WI**

A long straight wire carries a current of 1 A. Find the magnitude of the magnet field at a distance 1 m from it. **(Answer: 2×10^{-5} T**

A. MAGNETIC FIELD DUE TO A CURRENT CARRYING SOLENOID

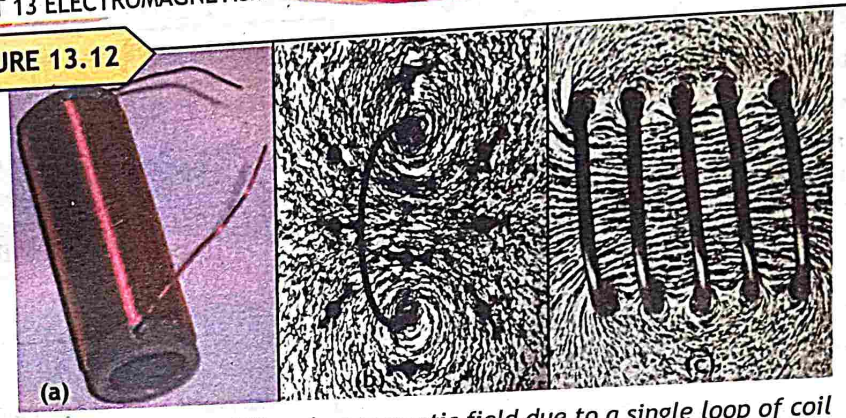
A coil wounded in the form of a spiral (helix) forms a solenoid. When curren passed through a solenoid a reasonably uniform magnetic field can be produce This field is strong along the axis of solenoid and weaker outside as shown in fig 13.12.

The magnetic field lines surrounding a loosely wound solenoid, shows that th lines in the interior are nearly parallel to one another, are uniformly distribute and are close together. For a tightly wound solenoid the field in the interior sp is very uniform and strong. The field lines resemble those of a bar magn meaning that the solenoid effectively has north and south poles. As the length the solenoid increases, the interior field becomes more uniform and the exter field becomes weaker as shown in figure 13.13.

An ideal solenoid is approached when the turns are closely spaced and the length much greater than the radius of the turns. In this case, the external field is close zero and the interior field is uniform over a great volume.

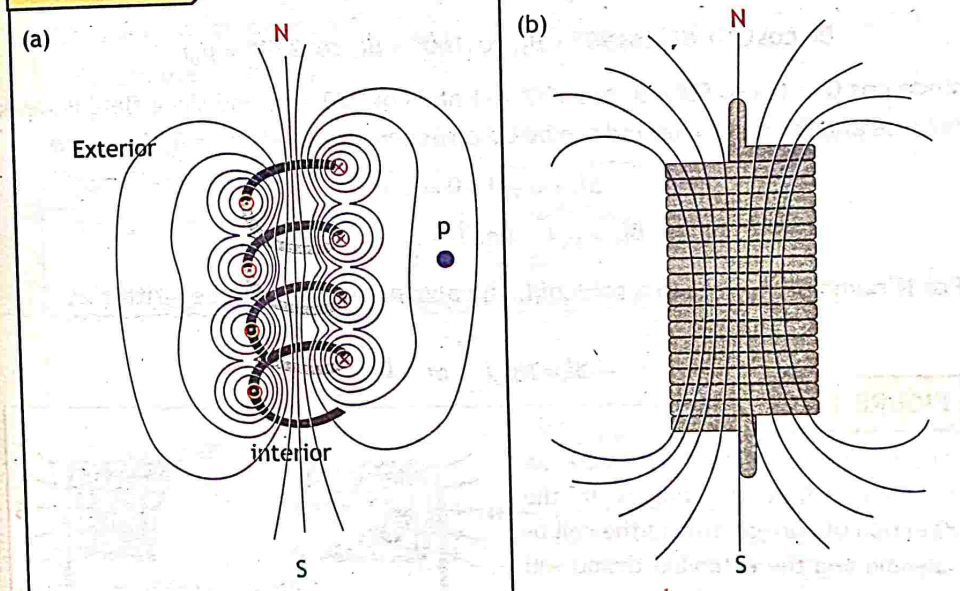
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FIGURE 13.12



(a) Solenoid (b) Iron fillings in a magnetic field due to a single loop of coil (c) Iron fillings in a magnetic field due to a solenoid

FIGURE 13.13



(a) The magnetic field lines for a loosely wound solenoid and (b) magnetic field lines for a tightly wound solenoid, carrying a steady current.

We can use Ampère's law to obtain a quantitative expression for the interior magnetic field in an ideal solenoid.

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Consider an closed Amperian path a-b-c-d, with lengths l_1, l_2, l_3 and l_4, where l_1 is inside the solenoid and l_3 outside the solenoid as shown in the figure 13.14. By Ampere Circuital law

$$\sum B \bullet \Delta l = \mu_o I$$

Since there are four length elements, therefore

$$B \bullet l_1 + B \bullet l_2 + B \bullet l_3 + B \bullet l_4 = \mu_o I$$

or $Bl_1 \cos\theta_1 + Bl_2 \cos\theta_2 + Bl_3 \cos\theta_3 + Bl_4 \cos\theta_4 = \mu_o I$

from the figure $\theta_1 = 0°$, $\theta_2 = 90°$, $\theta_3 = 180°$, and $\theta_4 = 270°$, hence

$$Bl_1 \cos 0° + Bl_2 \cos 90° + Bl_3 \cos 180° + Bl_4 \cos 270° = \mu_o I$$

since cos 0° = 1, cos 90° = 0, cos 180° = -1 and cos 270° = 0, and since field is wea outside and for ideal solenoid can be taken as zero hence at l_3, $B = 0$, therefore

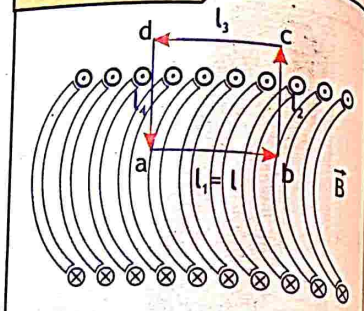
$$Bl_1 + 0 + 0 + 0 = \mu_o I$$

or $Bl_1 = \mu_o I$ Let $l_1 = l$ $Bl = \mu_o I$

For N number of turns in a solenoid, the above equation can be written as

$$Bl = N\mu_o I \quad \text{or} \quad B = \frac{N}{l}\mu_o I$$

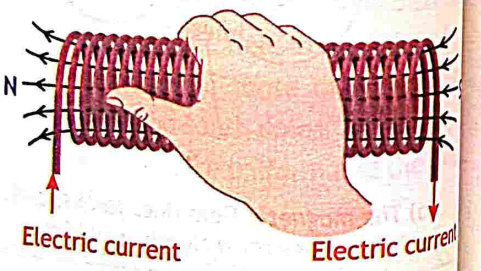
FIGURE 13.14



Magnetic field of Solenoid

FIGURE 13.15

RIGHT-HAND RULE III FOR A SOLENOID: Curl the fingers in the direction of current around the coil or solenoid and the extended thumb will point in the direction of north pole of a magnet. This rule is for direction of conventional current or flow of positive charges. For electronic current flow the same rule is applied but with left hand.



The right-hand rule (III) for a solenoid

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Let *n* be the number of turns per unit length ($n = N / l$), we can write the equation as

$$B = n\mu_o I \qquad \textbf{13.5}$$

The equation 13.5 can be used to determine the magnetic field of a solenoid.

EXAMPLE 13.3 — **DOUBLE LAYERED SOLENOID**

A solenoid is 10 cm long and is wound with two layers of wire. The inner layer has 50 turns and the outer layer has 40 turns. A current of 3A flows in both layers in the same direction. What is the magnitude of magnetic flux density along the axis of solenoid?

GIVEN

Length of a solenoid 'L' = 10 cm = 0.01 m
Turns of inner layer 'n_1' = 50 turns
Turns of outer layer 'n_2' = 40 turns
Current 'I' = 3A

REQUIRED

Magnetic flux density 'B' = ?

SOLUTION

The net magnetic field from inner and outer layer of the solenoid is

$$B_{net} = B_1 + B_2$$

To determine the magnetic field of a solenoid, put equation 13.5 we get

$$B_{net} = \frac{N_1}{L}\mu_o I + \frac{N_2}{L}\mu_o I$$

putting values $B_{net} = \dfrac{50}{0.01\cancel{m}} \times 4\pi \times 10^{-7} \dfrac{T\cancel{m}}{\cancel{A}} \times 3\cancel{A} + \dfrac{40}{0.01\cancel{m}} \times 4\pi \times 10^{-7} \dfrac{T\cancel{m}}{\cancel{A}} \times 3\cancel{A}$

therefore $B_{net} = 3.4 \times 10^{-3} T$ — **Answer**

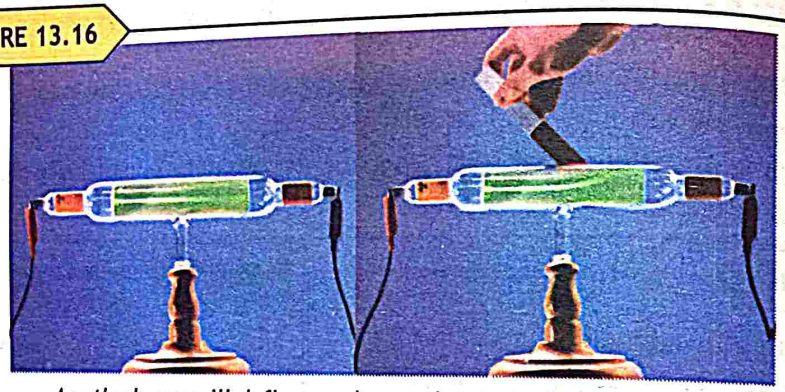
ASSIGNMENT 13.2 — **SOLENOID**

You are asked to design a solenoid that will give a magnetic field of 0.10 T, yet the current must not exceed 10.0 A. Find the number of turns per unit length that the solenoid should have. **(Answer: 7.96×10^3 m^{-1})**

13.6 MOTION OF CHARGED PARTICLE IN MAGNETIC FIELD

Moving charge also experience a magnetic field, as shown in figure 13.16 so it can be concluded that the force on the current carrying conductor in magnetic field results from the forces acting on individual moving charges.

FIGURE 13.16



A cathode ray will deflect as shown when it is also under the influence of an external magnetic field.

A. MAGNETIC FORCE ON A POINT CHARGE

When a point charge is placed in an electric field, it experiences an electric force. When a charge is placed in a magnetic field, it also experiences a force, provided that the following two conditions are met.

1. The charge must be moving, because no magnetic force acts on a stationary charge.

2. The velocity of the moving charge must have a component that is perpendicular to the direction of the magnetic field.

Consider a positive point charge '+q' moves at velocity 'v' at a point where the magnetic field is 'B', as shown in figure 13.17. The angle between 'v' and 'B' is 'θ'. The magnitude of the magnetic force acting on the point charge is the product of

The magnitude of the charge '|q|',

The magnitude of the field 'B', and

The component of the velocity 'v' perpendicular to the field

$$F_B = q(v\sin\theta)B$$

NOT FOR SALE

In some cases it is convenient to look at the factor 'sin θ' from a different point of view. If we associate the factor 'sin θ' with the magnetic field instead of with the velocity, then 'B sin θ' is the component of the magnetic field perpendicular to the velocity of the charged particle

$$F_B = qv(B\sin\theta)$$

The magnetic force can be written in terms of cross product of two vectors 'v' and 'B' as

$$\vec{F}_B = qv\vec{B}\sin\theta\,\hat{n} \qquad 13.6$$

or

$$\vec{F}_B = q\vec{v}\times\vec{B} \qquad 13.7$$

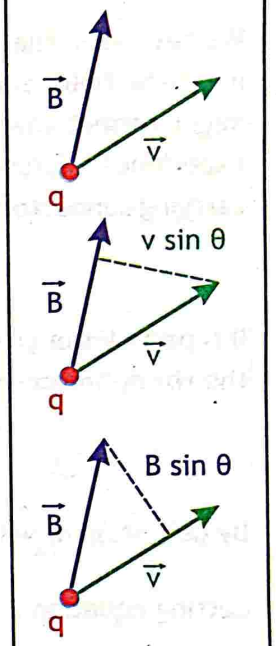
The force is greatest when the particle moves perpendicular to B ($\theta = 90°$) because $\sin 90° = 1$:

$$F_{max} = qvB$$

The force is minimum or zero if the particle moves parallel to the field lines ($\theta = 0°$) because $\sin 0° = 0$:

$$F_{min} = 0$$

FIGURE 13.17

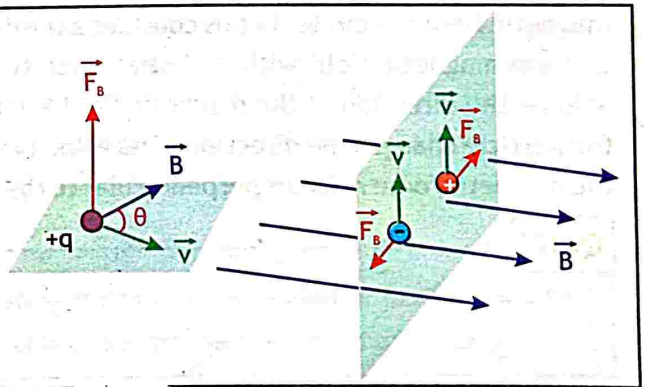


Velocity of particle in magnetic field

The direction of the force is perpendicular to the magnetic field B and to the velocity v of the particle. For a positive charge, the Right Hand Rule II and Fleming's Left Hand Rule for force on a current carrying conductor are used to determine the direction of force. Where the direction of current is replaced by velocity of charged particle.

FIGURE 13.18

The direction of the magnetic force F_B acting on a charged particle moving with a velocity v in the presence of a magnetic field B. (a) The magnetic force is perpendicular to both v and B. (b) Oppositely directed magnetic forces F_B are exerted on two oppositely charged particles moving at the same velocity in a magnetic field.



B. THE FORCE ON CURRENT CARRYING CONDUCTOR AND MOTION OF CHARGE PARTICLE IN MAGNETIC FIELD

We have seen that a current-carrying wire experiences a force when placed in a magnetic field. Since a current in a wire consists of moving electric charges, we might expect that freely moving charged particles (not in a wire) would also experience a force when passing through a magnetic field. The force on a current carrying conductor is

$$F_B = BIL\sin\theta \quad \text{——} (1)$$

If N particles of charge q pass by a given point in time , they constitute a current, then by definition of current

$$I = \frac{Nq}{t} \quad \text{——} (2)$$

By definition of velocity $v = \frac{L}{t}$ or $L = vt$ ——(3)

putting equation 2 and equation 3 in equation 1, we get $F_B = B \times \frac{Nq}{t} \times vt \times \sin\theta$

or $F_B = BNqv\sin\theta$

for a single particle N = 1 $F_B = Bqv\sin\theta$ or $F_B = qvB\sin\theta$

In vector form $F_B = q\vec{v} \times \vec{B}$ or $F_B = qvB\sin\theta\,\hat{n}$

C: CIRCULAR MOTION OF CHARGE PARTICLE IN UNIFORM MAGNETIC FIELD

The path of a charged particle moving in a plane perpendicular to a uniform magnetic field is a circle. Let us consider a positively charged particle moving in a uniform magnetic field with its initial velocity perpendicular to the field. Let's assume the direction of the magnetic field is into the page as in Figure 13.19. As the particle changes the direction of its velocity in response to the magnetic force, the magnetic force remains perpendicular to the velocity.

QUIZ?

1. Why wheat flour is usually passed near a magnet before being packed?
2. Why a steel ship becomes magnetized as it is constructed?

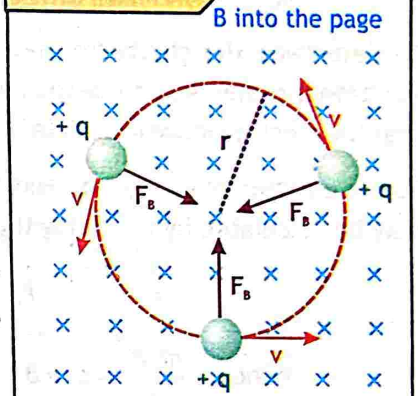
The particle moves in a circle because the magnetic force 'F_B' is perpendicular to 'v' and 'B' and has a constant magnitude 'qvB'. The centripetal force 'F_C' is provided by magnetic force 'F_B', therefore

$$F_C = F_B \quad \text{——} (1)$$

For a particle of mass m moving with velocity 'v' in a circle of radius 'r' the centripetal force 'F_C' is

$$F_C = \frac{mv^2}{r} \quad \text{——} (2)$$

FIGURE 13.19



Circular trajectory of charged particle in magnetic field.

If the charge on particle is +q, which is moving with velocity v perpendicular to magnetic field of strength B the magnetic force F_B is maximum which is

$$F_B = qvB \quad \text{——} (3)$$

putting equation 2 and equation 3 in equation 1, we get $\frac{mv^2}{r} = qvB$

$$\frac{mv}{r} = qB \quad \text{——} (4)$$

the relation between linear angular velocity is v = rω, therefore equation 4 can be written as

$$\frac{mr\omega}{r} = qB \quad \text{or} \quad m\omega = qB \quad \text{rearranging} \quad \omega = \frac{qB}{m} \quad \text{——} (5)$$

From the above equation we can determine the time period T of the charged particle

$$T = \frac{2\pi}{\omega} = \frac{2\pi}{qB/m} = \frac{2\pi m}{qB} \quad \text{since} \quad f = \frac{1}{T}$$

therefore $\boxed{f = \frac{qB}{2\pi m}}$ **13.8**

This is often called the cyclotron frequency of a particle in a field because this is the frequency at which particles revolve in a cyclotron

D. DETERMINATION OF CHARGE TO MASS RATIO FOR AN ELECTRON

To determine the charge to mass ratio (q_e/m_e) for an electron. The beam of electron is projected on a perpendicularly arranged uniform magnetic filed, such that the electron move in a circle.

For an electron of charge 'q_e' and mass 'm_e', the charge to mass ratio (q_e/m_e) may be calculated by balancing the centripetal and magnetic forces.

$$F_C = F_B$$

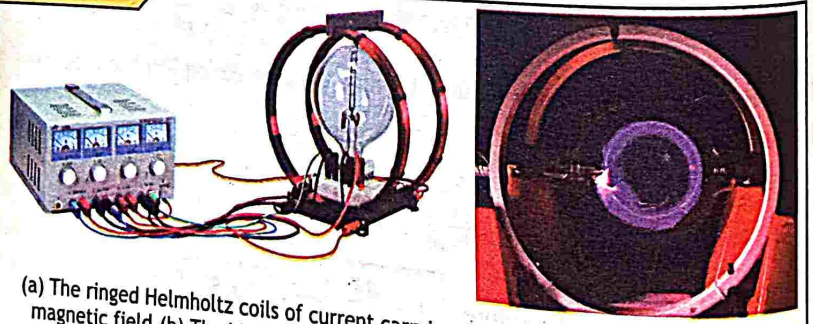
hence $\frac{m_e v^{\not 1}}{r} = q_e \not{v} B$ or $\frac{m_e v}{r} = q_e B$

rearranging $\frac{q_e}{m_e} = \frac{v}{Br}$ ——— (1)

Practically the values of 'B' can be calculated easily from the apparatus shown in the figure 13.20, from ringed coils (called Helmhold's Coils). The radius 'r' can also be calculated by making the electron beam visible through ionization and de-excitation of the gas molecules. However the velocity 'v' is determined by calculating the kinetic energy of electron by applying the potential 'V' of known value. Such that by law of conservation of energy

$$\frac{1}{2} m_e v^2 = q_e V \quad \text{or} \quad v^2 = \frac{2 q_e V}{m_e}$$

FIGURE 13.20



(a) The ringed Helmholtz coils of current carrying wire produce a nearly uniform magnetic field. (b) The blue ring inside the glass tube is the glow of a beam of electrons that ionize the gas molecules.

Taking square root on both sides $\sqrt{v^{\not 2}} = \sqrt{\frac{2 q_e V}{m_e}}$

hence $v = \sqrt{\frac{2 q_e V}{m_e}}$ ——— (2)

putting equation 2 in equation 1, we get $\frac{q_e}{m_e} = \frac{1}{Br}\sqrt{\frac{2 q_e V}{m_e}}$

squaring both sides $\left(\frac{q_e}{m_e}\right)^2 = \left(\frac{1}{Br}\sqrt{\frac{2 q_e V}{m_e}}\right)^2$ or $\left(\frac{q_e}{m_e}\right)^{\not 2} = \frac{2V}{B^2 r^2}\left(\frac{q_e}{m_e}\right)$

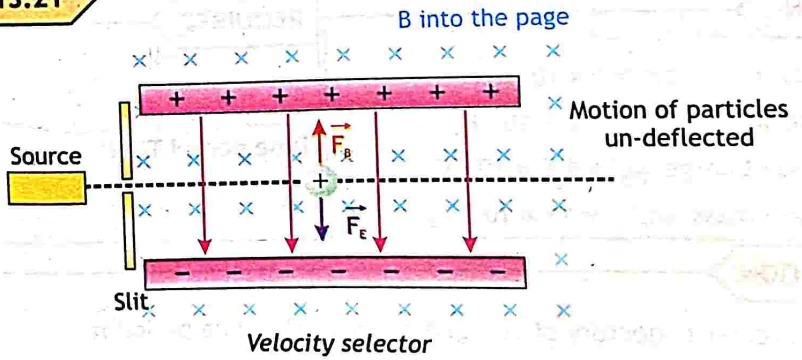
$$\frac{q_e}{m_e} = \frac{2V}{B^2 r^2} \qquad 13.9$$

Thus the knowing the values of potential 'V', magnetic field 'B' and radius 'r', the charge to mass ratio can be determined. The accurately known value of e/m for electron is 1.7588×10^{11} C kg^{-1}

E. VELOCITY SELECTOR

The device which allow only the particles with certain specific speed through it (thus permitting particles only with selected speeds) is called velocity selector.

FIGURE 13.21



NOT FOR SALE

If the electric and magnetic fields are applied perpendicular to each other and adjusted such that the magnitude of electric force is equal but direction is opposite to the magnetic force as shown in figure 13.21, then

$$F_{electric} = F_{magnetic}$$

since $F_{electric} = qE$ and $F_{magnetic} = qvB$

therefore $qE = qvB$

or $v = \frac{E}{B}$ — 13.10

If the beam of charged particles moving with different velocities pass through velocity selector only those particles will pass straight through the device which have velocities equal to the ratio of electric to the magnetic field. Particles moving slower than this speed will be deflected in the direction of electric force and those having greater speeds will be deflected in the direction of magnetic force.

EXAMPLE 13.4 — **TIME PERIOD FOR ELECTRON IN MAGNETIC FIELD**

The path of an electron in a uniform magnetic field of flux density 1.0×10^{-2} T in a vacuum is a circle of radius 1 cm. Calculate the period of its orbit?

GIVEN

Radius 'r' = 1 cm = 1×10^{-2} m
magnetic field 'B' = 1.0×10^{-2} T
Electron Charge 'q_e' = 1.6×10^{-19} C
Electron mass 'm_e' = 9.11×10^{-31} kg

REQUIRED

Time period T = ?

SOLUTION

From circular trajectory of charged particle, the time period is

$$T = \frac{2\pi m}{qB}$$

NOT FOR SALE

Putting values $T = \frac{2 \times 3.14 \times 9.11 \times 10^{-31}\ \text{kg}}{1.6 \times 10^{-19}\ \text{C} \times 1 \times 10^{-2}\ \text{T}}$

therefore $T = 3.57 \times 10^{-9}\ \text{s} = 3.57\ ns$ — Answer

ASSIGNMENT 13.3 — **VELOCITY SELECTOR**

A velocity selector in a mass spectrometer uses a 0.100 T magnetic field. What electric field strength is needed to select a speed of 4.00×10^6 m/s?

(Answer: 4.00×10^5 N/C)

13.7 TORQUE ON A CURRENT CARRYING COIL

When a current carrying coil or loop is placed in uniform magnetic field it experience a force, this force can exert torque on the coil or loop of wire.

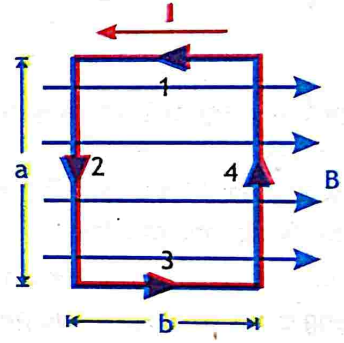
Let us consider a rectangular coil carrying a current I in the presence of a uniform magnetic field B directed parallel to the plane of the loop as shown in Figure 13.22. No magnetic forces act on sides 1 and 3 because these wires are parallel to the field $\theta = 0°$; the length of sides 1 and 3 is b, therefore magnetic force is

$$F_1 = F_3 = BIb \sin 0°$$

since $\sin 0° = 0$

Therefore $F_1 = F_3 = 0$ ——— (1)

FIGURE 13.22



A coil in a magnetic field

However maximum magnetic forces act on sides 2 and 4, because these sides are perpendicular to the field $\theta = 90°$; the length of sides 2 and 4 is a, therefore magnetic force is

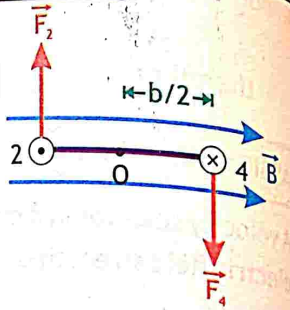
$F_2 = F_4 = BIL \sin 90°$ since $\sin 90° = 1$ Therefore $F_2 = F_4 = BIa$ ——— (2)

By applying Right hand rule II or Fleming's left Hand rule it can be seen that the forces on sides 2 and 4 (F_2 and F_4) are such that they produce a net torque.

If we view the loop from side 3 and sight along sides 2 and 4, we see the view shown in Figure 13.23. The two magnetic forces F_2 and F_4, that the two forces point in opposite directions such that they form a couple. If the loop is pivoted so that it can rotate about point O, these two forces produce a torque that rotates the loop (in this case clockwise). The magnitude of this torque is

$$\tau = F_2\frac{b}{2} + F_4\frac{b}{2} \quad \text{——} (3)$$

FIGURE 13.23



Side view of a coil in a magnetic field

putting values of F_2 and F_4 from equation 2 in equation 3, we get

$$\tau = IBa\frac{b}{2} + IBa\frac{b}{2} \quad \text{or} \quad \tau = 2IBa\frac{b}{2} \quad \text{Therefore} \quad \tau = IBab \quad \text{——} (4)$$

Since a is the length and b is the width of the coil, therefore

$$ab = A \quad \text{——} (5)$$

putting equation 5 in equation 4, we get $\tau = IBA$ **13.11**

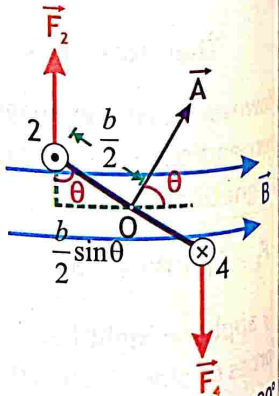
Equation 13.11 represents the maximum condition for torque on a current carrying loop of wire.

Now suppose the uniform magnetic field B makes an angle $\theta < 90°$ with a line perpendicular to the plane of the loop as in Figure 13.24.

The torque is given by relation

$\tau = IBA\sin\theta$ **13.12**

FIGURE 13.24



Torque at an angle $\theta < 90°$

EXAMPLE 13.5 **TORQUE ON A LOOP**

A square loop of wire of side 4.0 cm carries 3.0 A of current. A uniform magnetic field of magnitude 0.67 T makes an angle of 30° with the plane of the loop. (a) What is the magnitude of the torque on the loop? (b) What is the net magnetic force on the loop?

GIVEN

For single square loop number of turns 'N' = 1

Magnetic field 'B' = 0.6 T

Area 'A' = ab = 4.0 cm × 4.0 cm = 0.0016 m

Current 'I' = 3.0 A

Angle with plane of the loop 'φ' = 30°

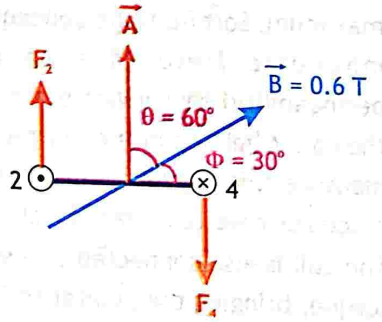
REQUIRED

Torque 'τ' = ?

Magnetic force 'F_B' = ?

SOLUTION

The angle 'θ' between vector area 'A' and magnetic field 'B' is $\theta = 90° - \Phi = 90° - 30° = 60°$



(a) The torque on current carrying coil is

$$\tau = NIAB\sin\theta$$

putting values

$$\tau = 1 \times (3.00\,A) \times 0.0016\,m \times 0.6\,T \sin 60°$$

Hence $\tau = 2.5 \times 10^{-3}\,Nm$ **Answer**

(b) B sin θ is the same at opposite sides of the loop and opposite sides of the loop have equal and opposite so the forces on opposite sides are equal and opposite. And net force is zero

$$\vec{F}_{net} = \vec{F}_{top} + \vec{F}_{bottom} + \vec{F}_{right} + \vec{F}_{left}$$

Therefore $\vec{F}_{net} = \vec{F}_{top} - \vec{F}_{top} + \vec{F}_{right} - \vec{F}_{right}$

Hence $\vec{F}_{net} = 0\,N$ **Answer**

NOT FOR SALE

13.8 GALVANOMETER

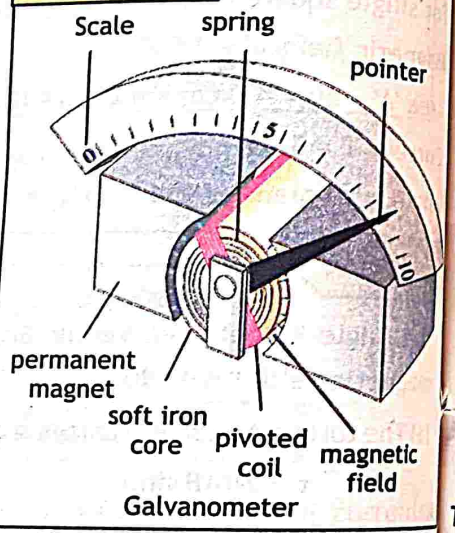
A device used for detection and measurement of small electric currents is call galvanometer.

The principle of moving coil galvanometer is the torque on current carrying coil the magnetic field.

Modern galvanometer are moving coil galvanometers, which are also calle d'Arsonval galvanometers.

Moving coil galvanometer consist of pivoted coil wrapped around soft iron core, placed in a concave poles of a permanent magnet as shown in the figure 13.25. The poles of the magnet are made concave to make the field stronger and radial, such that magnetic force is perpendicular and torque is always maximum. Soft iron core concentrates the magnetic field (due to its high permeability) thus giving more inertia to the coil. A light pointer or mirror is used to measure this angular deflection which is placed on a well calibrated scale.

FIGURE 13.25



Galvanometer

The coil is also connected to a spring from other side which produce a restoring torque, bringing the pointer to initial state when the current flow stops.

The net torque on the coil is the sum of torque produced due to magnetic force and the restoring torque due to spring. Let the magnetic torque be counterclockwise while the spring coil be the restoring torque opposite to it and is taken as negative.

Thus $\vec{\tau}_{net} = \vec{\tau}_{mag} + (-\vec{\tau}_{res})$ ——— (1)

When the pointer comes to rest equilibrium is achieved, the net torque is zero $\tau_{net} = 0$,

$$\vec{\tau}_{net} = 0 \quad \text{——— (2)}$$

When current is applied, a magnetic field B sets-up in the coil and iron core assembly which interacts with a permanent magnet producing a torque.

$$\vec{\tau}_{mag} = NIAB\sin\theta$$

Where N is the number of turns in the coil. Since the magnetic field is radial, therefore vector area is perpendicular to the field $\theta = 90°$ and $\sin 90° = 1$, therefore

$$\vec{\tau}_{mag} = NIAB \quad \text{——— (3)}$$

The restoring torque in its rotational form is

$$\vec{\tau}_{res} = c\varphi \quad \text{——— (4)}$$

Where c is the spring constant (restoring torque per unit twist) in rotation and φ is the angular displacement. Putting equations 2, 3 and 4 in equation 1, we get

$$0 = NIAB - c\varphi \qquad \text{or} \qquad NIAB = c\varphi$$

$$I = \frac{c\varphi}{NAB} \qquad \textbf{13.13}$$

The factor c/NAB is constant, thus the sensitivity of galvanometer can be adjusted by changing deflection angle φ, which is done by changing the factor c/NAB. Thus current I is proportional to angular displacement φ

$$I \propto \varphi$$

This relation shows that angular deflection can be used to detect and measure small currents. The cylindrical soft iron assembly in the core of galvanometer rotates in proportion with the current.

NOT FOR SALE

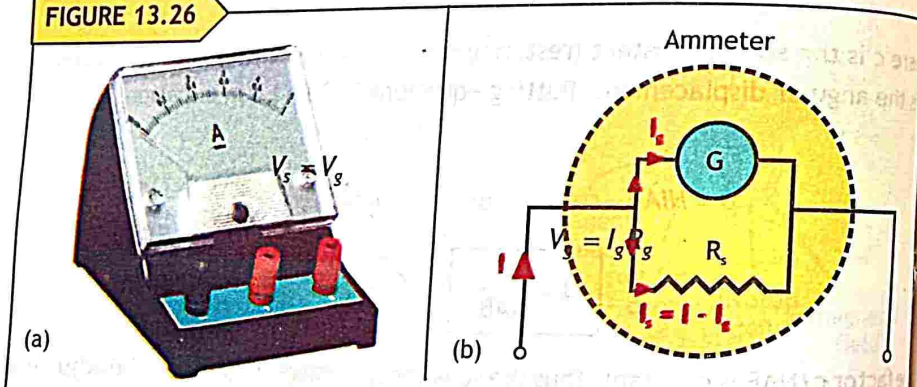
A. CONVERSION OF GALVANOMETER INTO AMMETER

An ammeter is a measuring instrument used to measure electric current in the circuit.

Galvanometer is a very sensitive device even a small current may show full sca deflection. Ammeter is modified form of galvanometer to measure large current.

The conversion of galvanometer into an ammeter is done by connecting a lo resistance called shunt in parallel with it. When this shunt resistance is connecte with galvanometer only small fraction of current flows through the galvanometer remaining large portion of current passes through the shunt resistance as shown i figure 13.26 .

FIGURE 13.26



(a) Ammeter (b) Internal circuit with shunt resistance 'R_s'

Let 'R_s' represents the shunt resistance and 'R_g' represents the internal resistance of galvanometer. Here 'I_g' is the current which produces full scale deflection i galvanometer and I is the total current through Ammeter. Since shunt resistance i connected parallel to the galvanometer, therefore the potential is same for both resistence.

$$V_s = V_g \quad \text{——} (1)$$

According to Ohm's law the potential drop across R_g is $V_g = I_g R_g$ ——(2)

Similarly by Ohm's law the potential drop across R_s is $V_s = I_s R_s$

But here $I_s = I - I_g$ therefore $V_s = (I - I_g)R_s$ ——(3)

putting equation 2 and equation 3 in equation 1, we get $(I - I_g)R_s = I_g R_g$

Hence $$R_s = \frac{I_g R_g}{(I - I_g)} \quad \text{13.14}$$

The shunt will convert a galvanometer into an ammeter which will give full scale deflection when current I passes through the main circuit. Ammeter must have small resistance, so that current change with it is small. Ideally an ammeter should not have any resistance.

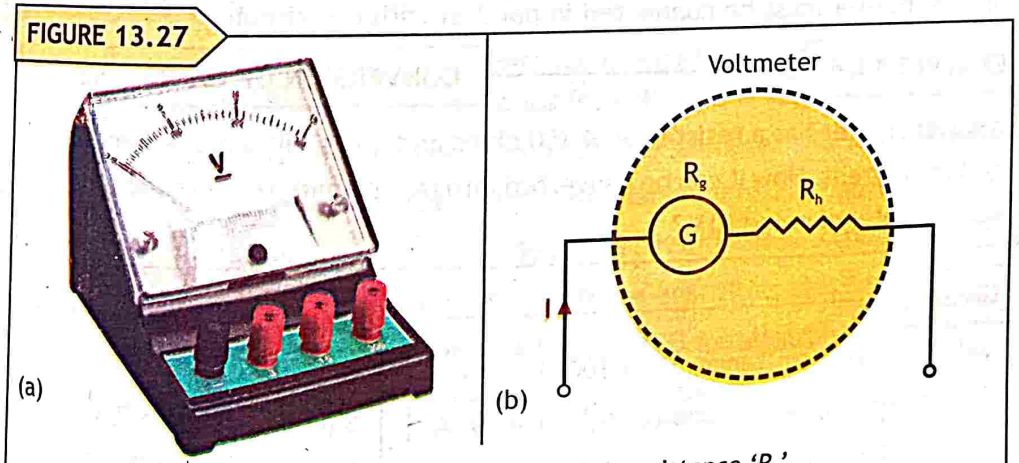
Note: Ammeter must be connected in series with the circuit.

B. CONVERSION OF GALVANOMETER INTO VOLTMETER

Voltmeter is a measuring instrument used to measure potential difference in the circuit.

Voltmeter is modified form of galvanometer to measure electric potential. The conversion of galvanometer into an voltmeter is made by connecting a high resistance in series with it.

FIGURE 13.27



(a) Voltmeter (b) Internal circuit with high resistance 'R_h'

Let R_g represents the internal resistance of galvanometer and current I_g is passing through it. The high resistance R_h also draws the same current I_g. Since in series combination the potential splits and the total potential V is the sum of the potential across the galvanometer V_g and the potential across the high resistance V_h

$$V = V_g + V_h \quad \text{——} (1)$$

According to Ohm's law the potential drop across R_g is $V_g = I_g R_g$ —— (2)

Similarly by Ohm's law the potential drop across R_h is $V_h = I_h R_h$

but since $I_h = I_g$ therefore $V_h = I_g R_h$ —— (3)

putting equation 2 and equation 3 in equation 1, we get $V = I_g R_g + I_g R_h$

or $I_g R_h = V - I_g R_g$ or $R_h = \dfrac{V - I_g R_g}{I_g}$ or $R_h = \dfrac{V}{I_g} - \dfrac{I_g R_g}{I_g}$

therefore $R_h = \dfrac{V}{I_g} - R_g$ **13.15**

The high resistor will convert a galvanometer into an voltmeter. Voltmeter must have high resistance, because it should not draw any current from the circuit. Ideally an voltmeter should have an infinite resistance.

Note: Voltmeter must be connected in parallel with the circuit.

EXAMPLE 13.6 **CONVERSION OF GALVANOMETER**

A galvanometer has a resistance of 100 ohms and gives full scale deflection on 1 mA current. How it can be converted into (a) an ammeter of range 10 A, (b) voltmeter of range 10 V?

GIVEN

Galvanometer resistance 'R_g' = 100 Ω

Current through galvanometer 'I_g' = 1×10^{-3} A

current range 'I' = 10 A

voltage range 'V' = 10 V

REQUIRED

Shunt resistance R_s = ?

High resistance R_h = ?

SOLUTION

(a) Galvanometer can be converted into an ammeter of range I = 10 A by connecting a shunt resistance 'R_s' in parallel, the shunt resistance is given as

$$R_s = \frac{I_g R_g}{(I - I_g)}$$

putting values $R_s = \dfrac{1 \times 10^{-3}\ A \times 100\Omega}{(10\ A - 1 \times 10^{-3}\ A)}$

therefore $R_s = 0.010\ \Omega$ **Answer**

(b) Galvanometer can be converted into a voltmeter of range V = 10 V by connecting a high resistance R_h in series, the high resistance is given as

$$R_h = \frac{V}{I_g} - R_g$$

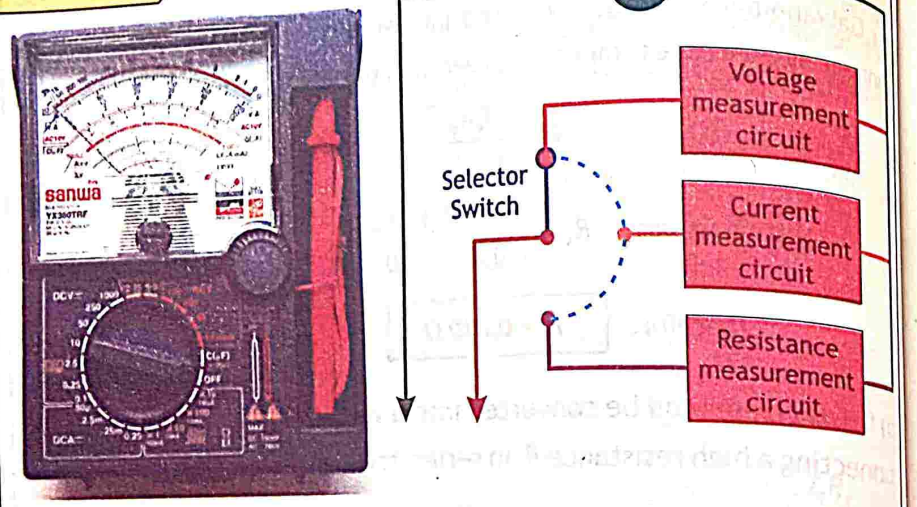
putting values $R_h = \dfrac{10V}{1 \times 10^{-3}\ A} - 100\,\Omega$

therefore $R_h = 9{,}900\ \Omega$ **Answer**

13.9 AVO METER/ MULTI-METER

A single device which can measure current, voltage and resistance is called AVO meter. Where A stands for amperes, V stands for volts and O stands for ohm. As we know that galvanometer can be converted into ammeter and voltmeter by adding resistors therefore AVO meter is also combination of resistor networks and a galvanometer. A single galvanometer is added in a circuitry in such a way that all the three quantities can be measured. All the three quantities also has range of values which can also be selected through switch. AVO meter is also capable of measuring alternating quantities as well. AVO meter and its circuit is shown in figure 13.28.

FIGURE 13.28



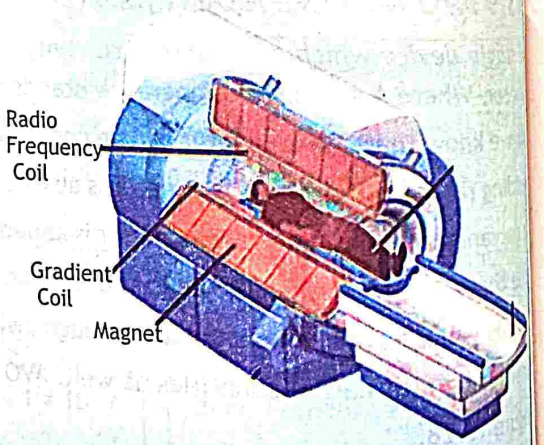
(a) AVO meter (b) Internal circuit

For your information | **MAGNETIC RESONANCE IMAGING**

Magnetic Resonance Imaging (MRI) uses a combination of a strong magnetic field and radio waves to produce high resolution images of the interior of the body.

The human body is composed primarily of fat and water, it is made up mostly of hydrogen atoms. Hydrogen protons within the body align with the magnetic field.

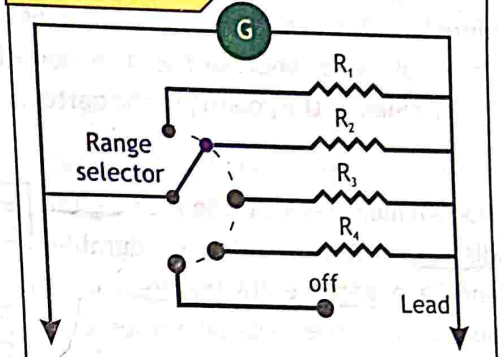
By applying short radio frequency (RF) pulses to a specific anatomical slice, the protons in the slice absorb energy at this resonant frequency, causing them to spin perpendicular to the magnetic field. As the protons relax back into alignment with the magnetic field, a signal is received by an RF coil. This signal acts as an antenna, and is processed by a computer to produce diagnostic images of areas of the body.



A. CURRENT MEASUREMENT

To measure current the selector switch is turned to measure ampere and proper scale is selected. This circuit contains resistors R_1, R_2 , .. of various resistance connected in parallel across the galvanometer as shown in the figure 13.29. These resistance are collectively called universal shunt. Any one of the shunt can be used to measure current in different ranges without making excessive current to flow through the galvanometer.

FIGURE 13.29

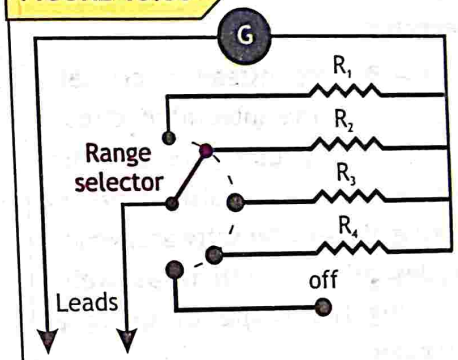


AVO meter switch turned to current measurement

B. VOLTAGE MEASUREMENT

To measure voltage the selector switch is turned to measure volts and proper scale is selected. This circuit contains resistors R_1, R_2 , .. of various resistances connected in series with the galvanometer as shown in the figure 13.30. The specific range is selected by adding proper resistance for measurement of specific voltage.

FIGURE 13.30

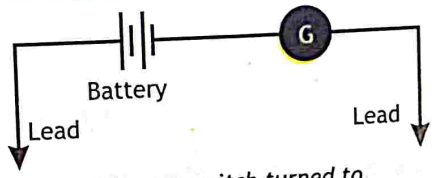


AVO meter switch turned to voltage measurement

C. RESISTANCE MEASUREMENT

To measure voltage the selector switch is turned to measure ohms. The leads are connected across the resistance to be measured as shown in figure 13.31. The battery supplies the current to the galvanometer for deflection. Since the amount of current through the galvanometer now depends upon the external resistance the scale can be calibrated in ohms.

FIGURE 13.31



AVO meter switch turned to resistance measurement

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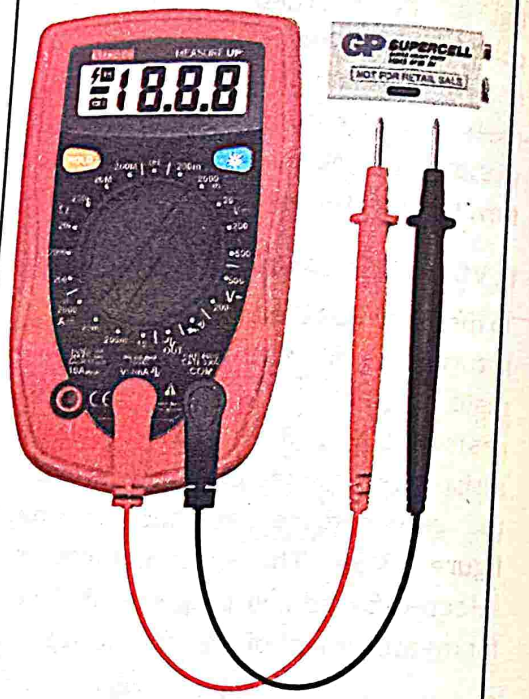
The amount of deflection in the galvanometer will now show the resistance directly. The ohm-meter reading does not depends upon the polarity of the terminal leads, because the direction of current through the galvanometer is determined by the polarity of the battery.

D. DIGITAL MULTI-METERS

Modern multimeters come with digital display, accurate, reliable, durable and have added extra features. It is also easy to use because values are displayed automatically in decimal with proper units. Thus the human errors (such as parallax) in reading the detail of the ordinary AVO meter are eliminated.

In these devices instead of ordinary galvanometer the integrated circuit electronically controls all the functions. Modern digital multimeters make use of computer software, which provides other functions as well, increasing the scope of using a multimeter.

FIGURE 13.32



NOT FOR SALE

KEY POINTS

Force on a current carrying conductor in a magnetic filed: A Current carrying wire has a magnetic field around it. When this field interacts with external magnetic field there is a force on it, which is given by

$$F = I\,L \times B$$

Magnetic flux: The scalar product of magnetic induction vector B and the area ΔA, mathematically

$$\Delta\Phi_B = \vec{B} \bullet \Delta\vec{A} = B\,\Delta A\cos\theta$$

Ampere's Law: This law relates the integrated magnetic field in a loop around a current carrying wire to the current passing through the wire.

$$\sum B.\Delta l = \mu_0 I$$

The magnetic field of a solenoid: The magnetic field of a solenoid is given by $B = n\,\mu_o\,I$

Force on a charged particle in magnetic field: The force acting on the charged particle results from the interaction of the external magnetic field and the magnetic field created by the moving charge.

Velocity selector: *The device which allow only the particles with certain specific speed through it (thus permitting particles only with selected speeds)*

Torque on a current carrying coil in a magnetic field: Torque on a current carrying coil in magnetic field is $\tau = N\,I\,A\,B\sin\theta$

Galvanometer: *A device used for detection and measurement of small electric currents*

Shunt resistance: The low resistance connected in parallel with galvanometer, mathematically $R_s = \dfrac{I_g R_g}{(I - I_g)}$

High resistance: The high value resistance connected in series with galvanometer, mathematically $R_h = \dfrac{V}{I_g} - R_g$

AVO Meter: A single device which can measure current, voltage and resistance.

NOT FOR SALE

Exercise

Choose the best possible answer

1. A current is flowing North in a magnetic field that points West. It experiences
   A. a force down. B. a force up. C. a force west. D. no force.
2. Two long, straight wires have currents flowing in them in the same direction, the force between the wires is
   A. attractive. B. repulsive. C. zero. D. infinite
3. One weber is equal to
   A. $N A^2/m$ B. $N m^2/A$ C. N A/m D. N m/A
4. Magnetic flux will be maximum if the angle between magnetic field strength and vector area is
   A. 0° B. 45° C. 60° D. 90°
5. Ampere's law is applied over any
   A. surface B. closed surface C. path D. closed path
6. When the number of turns in a solenoid is doubled without any change in the length of the solenoid its self induction will be
   A. Four times B. Doubled C. Halved D. One forth
7. If the charge is at rest in magnetic field, then force on charge is
   A. qvB B. qvB cos θ C. qvB sin θ D. zero
8. Work done on a charge particle moving in a uniform magnetic field is
   A. maximum B. minimum C. zero. D. infinite
9. The Earths northern magnetic pole acts like:
   A. the north pole of a magnet B. the south pole of a magnet
   C. it has a positive charge D. it has a negative charge
10. The pole pieces of the magnet in galvanometer are made concave to make the field
    A. Radial B. Stronger C. Weaker D. Both A & B

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LEARNING OUTCOMES

- explain the production of eddy currents and identify their magnetic and heating effects.
- explain the need for laminated iron cores in electric motors, generators and transformers.
- explain what is meant by motional e.m.f. Given a rod or wire moving through a magnetic field in a simple way, compute the potential difference across its ends.
- define mutual inductance (M) and self-inductance (L), and their unit henry.
- describe the main components of an A.C. generator and explain how it works.
- describe the main features of an A.C. electric motor and the role of each feature.
- explain the production of back e.m.f. in electric motors.
- describe the construction of a transformer and explain how it works.
- identify the relationship between the ratio of the number of turns in the primary and secondary coils and the ratio of primary to secondary voltages.
- describe how step-up and step-down transformers can be used to ensure efficient transfer of electricity along cables.

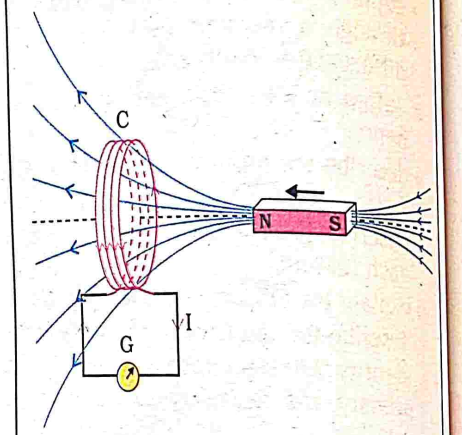
In 1831, English scientist Michael Faraday discovered that when the magnetic flux linking a conductor changes, an e.m.f is induced in the conductor. This phenomenon is known as electromagnetic induction.
The interplay of electric and magnetic forces is the basis for electric motors, generators, and many other modern technologies.
Faraday's Law of Induction describes how an electric current produces a magnetic field and, conversely, how a changing magnetic field generates an electric current in a conductor.
In this unit, we will study the various aspects of electromagnetic induction.

14.1 INDUCED E.M.F. AND MAGNETIC FLUX

In order to produce induced e.m.f. consider a coil C of wire connected to a sensitive galvanometer G as shown in Figure 14.1(a). The galvanometer is used to detect any current induced in the coil.
Near the coil is a stationary bar magnet. When the magnet is stationary the galvanometer shows no current. Now if the magnet moved towards the coil C, the galvanometer will show deflection in one direction.

If the magnet is moved away from the coil, the galvanometer again shows deflection but in the opposite direction. Furthermore, if the magnet is held steady and the coil of wire is moved toward or away from the magnet, again an e.m.f is induced and a current flows.

FIGURE 14.1



(a)

If the magnet is held stationary inside the coil though the flux is linking the coil there is no change in flux and hence no e.m.f is induced in the coil. Therefore the galvanometer shows zero deflection. If the magnet is moved faster, a greater deflection is observed.

In each case, an e.m.f is induced in a circuit when the magnetic flux through the circuit changes with time. It doesn't matter whether the magnet or the coil moves. It is their relative motion that counts.

TIP

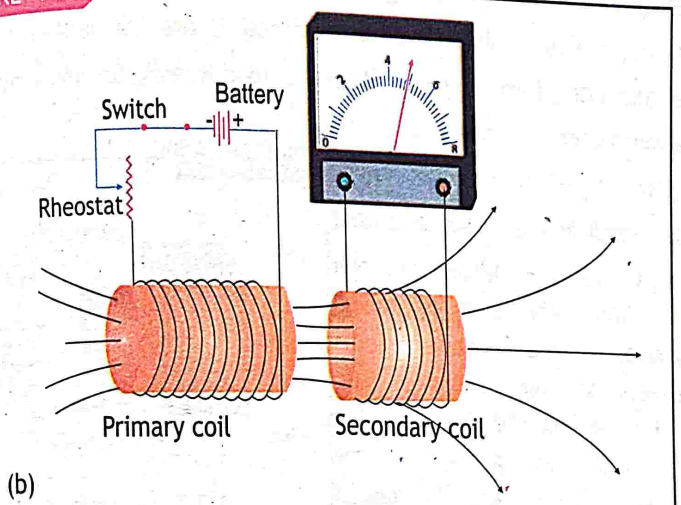
The basic requirement for electromagnetic induction is the change in flux linking the conductor (or coil).

When the conductor is stationary and the magnet is moving. Then the e.m.f. induced in this way is called statically induced e.m.f.

A similar effect can be produced by using the apparatus shown in Figure 14.1(b). It consists of a coil connected to a switch and a battery. We call this coil the primary coil and the corresponding circuit the primary circuit. A second coil, called the secondary coil, at the right, is connected to an ammeter. The corresponding circuit is called the secondary circuit. There is no source of e.m.f in the secondary circuit.

When the switch in the primary circuit is suddenly closed, the ammeter measures a current in the secondary circuit and then returns to zero! The two coils are magnetically linked together by a common magnetic flux. When the switch is opened again, the ammeter reads a current in the opposite direction and again returns to zero.

FIGURE 14.1



(b)

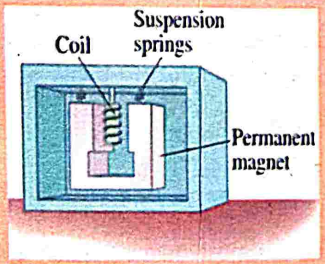
Electromagnetic induction

Finally, whenever there is a steady current in the primary circuit, the ammeter reads zero. The current produced in the secondary circuit occurs for only an instant while the magnetic field through the secondary coil is changing. Closing and opening the switch induces the current.

It is the change in magnetic field that creates the current. We therefore say that a changing magnetic field induces an e.m.f.

APPLICATIONS OF ELECTROMAGNETIC INDUCTION

To measure the earthquakes we use a device which is called seismometer.

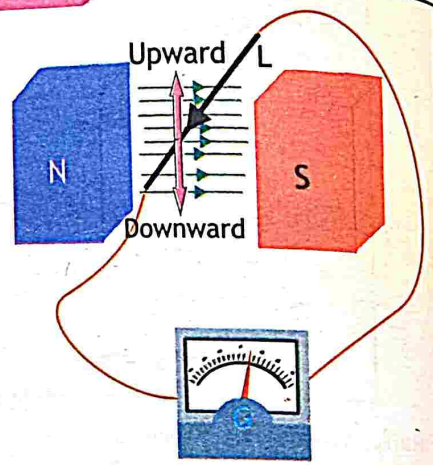


Electromagnetic seismometer.

The seismometer works on the principle of electromagnetic induction. It transforms received vibration energy into an electrical voltage. The relative motion between a magnet and a coil (one of which is attached to the inertial mass and one is attached to the frame) induces an e.m.f.

Let us consider a conducting rod L placed in a horizontal magnetic field as shown in figure. Both ends of the rod L are connected to a sensitive galvanometer, forming a loop. When the loop is held stationary in the field, the galvanometer indicates no deflection. When a loop is moved downwards across a magnetic field the galvanometer deflects to one side. When the loop is moved upwards, the galvanometer deflects to the opposite side briefly. Moving the loop quickly through the field gives a greater current. If the loop is moved parallel to the field lines there is no deflection on the galvanometer.

FIGURE 14.2



Electromagnetic induction

A changing magnetic field through a loop induces an e.m.f. in the coil which in turn causes current to flow.

Thus an electromotive force or e.m.f. is said to be induced when the flux linking with a coil changes. This phenomenon is known as electromagnetic induction.

14.1.1 FARADAY'S LAWS OF ELECTROMAGNETIC INDUCTION

The practical demonstration of electromagnetic induction in previous article proves that e.m.f. induced in a coil depend upon the following factors

1. e.m.f. is directly proportional to the rate of change of magnetic flux $\Delta\Phi$ in time Δt. Greater the rate of change in magnetic flux through the coil, greater is induced e.m.f.

2. e.m.f. is directly proportional to the number of turns N in the coil. Greater the number of turns, greater is induced e.m.f.

The equation for the e.m.f. induced is

Induced e.m.f., $\varepsilon \propto N\frac{\Delta\Phi}{\Delta t}$

$$\varepsilon = kN\frac{\Delta\Phi}{\Delta t}$$

Where k is constant and its value is $k = 1$

$$\varepsilon = N\frac{\Delta\Phi}{\Delta t}$$

Above equation is called Faraday law of induction.

The induced e.m.f. always opposes the change in flux. The direction of induced e.m.f. is given by Lenz's law.

$$\varepsilon = -N\frac{\Delta\Phi}{\Delta t} \qquad 14.1$$

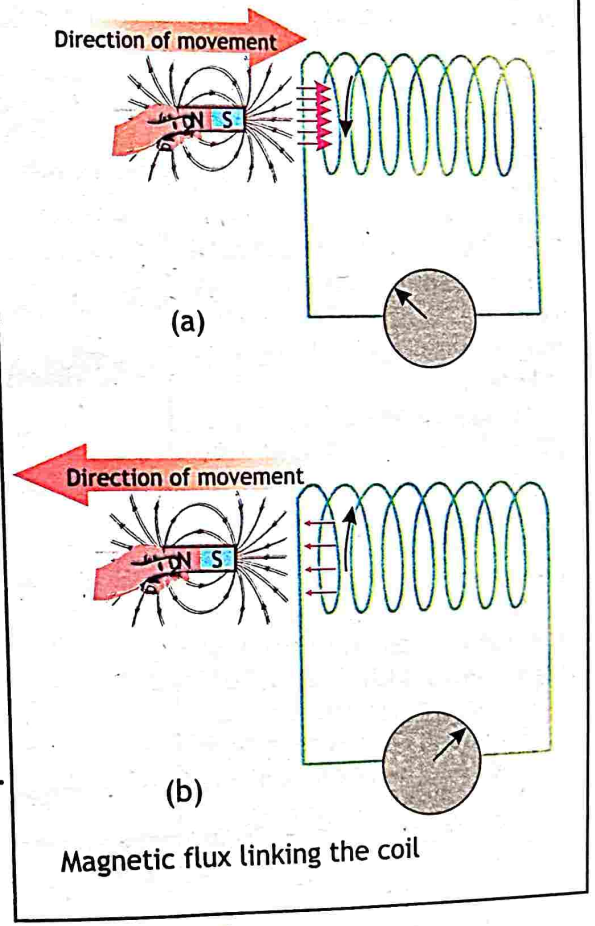
The negative sign in the equation represents Lenz's law.

14.3 LENZ'S LAW

Lenz's law is a convenient alternative method for determining the direction of an induced e.m.f or current. To demonstrate the lenz's law consider the South -pole of the magnet towards the coil as shown in figure 14.3 (a).

As the south pole of the magnet moves toward the coil, the flux through the coil increases.

FIGURE 14.3



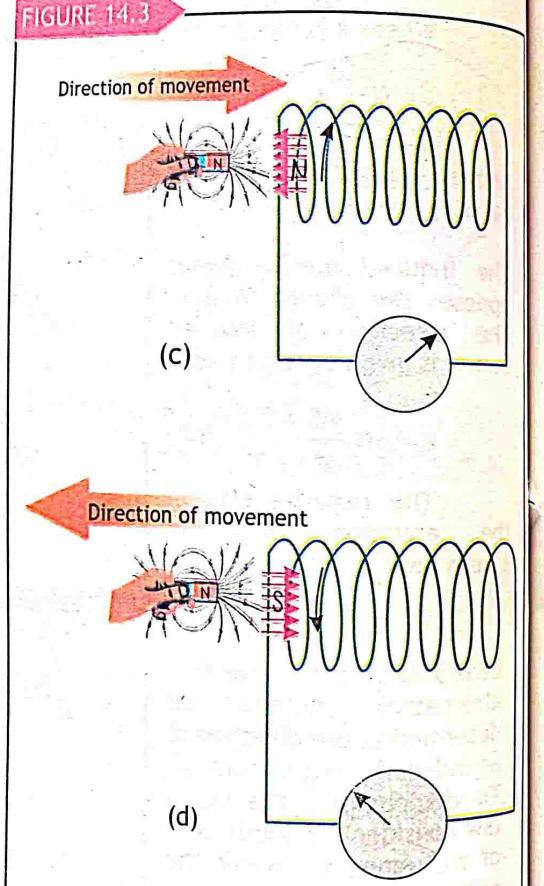
Magnetic flux linking the coil

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The coil resembles as South-pole and repels an approaching magnet. A changing magnetic flux induces the current through the coil which itself will produce its own magnetic field.
According to Lenz's law, the direction of the induced current will oppose the change in flux that created it.

On the other hand, if the South-pole of the magnet is moved away from the coil as shown in figure 14.3(b), the magnetic flux linked with the coil decreases. The coil resembles as north-pole and attracts the magnet when it is pulled away. The direction of the induced current must be such that its own magnetic field is directed in a way to oppose the changing flux caused by the field of the approaching magnet.
The direction of the induced current can be determined by applying right-hand rule if the magnetic polarity of the coil is known.
Similarly when the North-pole of the magnet is moved toward or away from the coil repulsion and attraction takes place between the coil and the moving magnet, and always opposes the motion of the magnet as illustrated in Figure 14.3 (c),(d).Thus **Lenz's Law** states that: the polarity of induced e.m.f. is such that it tends to produce a current which opposes the change in magnetic flux that produced it

FIGURE 14.3



Magnetic flux linking the coil

NOT FOR SALE

14.3.1 LENZ'S LAW AND CONSERVATION OF ENERGY

Lenz's law is a consequence of the law of conservation of energy. In previous example, when the *N*-pole of the magnet is approaching the coil, the repulsive force acts on the bar magnet due to the current induced in the coil.
The result is that the motion of the magnet is opposed. The mechanical energy spent in overcoming this opposition is converted into electrical energy which appears in the coil. Thus Lenz's law is consistent with the law of conservation of energy.

EXAMPLE 14.1

At what rate would it be necessary for a single conductor to cut the flux in order that a current of 1.2 mA flows through it when 10 Ω resistor is connected across its ends?

GIVEN

Current $=I=1.2$ mA , Resistor R= ?

REQUIRED

Time rate of change of flux, $\Delta\Phi/\Delta t$ = ?

SOLUTION

$$\mathcal{E}=N\frac{\Delta\Phi}{\Delta t}$$

Here $\mathcal{E}=IR=1.2\times10^{-3}\times10=1.2\times10^{-2}$ V;

$$\frac{\Delta\Phi}{\Delta t}=\frac{\mathcal{E}}{N}=\frac{1.2\times10^{-2}}{1}=1.2\times10^{-2}\ \text{Wb/s}$$

EXAMPLE 14.2

A coil of mean area 500 cm^2 and having 1000 turns is held perpendicular to a uniform field of 0.4 gauss. The coil is turned through 180^0 in 1/10 s. Calculate the average induced e.m.f.

GIVEN

When the plane of the coil is perpendicular to the field, $\theta = 0^0$.

When the coil is turned though 180^0, $\theta = 180^0$.

Therefore, initial flux linked with the coil is $\Phi_1 = NBA\cos\theta = NBA$

Flux linked with coil when turned through 180^0 = -NBA

Change in flux linking the coil is $\Delta\Phi = \Phi_2 - \Phi_1 = (-NBA) - (NBA) = -2NBA$

$N = 1000$; $B = 0.4\ G = 0.4\times10^{-4}\ T$

; $A = 500\times100^{-4}\ m^2$; $\Delta t = 0.1s$

REQUIRED

induced e.m.f. = $\mathcal{E}$ = ?

SOLUTION

$$\therefore \text{Average induced e.m.f.,}\ \mathcal{E} = \frac{\Delta\Phi}{\Delta t} = \frac{2NBA}{\Delta t}$$

$$\mathcal{E} = \frac{2\times1000\times(0.4\times10^{-4})\times500\times10^{-4}}{0.1} = 0.04V$$

ASSIGNMENT:14.1

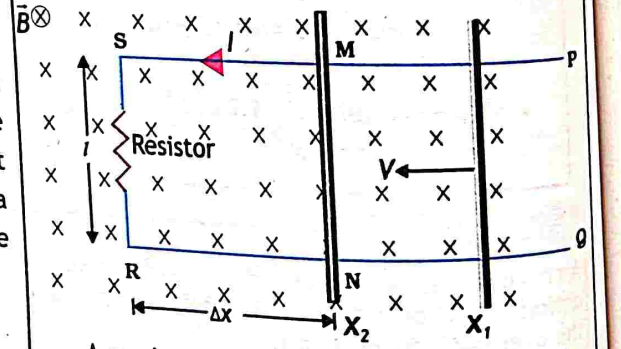
In the initial state (1), the magnetic flux is changed by 5 Wb in 2 s on a coil with 20 loops. In the final state (2), the same flux changed in 8 seconds. Determine the ratio of the initially induced e.m.f. and the final induced e.m.f.

Answer (4: 1)

14.4.1 MOTIONAL e.m.f.

Consider a conducting rod NM placed in a uniform magnetic field $\vec{B}$ directed into the page as shown in figure 14.4. The rectangle MNRS form a closed circuit enclosing a varying area due to the motion of the rod MN.

FIGURE 14.4



A conductor movement in a magnetic field

When rod MN is moved from position x_1 to position x_2 in small time interval Δt then there is a change in the flux linked with the conductor and a current I will start to flow in the circuit. Therefore, an induced e.m.f. is produced.

This induced e.m.f. due to the motion of an electric conductor in the presence of the magnetic field is called motional e.m.f. The distance travelled by the rod in time Δt is $x_1 - x_2 = \Delta x$. To find the magnitude of e.m.f. induced along the moving rod, we use Faraday's law of induction

$$\mathcal{E} = N\frac{\Delta\Phi}{\Delta t}$$

In this equation, $N = 1$ and the flux $\Phi = BA\cos\theta$. We have $\theta = 0°$ and $\cos\theta = 1$, since B is perpendicular to A. Where change in flux $\Delta\Phi = \Delta(BA) = B\Delta A$, since B is uniform. The area enclosed by the circuit MNRS is $\Delta A = \ell\Delta x$.

Putting the values of N and $\Delta\Phi$ into the above equation we get,

$$\mathcal{E} = \frac{B\Delta A}{\Delta t} = \frac{B\,\ell\Delta x}{\Delta t} \qquad \therefore\ \Delta A = \ell\Delta x$$

The velocity of the rod is $\Delta x/\Delta t = v$. Thus

$$\mathcal{E} = B\ell v \quad (B, \ell, \text{and } v \text{ perpendicular})$$

Thus, the e.m.f. generated in the circuit by the moving rod is simply the product of the magnetic field-strength, the length of the rod, and the velocity of the rod. This equation is valid as long as B, l and v are mutually perpendicular. If they are not, then their mutually perpendicular components are used. Motional e.m.f. is an example of dynamically induced e.m.f. It is so called because e.m.f. is induced in the conductor which is in motion.

When the conductor is moved in a stationary magnetic field in such a way that the flux linking it changes in magnitude. Then the e.m.f. induced in this way is called dynamically induced e.m.f.

The above Equation can be written as $I = \frac{\mathcal{E}}{R} = \frac{Blv}{R}$

From an energy perspective, F produces power Fv, and the resistor dissipates power I^2R. Since the rod is moving at constant velocity, the applied force F must balance the magnetic force $F_m = Bvl$ on the rod when it is carrying the induced current I.

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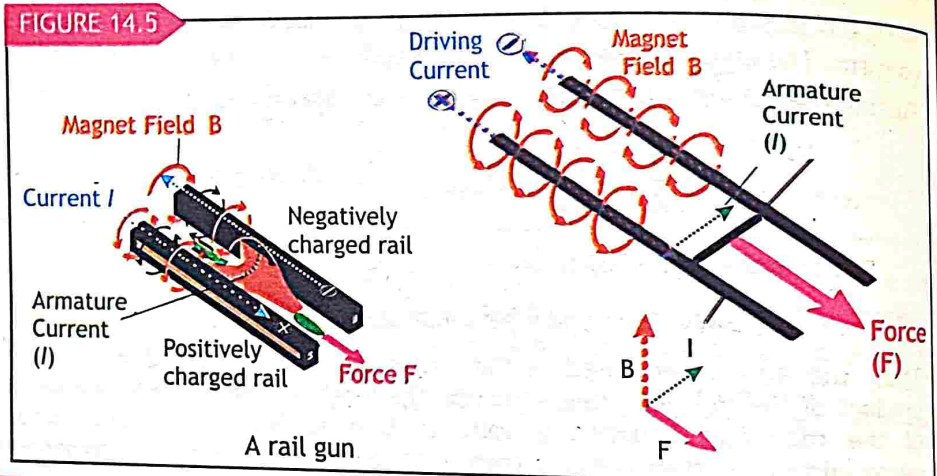
Thus the power produced is

$$Fv = BIlv = \frac{Blv}{R}Blv = \frac{B^2l^2v^2}{R} \qquad \therefore\ I = \frac{Blv}{R}$$

The power dissipated is $P = \frac{B^2l^2v^2}{R}$ 14.2

In satisfying the principle of energy conservation, the produced and dissipated powers are equal. This principle can be seen in the operation of a rail gun. A rail gun is an electromagnetic projectile launcher as shown in Figure 14.5.

FIGURE 14.5



A rail gun

EXAMPLE 14.3

A loop of resistance 0.1Ω is placed in a magnetic field of 2T. If a conductor of length 0.2m is sliding along a loop with a velocity of 0.2ms^{-1}. Find (a) the e.m.f. produced in the conductor if the motion of a conductor is perpendicular to the field (b) the current through the loop (c) the electrical power generated (d) the input mechanical power.

GIVEN

resistance R= 0.1Ω , magnetic field B= 2T, length of conductor l= 0.2m
velocity of conductor v= 0.2ms^{-1}

NOT FOR SALE

REQUIRED

(a) the e.m.f. produced in the conductor ε=? ,
(b) current through the loop I=?, (c) power P_1=? and
(d) input mechanical power P_2=?

SOLUTION

(a) The motional e.m.f ε
$vBL = 0.2 \times 2 \times 0.2 = 0.08V$

(b) The current through the loop is $= I = \varepsilon/R$
$$= \frac{0.08V}{0.1\Omega} = 0.8A$$

(c) Electrical power generated is $= P_1 = IV$
$= 0.8A \times 0.08V = 0.064W$

The magnetic force exerted on the current carrying loop of length L is
$F = BIL = 2\ T \times 0.8A \times 0.2m = 0.32\ N$

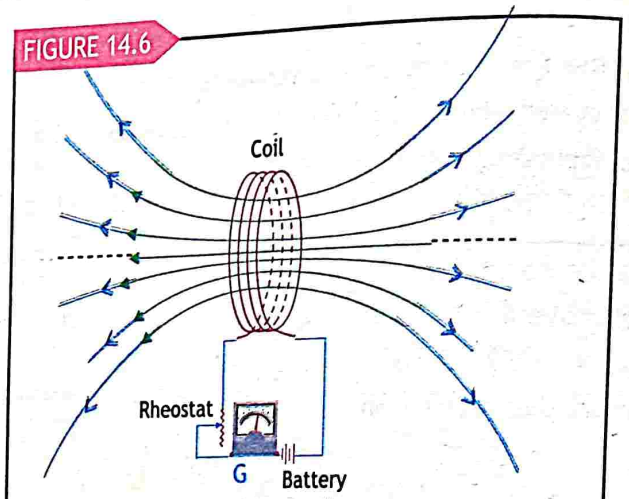
(d) The power necessary to move the loop against magnetic force F is
$P_2 = F\,v = 0.32N \times 0.2ms^{-1} = 0.064W$

14.4.2 SELF-INDUCED e.m.f.

We know that in previous article a changing magnetic flux was due to external source i.e. magnet. The relative movement between magnet and coil which causes induced current and hence induced e.m.f. in a coil.
But this time the e.m.f. induced in the coil is due to change of the current in the same coil. To explain phenomenon of self inductance consider a coil connected to a battery through a rheostat as shown in figure 14.6. By changing the resistance in the circuit, the current through the coil changes and the magnetic flux through the coil also changes as a result an e.m.f. will be induced in the coil itself. It is concluded that when current in a coil changes, the self-induced e.m.f. opposes the change of current in the same coil which is known as self-inductance or inductance.
The e.m.f. induced in a coil due to the change of its own flux linked with it is called self-induced e.m.f.

NOT FOR SALE

FIGURE 14.6



Self-induced e.m.f in a coil

In order to find the expression for magnitude of self-induced e.m.f. and self-inductance consider a coil of N turns carrying a current I. When the current in the coil changes then, the flux linking of the coil will also change. This will set up a self-induced e.m.f. $\mathcal{E}$ in the coil is given by;

$$\mathcal{E} = N\frac{\Delta\Phi}{\Delta t} = \frac{\Delta}{\Delta t}(N\Phi)$$

The flux linkages due to N turns of coil is proportional to current I

$$(N\Phi) \propto I$$

$$\mathcal{E} \propto \frac{\Delta I}{\Delta t}$$

$$\mathcal{E} = \text{constant} \times \frac{\Delta I}{\Delta t}$$

$$\mathcal{E} = L\frac{\Delta I}{\Delta t} = \frac{\Delta}{\Delta t}(LI) \qquad (1)$$

Where L is a constant called self-inductance or inductance of the coil. The unit of inductance is henry (H). Putting $\mathcal{E} = 1V$, $\Delta I/\Delta t = 1$ A/s, in Eq. (1) then $L = 1$ H.

Also we know that

$$\mathcal{E} = \frac{\Delta}{\Delta t}(N\Phi) \qquad (2)$$

Comparing Eq(1) and Eq (2) we have

NOT FOR SALE

$$LI = N\Phi \qquad 14.3$$

Or $$L = \frac{N\Phi}{I}$$

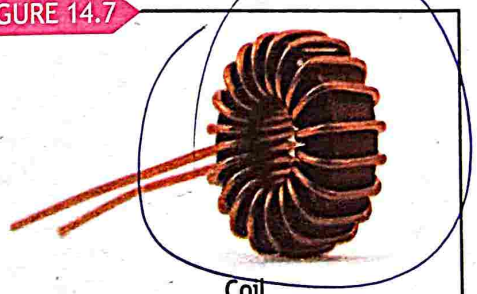
14.4.3.1 FACTORS AFFECTING INDUCTANCE

Inductors play a great role in electronic, electrical, electromechanical, wireless circuits etc. The inductance of a coil (figure 14.7) depends upon the following factors:

(i) shape and number of turns (N).
(ii) the material of the core.
(iii) coil area and length

The greater the magnetic permeability of the core which the coil is wrapped around, the greater the inductance i.e., by substituting an iron core with air the inductance increases.

FIGURE 14.7



Coil

14.4.3 MUTUALLY INDUCTANCE

In order to demonstrate the phenomenon of mutually induced e.m.f. let us place two coils A and B adjacent to each other as shown in Figure 14.8. When the current flows in the coil A then there will be magnetic field produced around it. A part of the magnetic flux produced by coil A passes through or links with coil B. This flux which is common to both the coils A and B is called mutual flux (Φ_m). The current in the coil A can be changed by a rheostat. A change in the current in coil A induces an e.m.f. in the coil B. The e.m.f. induced in coil A is called self-induced e.m.f. as already discussed.
The e.m.f. induced in coil B is known as mutually induced e.m.f.
Thus this phenomenon of the linking flux of the coil A with the other coil B is called Mutual Inductance.

The property of two neighbouring coils to induce e.m.f. in one coil due to the change of current in the other is called mutual inductance.

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Mutually induced e.m.f. in coil *B* is directly proportional to the rate of change of current in coil *A i.e.*,

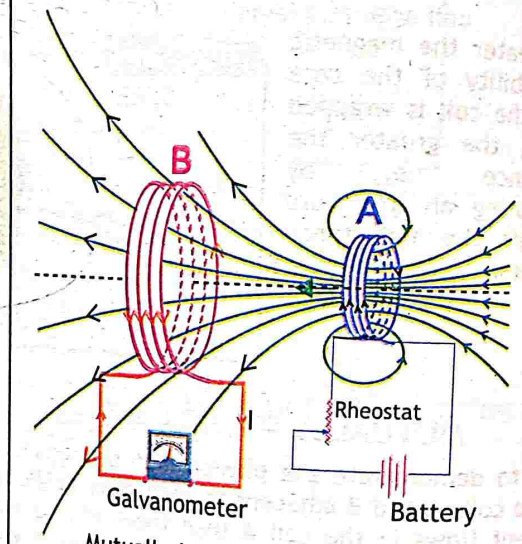
$$\mathcal{E} \propto -\frac{\Delta I}{\Delta t}$$

$$\mathcal{E} = -M\frac{\Delta I}{\Delta t} = -\frac{\Delta}{\Delta t}(MI) \qquad (1)$$

Where, *M* is a constant called mutual inductance. The minus sign is an expression of Lenz's law it show that this e.m.f. will set up a current which will oppose the change of flux linking with it.

The direction of mutually induced e.m.f. (by Lenz's law) is always such as to oppose the cause producing it. The cause producing the mutually induced e.m.f. in coil *B* is the changing mutual flux produced by coil *A*. Hence the direction of induced current in coil *B* will be such that the flux set up by it will oppose the changing mutual flux produced by coil *A*.

FIGURE 14.8



Mutually-induced e.m.f in a coil

The SI unit for mutual inductance M is called the **henry (H)** in honor of Joseph **Henry** (1799-1878), an American scientist who discovered induced emf independently of Faraday. Thus, we have 1H=1V·s/A.

Putting $\mathcal{E}$= 1V, $\Delta I/\Delta t$ = 1 A/s, in Eq. (1) then *M*= 1 H.

Also we know that

$$\mathcal{E} = -\frac{\Delta}{\Delta t}(N\Phi) \qquad (2)$$

NOT FOR SALE

Comparing Eq(1) and Eq (2) we have

$MI=N\phi$ *or* $M = \frac{N\Phi}{I}$ 14.4

Like capacitance, mutual inductance is a geometric quantity. It depends on the shapes and relative positions of the two coils, and it is independent of the currents in the coils.

STATICALLY INDUCED e.m.f.: it is defined as **"the e.m.f. induced in a coil due to change of flux linked with it is called statically induced e.m.f."** In this case, the coils are stationary and the magnetic field is moving around the conductor and produces e.m.f. Transformer is an example of statically induced e.m.f.

ASSIGNMENT 14.2

The current flowing in the first coil changes from 2 A to 10 A in 0.4 s. Find the mutual inductance between two coils if an e.m.f. of 60 mV is induced in the second coil. Also determine the induced e.m.f. in the second coil if the current in the first coil is changed from 4 A to 16 A in 0.03 s. Consider only the magnitude of induced e.m.f.

Answer(3×10^{-3} H, 1.2V)

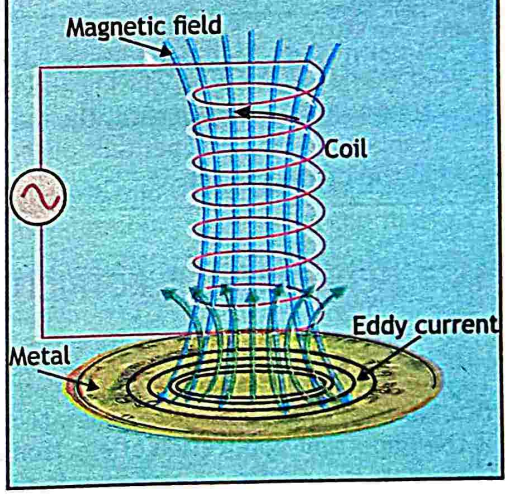
14.4.4 EDDY CURRENTS

Eddy currents are loops of electrical current induced within conductors by a changing magnetic field in the conductor, due to Faraday's law of induction.

Eddy currents are currents induced in conductor moving in a magnetic field or metals that are exposed to a changing magnetic field.

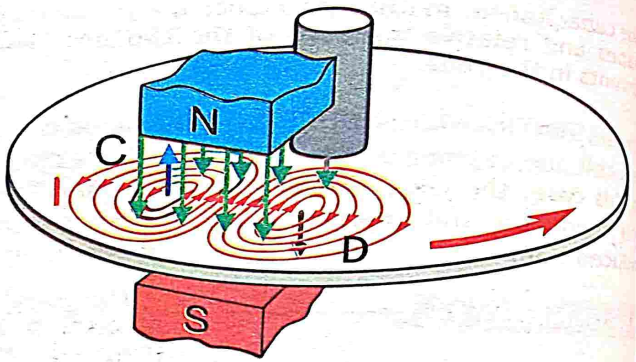
Do you know?

The metal detector consists of the oscillator producing the alternating current which passes through a coil producing the alternating magnetic field. If the piece of electrically conductive metal is close to the coil, eddy currents will be induced in the metal and this produces the magnetic field of its own. Thus the metallic object is notified with the alarm.



Eddy currents are created when a conductor passes through a magnetic field, which creates opposing forces that spin inside the conductor. Eddy currents flows in planes perpendicular to the magnetic field as shown in figure 14.9. The increasing field at point C induces a counterclockwise current. While the decreasing field at point D inducing a second eddy current in a clockwise direction in the conductor. According to Lenz's law, an eddy current produces a magnetic field that is in opposition to the magnetic field that produced it, and therefore eddy currents are an inverse response to the source magnetic field. The two magnetic fields repel each other and a braking force results. This eddy current braking system is generally used in high speed trains and roller coasters.

FIGURE 14.9



Eddy current brake.

Projects

A bar magnet is dropped inside a long vertical tube. If the tube is made of metal, the magnet quickly approaches a terminal speed, but if the tube is made of cardboard, the magnet falls with constant acceleration. Explain why the magnet falls differently in the metal tube than it does in the cardboard tube ?

14.5 GENERATING ELECTRICITY

Alternating current generator

The ability to produce an electromotive force by changing the magnetic flux through a coil is used to generate electricity. The generation of electricity is the important application of electromagnetic induction.

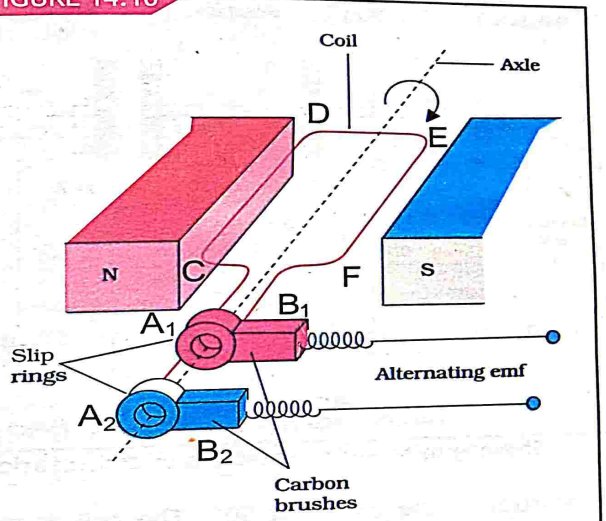
Generator is a device which converts Mechanical energy into electrical energy.

It consists of 2 poles (north and south) of a magnet in order to have uniform magnetic field. There is a coil of rectangular shape CDEF also known as armature.

It also consists of Slip rings which produces alternating current as shown in figure 14.10. When the coil CDEF rotates between the poles of a magnet an electromotive force is induced.

When the side CD moves upwards Fleming's Right-hand Rules shows that the direction of the current is from C to D and E to F. Half a revolution later FE will be in the position previously occupied by CD and the current direction is reversed, i.e. it is from F to E and D to C. Thus the direction of the induced electromotive force and the current changes every half revolution.

FIGURE 14.10



AC generator

The graph of electromotive force against time is shown in Fig14.11. The time taken for one revolution T is called the period and frequency f, is the number of revolutions per second. Hence

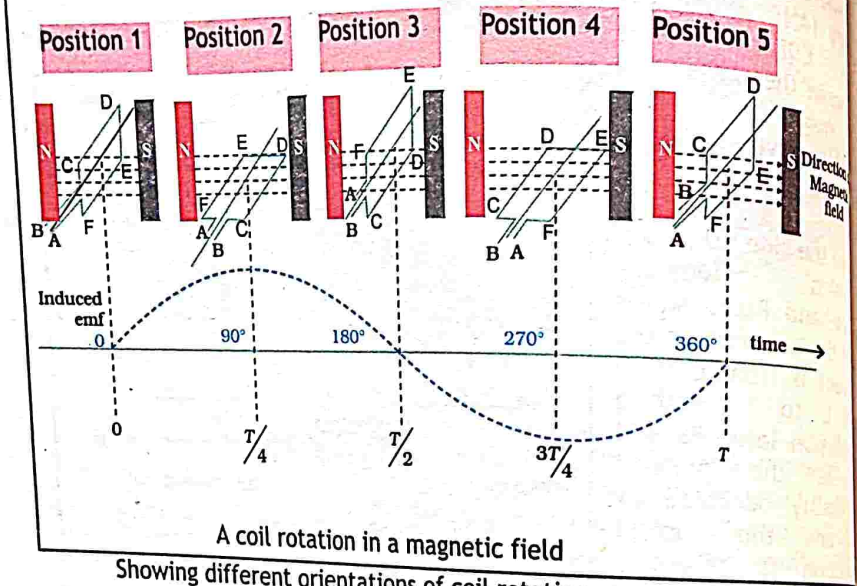
$$f = \frac{1}{T}$$

The domestic electricity supply has a frequency of 50 hertz, which means that the generator makes fifty revolutions each second. Figure 14.11 shows the positions of the coil that correspond to various points on the graph.

NOT FOR SALE

At position 1 the coil is at 0°. The coil is moving parallel to the direction the magnetic field and the magnetic flux is zero, so no e.m.f. is induced.

FIGURE 14.11



A coil rotation in a magnetic field

Showing different orientations of coil rotation.

At position 2 the coil is at 90°. The coil is moving perpendicular to the direction of the magnetic field and the magnetic flux is at its maximum hence induces maximum e.m.f.

At position 3 the coil is at 180°. The coil is moving parallel to the direction of the magnetic field and the magnetic flux is zero, so no e.m.f. is induced.

At position 4 the coil is at 270°. The coil is moving perpendicular to the direction of the magnetic field hence the induced e.m.f. is at its maximum. In this case the direction of induced e.m.f. is **opposite** to what it was at position 2.

At position 5 the coil is at 360°. The coil is moving parallel to the direction of the magnetic field, hence no e.m.f. is induced. At this position coil has completed full rotation and back to its starting point.

NOT FOR SALE

The induced electromotive force, is determined by the rate at which the number of flux linkages changes. The greater the angular velocity ω the coil will cut the lines of flux at a faster rate so more induced e.m.f. would be produced. Suppose the coil is rotating with angular velocity ω and at any instant t, θ be the angle which the coil makes with the field B. If N is the number of turns in the coil then the flux through the coil of area A is

$$\Phi = B.AN = NAB\cos\theta$$

$$= NAB\cos\omega t \qquad \therefore \theta = \omega t$$

The induced e.m.f is $$\mathcal{E} = -\frac{\Delta\Phi}{\Delta t} = -\frac{\Delta}{\Delta t}(NAB\cos\omega t)$$

$$\mathcal{E} = -NAB\lim_{\Delta t\to 0}\frac{\Delta(\cos\omega t)}{\Delta t} \qquad \text{As } \lim_{\Delta t\to 0}\frac{\Delta(\cos\omega t)}{\Delta t} = -(\omega\sin\omega t)$$

$$= NAB(\omega\sin\omega t) \qquad 14.5$$

For maximum value of induced e.m.f. $\sin\omega t = 1$, so $\mathcal{E}_{max} = NAB\omega$

Hence induced e.m.f at any instant of time is:

$$\mathcal{E} = \mathcal{E}_{max}\sin\omega t$$

$$\mathcal{E} = \mathcal{E}_{max}\sin(2\pi ft) \qquad 14.6$$

ASSIGNMENT 14.3

An electric generator consists of 100 turns of wire formed into a rectangular loop 50 cm by 30 cm, placed entirely in a uniform magnetic field of 3.50 T. What is the maximum value of the e.m.f. produced when the loop is spun at 1000 rev/min about an axis perpendicular to B?

Answer (5500 V)

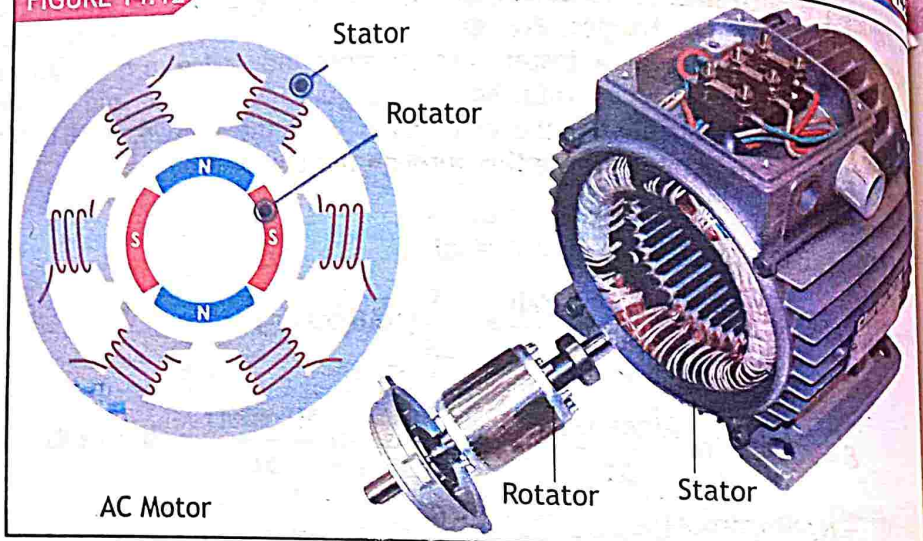
14.6 AC MOTOR

An electric motor is a device that converts electrical energy into mechanical energy.

An AC motor has two basic electrical parts: a "stator" and a "rotor" as shown in Figure 14.12. The stator is the stationary part of the motor while rotor is the rotating part of the motor. The stator consists of a group of individual electro-magnets arranged in such a way that they form a hollow cylinder, with one pole of each magnet facing toward the center of the group.

NOT FOR SALE

FIGURE 14.12



The rotor, obviously, is located inside the stator and is mounted on the motor shaft. The objective of these motor components is to make the rotor rotate which in turn will rotate the motor shaft. It also consists of a group of electromagnets arranged around a cylinder, with the poles facing toward the stator poles. When the stator windings are connected to an AC supply flux is produced in the air gap. The flux rotates at a fixed speed called synchronous speed. The rotating flux induces voltages in the stator and rotor winding.

If the rotor circuit is closed, the current flows through the rotor winding and react with the rotating flux and a torque is produced. In the steady state the rotor rotates at speed very close to synchronous speed. Eddy currents in iron cores of motors can cause troublesome energy losses. These are usually minimized by constructing the cores out of thin, electrically insulated sheets of iron. The rotor consists of coils wound on a laminated iron armature mounted on an axle. Motors are used in a wide range of applications, such as fans, power tools, appliances, electric vehicles, and hybrid cars etc.

14.6.1 BACK e.m.f.

When the coil of electric motor rotates in a magnetic field by applying it with a battery of potential difference V an induced e.m.f. $\mathcal{E}$ is produced. This induced e.m.f. is produced in such a direction so as to oppose the e.m.f. V of battery which is known as back e.m.f. The magnitude of the back or counter e.m.f. is proportional to the product of the flux and the speed.

NOT FOR SALE

The value of back e.m.f. ($\mathcal{E}$) is always less than the applied voltage, thus there is difference between these two potentials. It is the difference between these two quantities which actually drives current through the resistance of the armature circuit.

Thus we have

$$V = \mathcal{E} + I_a R_a \qquad 14.7$$

Where R_a is resistance of the armature circuit, I_a is the current, $\mathcal{E}$ is the back e.m.f. and V is the applied voltage.

The generator output of a motor is the difference between the supply voltage and the back e.m.f.

EXAMPLE:14.4

An AC motor has an internal resistance of 4 Ω. When powered by a 50Hz AC supply of peak voltage 120V it draws a peak current of 5 A. 1. What is the peak back- e.m.f. produced by the motor? 2. What is the peak power delivered to the motor by the AC supply? 3. What is the peak rate of energy loss as heat in the motor?

GIVEN

resistance R= 4 Ω,
f= 50Hz , current I= 5 A
peak voltage V=120V

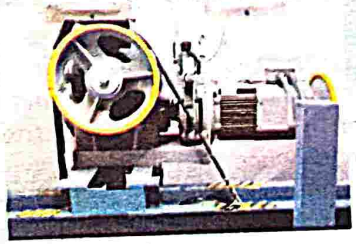
REQUIRED

1. peak back-e.m.f. $\mathcal{E}$ =?,
2. peak power P_{peak}=? and
3. peak rate of energy loss P_{heat}=?

FOR YOUR INFORMATION



(a)Elevator in the form of load



(b) Electric motor

When the motor is first turned on, the back e.m.f. is zero and the motor draws maximum current. This effect is noticeable when a water pump is first turned on, lights in the same circuit dim briefly due to the *IR* drop. As the motor speeds up the eddy currents and the resulting back e.m.f. also increase but reduces the amount of current through the coil. When a mechanical load is placed on the motor, like an Elevator going up a hill, the load opposes the rotation (Figure) and may slow it down , thus reducing back e.m.f. If the coil is prevented from turning by its load, then there is no back e.m.f. The applied potential difference can then drive a current that is large enough to overheat the wires and destroy the motor.

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SOLUTION

1. The equation for peak back-e.m.f., is given by

$\mathcal{E} = V - IR = 120 - (5\times4) = 100$ V

2. The peak power delivered by the AC supply is

$P_{peak} = VI = 120\times5 = 600$ w

3. Energy is lost as heat in the motor at the peak rate

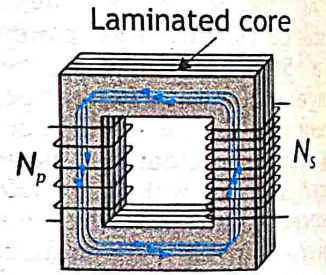
$P_{heat} = I^2R = (5)^2\times4 = 100$ w

14.7 TRANSFORMERS

A transformer is a device which is used to transform electrical power from one voltage and current level to another. The transformer depends on the use of alternating current. There are three main parts of a transformer primary coil, secondary coil and a laminated iron core connecting them as shown in figure 14.13.

The primary coil is connected to the input electrical supply, which has to be AC to work properly. An AC current through the coil creates a changing magnetic field which is concentrated through the iron core.

FIGURE 14.13



Step up transformer with laminated core.

Current passing through the primary coil creates a magnetic field. The primary and secondary coils are wrapped around a core of high magnetic permeability, such as iron, so that most of the magnetic flux passes through both the primary and secondary coils. The changing magnetic flux through the primary coil gives rise to an induced e.m.f. V_s in the secondary coil.

The voltage induced across the secondary coil is given by Faraday's law of induction, which states that:

$$V_s = N_s \frac{\Delta\Phi}{\Delta t}$$

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Since the same magnetic flux passes through both the primary and secondary coils in an ideal transformer, the voltage across the primary is

$$V_p = N_p \frac{\Delta\Phi}{\Delta t}$$

Taking the ratio of the two equations for V_s and V_p gives the basic equation for stepping up or stepping down the voltage

$$\frac{V_s}{V_p} = \frac{N_s}{N_p} \qquad 14.8$$

Where V_p = primary voltage, V_s = secondary voltage, N_p = primary turns.

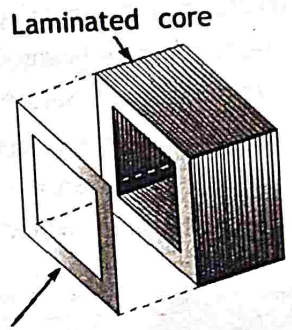
If $N_s > N_p$ then $V_s > V_p$ and the transformer is called a step-up transformer. When $N_s < N_p$ it follows that $V_s < V_p$ and it is called a step-down transformer. The amount of energy cannot be stepped up or down. The efficiency of the ideal transformer is 100%. So,

$$V_s I_s = V_p I_p$$

$$\frac{V_s}{V_p} = \frac{I_s}{I_p} \qquad 14.9$$

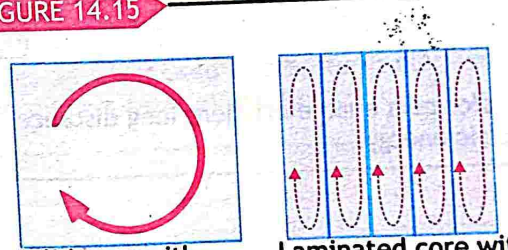
It follows that if the voltage is stepped up the current is stepped down and vice versa. If a high voltage is required a step-up transformer is used, whereas if a high current is required a step-down transformer is used.

FIGURE 14.14



Transformer cores are made of laminated iron, that is, many thin sheets of iron pressed together but separated by thin insulating layers. This limits the circulation of any eddy currents to the thickness of one lamina, rather than the whole core, thus reducing the overall heating effect.

FIGURE 14.15

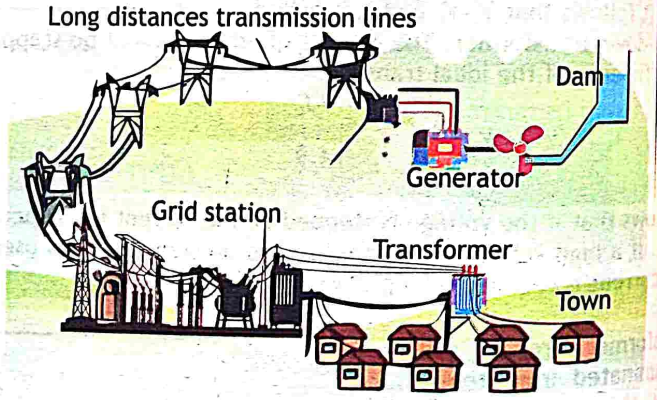


Eddy currents in an ordinary iron core, and a laminated iron core.

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The long thick cables of transmission lines are made of copper or alumin because they have a low resistance. High voltage transmission lines ca electricity long distances to a substation. The power lines go into Grid stati near factories and towns. From these Grid stations, electricity in differe power levels is used. Here transformers change the very high voltage electric back into lower voltage electricity. The voltage is eventually reduced to 2 volts for larger appliances, like stoves and clothes dryers, and 110 volts f lights, TVs and other smaller appliances.

FIGURE 14.16



Transformers enable efficient long distance high voltage transmission of electric energy.

NOT FOR SALE

KEY POINTS

Self-induction : The change of magnetic flux due to a variation in the current flowing in the same circuit.

Mutual induction : The change of magnetic flux due to a variation in the current flowing in the another circuit.

Lenz's law: the induced current will flow in such a direction that it opposes the cause that produce it.

Dynamically induced e.m.f. : When the conductor is moved in a stationary magnetic field in such a way that the flux linking it changes in magnitude.

Statically induced e.m.f.: When the conductor is stationary and the magnetic field is moving or changing.

Eddy currents : the currents induced in conductor moving in a magnetic field or metals that are exposed to a changing magnetic field.

Generator : which converts Mechanical energy into electrical energy.

Transformer : a device which is used to transform electrical power from one voltage and current level to another.

2003

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EXERCISE

MULTIPLE CHOICE QUESTIONS

Choose the best possible answer

1. For inducing e.m.f. in a coil the basic requirement is that
   (A) Flux should link the coil
   (B) change in flux should link the coil
   (C) coil should form a closed loop
   ✓(D) both (B) and (C) are true

2. When a single turn coil rotates in a uniform magnetic field, at uniform speed the induced e.m.f. will be
   A. ✓Alternating B)Steady C) Pulsating D) zero

3. Principle of dynamically induced e.m.f. is used in a
   A. Choke B) Transformer
   C. ✓Generator D) Thermo-couple

4. In Fleming's left-hand rule thumb always represents direction of
   A) Current flow B) Induced e.m.f.
   C) Magnetic field D. ✓Mechanical force

5. The field at any point on the axis of a current carrying coil will be
   ✓A) Perpendicular to the axis. B. Parallel to the axis.
   C) At an angle of 45° with the axis. D) Zero.

6. When a coil rotated in magnetic field the induced current in it
   ✓A. continuously changes B. remains same
   C. becomes zero D. becomes maximum

7. In A.C generator increasing the number of turns in the coil
   A. decreases the Electromotive force (e.m.f.)
   B. electromotive force (e.m.f.) remains same
   C. ✓increases the Electromotive force (e.m.f.)
   D. electromotive force (e.m.f.) becomes zero

8. The device in which induced e.m.f. is statically induced e.m.f.is
   ✓(A) transformer (B) AC generator
   (C) alternator (D) dynamo.

9. What is the coefficient of mutual inductance, when the magnetic flux changes by 2×10^{-2} Wb, and change in current is 0.01 A?
   ✓(A) 2 H (B) 3H (C) 1/2 H (D) zero

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LEARNING OUTCOMES

- construct phasor diagrams and carry out calculations on circuits including resistive and reactive components in series.
- solve the problems using the formulae of A.C Power.
- explain resonance in an A.C circuit and carry out calculations using the resonant frequency formulae.
- describe that maximum power is transferred when the impedances of source and load match to each other.
- describe the qualitative treatment of Maxwell's equations and production of electromagnetic waves.
- become familiar with electromagnetic spectrum (ranging from radio waves to γ-rays).
- identify that light is a part of a continuous spectrum of electromagnetic waves all of which travel in vacuum with same speed.
- describe that the information can be transmitted by radiowaves.
- identify that the microwaves of a certain frequency cause heating when absorbed by water and cause burns when absorbed by body tissues.
- describe that ultra violet radiation can be produced by special lamps and that prolonged exposure to the Sun may cause skin cancer from ultra violet radiation.

The electricity produced by most generators is in the form of alternating current (AC). It is true that in some cases AC holds no practical advantage over DC. However, with AC it is possible to build electric generators, motors and power distribution systems that are far more efficient than DC, and so we find AC being used predominantly across the world in high power applications. A theory describing relation between accelerating charges, circuits and electric and magnetic fields was given by James Clerk Maxwell in 1864 called electromagnetic theory. The theory predicts that accelerating electric charges radiate electromagnetic waves, which propagate at the speed of light.

15.1 ALTERNATING VOLTAGE AND CURRENT

The supply of current for electrical devices may come from a direct current source (DC), or an alternating current source (AC). In direct current electricity, electrons flow continuously in one direction from the source of

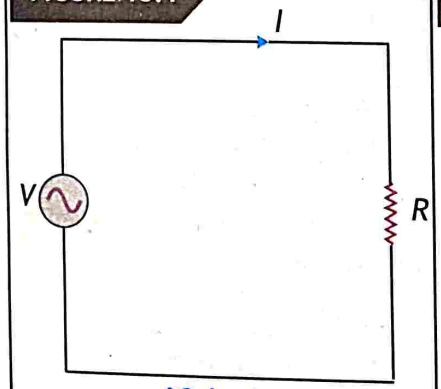
NOT FOR SALE

power through a conductor to a load and back to the source of power. The voltage in direct current remains constant. DC power sources include batte and DC generators.

In alternating current an AC generator is used to make electrons flow first one direction then in another. A source which produces potential difference changing polarity with time is called as alternating source. A voltage which *changes its polarity at regular interval of time is called an alternating volt*

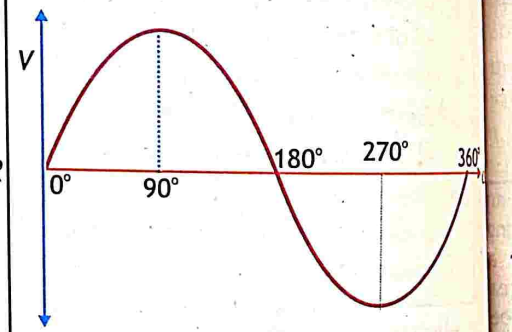
Fig 15.1: shows an alternating voltage source connected to a resistor R. Wh the upper terminal of alternating voltage source is positive and lower term negative so that current flows in the circuit.

FIGURE 15.1



AC circuit

FIGURE 15.2



Alternating current and voltag

After some time, the polarities of the voltage source are reversed, so that current now flows in the opposite direction. This is called alternating current. AC voltage has a time-varying waveform known as a **Sinusoidal Waveform** as shown in Fig.15.2. The instantaneous value of a sine-wave voltage for any an of rotation is expressed in the equation

$$V = V_m \sin\omega t \quad \ldots(15.1)$$

Using this chapter $\mathcal{E} = \mathcal{E}_m \sin\omega t$, $V = V_m \sin\omega t$, $I = I_m \sin\omega t$

Where V is instantaneous value of alternating voltage, V_m is maximum value o alternating voltage and ω is angular velocity of the coil. Fig15.2: shows that sinusoidal voltage or current not only changes direction at regular intervals b the magnitude is also changing continuously. The change from one polarity to

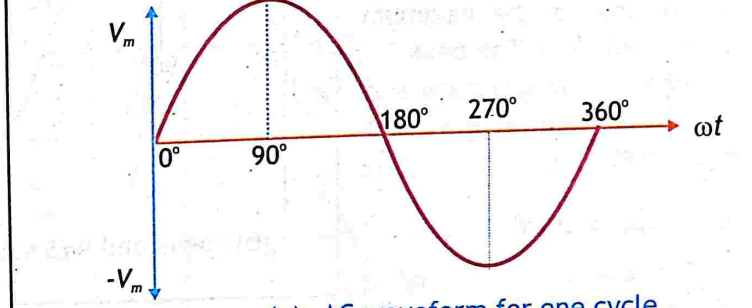
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the other is a smooth one, the voltage level changing most rapidly at the zero point and most slowly at its peak.

15.3 A.C. TERMINOLOGIES

Alternating voltage or current changes continuously in magnitude and alternates in direction at regular intervals of time. It rises from zero to maximum positive value, falls to zero, increases to a maximum in the reverse direction and falls back to zero again. The important A.C. terminology is defined below:

FIGURE 15.3



(a): AC waveform for one cycle

1. **CYCLE.** One complete set of positive and negative values of an alternating quantity is known as a cycle. Fig. 15.3 **(a)** shows one cycle of an alternating voltage. A cycle can also be defined in terms of angular measure. One cycle corresponds to 360° or 2π radians.
2. **TIME PERIOD.** The time taken in seconds to complete one cycle of an alternating quantity is called its time period. It is generally represented by T.
3. **FREQUENCY.** The number of cycle that occurs in one second is called the frequency (f) of the alternating quantity. It is measured in cycle per second or Hertz (Hz). The frequency of power system in Pakistan is 50 Hz. It means that alternating voltage or current completes 50 cycles in one second.
4. **INSTANTANEOUS VALUE.** The value of an alternating quantity at any instant is called instantaneous value. The instantaneous values of alternating voltage and current are represented by V and I respectively.

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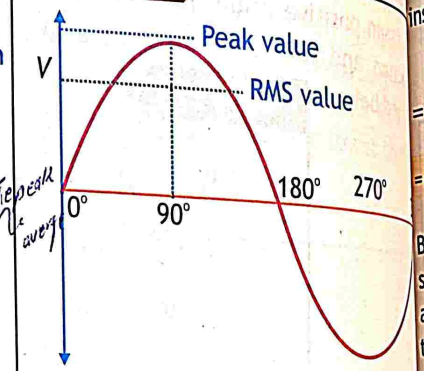
As an example, the instantaneous values of voltage at 0°, 90° a... are 0, + V_m, - V_m respectively as shown in Fig 15.3(a).

The AC waveform is constantly changing with time. Therefore it c... expressed as, Peak value, Average value or mean value, and R.M.S. va... effective value.

5. PEAK VALUES: The maximum value attained by an AC waveform is called its peak value.

It is also known as the maximum value or amplitude. The peak values of alternating voltage and current is represented by V_m and I_m respectively.

FIGURE 15.3



(b): peak and RMS value of voltage

6. AVERAGE VALUE

The average value of a waveform is the average of all its values over a period of time. Findi... average value over time means adding all the values that occur in a speci... time interval and dividing the sum by that time. In performing su... computation, we regard the area above the time axis as positive area and ... below the time axis as negative area. The algebraic signs of the areas mus... taken into account when computing the total (net) area.

$$\text{Average value of AC} = \frac{\text{Total (net) area under curve for time T}}{\text{Time T}}$$

7. R.M.S. OR EFFECTIVE VALUE: The effective or r.m.s. value of an alternating current is that steady current (d.c.)which when flowing through ... resistor produce the same amount of heat as that produced by the alternati... current when flowing through the same resistance for the same time.

15.4 R.M.S. VALUE OF SINUSOIDAL CURRENT AND VOLTAGE

Although peak, average and peak to peak values may be important in so... engineering applications, but it is the r.m.s. or effective value which is used ... express the magnitude of an alternating voltage or current. The peak a... r.m.s. value of current are illustrated in Fig 15.4.

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The equation of the alternating current varying sinusoidally is given by:

$$I = I_m \sin \omega t \qquad \ldots(15.2)$$

If this current is passed through a resistance R, then power delivered at any instant is

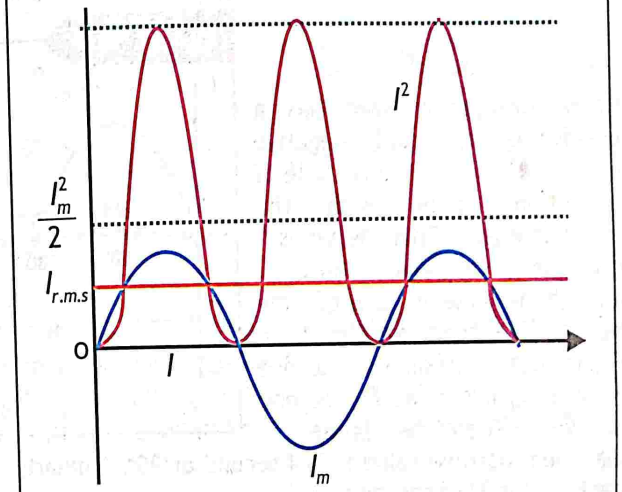
$$P = I^2 R$$

$$= (I_m \sin \omega t)^2 R$$

$$= I_m^2 R \sin^2 \omega t \qquad \ldots(15.3)$$

Because the current is squared, power is always positive. Since the value of $\sin^2 \omega t$ varies between 0 and 1, its average value is 1/2

FIGURE 15.4



Peak and r.m.s. value of current

∴ Average power delivere $P = \frac{1}{2} I_m^2 R \qquad \ldots(15.4)$

If $I_{r.m.s.}$ is the r.m.s. (or effective) value of alternating current, then by definition,

Power delivered, $P = I_{r.m.s}^2 R \qquad \ldots(15.5)$

From Eqs. (15.4) and (15.5), we have,

$$I^2_{r.m.s} R = \frac{1}{2} I_m^2 R$$

$$I_{r.m.s} = \frac{I_m}{\sqrt{2}} = 0.7071\, I_m$$

$$I_{r.m.s} = 0.707\, I_m \qquad \ldots(15.6)$$

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An alternating current can also be represented as a cosine function of time.

$$I = I_m \cos\omega t.$$

Similarly, r.m.s. value of alternating voltage is $V_{r.m.s} = \frac{V_m}{\sqrt{2}}$

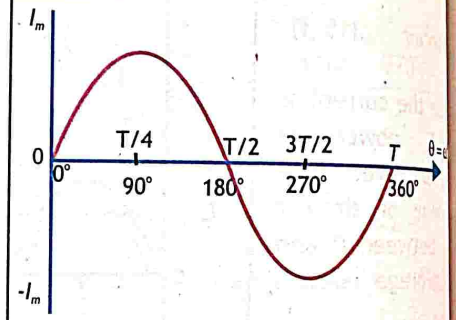
$$V_{r.m.s} = 0.707\ V_m \qquad ...(15.7)$$

Thus alternating voltage can be represented as $V = V_m \cos\omega t$.

15.5 PHASE OF A.C.

Every alternating wave has a positive half cycle and a negative half cycle in its complete cycle of revolution, along with the coordinate axis. This wave is continues. Consider an alternating voltage wave of time period T second as shown in Fig.15.5.The maximum positive value ($+I_m$) occurs at $T/4$ second or 90°. Therefore phase of maximum positive value is $T/4$ second or 90°. Similarly, the phase of negat peak ($-I_m$) is $3T/4$ second or 270 °.

FIGURE 15.5



Alternating voltage wave form

So Phase of a particular amplitude of an alternating quantity is the fracti part of time period or cycle through which the quantity has progressed fr the selected zero position of reference. The word "phasor" is short for "pha vector." It is a way to represent a sine or cosine function graphically.

The sinusoidal voltage wave can be represented by a phasor rotating anticlockwise, at an angular velocity ω rad/s about point O. The length of t phasor OA represents the magnitude of (on a suitable scale) of the alternati quantity. The phase of the waveform for one complete revolution is 2π or 36 Let the line OA representing phasor to be rotating in anticlockwise direction an angular velocity ω rad/s about the point *O*. If we take the projection of t phasor OA on Y-axis, we get the instantaneous value of the sinusoidal wave

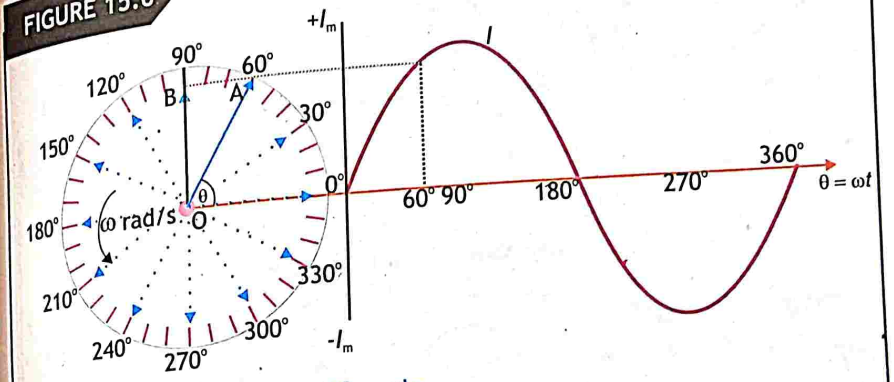
$$OB = OA \sin\theta$$

Any sinusoidal wave whether it represent current or voltage cycles or something else are actually represented in the form of equation

$$I = I_m \sin\omega t \qquad \text{(i)}$$

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FIGURE 15.6



Phasor at 60° angle.

Where, I is the value of current at that instant, I_m is the amplitude of current and $\theta=\omega t$ is the angle through which the vector rotate. The phasor diagram represents the sinusoidal alternating wave for every instant of time. The wheel like shape represents wave location at 60° as shown in figure 15.6.

PHASE DIFFERENCE

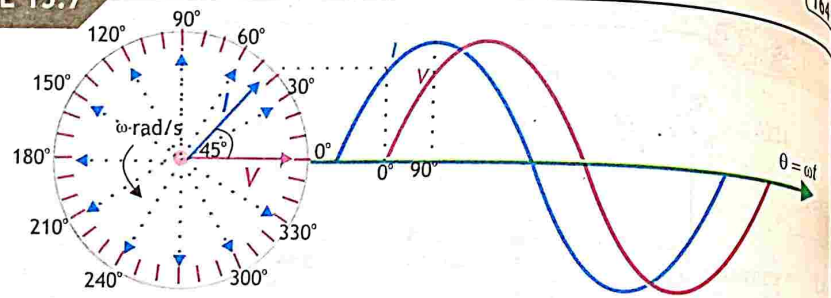
Things start to get complicated when we need to relate two or more AC voltages or currents that have phase difference with each other. Fig 15.7(a) shows two waveforms that are not synchronized i.e., their peaks and zero points do not match up at the same points in time.

Thus *when two alternating quantities of the same frequency have different zero point, they are said to have a phase difference.*

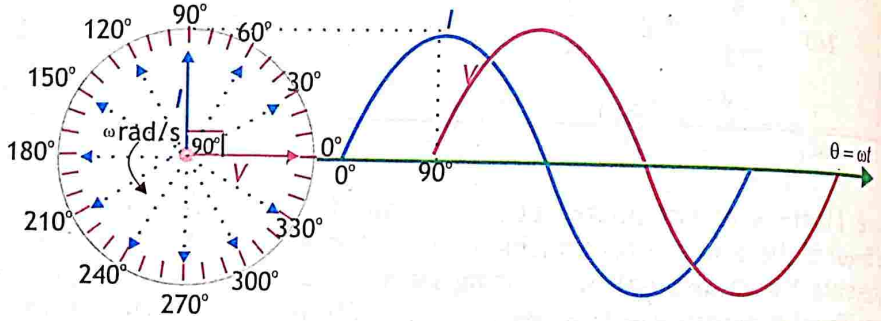
The quantity which crosses through its zero point earlier is said to leading while the other is said to be lagging. A few more examples of phase difference are given in the following graphs to better illustrate this concept. The two waves I versus V shown in figure 15.7(a) have same amplitude and frequency, but they have phase difference with each other.

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FIGURE 15.7



(a): Wave *I* leads wave *V* by 45°



(b): Wave *I* leads wave *V* by 90°

Since both alternating quantities have the same frequency, the phase difference between them remains the same through the cycle. The phase difference between voltage and current at any angle ϕ can be expressed in the equations form as

$$V = V_m \sin(\omega t - \phi) \qquad \text{(ii)}$$

15.6 A.C. THROUGH RESISTOR

Consider a circuit containing a resistance *R* connected across an alternating voltage source as shown in Fig15.8 (a), then free electrons flow in one direction for the first half-cycle of the supply and then flow in the opposite direction during the next half-cycle, thus constituting alternating current in the circuit. The applied voltage and current pass through their zero values at the same instant and attain their positive and negative peaks at the same instant such that current is in phase with the applied voltage as shown in fig15.8(b).

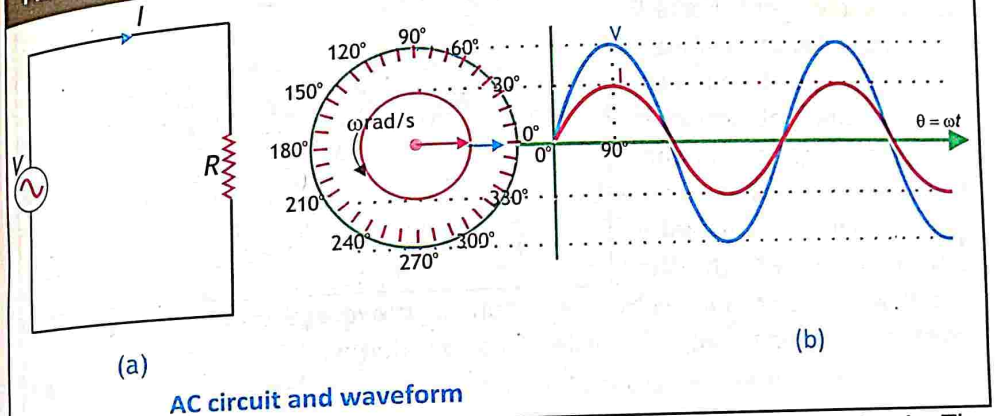
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The alternating voltage is given by

$$V = V_m \sin \omega t \qquad \text{(i)}$$

where, V_m is the peak value of the alternating voltage.

FIGURE 15.8



AC circuit and waveform

As a result of this voltage, an alternating current *I* will flow in the circuit. The applied voltage has to overcome the potential drop in the resistance only i.e., $V = IR$

Or $$I = \frac{V}{R} = \frac{V_m}{R}\sin \omega t \qquad \therefore \quad I_m = \frac{V_m}{R}$$

$$I = I_m \sin \omega t \qquad \text{(ii)}$$

The value of *I* will be maximum (i.e. I_m) when $\sin \omega t = 1$. Eqs. (i) and (ii) shows that the applied voltage and the circuit current are in phase with each other. This is also indicated by the phasor diagram shown in Fig15. 8 (b).
In terms of r.m.s. value,

$$\frac{V_m}{\sqrt{2}} = \frac{I_m}{\sqrt{2}} \times R \qquad \ldots(15.8)$$

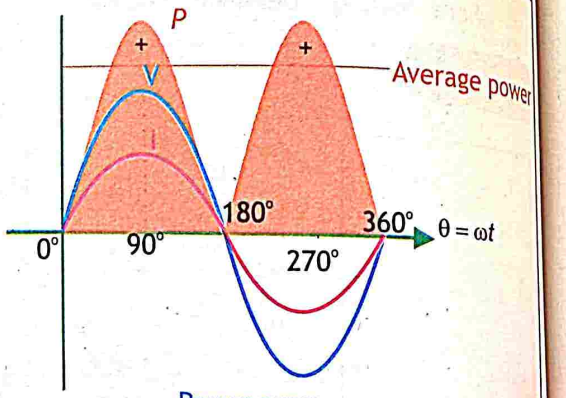
Or

$$V_{rms} = I_{rms} R \qquad \ldots(15.9)$$

15.6.1 POWER LOSS IN AN RESISTOR

The power curve for a pure resistive circuit is obtained from the product of the corresponding instantaneous values of voltage and current. Fig15.9 shows that power is always positive except at points 0°, 180° and 360° at which it drops to zero for a moment. This means that the voltage source is constantly delivering power to the circuit which is consumed by the circuit. The average power dissipated in resistor R over one complete cycle of the applied is:

FIGURE 15.9



Power curve

$$P = \langle VI \rangle = \langle V_m \sin\omega t \times I_m \sin\omega t \rangle \quad \ldots(15.10)$$

$$= V_m I_m \langle \sin^2 \omega t \rangle$$

$$= \frac{V_m I_m}{2} \qquad \because \langle \sin^2 \omega t \rangle = \frac{1}{2}$$

$$P = \frac{V_m}{\sqrt{2}} \times \frac{I_m}{\sqrt{2}} = V_{rms} I_{rms} \quad \ldots(15.11)$$

EXAMPLE 15.1

An A.C. circuit consists of a pure resistance of 20Ω and is connected across A.C. supply of 220V, 50Hz. Calculate (a) current (b) power consumed and (c) equation for voltage and current.

GIVEN

Frequency f = 50 Hz Resistance R = 20 Ω Voltage V= 220 V

REQUIRED

(a) current I=? (b) power consumed P =?
(c) equation for voltage and current =?

SOLUTION

Maximum value of an alternating voltage is $V_m = \sqrt{2}\, V = \sqrt{2} \times 220 = 311.1$V

(a) Current, $I = V/R = 220/20 = 11$A

(b) Average power P dissipated in the resistor is

$$P = VI = 220 \times 11 = 2420 \text{ w}$$

Maximum value of an alternating current $I_m = \sqrt{2}\, I = \sqrt{2} \times 11 = 15.55$ A

$$\omega = 2\pi f = 2\pi \times 50 = 314 \text{ rads}^{-1}$$

(c) Equations for voltage and current is

$V = V_m \sin(\omega t)$ & $I = I_m \sin(\omega t)$

putting values

$V = 311.1 \sin(314t)$ & $I = 15.55 \sin(314t)$

ASSIGNMENT 15.1

A 60 Ω resistor is connected across A.C. supply of 220V. Calculate the current drawn from the supply and the power consumed by the heating element.

Ans(3.66A, 860w)

15.7 A.C. THROUGH INDUCTOR

An inductor is a two-terminal electrical component which resists changes in electric current passing through it. It consists of a conductor such as a wire, usually wound into a coil. Consider an alternating voltage applied to a pure inductance of L as shown in Fig15.10 when a sinusoidal current I flow in time t then a back e.m.f. ($L\Delta I/\Delta t$) is induced due to the inductance of the coil. This back e.m.f. at every instant opposes the change in current through the coil. As there is no drop in potential, so the applied voltage has to overcome the back e.m.f.

∴ Applied alternating voltage = Back e.m.f.

So the energy which is required in building up current in inductance L, is returned back during the decay of the current. Let the equation for alternating current is :

$$I = I_m \sin \omega t \quad \ldots(i)$$

The changing current sets up a back e.m.f in the coil.

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The magnitude of back e.m.f is $\varepsilon = L\dfrac{\Delta I}{\Delta t}$

To maintain a constant current the applied e.m.f must be constantly applied. The magnitude of applied voltage is

$$V = L\frac{\Delta I}{\Delta t} = L\frac{\Delta(I_m \sin\omega t)}{\Delta t}$$

$$= LI_m \frac{\Delta(\sin\omega t)}{\Delta t} \qquad \text{(ii)}$$

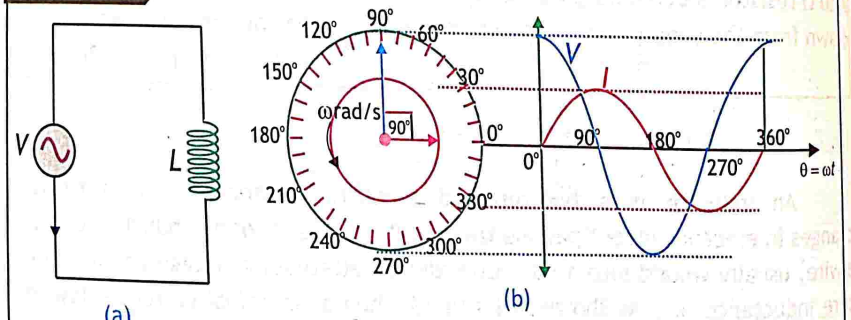
Using the result of simple calculus:

$$\frac{\Delta(\sin\omega t)}{\Delta t} = \omega\cos\omega t \qquad \text{(iii)}$$

putting the values of Eq (iii) in (ii) we get

$$V = \omega LI_m \cos\omega t \qquad \therefore (\omega LI_m = V_m)$$

FIGURE 15.10



Inductor in AC circuit

$$\text{or} \quad V = V_m \cos\omega t$$

$$V = V_m \sin(\omega t + \frac{\pi}{2}) \qquad \text{(iv)}$$

From Eqs (i) and (iv) it is clear that current lags behind the voltage by $\pi/2$ radians or 90°. Hence in a pure inductance, current lags behind the voltage by 90°. Fig. 15.10(b) also shows that current lags the voltage in an inductive coil. Inductance opposes the change in current and serves to delay the increase or

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decrease of current in the circuit. This causes the current to lag behind the applied voltage which is indicated by the phasor diagram shown in Fig.15.10(b). Inductance opposes the flow of current in the circuit.

So the opposition offered by an inductor to the flow of A.C. is called inductive reactive reactance X_L.

Therefore in analogy to ohm law we can write:

$$V_m = I_m X_L$$

Since inductive reactance is ratio of voltage to current. So

$$X_L = \frac{V_m}{I_m} = \frac{V}{I} = \omega L$$

$$\text{or} \quad X_L = \omega L \qquad \ldots(15.12)$$

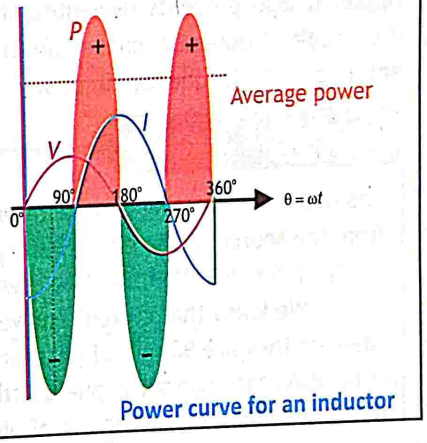
$$X_L = 2\pi fL \qquad \ldots(15.13)$$

The reactance of coil depends upon frequency of A.C. In case of D.C. inductive reactance X_L is zero.

15.7.1 POWER LOSS IN AN INDUCTOR

Fig15.11: shows the power curve for a pure inductive circuit. During the first 90° of the cycle, the voltage is positive and the current is negative, therefore, the power supplied is negative. This means the power is flowing from the coil to the source.

FIGURE 15.11



Power curve for an inductor

During the next 90° of the cycle, both voltage and current are positive and the power supplied is positive. Therefore, power flows from the source to the coil. Similarly, for the next 90° of the cycle, power flows from the coil to the source and during the last 90° of the cycle, power flow from the source to the coil. The power curve over one

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cycle shows that positive power is equal to the negative power. Hence the resultant power over one cycle is zero i.e. a pure inductance consumes no power. The electric power merely flows from the source to the coil and back again. In any circuit, electric power consumed at any instant is the product of voltage and current at that instant. The average power loss in an inductive circuit is,

$$P = < VI > = < V_m \cos \omega t \times I_m \sin \omega t >$$
$$= V_m I_m < \sin \omega t >< \cos \omega t >$$
$$= 0 \qquad \because < \sin \omega t >< \cos \omega t > = 0$$

15.8 CHOKE COIL

A Choke is an inductor used in a circuit. It offers high impedance to frequencies above a certain frequency range, without appreciable limiting the flow of current. In a DC circuit, a resistor is used to restrict the current.

If I is the current and R is the resistance, the power loss in the form of heat is I^2R. In ac circuit, inductor is used. Its impedance is X_L and is large at high frequencies. In general, a choke is used to prevent electric signals along undesired paths. The choke is used as a filter in power supply to prevent ripple. It also prevents unwanted signals to enter other parts of the circuits, e.g. radio frequency choke (RFC) prevents radio frequency signals from entering audio frequency circuits.

FOR YOUR INFORMATION

The purpose of passing current through a circuit is to transfer power from the source to the circuit. *The power which is actually consumed in the circuit is called the true power or active power.*

We know that current and voltage are in phase in a resistance whereas they are 90° out of phase in L or C. Therefore, we come to the conclusion that current in phase with voltage produces true or active power whereas current 90° out of phase with voltage contributes to reactive power *i.e.*

True Power = Voltage × Current in phase with voltage

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EXAMPLE 15.2

A pure inductive coil allows a current of 20A to flow from a 220 V, 50Hz supply. Find (1) inductive reactance (2) inductance of the coil (3) power absorbed. Write down the equation for voltage and current.

GIVEN

Current I= 20 A, Voltage V = 220 V Frequency f = 50 Hz ,

REQUIRED

Inductive reactance, X_L =? Inductance, L=?
Power absorbed, P=? Equation for voltage and current=?

SOLUTION

1. Circuit current, $I = V/X_L$
   Inductive reactance, $X_L = V/I = 220/20 = 11\ \Omega$
2. Now, $X_L = 2\pi f L$
   $$L = \frac{X_L}{2\pi f} = \frac{11}{2\pi \times 50} = 0.035\text{H}$$
3. Power absorbed P = Zero
   $V_m = 220 \times \sqrt{2} = 311.1\text{V}$; $I_m = 20 \times \sqrt{2} = 28.28$ A ;
   $\omega = 2\pi \times 50 = 314$ rad s^{-1}
   Since in a pure inductive circuit, current lags behind the voltage by $\pi/2$ radians, the equations are:
   $V = 311.1 \sin 314t$ V $\qquad I = 28.28 \sin (314t - \pi/2)$ A

EXAMPLE 15.3

The current through an 60 mH inductor is 0.2 sin (377t -25°)A. Write the mathematical expression for the voltage across it.

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GIVEN Inductance L = 60 m H , current I =0.2 sin (377t -25°)A

REQUIRED Mathematical expression for the voltage V= ?

SOLUTION

Inductive reactance, $X_L = 2\pi fL = 377 \times 60 \times 10^{-3} = 22.62\Omega$

maximum value of an alternating $V_m = I_m X_L = 0.2 \times 22.62 = 4.5V$

Since the voltage leads the current by 90^0 therefore 90^0 is added to the phase angle of voltage.

$$V = V_m \sin(377t - 25^0 + 90^0)$$

$$V = 4.5\sin(377t + 65^0)\,V$$

ASSIGNMENT 15.2

A pure inductor is connected across a 10 V, 200 Hz supply, and the current flowing through it is measured as 0.4 A. Determine the value of its inductance.

Answer(19.9 mH)

15.9 A.C. THROUGH CAPACITOR

Consider an alternating voltage applied to a capacitor of capacitance C as shown in Fig15.12. When an alternating voltage is applied across the plates of a capacitor, the capacitor is charged in one direction and then in the other as the voltage reverses. The result is that electron move to and fro around the circuit, connecting the plates, thus constituting alternating current. The basic relation between the charge q on the capacitor and voltage V across its plates i.e. q=CV holds at every instant. Let the applied alternating voltage is

$V = V_m \sin \omega t$ (i)

Then, at any instant I be the current and q be the charge on the plates.

Charge on capacitor, $q = CV = C\,V_m \sin \omega t$

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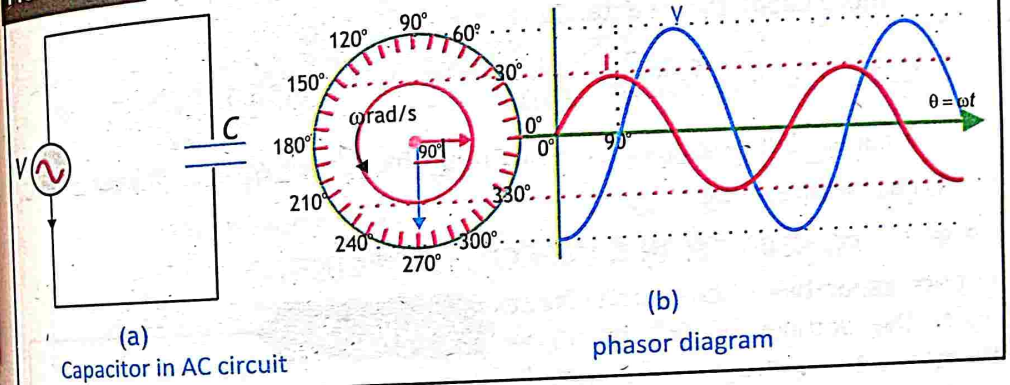
$$I = \frac{\Delta q}{\Delta t} = \frac{\Delta(CV_m \sin(\omega t))}{\Delta t} = \frac{CV_m(\Delta \sin(\omega t))}{\Delta t}$$

by using maths formulae

$$\therefore \Delta \sin(\omega t) = \omega \cos(\omega t)$$

$$= CV_m \omega \cos(\omega t) = CV_m \omega \sin(\omega t + \frac{\pi}{2})$$

FIGURE 15.12



(a) Capacitor in AC circuit

(b) phasor diagram

$$\therefore CV_m \omega = I_m \quad \ldots(15.14)$$

$$I = I_m \sin(\omega t + \frac{\pi}{2}) \quad \ldots(ii)$$

Eqs. (i) and (ii) shows that current leads the voltage by $\pi/2$ radians or 90°. Hence in a pure capacitance, current leads the voltage by 90°. Capacitance opposes the change in voltage and serves to delay the increase or decrease of voltage across the capacitor. This causes the voltage to lag behind the current. This is also illustrated in the phasor diagram shown in Fig:15.12(b):

Like inductor which opposes the flow of A.C. capacitor also opposes the flow of A.C. in the circuit. From the above:

$$I_m = \omega C\, V_m \quad \ldots(15.15)$$

Or $$\frac{V_m}{I_m} = \frac{1}{C\omega}$$

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Just like ohm law the ratio of V/I is the measure of opposition offered by resistor to the flow of current. In case of capacitor this opposition capacitive reactance which opposes the flow of current.

$$\frac{V_m}{I_m}=\frac{V_c}{I}=\frac{1}{C\omega} \qquad \ldots(15.16)$$

Clearly, the opposition offered by capacitance to current flow is $1/\omega$. This quantity $1/\omega C$ is called the capacitive reactance X_c of the capacitor. has the same dimensions as resistance and is, therefore, measured in Ω.

$$I = Vc/Xc$$

Where capacitive reactance is

$$X_c=\frac{1}{\omega C}=\frac{1}{2\pi fC} \qquad \ldots(15.17)$$

The capacitive reactance depends upon frequency of A.C. In case of D.C X_c has infinite value.

15.9.1 POWER LOSS IN A CAPACITIVE CIRCUIT

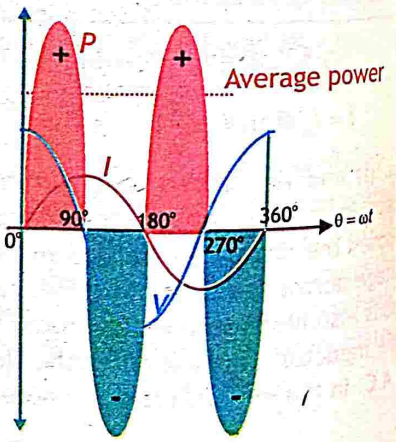
In pure capacitive circuit the current leads the voltage by 90^0 in phase therefore the average power loss in capacitive circuit is,

$$P = < VI > = < V_m \sin\omega t \times I_m \cos\omega t >$$
$$= V_m I_m < \sin\omega t >< \cos\omega t >$$
$$= 0$$

$\because < \sin\omega t >< \cos\omega t > = 0$

This fact is also illustrated in the wave diagram shown in Fig:15.13:Which shows that in one cycle the positive power is equal to negative power so power absorbed by capacitor in one cycle is zero.

FIGURE 15.13



power curve for pure capacitive circuit

NOT FOR SALE

EXAMPLE 15.4

A318μF capacitor is connected across a 220V, 50Hz system. Determine (a) the capacitive reactance (b) r.m.s. value of current and (c) equations for voltage and current.

GIVEN

Capacitance, $C = 318\mu F = 318\times10^{-6}$ F Voltage V=220 V
Frequency f = 50 Hz

REQUIRED

(a) the capacitive reactance X_C =? (b) RMS value of current I=? (c) equations for voltage and current =?.

SOLUTION

(a) capacitive reactance, $X_c=\frac{1}{2\pi fC}=\frac{1}{2\pi\times50\times318\times10^{-6}}=10.26\,\Omega$

(b) r.m.s. value of current, $I = V / Xc = 220 / 10.26 = 21.44$A

(c) maximum value of an alternating voltage & current is

$V_m = 220\times\sqrt{2} = 311.1$V, $\quad I_m = I\times\sqrt{2} = \sqrt{2}\times21.44 = 30.32$A,

Frequency $\omega = 2\pi\times50 = 314$Hz

∴Equations for voltage and current are:

$$V = V_m \sin(\omega t) \;\&\; I = I_m \sin(\omega t + \pi/2)$$

putting values

$$V = 311.1\sin 314t, \quad I = 30.32 \sin(314t + \pi/2),$$

ASSIGNMENT 15.3

A perfect capacitor is connected across a 6 V, 5 kHz supply, and the resulting current flow is 88.6 mA. Calculate the capacitance value.

Answer (0.47μF)

15.10 R.L SERIES A.C. CIRCUIT

In an RL series circuit, a pure resistance (R) is connected in series with pure inductance (L). To draw the phasor diagram of RL series circuit, the current I (r.m.s. value) is taken as reference vector because it is common to both elements.

NOT FOR SALE

Voltage drop V_R (= $I\,R$) in resistor is in phase with current vector, whereas, the voltage drop V_L (= $I\,X_L$) in inductor leads the current vector by 90° since current lags behind the voltage by 90° in the purely inductive circuit. In phasor diagram V_L is represented by the phasor AD while V_R is represented by phasor AB. The vector sum of these two voltage drops is equal to the applied voltage V (r.m.s. value).*i.e.*

$$V^2 = V_R^2 + V_L^2 \qquad \ldots(15.18)$$

or

$$V = \sqrt{V_R^2 + V_L^2} = \sqrt{(IR)^2 + (IX_L)^2}$$

$$= I\sqrt{R^2 + X_L^2} \qquad \ldots(15.19)$$

or $I = \dfrac{V}{\sqrt{R^2 + X_L^2}}$

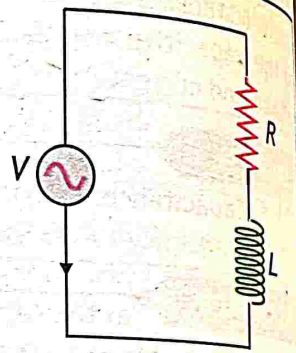
The quantity $\sqrt{R^2 + X_L^2}$ is the opposition offered to current flow and is called impedance of the circuit. It is represented by Z and is measured in ohms (Ω)

$$I = V/Z \qquad \ldots(15.20)$$

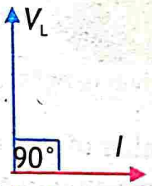
where $Z = \sqrt{R^2 + X_L^2}$ $\qquad \ldots(15.21)$

The phasor diagram is shown in Fig15.14(a). The phasor diagram is a triangle whose sides represent R, X_L and Z. The triangle that is created when adding the resistance to the reactance X_L is known as an **impedance triangle.**

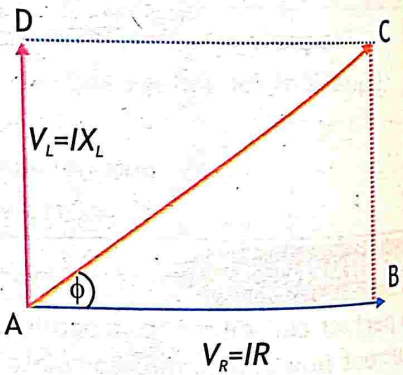
FIGURE 15.14



(a) : RL series circuit



(b) phasor diagram



(c):phasor diagram of RL series circuit

The phasor diagram shows that circuit current I lags behind the applied voltage V by ϕ^o. The wave diagram in Fig.15.14 (c) also shows the phase difference ϕ^o between current I and voltage V. The value of phase angle ϕ^o can be determined from the phasor diagram.

$$\tan\phi = \frac{V_L}{V_R} = \frac{IX_L}{IR} = \frac{X_L}{R} \qquad \ldots(15.22)$$

Since X_L and R are known, ϕ can be calculated. If the applied voltage is $V = V_m \sin\omega t$, then equation for the circuit current will be:

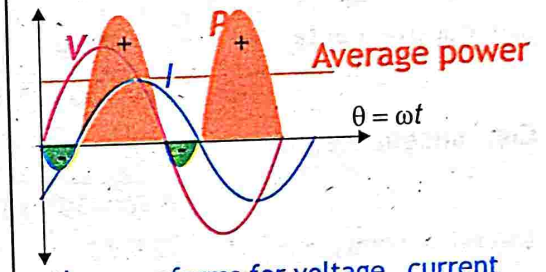
$$I = I_m \sin(\omega t - \phi) \text{ where } I_m = V_m / Z$$

In an inductive circuit current lags behind the applied voltage. The angle (i.e. ϕ) of lagging is greater than 0° but less than 90°. It is determined by the ratio of inductive reactance to resistance ($\tan\phi = X_L / R$) in the circuit. The greater the value of this ratio, the greater will be the phase angle ϕ

15.10.1 POWER

For purely resistive circuit, the power factor is $\cos 0° = 1$ as current and voltage are in phase. For the inductance or capacitance circuit, the power factor is $\cos 90° = 0$ as current and voltage are 90° out of phase. Therefore power consumed by pure L or C is zero.

FIGURE 15.15



the waveforms for voltage, current and power in a series R-L circuit.

$$\therefore \text{ Average Power, } P = \frac{V_m I_m}{2}\cos\phi = \frac{V_m}{\sqrt{2}} \times \frac{I_m}{\sqrt{2}} \times \cos\phi$$

or

$$P = V I \cos\phi \qquad \ldots(15.23)$$

Where V and I are the r.m.s. values of voltage and current. The term $\cos\phi$ is called power factor of the circuit.

In Fig:15.15 the negative area of curve is indicated by green colour and positive area of curve is indicated by orange colour. The negative area means that the inductance of the circuit returns the power to the source. The area of positive

NOT FOR SALE

curve is greater than negative area of curve so net power over one cycle is positive. This shows that power is consumed in R-L series circuit.

EXAMPLE 15.5

A coil having a resistance of 7Ω and an inductance of 31.8 mH is connected to 220V, 50Hz supply. Calculate (a) the circuit current (b) phase angle (c) power factor and (d) power consumed.

GIVEN

Inductance, L= 31.8 m H= 31.8×10^{-3}H
Voltage V=220 V coil resistance R=7Ω
Frequency f = 50 Hz

REQUIRED

(a) the circuit current I=? (b) phase angle ϕ =?
(c) power factor =? (d) power consumed P=?

SOLUTION

(a) Inductive reactance, $X_L = 2\pi f L$

$= 2\pi\times50\times31.8\times10^{-3} = 10\Omega$

Coil impedance, $Z=\sqrt{R^2+X_L^2}$

$=\sqrt{7^2+10^2} = 12.2\Omega$

Circuit current, $I = V / Z$

$= 220 / 12.2 = 18.03$A

(b) $\tan\phi = X_L / R = 10 / 7$

∴ Phase angle, $\phi = \tan^{-1}(10/7) = 55^0$ lag

(c) Power factor $= \cos\phi = \cos55^0 = 0.573$ lag

(d) Power consumed, $P = VI\cos\phi$

$= 220\times18.03\times0.573 = 2272.8$ w

ASSIGNMENT 15.4

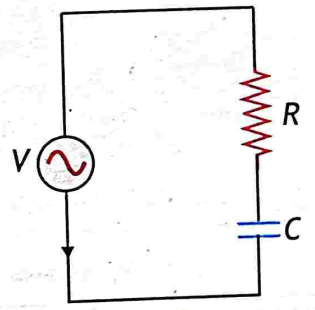
220 V, 50 Hz, AC source is connected to an inductance of 0.2 H and a resistance of 20 Ω in series. What is the current in the circuit? Answer (3.33A)

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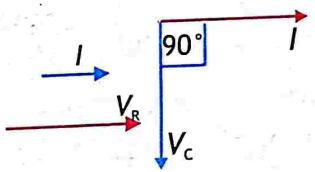
15.11 R.C SERIES A.C. CIRCUIT

In an RC series circuit, a pure resistance (R) is connected in series with a pure capacitor (C) as shown in fig15.16(a). The voltage, V across the combination is equal to the phasor sum of the two component voltages, V_R and V_C. Where $V_R = IR$ and, $V_C = IX_C$.

FIGURE 15.16



(a) RC series circuit



(b) phasor diagram

In a series AC circuit the current is common and can therefore be used as the reference source because the same current flows through the resistance and capacitance. The individual vector diagrams for a pure resistance and a pure capacitance is shown in Fig15.16(b).

Voltage drop ($V_R = IR$) is in phase with current vector, whereas, the voltage drop in ($V_C = IX_C$) lags behind the current vector by 90°, since current leads the voltage by 90° in the pure capacitive circuit. The vector sum of these two voltage drops is equal to the applied voltage V (r.m.s. value).

$$V^2 = V_R^2 + V_C^2 \qquad \ldots(15.24)$$

$$V = \sqrt{V_R^2+V_C^2} = \sqrt{(IR)^2+(-IX_C)^2} = I\sqrt{R^2+X_C^2}$$

$$\text{or } I = \frac{V}{\sqrt{R^2+X_C^2}} \qquad \ldots(15.25)$$

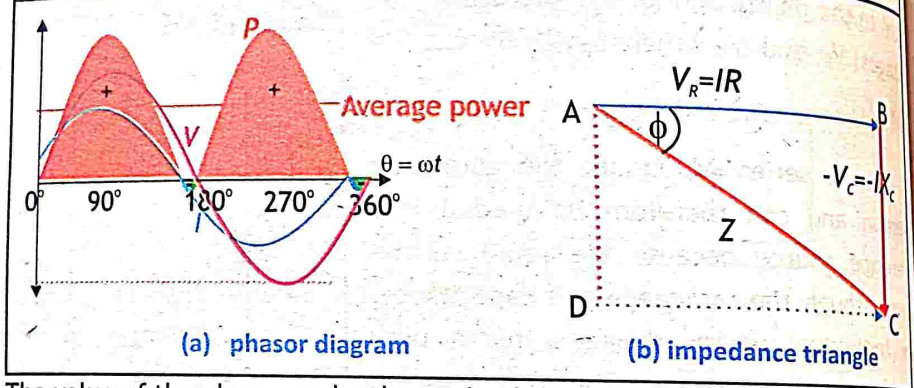
The quantity $\sqrt{R^2+X_C^2}$ offer opposition to current flow and is called impedance of the circuit. $I = V/Z$

$$\text{where } Z = \sqrt{R^2+X_C^2} \qquad \ldots(15.26)$$

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The phasor diagram shows that circuit current *I* leads the applied voltage *V* by ϕ. This fact is also illustrated in the wave diagram and impedance triangle (as shown in Fig15.17(a), (b)) of the circuit.

FIGURE 15.17



(a) phasor diagram (b) impedance triangle

The value of the phase can be determined as under:

$$\tan\phi = -\frac{V_C}{V_R}$$

$$= -\frac{IX_C}{IR} = -\frac{X_C}{R} \qquad \ldots(15.27)$$

Since current is taken as the reference phasor, negative phase angle implies that voltage lags behind the current. This is the same thing as current leads the voltage.

15.11.1 Power

The power waveform for RC series circuit is shown in the fig15.17(a). The negative area of curve is indicated by green colour and positive area of curve is indicated by orange colour. The area of positive curve is greater than negative area of curve, thus power is consumed by the RC series circuit. But power is consumed in resistance only; capacitor does not consume any power. The equation for voltage and current are:

$$V = V_m \sin\omega t \quad ; \quad I_m \sin(\omega t + \phi)$$

$\therefore$ Average power, $\langle P \rangle = \langle V \rangle \langle I \rangle = VI\cos\phi$

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EXAMPLE 15.6

A 100V, 50Hz AC supply is applied to a capacitor of capacitance 79.5 μF connected in series with a non-inductive resistance of 30 Ω. Find (1) impedance (2) current (3) phase angle and (4) equation for the instantaneous value of current.

GIVEN

Voltage V=100 V, resistance R=30
Frequency f = 50 Hz, capacitance C = 79.5 μ F

REQUIRED

(1) impedance Z=? (2) current I=? (3) phase angle ϕ =? and
(4) equation for the instantaneous value of current I_{inst} =?

SOLUTION

(1) Capacitive reactance, $X_C = \frac{1}{2\pi f C} = \frac{10^6}{2\pi \times 50 \times 79.5} = 40\Omega$

Circuit impedance, $Z = \sqrt{R^2 + X_C^2} = \sqrt{30^2 + 40^2} = 50\Omega$

(2) Circuit current, $I = V/Z = 100/50 = 2$ A

(3) $\tan\phi = X_C/R = 40/30 = 1.33$

$\therefore$Phase angle, $\phi = \tan^{-1} 1.33 = 53°$ *lead*

$$I_m = I \times \sqrt{2} \Rightarrow I_m = 2 \times \sqrt{2} = 2.828\,\text{A}$$

$$\omega = 2\pi f = 2\pi \times 50 = 314\,\text{rads}^{-1}$$

(4) equation for current is $I_{inst} = 2.828\sin(314t + 53°)$

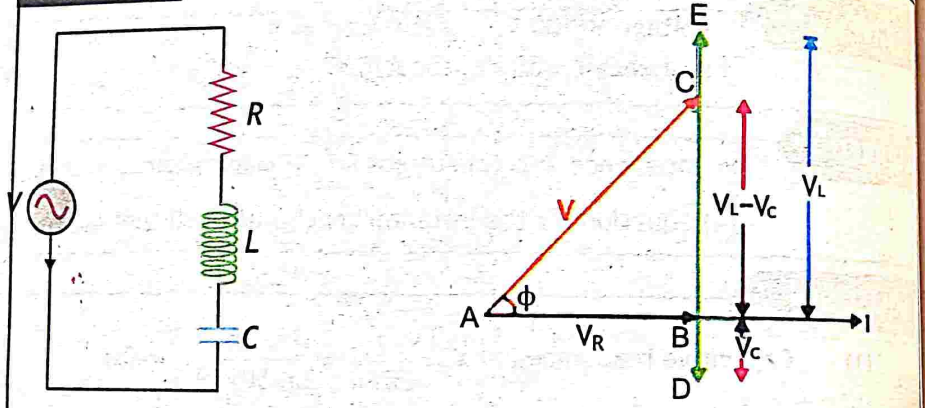
15.12 R-L-C Series A.C Circuit

When a pure resistor (R), an inductor (L), and a capacitor (C) are connected together in series combination with each other then **RLC Series** Circuit is formed as illustrated in Fig15.18 (a). The analysis of this circuit is quite easy since all the circuit elements share the same current. We can draw a phasor diagram for the current and voltages across the inductor, capacitor, and resistor. The P.D. across R, is $V_R = IR$ in this case V_R is in phase with I.

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The P.D. across L, is $V_L = IX_L$ in this case V_L leads I by 90^0. The P.D. across C, is $V_C = IX_C$ in this case where V_C lags I by 90^0. V_L and V_C are thus 180^0 out of phase. In phasor diagram (Fig15.18 (b)), AB represents V_R, BE represents V_L and BD represents V_C. It may be seen that V_L is in phase opposition to V_C.

FIGURE 15.18



(a) AC circuit of R, L and C connected in series across a supply voltage V (r.m.s.). The resulting circuit current is I (r.m.s.). (b) phasor sum

It follows that the circuit can either be effectively inductive or capacitive depending upon which voltage drop (V_L or V_C) is predominant. If $V_L > V_C$ then the net voltage drop across L-C combination is V_L-V_C and their resultant is in the direction V_L represented by BC. Therefore, the applied voltage V is the phasor sum of V_R and V_L-V_C and represented by AC.

$$V^2 = V_R^2 + (V_L - V_C)^2 \qquad \ldots(15.28)$$

$$V = \sqrt{V_R^2 + (V_L - V_C)^2} = \sqrt{(IR)^2 + (IX_L - IX_C)^2}$$

$$= I\sqrt{(R)^2 + (X_L - X_C)^2} = IZ$$

Where $Z = \sqrt{(R)^2 + (X_L - X_C)^2}$ $\qquad \ldots(15.29)$

The quantity $(X_L - X_C)$ is called the reactance of the circuit, denoted by X

i.e., $X^2 = (X_L - X_C)^2$

Finally we can write

NOT FOR SALE

$Z = \sqrt{R^2 + X^2}$ is the opposition offered to current flow and is called impedance of the circuit.

Circuit power factor, $\cos\phi = \frac{R}{Z} = \frac{R}{\sqrt{R^2 + (X_L - X_C)^2}}$ $\qquad (15.30)$

Since X_L, X_C and R, are known, phase angle ϕ of the circuit can be determined.

$$\tan\phi = \frac{V_L - V_C}{V_R}$$

$$= \frac{X_L - X_C}{R} = \frac{X}{R} \qquad (15.31)$$

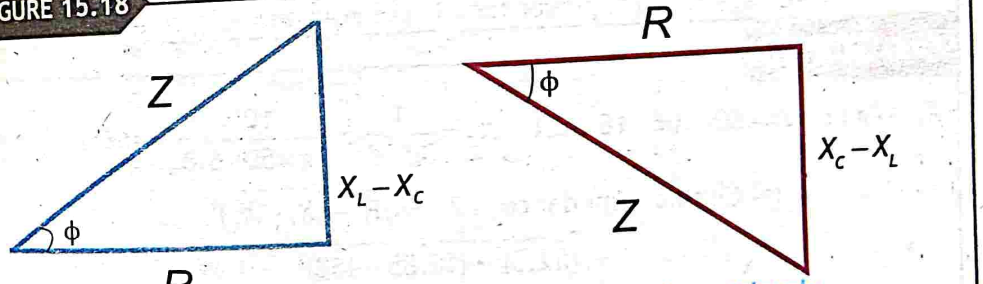
So if the current is represented by a cosine function, $I = I_m \cos\omega t$

The source voltage leads the current by an angle and its equation is

$$I = I_m \cos(\omega t + \phi)$$

Power consumed, $P = V I \cos\phi$

FIGURE 15.18



(c) (d) : impedance triangle

The impedance triangle is shown in Fig 15.18(c,d) and the Equation for impedance of a R-L-C series circuit is given by:

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

(i) When X_L - X_C is positive (*i.e.* $X_L > X_C$), phase angle φ is positive and the circuit will be inductive.

(ii) When X_L - X_C is negative (*i.e.* $X_C > X_L$), phase angle ϕ is negative and the circuit is capacitive.

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(iii) When $X_L - X_C = 0$, the circuit is purely resistive and phase angle $= 0°$ the circuit will then have unity power factor.

If the equation for the applied voltage is $V = V_m \sin\omega t$, then equation for the circuit current will be

$$I = I_m \sin(\omega t \pm \phi) \text{ where } I_m = V_m / Z$$

EXAMPLE 15.7

A 220V, 50Hz A.C. supply is applied to a coil of 0.06 H inductance and 2.5 Ω resistance connected in series with a 6.8 μ F capacitor. Calculate (a) impedance (b) current (c) phase angle between current and voltage (d) power factor and (e) power consumed.

GIVEN

inductance $L = 0.06$ H resistance $R = 2.5\,\Omega$ voltage $V = 220$

Frequency $f = 50$Hz capacitance $C = 6.8\ \mu$ F

REQUIRED

(a) impedance Z=?(b) current I=? (c) phase angle between current and voltage ϕ =? (d) power factor $\cos\phi$ =? and (e) power consumed P=?

SOLUTION

$$X_L = 2\pi f L = 2\pi \times 50 \times .06 = 18.85\Omega \qquad X_C = \frac{1}{2\pi f C} = \frac{10^6}{2\pi \times 50 \times 6.8} = 468\Omega$$

(a) Circuit impedance, $Z = \sqrt{R^2 + (X_L - X_C)^2}$

$$= \sqrt{(2.5)^2 + (18.85 - 468)^2} = 449.2\Omega$$

(b) Circuit Current, $I = V / Z = 220 / 449.2 = 0.4897$A

(c) $$\tan\phi = \frac{X_L - X_C}{R} = \frac{18.85 - 468}{2.5} = -179.66$$

∴ Phase angle, $\phi = \tan^{-1}(-179.66) = -89.7°$

The negative sign with ϕ shows that current is leading the voltage

(d) Power factor, $\cos\phi = \frac{R}{Z} = \frac{2.5}{449.2} = 0.00557$

(e) Power consumed, $P = VI\cos\phi = 220 \times 0.4897 \times 0.00557 = 0.60007$W

NOT FOR SALE

15.13 RESONANCE IN R-L-C SERIES A.C. CIRCUIT

In R-L-C Series AC circuit, inductors, capacitors, and resistors all impede current. There impedance and reactance is given by the equations:

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

$$X_L = \omega L \text{ and } X_C = \frac{1}{\omega C}$$

When the frequency is very small, the capacitive reactance is large and X_C Z. When the frequency is very large, the inductive reactance is large and $X_L > Z$. But when the inductive reactance X_L is equal to the capacitive reactance X_C, $X_L = X_C$ or $(X_L - X_C = 0)$

The circuit power factor is unity and R-L-C series circuit is said to be in resonance. The frequency f_r at which it occurs is called resonant frequency.

FIGURE 15.19

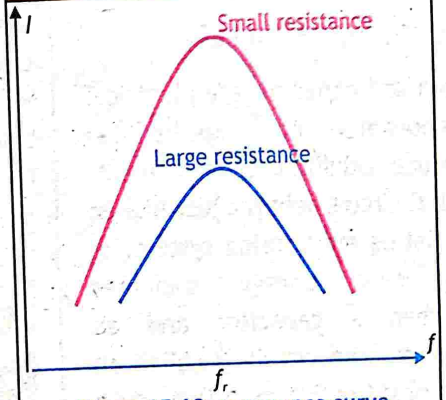


Figure 15.19: resonance curve

At series resonance, $X_L = X_C$ ...(15.32)

Or $$2\pi f_r L = \frac{1}{2\pi f_r C}$$

∴ Resonant frequency, $$f_r = \frac{1}{2\pi\sqrt{LC}} \quad ...(15.33)$$

From Eq. (15.33), it is clear that on increasing either the inductance or the capacitance causes the resonant frequency to decrease. For a given value of inductance and capacitance, there is only one resonant frequency at resonant frequency the current is maximum and impedance of circuit is minimum. Z=R

The magnitude of the current as a function of frequency is plotted as resonance curve Fig 15.19 which shows that the current I starts at near to zero, reaches maximum value at the resonance frequency f_r and then drops again to nearly zero as f becomes infinite.

NOT FOR SALE

An A.C. circuit containing reactive elements (L and C) is said to be in resonance when the circuit power factor is unity.

15.14 PRINCIPLE OF METAL DETECTORS

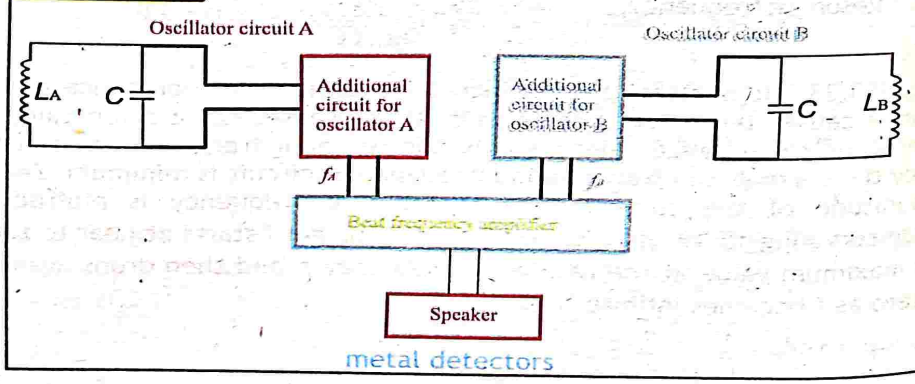
A coil and capacitor are electrical components, which together can produce oscillations of current. An L-C circuit behaves just like an oscillating mass-spring system. In this case energy oscillates between a capacitor and an inductor. The circuit is called an electrical oscillator. Two such oscillators A and B are used for the operation of common type of metal detector (Fig 15.20). In the absence of any nearby metal object, the inductances L_A and L_B

FOR YOUR INFORMATION

When a metal detector comes near a piece of metal, the self-inductance of one of its coils changes. This causes a shift in the resonant frequency of a circuit containing the coil. That shift is detected by the circuitry and transmitted to the diver by means of the headphones.



FIGURE 15.20



metal detectors

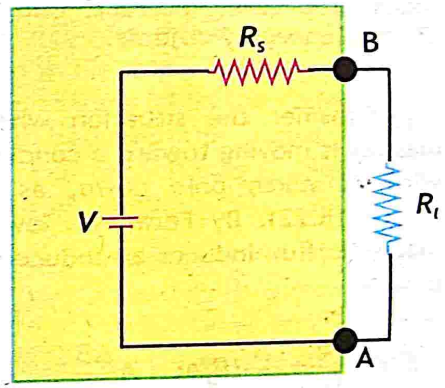
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are the same and hence the resonance frequency of the two circuits is also same. When inductor B, called the search coil comes near a metal object the inductance L_B decreases and corresponding oscillator frequency increases and thus a beat note is heard in the attached speaker. Such detectors are extensively used not only for various security checks but also to locate buried metal objects.

15.15 MAXIMUM POWER TRANSFER

When we connect a load resistance, R_L across the output terminals of the power source, the impedance of the load will vary from an open-circuit state to a short-circuit state resulting in the power being absorbed by the load becoming dependent on the impedance of the actual power source. The source and load R_L are shown in figure 15.21. Then for the load resistance to absorb the maximum power possible it has to be "Matched" to the impedance of the power source and this forms the basis of **Maximum Power Transfer.**

FIGURE 15.21



Maximum power is transferred from a source to a load when the load resistance equals the source resistance.

The maximum power transfer theorem states that *"the maximum amount of power will be dissipated in the load resistance if it is equal in value to the source resistance of the network supplying the power"*.

In other words, the load resistance resulting in greatest power dissipation must be equal in value to the equivalent source resistance, then $R_L = R_S$ but if the load resistance is lower or higher in value than the source resistance of the network, its dissipated power will be less than maximum.

$$R_L = R_i \text{ or } Z_L = Z_s$$

NOT FOR SALE

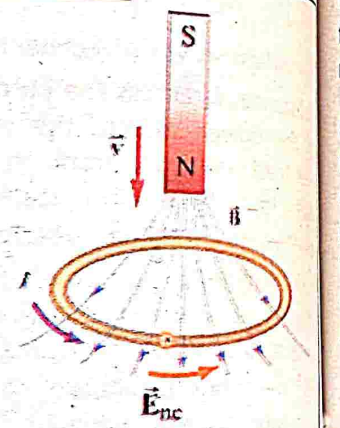
15.16 MAXWELLS EQUATIONS

We already studied the Gauss' law, Faraday's law and Ampere's law. James Clerk Maxwell [1831-1879] unified these experimental laws into a set of Equations known as Maxwell's Equations. These equations predict the existence of electromagnetic waves and that such waves are radiated by accelerating charges.

Maxwell's Equations are a set of equations that describe how electric and magnetic fields propagate, interact, and how they are influenced by objects.

(a). Consider the situation where a bar magnet is moving toward a conducting loop with its north pole down, as shown in Figure 15.22). By Faraday's law changing magnetic flux induces an induced emf in a loop.

FIGURE 15.22



Inducing emf by varying the magnetic field strength

$$\mathcal{E} = \frac{\Delta\Phi}{\Delta t} = \frac{\Delta}{\Delta t}(B.A) = A\frac{\Delta B}{\Delta t} \qquad \ldots(15.34)$$

Let a unit positive charge completes one circular trip in a loop of radius r, the work done will be

$$W = 2\pi r(F) = 2\pi r(qE)$$

An electric field E is induced to drive the current around the loop, and a charge on the loop experiences an electric force $F=qE$.

$$\frac{W}{q} = \frac{2\pi r q E}{q} = 2\pi r E \qquad \ldots(15.35)$$

$$\mathcal{E} = 2\pi r E \qquad \ldots(15.36) \quad \therefore \mathcal{E} = \frac{W}{q}$$

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comparing Eq(15.34) & Eq(15.36) we get

$$2\pi r E = A\frac{\Delta B}{\Delta t}$$

$$E = \frac{A}{2\pi r}\frac{\Delta B}{\Delta t} \qquad \ldots(15.37)$$

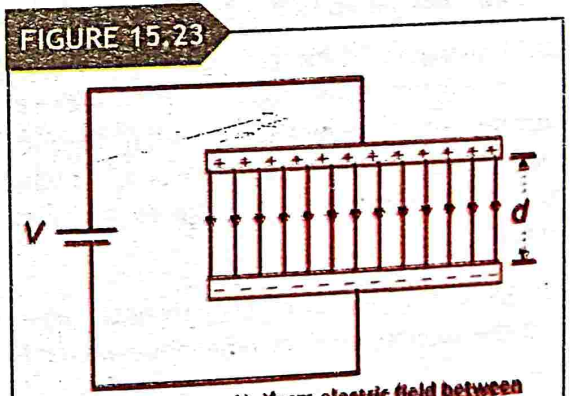
This equation shows that a changing magnetic flux gives rise to an electric field. Experiments have shown that the electric field produced by changing magnetic field is present even if the conducting loop is absent.

(b): Analogues to changing magnetic flux it is found that a changing electric flux gives rise to a magnetic field. In order to arrive at this statement, let a capacitor be connected to a battery as arranged in Fig. (15.23). Current starts growing in the circuit but very quickly decreases to zero when the capacitor is fully charged. An electric field is established between the plates of the capacitor. The charge Q on an air filled capacitor of capacitance C, plate area A, plate separation d and potential difference V is given by

$$Q = CV = \frac{\varepsilon_o A}{d}V = \varepsilon_o AE \qquad \ldots(15.38)$$

$$\therefore \frac{V}{d} = E$$

FIGURE 15.23



Uniform electric field between a pair of charged plate.

Suppose the capacitor is now connected to an alternating e.m.f. source. It is observed that the current flows continuously in the circuit. In this case the electric field E between the plates of the capacitor changes with time $\Delta E/\Delta t$. We saw in former case the current stop while in later case current flow is continue

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the reason for this continuity is change in the electric field. It was first conceived by Maxwell that the change in the electric field is the cause of current in the capacitor. From Eq. (15.38'), we have

$$\frac{\Delta Q}{\Delta t} = \frac{\Delta(\varepsilon_o AE)}{\Delta t} = \frac{\varepsilon_o \Delta(AE)}{\Delta t} \qquad \ldots(15.39)$$

$$I = \frac{\varepsilon_o \Delta(\Phi)}{\Delta t} \qquad \ldots(15.40)$$

Where I is the current and Φ_E is the electric flux through the area A. E (15.40) shows that a changing electric flux is equivalent to a current. This ty of current, which is due to changing electric flux is called displaceme current. While a current due to the flow of charges is called conducti current. According to Ampere's law, each type of current produces magne field around itself.

Using Ampere's law $B = \mu_o n I \qquad \ldots(15.41)$

Putting the value of I from Eq (15.40) in Eq (15.41)

$$B = \mu_o n I = \mu_o n \frac{\varepsilon_o \Delta(\Phi)}{\Delta t} \qquad \ldots(15.42)$$

We have thus shown that a changing Electric field E creates a Magnetic field B.

(c). A changing E-field creates a B-field, which in turn creates an E-field, a electromagnetic disturbance or waves are generated. The fundamenta requirement for generation of electromagnetic waves is an electric charge wit changing velocity (acceleration) since it will create changing electric flux. The velocity of an oscillating charge as it moves to and fro along a wire is alway changing.

(d). Light is a type of electromagnetic waves. Maxwell predicted theoretically that the velocity of electromagnetic waves in free space is given by

$$c = \frac{1}{\sqrt{\varepsilon_o \mu_o}} \qquad \ldots(15.43)$$

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Where $\varepsilon_o = 8.85\times10^{-12} C^2\ N^{-1}m^{-2}$ is the permitivity of free space and $\mu_o = 4\pi\times10^{-7} Wb\ A^{-1}m^{-1}$ is the permeability of free space.

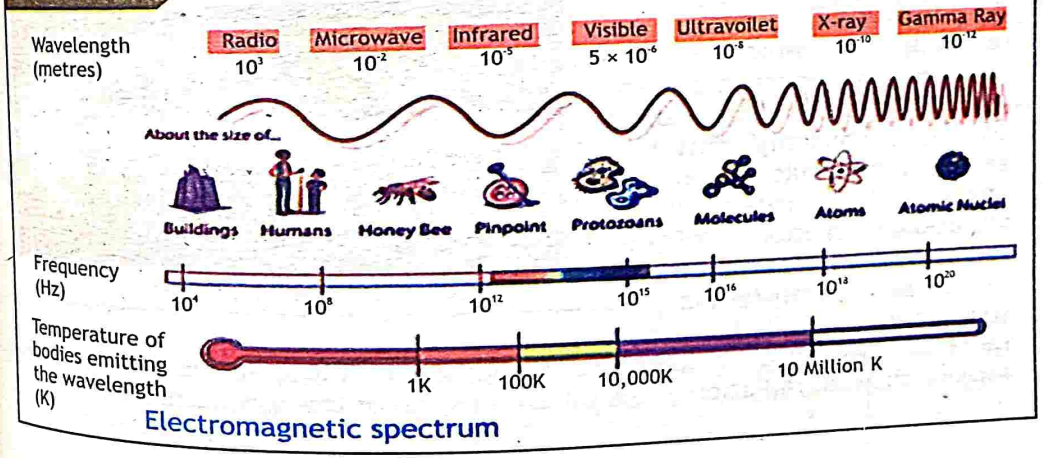
Put these values in the above relation we find that the velocity of lights is given by $c = \frac{1}{\sqrt{8.85\times10^{-12}\times4\pi\times10^{-7}}} = 3\times10^8 ms^{-1}$

Maxwell was one of the first to determine the speed of propagation of electromagnetic waves was the same as the speed of light - and hence to conclude that electromagnetic waves and visible light are the same things. Faraday's law shows that a changing magnetic field gives rise to an electric field. Ampere-Maxwell law shows that a changing electric field gives rise to a magnetic field. It follows that when either electric or magnetic field varies with time, the other field is induced in space. The net effect is that an electromagnetic disturbance is generated due to changing electric and magnetic fields. The disturbance propagates in the form of an electromagnetic wave.

15.17 ELECTROMAGNETIC WAVE

Electromagnetic radiations such as infrared ,ultravoilet,etc are different from each other due to their properties. But they have some features in common such as electric field and magnetic field. Therefore it can be described in terms of electric and magnetic fields, and they all travel through vacuum with the same speed (the speed of light).

FIGURE 15.24

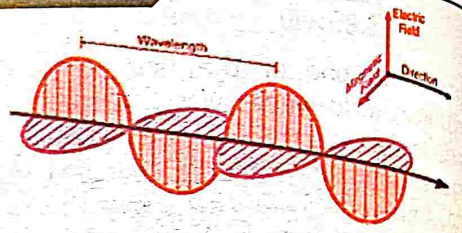


Electromagnetic spectrum

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Fundamentally these radiations are different only in wavelength or frequency. The names given to them in Fig. 15.24 shows various regions of the spectrum along with given names. There are no gaps in the spectrum, nor their sharp boundaries between the various categories. (Certain regions of the spectrum are assigned by law for commercial or other uses, such as TV. AM. or FM broad casting).

FIGURE 15.25



Electromagnetic waves

Let us consider some of these types of electromagnetic radiation in more details.

1. Light. The visible region of the spectrum, most familiar to us, is the electromagnetic radiation emitted by the Sun. The wavelength of the visible region ranges from about 400 nm (violet) to about 700nm (red).

Light is often emitted when the outer (or valence) electrons in atoms change their state of motion: for this reason, such transitions in the state of the electron are called optical transitions. The color of the light tells us something about the atoms or the object from which it was emitted. The study of the light emitted from the Sun and from distant stars gives infomation about their composition.

FIGURE 15.26



Infrared image of Milky Way galaxy

2. Infrared. Infra red radiation, which has wavelengths longer than the visible (from 0.7 μm to about 1 mm), is commonly emitted by atoms or molecules when they change their rotational or vibrational motion. Infrared radiation is an important means of heat transferand is sometimes called heat radiation. Objects of temperatures ranges from , 3 K to 3000 K emit their most intense thermal radiation in the infrared region of the spectrum.

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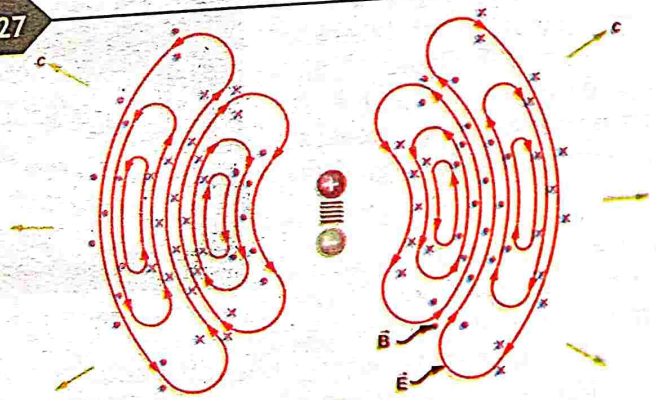
The main technology used in home remote controls is infrared light. The signal between a remote control handset and the device it controls consists of pulses of infrared light, which is invisible to the human eye.

3. Microwaves. Microwaves can be regarded as short radio waves, with typical wavelengths in the range 1 mm to 1 m. They are commonly produced by electromagnetic oscillators in electric circuits, as in the case of microwave ovens. Microwaves are often used to transmit telephone conversations. Microwaves also reach us from extraterrestrial sources.

Neutral hydrogen atoms, which populate the regions between the stars in our galaxy, are common extraterrestrial source of Microwaves emitting radiation with a wavelength of 21 cm.

4. Radio waves. Radio waves have wavelengths longer than 1 m. They are produced from terrestrial sources through electrons oscillating in wires of electric circuits. By carefully choosing the geometry of these circuits, as inan antenna,we can control the distribution in space of the emitted radiation (if the antenna acts as a transmitter) or the sensitivity of the detector (if the antenna acts as a receiver. Traveling outward at the speed of light, the expanding of TV signals transmitted on Earth as shown in Fig 15.27.

FIGURE 15.27



The oscillatory motion of the charges in a dipole antenna produces electromagnetic radiation.

Radio waves reach us from extraterrestrial sources, the sun being a major source that often interferes with radio or TV reception on Earth. Mapping the radio emissions from exraterrestrial sources, known as radio astronomy, has provided infomation about the universe that is often not obtainable using optical telescopes.

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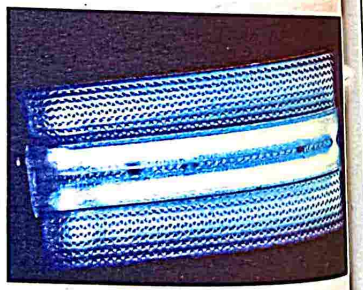
Do you know?

The researchers believe that a handheld UV light device that emits high intensity rays could help to kill the novel COVID-19 virus. A new study has shown that 99.9% of corona viruses can be killed when exposed to far-UVC light.

5. **Ultraviolet.** The radiations of wavelengths shorter than the visible begin with the ultraviolet(1 nm to 400nm), which can be produced in atomic transitions of theouter- electrons as well as in radiation from thermal sources such as the Sun. Because our atmosphere absorbs strongly at ultraviolet wavelengths, little of this radiation from the Sun reaches the ground. However, the principal agent of this absorption is atmospheric ozone, which has been depleted in recent years as a result of chemical reactions with fluorocarbons released from aerosol sprays,refrigeration equipment, and other sources. Brief exposure to ultraviolet radiation causes common sunburn butlong-term exposure can lead to more serious effects including skin cancer.

Ultraviolet Lamp,(UV Light). A lamp producing Ultraviolet (UV) radiation is emitted through clear, pre-filtered, particle free water shown in Figure 15.28. This UV light is extremely effective in killing and eliminating bacteria, yeast's, viruses, molds and other harmful organisms known to man.

FIGURE 15.28



Ultraviolet lamp

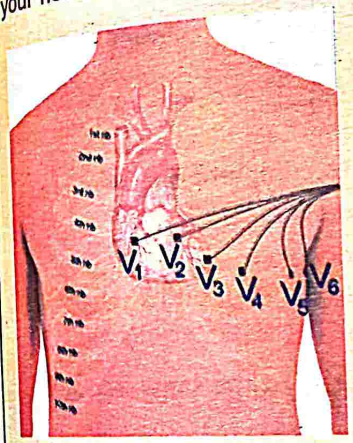
6. **X-rays.** X rays (typical wavelengths 0.01 nm to 10 nm) can be produced with discrete wavelengths in individual transitions among the inner (most tightly bound) electrons of an atom, and they can also be produced when charged particles (such as electrons) are decelerated.X rays can easily penetrate soft tissue but are stopped by bone and other solid matter: for this reason they have found wide use in medical diagnosis.

7. **Gamma rays.** Gamma rays are electromagnetic radiations with the shortest wavelengths (less than 10 pm). They are the most penetrating of electromagnetic radiations, and exposure to intense gamma radiation can have a harmful effect on the human body.

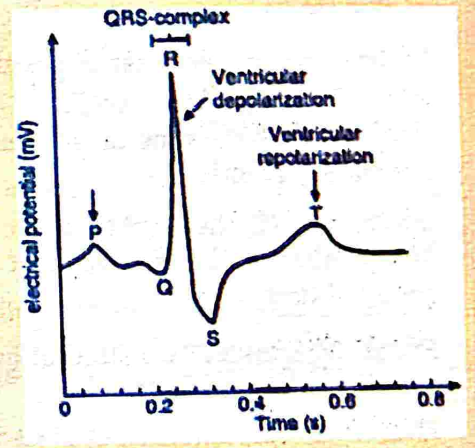
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ELECTROCARDIOGRAM or (E.C.G)

The electrocardiogram is worldwide used for diagnosing heart conditions. The electric waves in the heart are recorded in millivolts by the electrocardiograph. Our heart produces time-varying voltages as it beats. These heart voltages produce small voltage differences between points on your skin that can be measured and used to diagnose the condition of your heart as shown in figure (a).



(a) : Sensitive electrodes are placed on certain parts of the body.



(b) : An ECG curve.

Some of the characteristics of ECG curve are shown in figure (b): When the curve falls below the base line it shows a negative deflection and when it rises above the base line it shows a positive deflection. A negative deflection indicates that the recorded wave has traveled away from the electrode and a positive deflection means it has traveled towards it.

A typical plot of voltage difference between two points on the human body vs time is shown in fig 15.21(b). The P deflection corresponds to the contraction of the atria at the start of the heart beat. The QRS group corresponds to the contraction of the ventricles. The T deflection corresponds to a re-polarization or recovery of the heart cells in preparation for the next beat.

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KEY POINTS

Alternating voltage: a voltage which changes its polarity at regular interval of time.

The sinusoidal alternating voltage: it can be expressed by the equation: $V = V_m \sin\omega t$

Waveform or wave shape: the shape of the curve obtained by plotting the instantaneous values of voltage or current as ordinate against time as abscissa.

Cycle : One complete set of positive and negative values of an alternating quantity.

Time period: the time taken in seconds to complete one cycle of an alternating quantity.

Frequency (*f*): the number of cycle that occurs in one second.

The average value of a waveform: the average of all its values over a period of time.

Phase difference: Two alternating quantities of the same frequency but different zero points.

Phasor : a representation of Sinusoidal alternating voltage or current by a line of definite length rotating in counter clock wise direction at a constant angular velocity (ω).

Inductive reactance X_L : the opposition offered by an inductor to the flow of charges.

Peak Value: the maximum value attained by an AC waveform.

Resonance of an A.C. circuit : A circuit containing reactive elements (L and C) for which the power factor is unity.

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EXERCISE

MULTIPLE CHOICE QUESTIONS

Choose the best possible answer:

1. The r.m.s. value of a sine wave is 100 A. Its peak value is
   A. 70.7A B. 141.4A C. 150A D. 282.8A
2. A sine wave has a frequency of 50 Hz. Its angular frequency is ..... radian/second.
   (A) 100 π (B) 50 π (C) 25 π (D) 5 π
3. The power factor of a purely resistive circuit is
   A. zero B. unity C. lagging D. leading
4. A capacitor is perfectly insulator for
   (A) Direct current (B) Alternating current
   (C) Direct as well as alternating current (D) Induced e.m.f
5. The peak value of alternating current is $5\sqrt{2}$ A. The mean square value of current will be
   (A) 5A, (B) 2.5A, (C) $5\sqrt{2}$ A (D) 5^2
6. In choke coil the reactance X_L and resistance R are related as
   (A) $X_L = R$ (B) $X_L \ll R$
   (D) $X_L \gg R$ (D) $X_L = \infty$
7. The phase difference between the current and voltage at resonance is
   (A) 0 (B) π (C) -π (D) π/2
8. In AC system we generate sine wave form because
   (A) It can be easily draw
   (B) It produces least disturbance in electrical circuits
   (C) It is nature standard
   (D) Other waves cannot be produced easily.

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MULTIPLE CHOICE QUESTIONS

9. An alternating voltage is given by 20sin 157t. The frequency of alternating voltage is

(A) 50Hz (B) 25Hz (C) 100Hz (D) 75Hz

10. In LR current which one of the following statements is correct?

(A) *L* and *R* opposes each other

(B) *R* value increases with frequency

(C) The inductive reactance increases with frequency

(D) The inductive reactance decreases with frequency.

11. An alternating quantity (voltage or current) is completely known if we know it's

(A) maximum value (B) frequency and phase.
(C) effective value (D) both (a) & (b)

12. For electromagnetic waves, Maxwell generalized

(A) gausses law for magnetism
(B) gausses law for electricity
(C) faradays law (D) amperes law

13. An electromagnetic wave goes from air to glass which of the following does not change?

(A) Radio waves (B) X-rays
(C) Ultra violet radiation (D) Ultra sound waves

14. The circuit in which current and voltage are in phase, the power factor is

(A) Zero (B) 1 (C) −1 (D) 2

15. With increase in frequency of an AC supply, the impedance of an RLC series circuit

(A) remains constant (B) increases (D)decreases

(D) capacitive reactance X_C decreases only.

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What makes steel hard, lead soft, iron magnetic, and copper electrically conducting? It depends upon the structure - the particular order and bonding of atoms in a material. This clue has made it possible to design and creates materials with new and unusual properties for use in modern technology.
The crystal structures are analyzed using x-ray diffraction technique invented by Max von Laue and extensively employed by Bragg. The study of crystal geometry helps us to understand the diverse behavior of solids in their mechanical, metallurgical, electrical, magnetic and optical properties. In this unit we will study some important properties of solids.

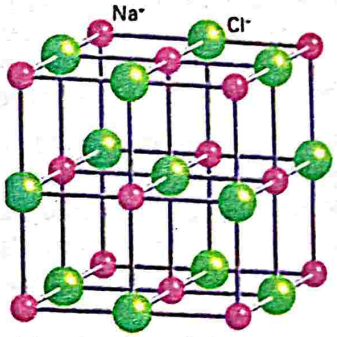
16.1 CLASSIFICATION OF SOLIDS

On the basis of atomic arrangement solids may be classified into three categories, namely crystals, polycrystalline solids and amorphous solids.

CRYSTALLINE SOLIDS

In a crystalline solid, the particles (ion, molecule or atoms) are arranged in definite geometric pattern in the three dimensional network. This is known as long range order. This arrangement repeats periodically over the entire crystal. Due to this arrangement, they have short range as well as long range order.
Crystals have smooth faces and straight edges. When a crystal is broken, it cleaves along certain preferred directions. Quartz, Sucrose (sugar), diamond and rock salt (NaCl) are examples of solids that occur as large size single crystals. Structure of NaCl crystal is shown in Fig.16.1.

FIGURE 16.1

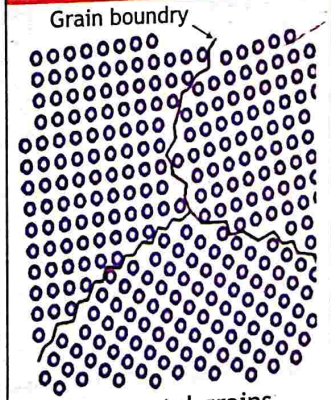


NaCl crystal

POLYCRYSTALLINE SOLIDS

Polycrystalline is a material made up of *many small single crystals* (also called crystallites or grains). Polycrystalline solids consist of fine grains, having a size of 10^3 A° to 10^4 A°, separated by well define boundaries and oriented in different directions. Each such grain is a single crystal of an irregular shape.

FIGURE 16.2



Crystal grains

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Since the grains are oriented haphazardly, a polycrystalline material is isotropic and exhibits the same properties in all directions. Metals are examples of polycrystalline solids. In these solids the ordered regions, vary in size and orientation with respect to one another.

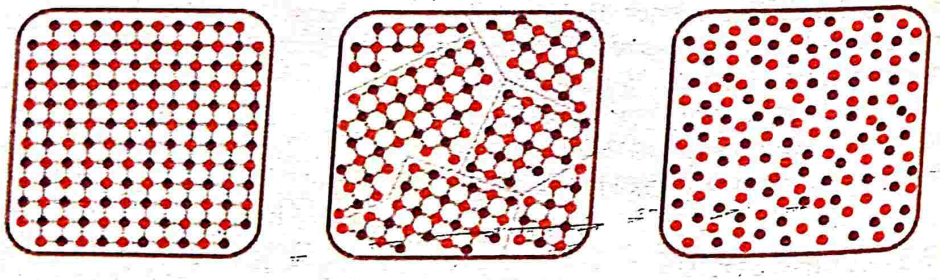
These regions are called as grains(domain) and are separated from one another by grain boundaries as shown in Fig.16.2. The atomic order can vary from one domain to the next. The grains are usually 100 nm-100 microns in diameter.

AMORPHOUS SOLIDS

Amorphous (Non-crystalline) solid is composed of randomly orientated atoms, ions, or molecules that do not form defined patterns or lattice structures. So in amorphous solids the arrangement of atoms is random. These are the substance whose constituent particles don't possess a regular orderly arrangement.

Some liquids when cooled become more and more viscous and then rigid, retaining random atom characteristic distribution. This state is called under cooled liquid or amorphous solid. Glass, rubber, glues and most of polymers are examples of amorphous solids. The atomic arrangement of the three classes of solids is illustrated in Fig. 16.3

FIGURE 16.3



two dimensions **arrangement** of solids

The crystal structures are analyzed using x-ray diffraction technique invented by Max von Laue and extensively employed by Bragg.

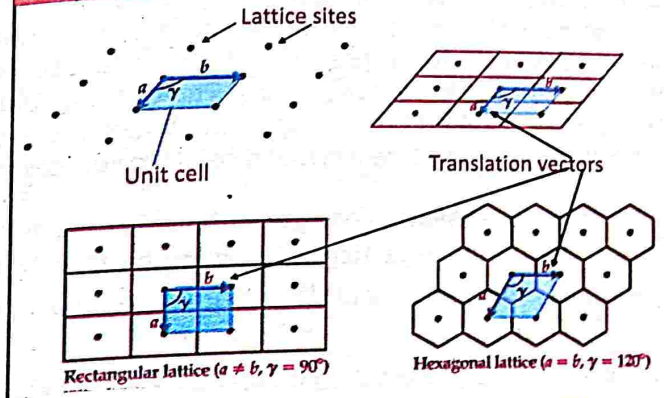
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X-ray investigations show that the crystals are composed of atoms (or group of atoms) held in an orderly three-dimensional array. The array may be viewed as produced when the group of atoms, henceforth called a basis or unit, is repeated at regular intervals along all directions in the crystal. The regular and periodic arrangement of the basis is the basic feature of crystals. Geometrical analysis of crystal structure is made by referring to an imaginary array of points in space. This is illustrated in Figure 16.4. It is conventional to represent the periodicity by replacing the basis with a point.

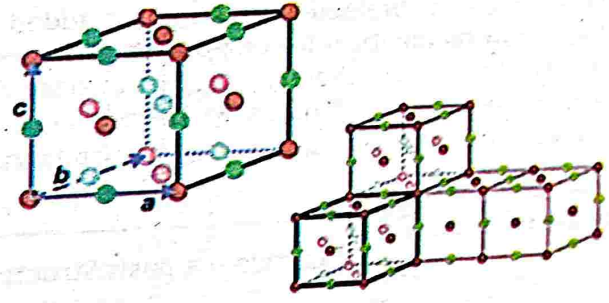
The collection of infinite number of points in a periodic arrangement is called a lattice.

A lattice is merely an imaginary geometrical framework.

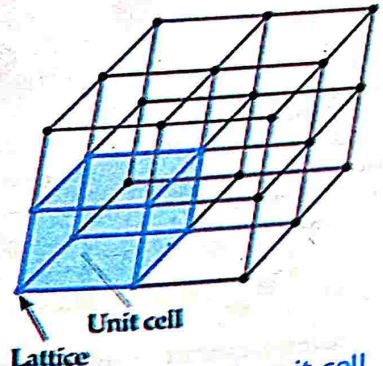
FIGURE 16.4



(a)two dimensional lattice points with translation vectors a & b .



(b) three dimensional lattice forming a unit cell



(c) :unit cell

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The space lattice is a skeleton upon which crystal structure is built by placing atoms on or near the lattice points. Therefore, the study of crystal structure becomes simpler when it is represented by a space lattice. The points which are forming a lattice are called lattice sites. The distance between the consecutive neighbours sites is called lattice constant. When we assign direction to these lattice constant, they become lattice translation vectors.

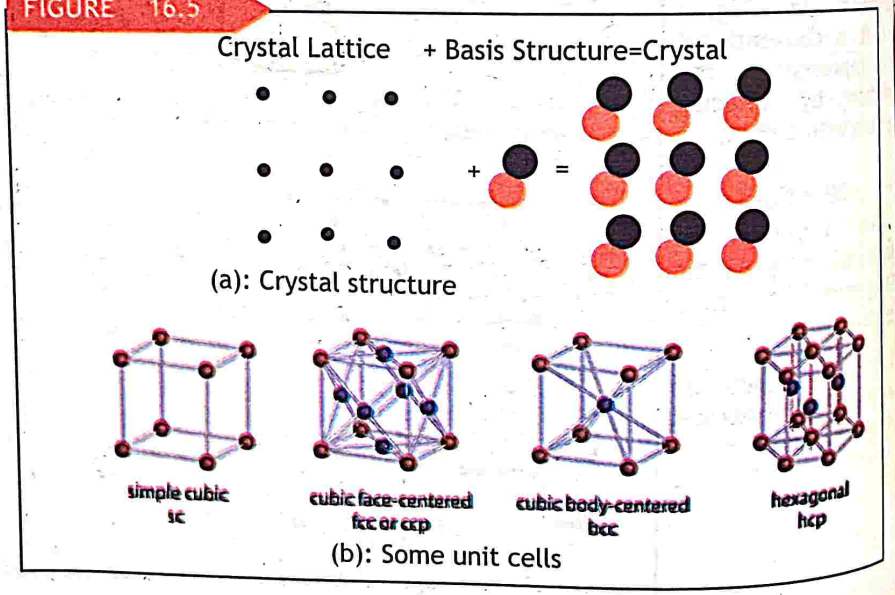
The two dimensional arrangements of lattice is shown in Fig: 16.4 (a). Which shows that a plane lattice is obtained by translation of $\vec{a}$ and $\vec{b}$ and a space lattice is obtained by translation of $\vec{a}$, $\vec{b}$ and $\vec{c}$ as shown in Fig16.4(a) & (b).

The smallest geometric figure or unit whose periodic repetition in two or three dimension form a crystal is called unit cell. Unit cell is shown in Fig 16.4 (b) & (c).

CRYSTAL STRUCTURE

Crystal structure is obtained when a basis is added at each point in the lattice. The basis must be identical in composition, arrangement and orientation such that the crystal appears exactly the same at one point as it does at other equivalent points. Fig.16.5 (a) shows the basis consisting of a group of two atoms. When the basis is associated with each lattice site, the crystal structure is obtained.

FIGURE 16.5



(a): Crystal structure

(b): Some unit cells

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16.2 ELASTIC MODULI

When an external force is applied on the object, it changes its shape or size. Generally this deformation is small and often temporary. If an object regains its original shape when external force is removed it is called elastic. If it remains in deformed state it is called plastic. There are three types of deformations and corresponding three elastic moduli. The deforming force is expressed in terms of stress and the deformation is expressed in terms of strain. For elastic solids, the ratio of stress to strain is constant and it is called elastic modulus. That is

$$\text{Elastic modulus} = \frac{\text{Stress}}{\text{Strain}}$$

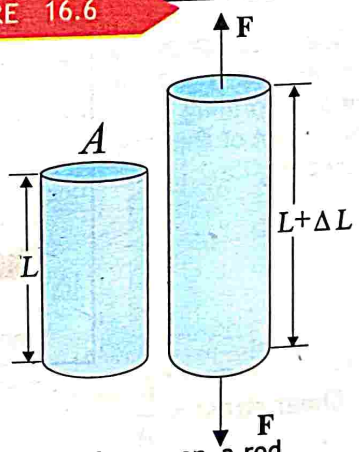
This is known as Hooke's law. There are three elastic moduli: Young's modulus (Y), Shear or Rigidity modulus (S) and Bulk modulus (B).

Material	Young modulus Y(Pa)	Bulk modulus B(Pa)	Shear modulus S(Pa)
Aluminium	7×10^{10}	7.5×10^{10}	2.5×10^{10}
Brass	9×10^{10}	6×10^{10}	3.5×10^{10}
Copper	11×10^{10}	14×10^{10}	4.4×10^{10}
Crown glass	6×10^{10}	5×10^{10}	2.5×10^{10}
Iron	21×10^{10}	16×10^{10}	7.7×10^{10}
Lead	1.6×10^{10}	4.1×10^{10}	0.6×10^{10}
Nickel	21×10^{10}	17×10^{10}	7.8×10^{10}
Steel	20×10^{10}	16×10^{10}	7.5×10^{10}

16.2.1 YOUNG'S MODULUS

The change in the length due to deforming force is described by Young's modulus. Consider a rod of length L having cross-sectional area A as shown in Fig 16.6. If it is clamped at one end and a force is applied perpendicular to the area of cross-section, it changes its length, which is greater than the original length. The internal forces of the rod resist change in length

FIGURE 16.6



deforming forces on a rod

NOT FOR SALE

but attain an equilibrium in which the length is $(L+\Delta L)$ where, ΔL is the change in length.

The ratio of the magnitude of external force F to the area of cross-section A is called as tensile stress. Where

$$\text{Tensile stress} = \frac{F}{A} \qquad \ldots(16.1)$$

The ratio of the change in length to the original length is called as tensile strain. And

$$\text{Tensile strain} = \frac{\Delta L}{L} \qquad \ldots(16.2)$$

Young's modulus is defined as the ratio of tensile stress to tensile strain.

$$Y = \frac{\text{Tensile stress}}{\text{Tensile strain}} = \frac{F/A}{\Delta L/L} \qquad \ldots(16.3)$$

Its SI unit is N/m^2.

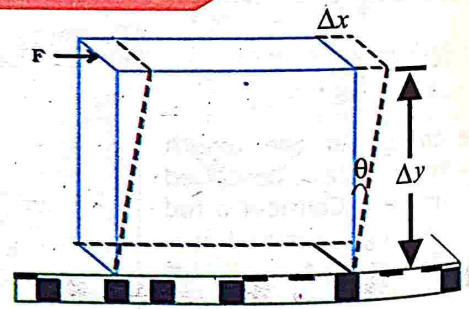
The Hooke's law is valid within the elastic limit and for small strains. When the metal rod is subjected to increasing deforming force, the relation between stress and strain is shown in Fig.16.6.

16.2.2 SHEAR OR RIGIDITY MODULUS

When an object is subjected to a force tangential to one of its faces while the opposite face is held fixed there occurs a deformation (Fig 16.7).

The shear stress is defined as the ratio of tangential deforming force F to the area A of the face being sheared, i.e.

FIGURE 16.7



tangential deforming force on a box

$$\text{Shear stress} = \frac{F}{A} \qquad \ldots(1)$$

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The shear strain is the ratio of displacement of the sheared face Δx and the fixed face y.

$$\text{Shear strain} = \frac{\text{displacement of Sheared face}}{\text{displacement of fixed face}}$$

$$= \frac{\Delta x}{y} \qquad \ldots(2)$$

It may be described in terms of angle θ, which is called as angle of shear.

Hence

$$\tan\theta = \frac{\Delta x}{y} \qquad \ldots(16.4)$$

When the angle is small,

$$\tan\theta \approx \theta \qquad \ldots(16.5)$$

The shear modulus is defined as the ratio of shear stress to the shear strain.

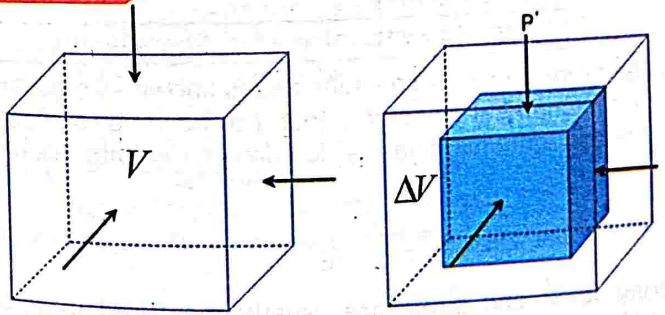
$$S = \frac{\text{shear stress}}{\text{shear strain}} = \frac{F/A}{\Delta x/y} \qquad \ldots(16.6)$$

$$= \frac{F/A}{\tan\theta} \approx \frac{F}{A\theta} \qquad \ldots(16.7)$$

16.2.3 BULK MODULUS

When deforming forces, acting on all the surfaces of a body, are at right angles, the body undergoes deformation. The forces are distributed uniformly on all the surfaces as illustrated in Fig 16.8.

FIGURE 16.8



Change in volume V of a box

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In this case there is a change in the volume and not in the shape. The volume stress is the ratio of magnitude of the normal force F to the area A. Therefore

$$\text{Bulk or Volume stress} = \frac{F}{A}$$

In case of fluids it is called as pressure

$$\Delta P = \frac{F}{A}$$

The ratio of change in volume ΔV and original volume V is the volume strain. Where

$$\text{Volume strain} = -\frac{\Delta V}{V} \qquad \ldots(16.8)$$

The bulk modulus is defined as the ratio of volume stress to volume strain. Therefore,

$$B = \frac{\text{Volume stress}}{\text{Volume strain}} = \frac{F/A}{(-\Delta V/V)}$$

$$B = \frac{\Delta P}{(-\Delta V/V)} \qquad \ldots(16.9)$$

The negative sign is inserted because increase in pressure cause decrease in volume. The value of bulk modulus is always taken as positive.

16.3 HOOKE'S LAW

Stress and strain take different forms in the situations shown in the Fig. (16.9). For small deformations the stress and strain are proportional to each other. This is known as Hooke's law.
Thus,

$$\text{Stress} \propto \text{strain}$$

$$\text{Stress} = k \times (\text{strain}) \qquad \ldots(16.10)$$

Where, k is the proportionality constant and is known as modulus of elasticity. Hooke's law is an empirical law and is found to be valid for most materials. However, there are some materials which do not exhibits this linear relationship

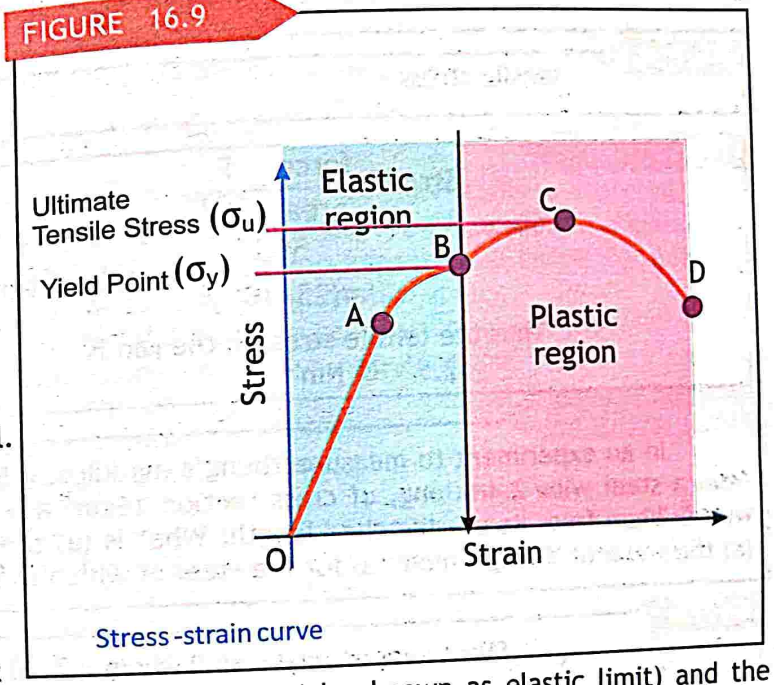
16.3.1 STRESS-STRAIN CURVE

Engineering stress and strain are usually measured using a machine that strains the material at a fixed linear rate and records the stress.
The applied stress is gradually increased in steps and the change in length is noted.

NOT FOR SALE

These values are then plotted on a graph. A typical graph for a metal is shown in Fig16.9. The stress-strain curves vary from material to material. These curves help us to understand how a given material deforms with increasing loads. From the graph, we can see that in the region between O to A, the curve is linear. In this region, Hooke's law is obeyed. The body regains its original dimensions when the applied force is removed. In this region, the solid behaves as an elastic body. In the region from A to B, stress and strain are not proportional.

FIGURE 16.9



Stress-strain curve

Nevertheless, the body still returns to its original dimension when the load is removed. The point B in the curve is known as yield point (also known as elastic limit) and the corresponding stress is known as yield strength (σ_y) of the material.
If the load is increased further, the stress developed exceeds the yield strength and strain increases rapidly even for a small change in the stress. The region of the plasticity is represented by the portion of the curve between B and C.
Where, point C in the Fig16.9: shows the ultimate tensile strength (σ_u) of the material. If the stress is increased beyond point C, the material is said to be permanently changed, and the body does not regain its original dimension. In this case, even when the stress is zero, the strain is not zero. This type of deformation is called plastic deformation. At point D the material cannot be stretched further and smallest increase in stress can result in breaking the sample.

If the ultimate strength and fracture points C and D are close, the material is said to be brittle. If they are far apart, the material is said to be ductile.

NOT FOR SALE

EXAMPLE 16.1

A force of 500N is applied to one end of a cylindrical steel rod of diameter 50cm. What is the tensile stress?

GIVEN

force F= 500N, radius of rod r=D/2= 50cm/2=25cm

REQUIRED

tensile stress = ?

SOLUTION

$$\text{Stress} = \frac{\text{force}}{\text{area}} = \frac{F}{\pi r^2}$$

Since

$$= \frac{500}{\pi(25\times10^{-2})^2} = 2.5\times10^{5}\,\text{Nm}^{-2}$$

Thus the tensile stress in the rod is $2.5\times10^{5}\ \text{Nm}^{-2}$

EXAMPLE 16.2

In an experiment to measure Young's modulus, a load of 500Kg hanging from a steel wire 2.4m long, of cross section 16cm^2,was found to stretch the wire 0.30cm from its un-stretched length. What is (a) the stress? (b) the strain (c) the value of Young's modulus for the steel of which the wire is composed?

GIVEN

Stretching in wire = x= 0.30cm = 3×10^{-3}m

Cross section of wire =A= 0.16cm^2 = 1.6×10^{-5}m^2

Load= 500Kg, length of steel wire = L =2.4m

REQUIRED

(a) the stress= ? (b) the strain=?

(c) the Young's modulus for the steel y = ?

SOLUTION

(a) $\text{Stress} = \frac{F}{A} = \frac{5000}{1.6\times10^{-5}m^2} = 3.1\times10^{8}\,\text{Nm}^{-2}$

(b) $\text{Strain} = \frac{x}{L} = \frac{3.0\times10^{-3}}{2.4} = 1.25\times10^{-3}$

(c) $\text{Young's Modulus } y = \frac{\text{Stress}}{\text{Strain}} = \frac{3.1\times10^{8}}{1.25\times10^{-3}} = 2.48\times10^{11}\,\text{Nm}^{-2}$

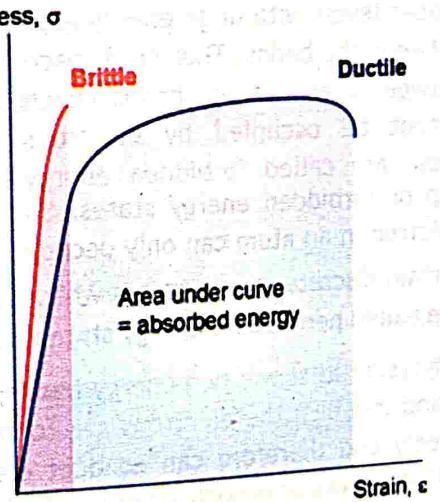
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16.4 MECHANICAL PROPERTIES OF SOLIDS

The mechanical properties of a material are those properties that involve a reaction to an applied load. The mechanical properties of metals determine the range of usefulness of a material and establish the service life that can be expected. Mechanical properties are also used to help classify and identify material. The most common properties considered are strength, ductility, hardness, impact resistance, and fracture toughness.

1. **Strength:** The general ability of a material to withstand an applied force.
2. **Hardness:** Hardness is a measure of how easily a material can be scratched or indented. Hard materials are often also very brittle - this means they have a low resistance to impact. Well known hard materials include diamond and hardened high carbon steels.
3. **Brittleness:** A material that has a tendency to break easily or suddenly without any extension first. Good examples are Cast iron, concrete, high carbon steels, ceramics, and some polymers such as urea formaldehyde (UF).
4. **Toughness:** A material that absorbs impact (sudden forces or shocks such as hammer blows) well is tough - this is the opposite to brittleness. [units for toughness are energy per unit area - J/m^2]
5. **Plasticity:** The materials which deform permanently when small forces are applied show plasticity. Plasticine and clay are good examples.
6. **Elasticity:** The ability of a material to return to its original form after a load has been applied and

FIGURE 16.10



Stress-strain curves for brittle and ductile materials. Brittle materials fracture at low strains and absorb little energy. Conversely, ductile materials fail after significant plastic strain (deformation) and absorb more energy.

removed. Good examples include rubber, mild steel and some plastics such as nylon.

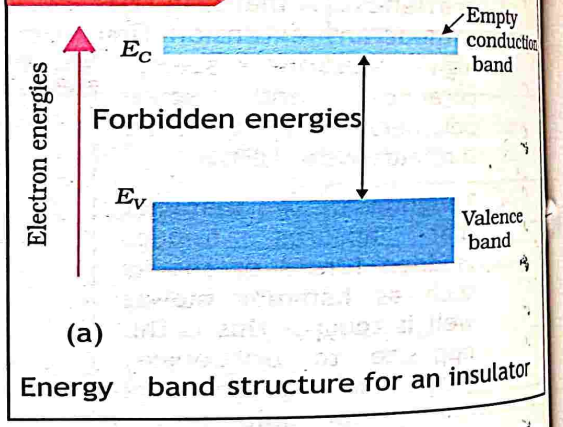
7. **Stiffness:** The ability to resist bending.

8. **Ductility:** The ability to be drawn out into a thin wire or threads. It is a measure of how easily a material can be worked. Good examples are gold, copper, titanium, wrought iron, low carbon steels and brass. Stress-strain curves for brittle and ductile material is shown in Figure 16.10.

16.5 ENERGY BAND THEORY

When atoms bond together to become molecules their energy levels merge and split-this results in the splitting of spectral lines in molecular spectra. In a solid this process takes place between large numbers of atoms, and the energy levels divide into bands of closely spaced levels with large energy gaps between the bands. There is a space between these energy bands which cannot be occupied by electrons these are called forbidden energy gap or forbidden energy states. So electron in an atom can only occupy certain discrete energy states which are called permissible energy states.

FIGURE 16.11



Energy band structure for an insulator

Fig:16.11 a: shows two energy bands, the upper band is called the conduction band in which the electrons are forced to move. In this band electrons move freely and therefore can conduct electric current through solids. It may be either empty or partially filled with electrons.

The lower energy band is called valence band, in which the electrons are tightly bound to their atoms and are not free to move about.

INSULATOR

In insulators the valence band is fully occupied with electrons due to sharing of outer most orbit electrons with the neighboring atoms so the

electrons are not available as charge carriers. The conduction band is empty, i.e, no electrons are present in conduction band.

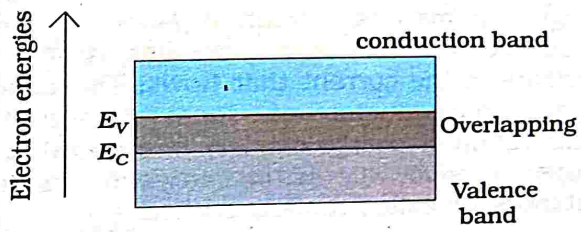
In an insulator, electrons belong to completely filled bands and the forbidden gap between the valence band and conduction band is very large which does not allow the electrons to gain energy from an applied electric field and move into conduction band. The energy gap of insulator is approximately equal to 15 electron volts (eV).

But even with large amount of external energy it is impossible to move the valence band electrons in to conduction band. As a result, insulator does not conduct electricity. Rubber, wood, diamond, plastic are some examples of insulators.

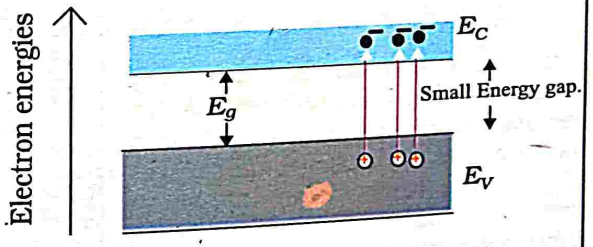
CONDUCTORS

The materials which allow the flow of electric current through them are called as conductors. In a conducting material the energy levels of adjacent atoms have spread to form bands that overlap. Energy band structure for a conductor is shown in Figure 16.11 (b). The top of the valence band is above the bottom of the conduction band. This means that electrons in the valence band can easily move to vacant energy levels in the partially filled conduction band. In practice this means that an applied electric field (e.g. created by a cell connected across the conductor) supplies the tiny amount of energy needed to move electrons from one atom to a vacant state in the conduction band of an adjacent atom and then accelerates the electrons through the material.

FIGURE 16.11



(b): Energy band structure for a conductor.



(c) Energy band structure for a semiconductor.

Metals such as copper, silver, iron, aluminum etc. are good conductors of electricity.

SEMICONDUCTORS

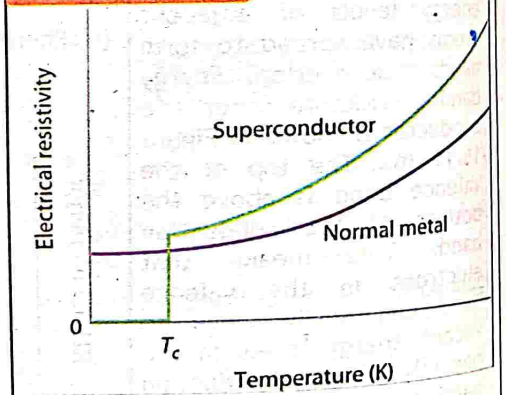
A semiconductor has a filled valence band, and an empty conduction band, just like an insulator. In fact, all semiconductors are insulators at very low temperatures. The band gap, however, is much smaller than in materials that are insulators at room temperature. As a result, some electron will be thermally excited into the conduction band where they can move freely through the material. When this happens the electrons leave 'holes' in the valence band as shown in Figure 16.11 (c).

These holes behave just like positive charge carriers and can also move through the material. When a potential difference is connected across a semiconductor, holes and electrons drift in opposite directions and both contribute to the current that flows. The concentration of charge carriers in a typical semiconductor at room temperature is about 10^{21} m^{-3}. The concentration of charge carriers in a metal is about ten million times greater; as their conductivity is in between conductors and insulators so these substances are called semiconductors.

16.6 SUPERCONDUCTORS

A superconductor is a material that can conduct electricity or transport electrons from one atom to another with no resistance. This means no heat, sound or any other form of energy would be released from the material when it has reached "critical temperature" (T_c), or the temperature at which the material becomes superconductive. Unfortunately, most materials must be in an extremely low energy state (very cold) in order to become superconductive. The resistance of a superconductor is zero, since there are no heat losses for

FIGURE 16.12



(a)

A graph of resistivity versus temperature for a superconductor shows a sharp transition to zero at the critical temperature Tc. High temperature superconductors have variable T_c.

currents through them; they are used in magnets needing high currents, such as in MRI machines, and it does not offer resistance to transmission line. In the past decade, tremendous advances have been made in producing materials that become superconductors at relatively high temperatures. A graph of resistivity versus temperature for a superconductor is shown in Figure 16.12 a:

The temperature at which and below which a material becomes a superconductor is said to be its critical temperature, denoted by T_c.

In 1988 some ceramic (thallium, calcium, barium, copper, and oxygen) was found to become superconductors even at T_c = 125 K. The search is on for even higher T_c superconductors.

Superconductors are used for applications like MRIs, maglev trains and particle accelerators. In Maglev, superconducting magnets suspend a train car above a U-shaped concrete guideway. Like ordinary magnets, these magnets repel one another when matching poles face each other.

A cube of magnetic material levitates above a superconductor as shown in Fig 16.12 b. The field of the magnet induces currents in the superconductor that generate an equal and

For your Information

Magnetic-levitation is an application where superconductors perform extremely well. Transport vehicles such as trains can be made to "float" on strong superconducting magnets, virtually eliminating friction between the train and its tracks. It can attain an incredible speed of 361 mph (581 kph). On the other hand conventional electromagnets waste much of the electrical energy as heat.

FIGURE 16.12



(b)

: The black ceramic material in the illustration is a sample of the yttrium based superconductor. If a small permanent magnet is placed above a superconductor, it can be levitated by repulsive force.

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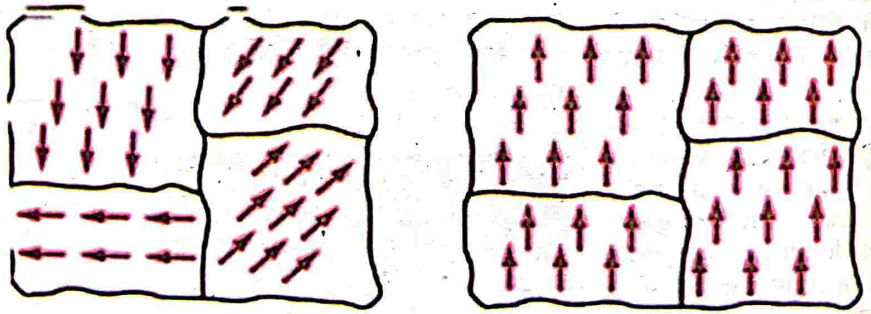
opposite field, exactly balancing the gravitational force on the cube. Superconducting magnets are electromagnets that are cooled to extreme temperatures during use, which dramatically increases the power of the magnetic field.

16.7 THEORY OF MAGNETISM

The molecule of a magnetic substance (where magnetized or not) is a complete magnet in itself having a north pole and a south pole of equal strength.

(i) In an un-magnetized substance, the molecular magnets are randomly oriented as shown in Fig. 16.13 (a). The north pole of one molecular magnet cancels the effect of the south pole of the other so that the substance does not show any net magnetism.

FIGURE 16.13



In presence of magnetic field In absance of magnetic field

(ii) When a magnetizing force is applied to the substance, the molecular magnets are turned and tend to align in the same direction with N-pole of one molecular magnet facing the S-pole of other as shown in Fig.16.13 (b). The result is that magnetic field of the molecular magnets aid each other and two definite N and S-pole are developed near the ends of the specimen; the strength of the two poles being equal. Hence the substance gets magnetized.

(iii) The extent of magnetization of the substance depends upon the extent of alignment of molecular magnets. When all the molecular magnets are fully aligned, the substance is said to be saturated with magnetism.

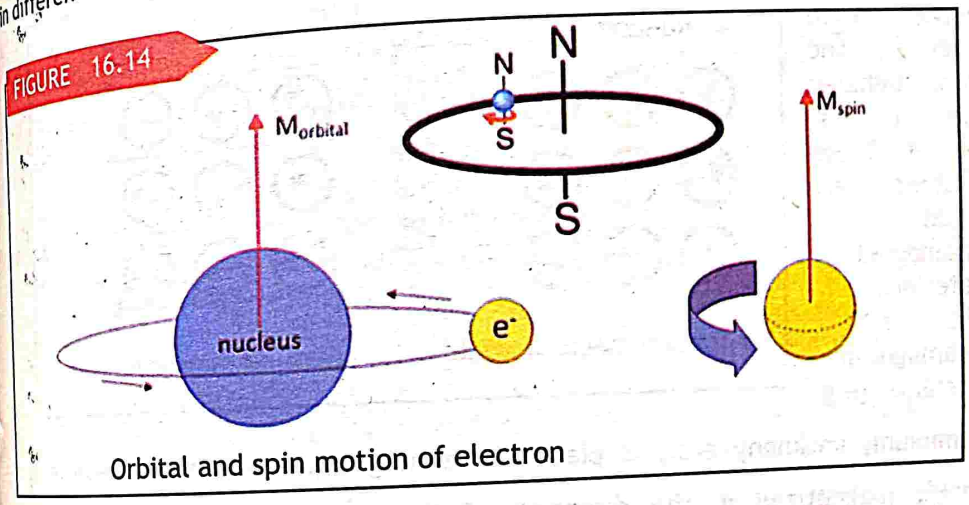
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(iv) When a magnetized substance (or a magnet) is heated, the molecular magnets acquire kinetic energy and some of them loss their arrangement. For this reason, a magnet loses some magnetism on heating.

16.8 MODERN VIEW ABOUT MAGNETISM

According to modern view, the magnetic properties of a substance are due to the motions of electrons (orbital and spin) in the atoms. We know that an atom consists of central nucleus with electrons revolving around the nucleus in different orbits. This motion of electrons is called orbital motion (Fig 16.14).

FIGURE 16.14



Orbital and spin motion of electron

The electrons also rotate around their own axis. This motion of electrons is called spin motion (Fig 16.14).

Due to these two motions, each atom is equivalent to a current loop i.e. each atom behaves as a magnetic dipole.

1. In the un-magnetized substances, the magnetic dipoles are randomly oriented so that magnetic fields mutually cancel. When the substance is magnetized, the magnetic dipoles are aligned in the same direction. Hence the substance shows net magnetism.
2. Since the revolving and spinning electrons in each atoms cause magnetism, no substance is non-magnetic.
3. It is important to note that spinning motion of electrons in particular is responsible for magnetism of a substance.

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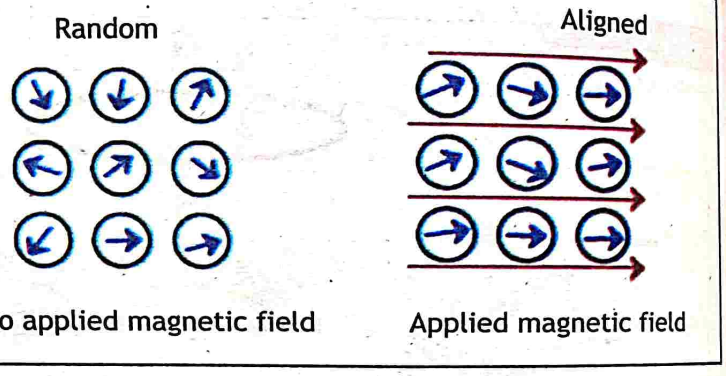
16.8.1 CLASSIFICATION OF MAGNETIC MATERIALS

We can classify materials into three categories *i.e*, diamagnetic, paramagnetic and ferromagnetic. The behaviour of these three classes of substances is different in an external magnetic field.

1. PARAMAGNETIC MATERIAL

In these substances the orbital and spin axis of the electrons in an atom are so oriented that their field support each other and the atom behaves like a tiny magnet. These substances are called paramagnetic materials. When a paramagnetic substance (e.g. aluminium, antimony etc.) is placed in a magnetic field, the substance is weakly magnetized in the direction of the applied field (Figure 16.15). Therefore, a paramagnetic substance is weakly attracted by a strong magnet.

FIGURE 16.15

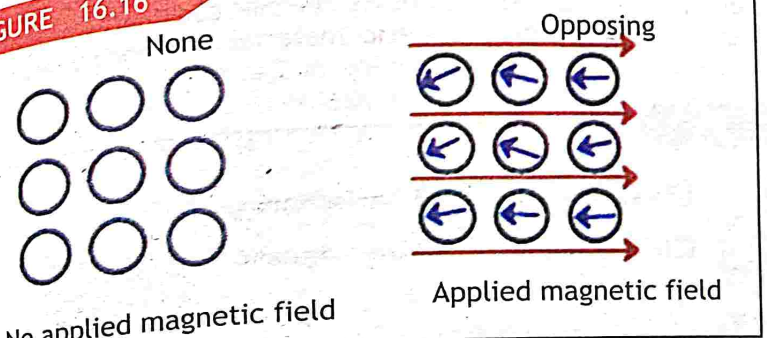


2. DIAMAGNETIC MATERIALS

The substances in which the orbits and spin axis of the electron in an atom are so oriented that their field cancel the effect of each other so that their resultant field is zero. Such substances are called diamagnetic materials. When a diamagnetic substance (e.g. copper, zinc, bismuth etc.) is placed in a magnetic field, the substance is weakly magnetized in a direction opposite to that of the applied field (Figure 16.16). Therefore, a diamagnetic substance is weakly repelled by a strong magnet.

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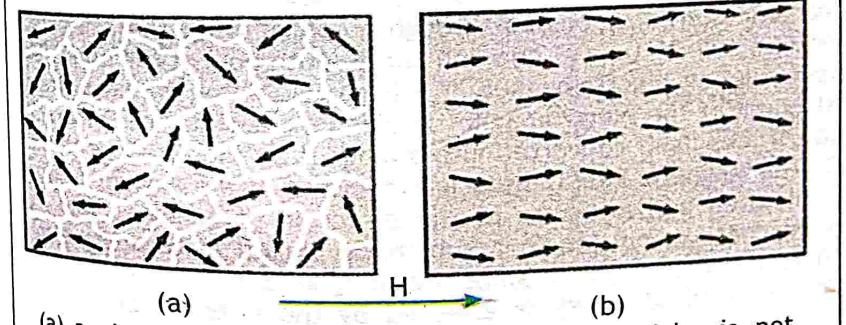
FIGURE 16.16



3. FERROMAGNETIC MATERIALS

In these substances the individual atoms act like tiny magnets. The interaction between these tiny atomic magnets is so strong that it line up parallel to each other even when no external magnetic fields is present. Such substances are called ferromagnetic materials. These tiny magnets are called magnetic domains (Figure 16.17). The size of these domains is very small of the order of millimeters or less but large enough to contain atoms from 10^{12} to 10^{16}. Each domain acts like a small magnet with its own north and South Pole. The coupling or interaction between the neighboring tiny magnets is reduced by increasing the temperature of a substance. The temperature at which a ferromagnetic material becomes paramagnetic is called its curie temperature or curie point.

FIGURE 16.17

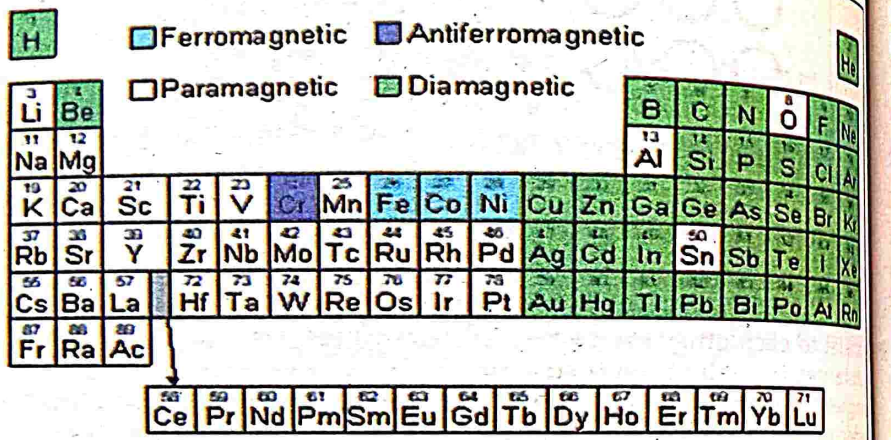


(a) a piece of ferromagnetic material which is not magnetised, where the domain poles are not aligned; (b) the domain poles aligned with an external magnetising force (*H*).

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When a ferromagnetic substance (e.g. iron, nickel, cobalt etc.) is placed in a magnetic field, the substance is strongly magnetised in the direction of the applied field. Therefore, ferromagnetic material is strongly attracted by a magnet.

FIGURE 16.18



Paramagnetic, diamagnetic, ferromagnetic and anti ferromagnetic materials in periodic table.

16.9 MAGNETIC HYSTERESIS

HYSTERESIS LOOP

When an electric current is passed through a coil of wire, the coil acts like a bar magnet with a north pole at one end and a south pole at the other. In other words, it acts like an electromagnet. If a bar of soft iron is placed inside the coil, the strength of the electromagnet is much increased. This is because the piece of soft iron is itself converted into a magnet by the effect of the current in the coil. The Magnetic Flux Density is a measure of the amount of magnetic flux in a unit area perpendicular to the direction of magnetic flow, or the amount of magnetism induced in a substance placed in the magnetic field. Magnetic field strength (H) is the amount of magnetizing force. The intensity of the Magnetic Flux Density, (B), is affected by the intensity of the Magnetic Field, (H) the quantities of the substance and the intervening media between the source of the magnetic field and the substance.

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A hysteresis loop shows the relationship between the induced magnetic flux density (B) and the magnetizing force (H), thus:

$$B = \mu_o H$$

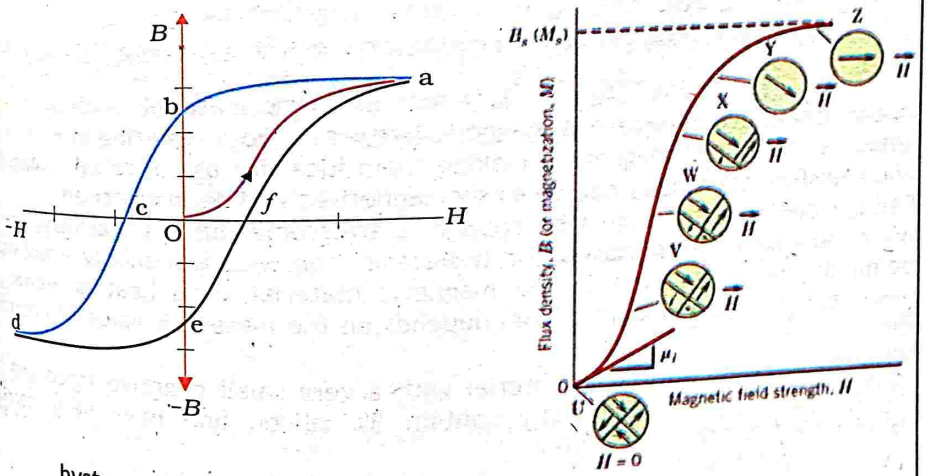
When a magnetic material is subjected to a cycle of magnetism (i.e. it is magnetised first in one direction and then in the other), it is found that flux density B in the material lags behind the applied magnetizing force H. This phenomenon is known as hysteresis.

The phenomenon of lagging of flux density (B) behind the magnetizing force (H) in a magnetic material subjected to cycle of magnetisation is known as magnetic hysteresis.

If the magnetisation current, I is increased in a positive direction to some value the magnetic field strength H increases linearly with I and the flux density B will also increase as shown by the curve from point O to point a as it heads towards saturation. Now if the magnetising current in the coil is reduced to zero the magnetic field around the core reduces to zero but the magnetic flux does not reach zero due to the residual magnetism present within the core and this is shown on the curve from point a to point b (Figure 16.19).

To reduce the flux density at point b to zero we need to reverse the current flowing through the coil. The magnetising force which must be applied to null the residual flux density is called a "Coercive Force". This coercive force reverses the magnetic field re-arranging the molecular magnets until the core

FIGURE 16.19



hysteresis loop

NOT FOR SALE

becomes un-magnetised at point c. An increase in the reverse current causes the core to be magnetised in the opposite direction and increasing this magnetisation current will cause the core to reach saturation but in the opposite direction, point d on the curve. If the magnetising current is reduced again to zero the residual magnetism present in the core will be equal to the previous value but in reverse at point e. Again reversing the magnetising current flowing through the coil this time into a positive direction will cause the magnetic flux to reach zero, point f on the curve and as before increasing the magnetisation current further in a positive direction will cause the core to reach saturation at point a. Then the *B-H* curve follows the

From the hysteresis loop, a number of magnetic properties of a material are

1. **Retentivity** - It is a material's ability to retain a certain amount of residual magnetic field when the magnetizing force is removed after achieving saturation.
2. **Residual Magnetism or Residual Flux** - the magnetic flux density that remains in a material when the magnetizing force is zero.
3. **Coercive Force**- The amount of reverse magnetic field which must be applied to a magnetic material to make the magnetic flux return to zero.
4. **Reluctance** - Is the opposition that a ferromagnetic material shows to the establishment of a magnetic field. Reluctance is analogous to the resistance in an electrical circuit.

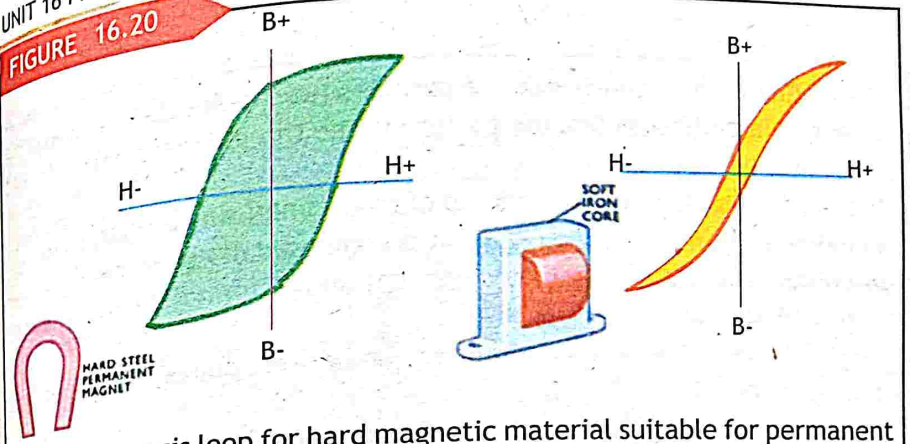
16.9.1 MAGNETIC HYSTERESIS LOOPS FOR SOFT AND HARD MATERIALS

SOFT MAGNETIC MATERIALS: Soft ferromagnetic materials such as iron or silicon steel have very narrow magnetic hysteresis loops resulting in very small amounts of residual magnetism making them ideal for use in relays, solenoids and transformers as they can be easily magnetised and de-magnetised.
Since a coercive force must be applied to overcome this residual magnetism, work must be done in closing the hysteresis loop with the energy being used being dissipated as heat in the magnetic material. This heat is known as hysteresis loss, the amount of loss depends on the material's value of coercive force.

By adding silicon, to iron a material with a very small coercive force can be made, such materials typically contain 5% silicon and have very narrow hysteresis loop (figure 16.20b).

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FIGURE 16.20

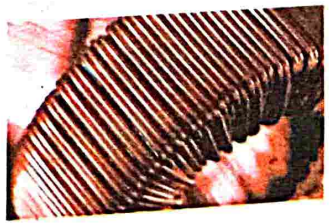


(a) the hysteresis loop for hard magnetic material suitable for permanent magnet; (b) the hysteresis loop for soft magnetic material suitable for a transformer core.

Materials with narrow hysteresis loops are easily magnetised and de-magnetised and known as soft magnetic materials.
Magnetic Hysteresis results in the dissipation of wasted energy in the form of heat with the energy wasted being in proportion to the area of the magnetic hysteresis loop. The Hysteresis losses will always be a problem in AC transformers.

HARD MAGNETIC MATERIALS: In order to create a permanent magnet, a material with a very fat hysteresis loop may be used (figure 16.20a). Such materials, once magnetised, are very difficult to demagnetise and when the magnetising force is removed a substantial magnetic flux density remains. These materials are known as hard magnetic materials. Its examples are Tungsten steel, Cunife, Cobalt rare earth 1, Sintered ferrite 3, and Sintered alnico 8 etc.,

Materials with fat hysteresis loops are difficult to de-magnetise and magnetic flux density remains even magnetising force is removed are known as hard magnetic materials.



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KEY POINTS

Crystalline solid: it consists of the particles (ion, molecule or atoms) arranged in definite geometric pattern in the three dimensional network.

Polycrystalline: a material made up of *many small single crystals.*

Amorphous (Non-crystalline) Solid: it is composed of randomly orientated atoms, ions, or molecules that do not form defined patterns or lattice structures.

Lattice: the collection of infinite number of points in a periodic arrangement.

Unit cell : the smallest geometric figure or unit whose periodic repetition in two or three dimension form a crystal.

Elastic modulus : the ratio of stress to strain.

Hooke's law : for small deformations the stress and strain are proportional to each other.

Hardness: it is a measure of how easily a material can be scratched.

Brittle :a material that has a tendency to break easily.

Stiffness: the ability to resist bending.

Hysteresis: lagging of the magnetization of a ferromagnetic material, behind variations of the magnetizing field.

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Electronics is the science that deals with electronic circuits that operate by controlling the flow of electrons or other electrically charged particles or electronics deals with flow of charge (electron) through non-metal conductors (semiconductors).

Imagine life without electronic devices. There would be no TV's, no computers, and poor medical diagnostic equipment. The developments in semiconductor technology during the past 50 years have made electronic devices smaller, faster, and more reliable. In this unit we will discuss the important applications of semiconductors.

17.1 SEMICONDUCTOR

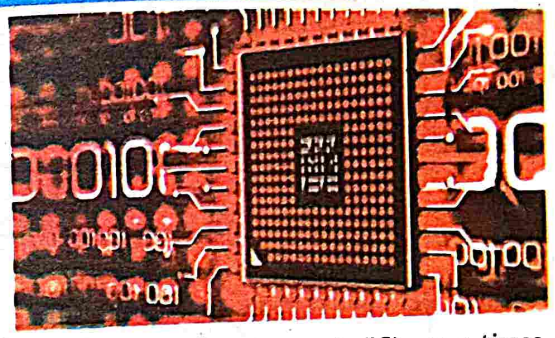
Semiconductors are materials having an intermediate electric conductivity between conductors and insulators.

A perfect, pure semiconductor crystal containing no impurities is called an intrinsic semiconductor.

A semiconductor is considered to be pure when there is less than one impurity atom in a billion host atoms. In a silicon crystal at low temperature, the bonding arrangement is shown in Fig17.1.

In the Fig 17.1: the hatched circles represent the core of the silicon atom. The four valence electrons are shown by the small black dots. The probability of valence electrons being in any place between the bonding atoms is indicated by the dotted curves. When temperature approaches to 0K, then all valence electrons are strongly bound to their atoms.

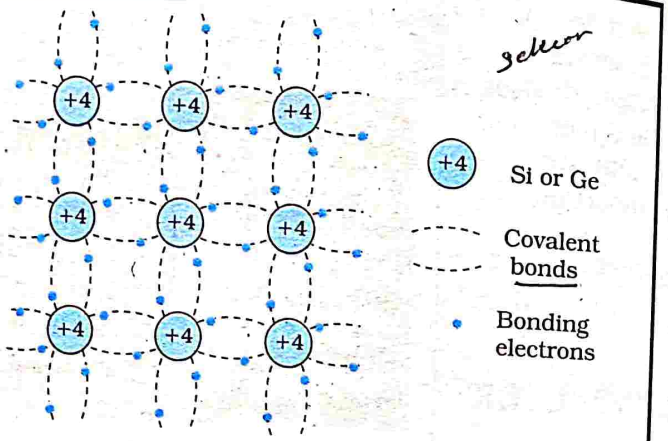
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An integrated circuit (IC), sometimes called a chip or microchip, is a semiconductor wafer on which thousands or millions of tiny resistors, capacitors, and transistors are fabricated. An IC can function as an amplifier, oscillator, timer, counter, computer memory, or microprocessor. Any device working under Digital Techniques are called Digital Systems and the Electronic Network used to make them operational is called Digital Circuits. The subject as a whole is often referred as Modern Digital Electronics. Digital calculators, watches, modern communication systems and computers are widely used in everyday life.

The electrons completely occupy the valence band leaving the conduction band vacant. The energy band structure of a semiconductor is characterized by a valence band and a conduction band separated by the bandgap E_g as shown in the Fig 17.2 a. Electrons in the valence band do not possess enough energy to jump into the conduction band.

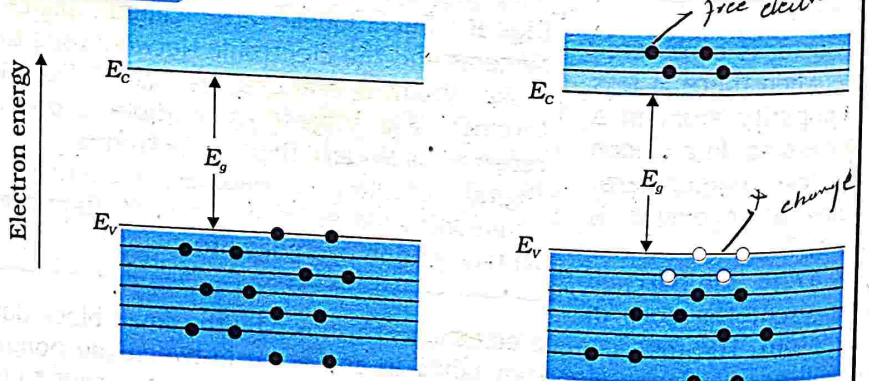
FIGURE 17.1



Two dimensional representation of Si or Ge structure. +4 symbols indicate inner cores of Si or Ge.

Therefore, an externally applied electric field cannot cause a flow of current and the semiconductor nearly at 0K behaves as an insulator.

FIGURE 17.2



(a) bandgap energy E_g

(b) electron jumping from valence band to conduction band.

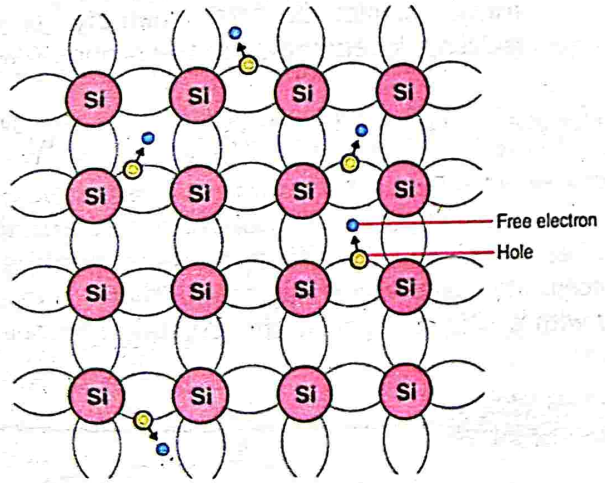
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17.2 SEMICONDUCTORS AT HIGH TEMPERATURE

At temperatures higher than 0 K the bonds start to break due to the absorption of thermal energy. This process results in the creation of mobile electrons and holes. The bandgap energy E_g is required to break such a covalent bond where E_g =0.72 eV for Ge and E_g =1.1 eV for Si at room temperature (300° k). Those electrons, which acquire potential energy equal to, or in excess of, the bandgap energy E_g are excited from the valence band to the conduction band. Thus, the bandgap energy E_g is the minimum amount of energy required to excite an electron from valence band to conduction band.

When a covalent bond breaks and electron jumps to the conduction band, an empty state arises in the valence band. Figure 17.3 shows a situation when a covalent bond is broken and one electron departs from the bond leaving a so-called hole behind.

FIGURE 17.3



Model of bond breaking by thermal energy, production of free electrons and generation of holes.

When a bond is broken so that a hole is exist, it is easy for a valence -e in a neighboring atom to leave its covalent bond in order to fill this hole, which in turn leaves a hole in its original position. Hence, holes move in opposite direction to that of electron and participate in the conduction of electricity. The electron moves in the conduction band and the hole moves in the valence band.

We can also define a semiconductor as intrinsic semiconductor in which free electrons and holes are created only by excitation of electrons from the valence band to the conduction band. If N denotes the number density of

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electrons in the conduction band and P the number density of holes in the valence band, then, $N = P$

17.3 DOPING OF IMPURITIES

The intrinsic semiconductors have low conductivity which is of little interest. But, when a small amount of impurity is added to semiconductor crystal then it greatly increases the conductivity of the intrinsic semiconductor. An addition of impurity into an intrinsic semiconductor is called doping. The impurity added is called a dopant. A semiconductor doped with impurity atoms is called an extrinsic semiconductor. Pentavalent elements from Group V or trivalent elements from Group III are used as dopants. The atoms belonging to these two groups are nearly of the same size as silicon or germanium atoms and easily substitute themselves in place of some of the host atoms in the semiconductor crystal. Thus, they are substitutional impurities and do not cause any distortion in the original crystal structure.

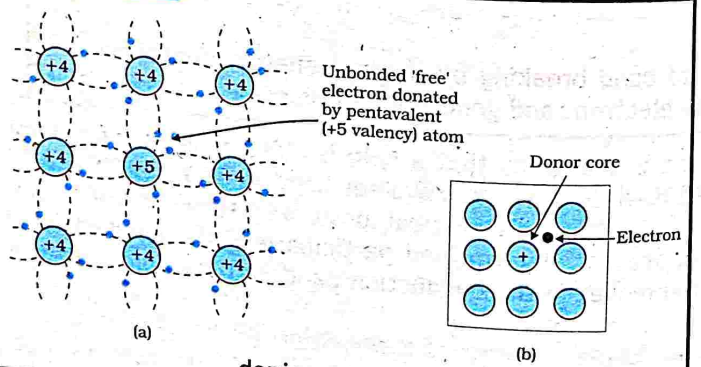
Two types of extrinsic semiconductors, namely N-type and P-type semiconductors are produced depending upon the group of impurity atom.

17.3.1 N-TYPE SEMICONDUCTOR

group 5

An N-type semiconductor is produced when a pure semiconductor is doped with a pentavalent impurity. Phosphorous and arsenic are the dopants normally used. Let us examine the effect of these pentavalent impurities on the carrier concentration and electrical conductivity. Suppose a phosphorous atom is doped with a silicon atom in the crystal. Phosphorus atom has five valence electrons.

FIGURE 17.4



doping of semiconductors

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Out of the five electrons, only four can participate in the bonding, since there are only four bonds as shown in Fig. 17.4 (b). The fifth electron does not form a bond and remains loosely bound to the atom.

The impurity atoms which contribute electrons to the conduction band are called donor atoms. They produce electrons without producing holes in the valence band. At very low temperature, the donor atoms are not ionized and the conduction band is empty. At slightly high temperatures, the donor electrons populate the conduction band. At ordinary temperatures, some electrons from the valence band are also excited into the conduction band through the intrinsic process. The holes in the valence band are smaller at ordinary temperatures.

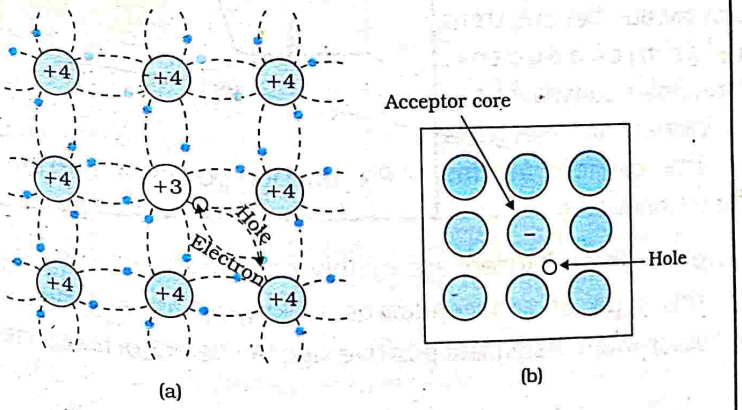
The electrons which are in majority are called majority carriers whereas the holes are called minority carriers since they are very small in number. As the current is mainly carried by electrons which are negative charge carriers, the semiconductor is called an N-type extrinsic semiconductor, where N indicates the negative sign of the majority carriers.

17.3.2 P-TYPE SEMICONDUCTOR

group 3

A P-type semiconductor is obtained by doping an intrinsic semiconductor with trivalent elements such as boron and aluminum. When a trivalent impurity atom is added with a silicon atom, it falls short of one electron for completing the four covalent bonds with its neighbors. The substitution of a host silicon atom with, say, a boron atom does not disturb the neutral environment around the boron atom.

FIGURE 17.5

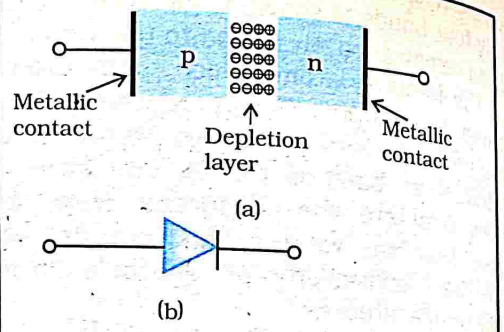


semiconductors doping

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However, when an electron from a neighboring atom acquires energy and jumps to form a bond, it leaves behind a hole (Figure 17.6). The boron atom having acquired an additional electron becomes a negative ion. The hole can move freely in the valence band whereas the impurity ion is immobile.

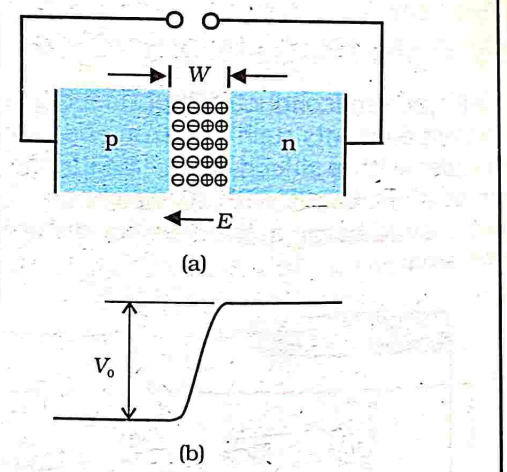
FIGURE 17.6



PN junction

The impurity atoms which accept electrons from the valence band are known as acceptor atoms. The acceptor impurity atoms produce holes without the simultaneous generation of the electrons, in the conduction band. At ordinary temperatures, holes are produced due to intrinsic process also, by promoting electrons from valence band to conduction band. The result is that holes out number electrons in the semiconductor. Therefore, holes constitute the majority carriers and electrons are minority carriers in this type of semiconductor.

FIGURE 17.7



PN junction potential barrier

As positively charged carriers are mainly contributing to the conduction process, this type of semiconductor is known as a P-type extrinsic semiconductor where P signifies positive sign of the majority carriers.

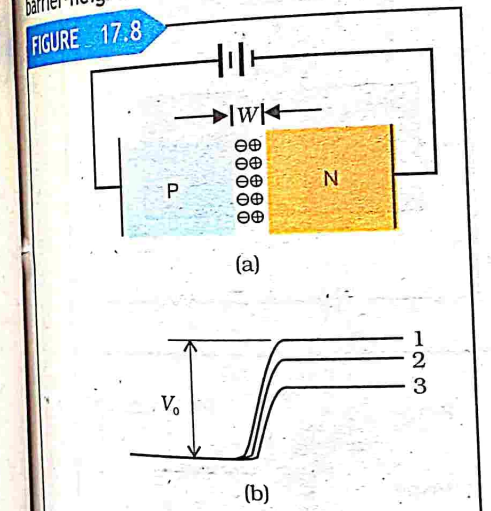
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17.4 PN JUNCTION

Junction diode is formed by placing a P-type crystal with in contact with N-type crystal and subjected to high pressure so that it becomes a single piece. PN junction has special properties such as rectification. At the junction, electrons from N-type fill the vacancies in P-region; thus negative and positive ions are formed. These ions create an electric field directed from N- to P- type region (Fig. 17.6 a). It stops further diffusion of electrons and holes and maintains the separation of charge carriers. The junction region is now free of mobile charges and it is called depletion region or layer.

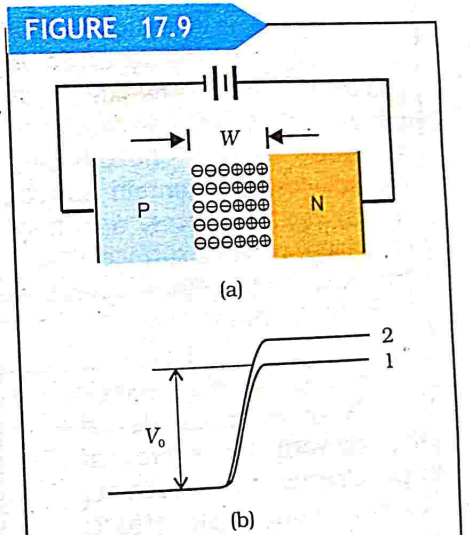
The width of depletion layer depends upon carrier concentration. Thus, a potential wall or barrier is formed at the junction. The symbol of PN junction (diode) is shown in Fig17.6. When P-type region is connected with positive potential with respect to N-type region and the potential drop is increased slowly, the junction barrier-height decreases.

FIGURE 17.8



P-N junction diode under forward bias current.

FIGURE 17.9



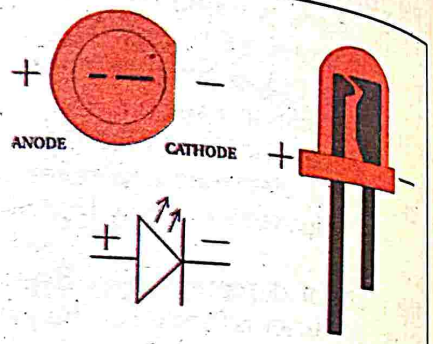
P-N junction diode under reverse bias current.

At one point, called as knee voltage, majority charge carriers cross the junction and the current flows, Fig 17.8. This is called forward bias and the current is called forward current. On the other hand, if P-type region is made negative with respect to N-type, no majority charge carriers cross the junction and hence there is no current. A small amount of current flows due to minority charge carriers. This biasing is called the reverse bias and the current is called as reverse current. The reverse current is generally of the order of few microamperes.

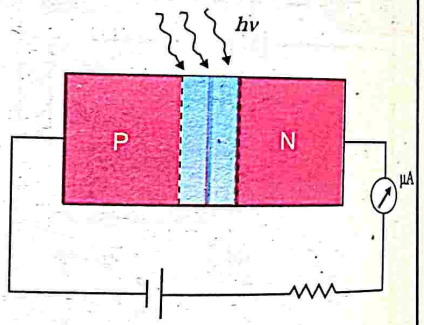
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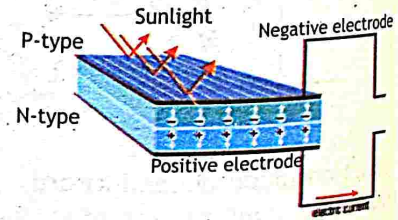
A light-emitting diode (LED) is a semiconductor light source that emits light when current flows through it. Electrons in the semiconductor recombine with electron holes, releasing energy in the form of photons. It is a heavily doped P-N junction which under forward bias emits spontaneous radiation.



A photodiode is a semiconductor device that converts light into an electrical current. The current is generated when photons are absorbed in the photodiode. Photodiodes may contain optical filters, built-in lenses, and may have large or small surface areas. It is a P-N junction diode, operated under reverse bias.



A solar cell, or photovoltaic cell, is an electrical device that converts the energy of light directly into electricity by the photovoltaic effect, which is a physical and chemical phenomenon.



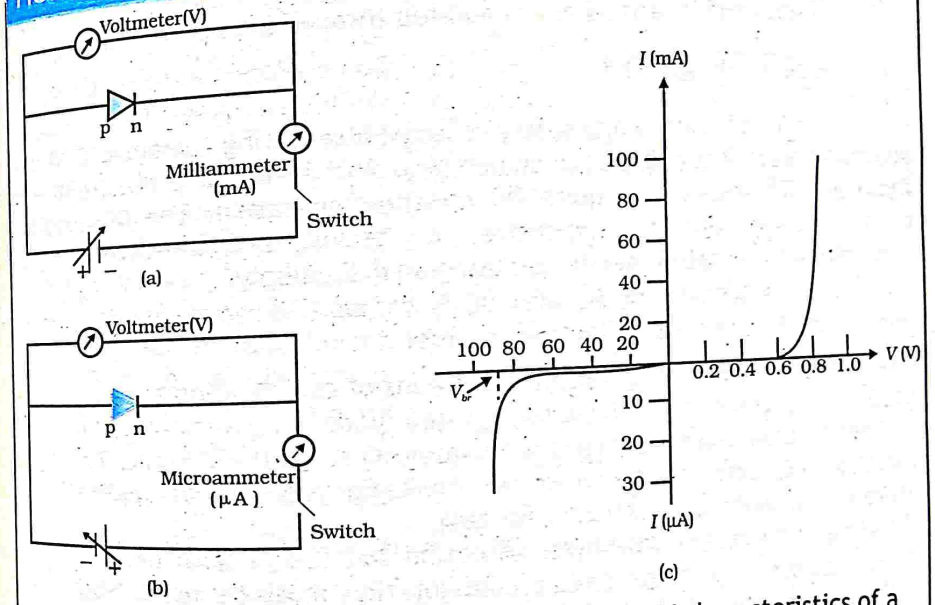
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17.4.1 IV CHARACTERISTICS OF PN JUNCTION

The *IV* characteristics of PN junction are shown in Fig 17.10. The knee voltage is 0.3V for germanium and 0.7V for silicon junction.From the *IV* characteristics, we see that the forward current increases rapidly beyond the knee voltage. There exists a maximum current limit for junction, which is decided by power ratio of the junction. Beyond that, the junction is destroyed.

In reverse bias, if voltage is increased, due to available energy, covalent bonds break and large number of electrons are released. This causes a sudden increase in current. This is called as zener effect.

FIGURE 17.10



Experimental circuit arrangement for studying IV characteristics of a P-N junction diode (a) in forward bias , (b) in reverse bias. (c) Typical IV characteristics of a silicon diode.

If reverse bias is increased further, minority charge carriers attain high velocity and knock down the bound electrons from covalent bonds and the current increases. This is called as avalanche effect. Using these effects, zener diodes are formed.

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17.4.2 DRIFT OF MINORITY CARRIER

It is seen that the electric field across the junction prevents the diffusion of majority carriers. However, the electric field has the right direction to promote the flow of minority carriers across the junction. Electrons arriving at the junction from the bulk of P-region are assisted by the electric field to move into N-region. Similarly, holes in the N-region are helped to move into P-region. As a consequence, an electric current flows across the junction.

As the current is caused by an electric field it is a drift current. The net drift current through the junction is due to electron and hole which is given by.

$$I_{(drift)} = I_e + I_h \qquad (17.1)$$

The minority carriers are generated through breaking of covalent bonds.

17.5 RECTIFICATION

Due to efficiency and safety reasons, alternating current (AC) is used for providing electrical power. But some electronic devices like electronically tune radio and TV receivers require DC for their operation. The DC supplies like cells, batteries etc. are expensive, low power, and short-lived. Therefore generally a DC supply is generated using an A.C. supply.

The conversion of AC into DC is called the rectification and a device used for rectification is called the rectifier.

Diodes provide compact, inexpensive means of rectification therefore it can be used as a rectifier. As we have seen, when diode is forward biased it allows the current to pass and in reverse bias it (almost) stops the current. Thus it can be used as unidirectional device (or rectifier). For most power applications, half-wave rectification is insufficient for task.

If we need to rectify AC power to obtain full use of both half-cycles of sine wave, different rectifier circuit configuration must be used. Such circuit is called full-wave rectifier.

17.5.1 HALF WAVE RECTIFIER

Simplest kind of rectifier circuit is half-wave rectifier. Fig 17.11 (a) shows Half wave rectifier circuit which uses transformer to couple the ac input voltage from the source to the rectifier. Transformer coupling provides two advantages. First, it allows the source voltage to be stepped up or stepped down as needed. Second, the AC source is electrically isolated from the rectifier, thus preventing a shock hazard in the secondary circuit.

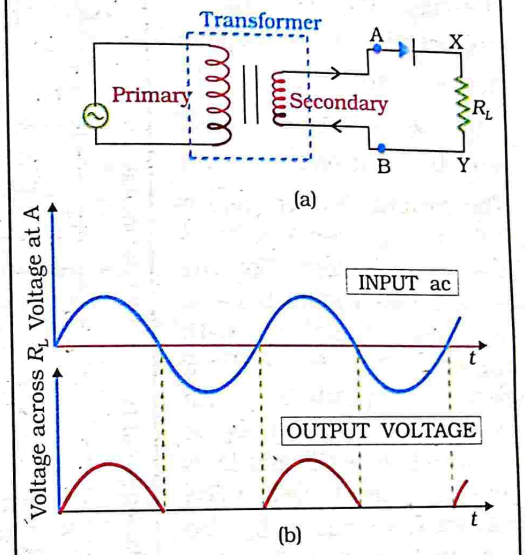
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The voltage across the secondary of the transformer, i.e. between A and B is represented as $V = V_m \sin\omega t$ and graphically it is shown in Fig 17.11 b. V_m is the peak value of the alternating voltage.

During the positive half cycle of AC, the point A becomes positive with respect to B. The diode is forward biased and the current flows through the load. For negative half cycle, point A becomes negative with respect to B and the diode is reveres biased. Practically, no current flows through the load.

Thus, only half wave is rectified and it is called half-wave rectifier. During the negative half cycle of AC, diode is reverse biased and the total voltage appears across the diode. Peak inverse voltage (PIV) is the maximum voltage V_m that the rectifying diode has to withstand, when it is reversed-biased. During negative half-cycle of the input voltage, the diode is reversed biased, no current flows through the load resistance R_L and so causes no voltage drop across load resistance R_L and consequently the whole of the input voltage appears across the diode. Thus the maximum voltage that appears across the diode is equal to the peak value V_{max}.

FIGURE 17.11



(a) Half-wave rectifier circuit, (b) Input ac voltage and output voltage waveforms from the rectifier circuit.

17.5.2 FULL-WAVE RECTIFIER

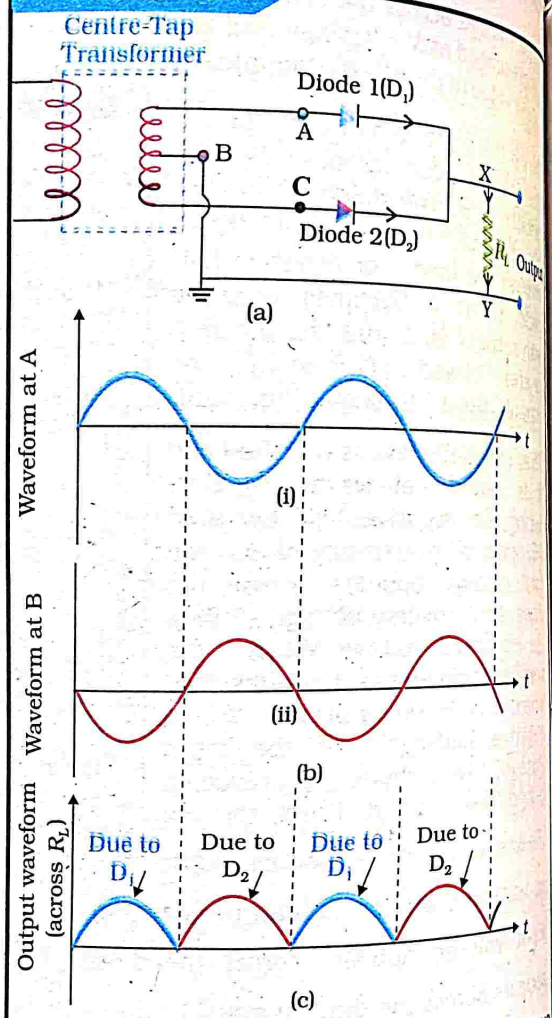
One kind of full-wave rectifier, called center-tap design, uses transformer with center-tapped secondary winding and two diodes in alternate switching mode as shown in Fig 17.12. A full wave rectifier allows unidirectional (one way) current through the load during the entire cycle of the input, whereas a half wave rectifier allows current through the load only during one half of the cycle.

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The diodes D_1 and D_2 operate in alternate switching mode. For the first half cycle point, A becomes positive with respect to B and B becomes positive with respect to C. Thus, D_1 is forward biased and D_2 is reverse biased. The current through load is only due to D_1while current due to D_2 is zero. For the second half cycle, point C becomes positive with respects to B and B becomes positive with respect to A. Now D_2 is forward biased ON and D_1 is reverse biased OFF. The current flows due to D_2. For the first half cycle, the current is due to D_1 and for the second half cycle, the current is due to D_2. Thus full wave is rectified.

One disadvantage of this full-wave rectifier design is necessity of transformer with center-tapped secondary winding.

FIGURE 17.12



(a) A Full-wave rectifier circuit; (b) Input wave forms given to the diode D_1 at A and to the diode D_2 at B; (c) Output waveform across the Load R_L connected in the full-wave rectifier circuit.

17.6 TRANSISTOR

A transistor consists of three regions of doped semiconductors in which the current flowing is modulated by the voltage or current applied to one or more electrodes.

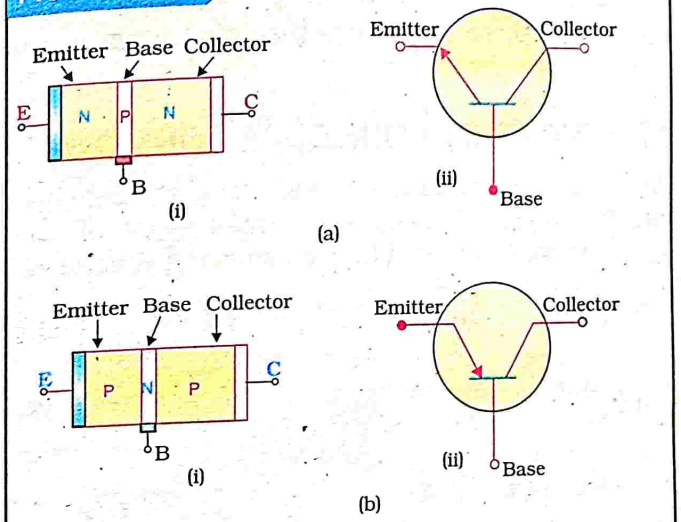
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Modern transistors are of two types: bipolar, whose function depends upon both (majority and minority) charge carriers and unipolar, whose function depends upon majority charge carriers, e.g. field effect transistors. Here we shall study only bipolar transistors. Sometimes these are called bipolar junction transistor (BJTs).

In transistor, there are two PN junctions which form either PNP or NPN transistor is shown in Fig17.13. In NPN, electrons and in PNP, holes are the majority charge carriers.

The first region is emitter and it is heavily doped. Its function is to emit the charges. The last region collects the charges and it is called collector. The middle region is thin and lightly doped and it is called base. The arrow in the symbol indicates the direction of current. From Fig17.13 (a) we see that there are two junctions, one is emitter junction and other is collector junction.

FIGURE 17.13



(a) N-P-N transistor and P-N-P transistor, and
(b) Symbols for N-P-N and P-N-P transistors.

The emitter junction is forward biased and collector junction is reveres biased. As the emitter junction being forward biased, so it offers low resistance. The charges emitted by the emitter are attracted by the collector. The collector junction being reverse biased, there exists a large potential gradient, which attracts the charges. If the collector is open (means not connected to power supply) charges return via base region. Most of the charges are collected by collector, therefore the collector current I_C is almost equal to the emitter current I_E.

Some charges, which cannot reach the collector, move via base, constituting the base current I_B, which is small. Thus addition of base current and collector current is equal to the emitter current. Therefore,

$$I_E = I_B + I_C$$

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$$I_E = I_B + I_C \qquad (17.2)$$

The base is made thin and it is lightly doped, therefore, the recombination of charges is less and the transit time of charges is also less. There is no difference in operation of PNP and NPN transistor except the polarity of biasing. In most of the cases NPN, transistors are preferred because mobility of electrons is three times more than that of holes and therefore the operation is faster.

17.7 TYPES OF CONFIGURATIONS

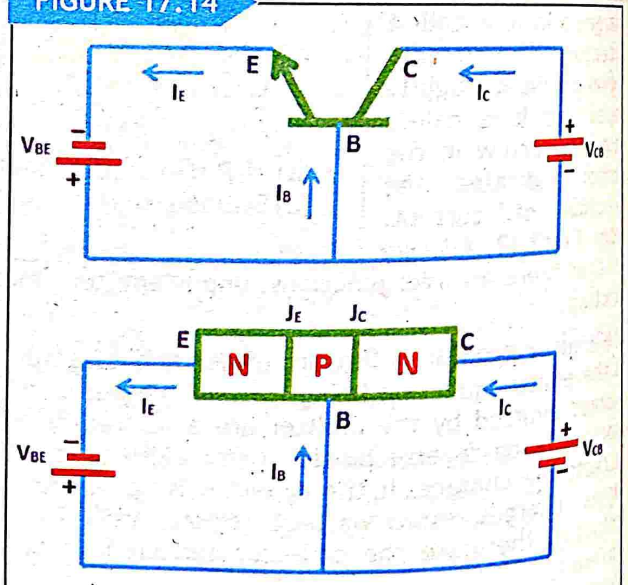
In a transistor circuit, one electrode is common to both input and output circuits. Therefore there exist three types of configurations: common base (CB), common emitter (CE) and common collector (CC), as shown in Fig17.14.

17.7.1 COMMON BASE CONFIGURATION

The Common Base configuration is another type of configuration where the base terminal of the transistor is a common terminal to both the input and output signals, hence it is named as common base (CB).

In common base configuration, emitter is the input terminal, collector is the output terminal and base terminal is connected as a common terminal for both input and output. That means the emitter terminal and common base terminal are known as input terminals whereas the collector terminal and common base terminal are known as output terminals. In

FIGURE 17.14

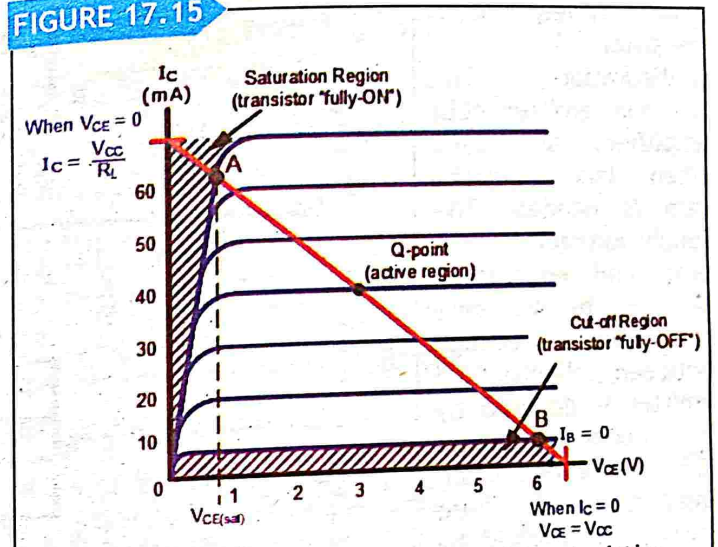


Transistors in CB mode: (a) circuit

common base configuration, the base terminal is grounded so the common base configuration is also known as grounded base configuration. Sometimes common base configuration is referred as common base amplifier, CB amplifier, or CB configuration. The supply voltage between base and emitter is denoted by V_{BE} while the supply voltage between collector and base is denoted by V_{CB}.

The output characteristic has three regions of operation, namely, active, cut-off and saturation. When the base-emitter junction is forward biased and the collector-base junction is reverse biased, it is active region. When both, collector-base and base-emitter junctions are reverse biased it is cut-off region. The output current is zero in this case. When both the junctions are forward biased, it is saturation region. Figure 17.15 shows these regions.

FIGURE 17.15



Transistors in CB mode: (b) output characteristics.

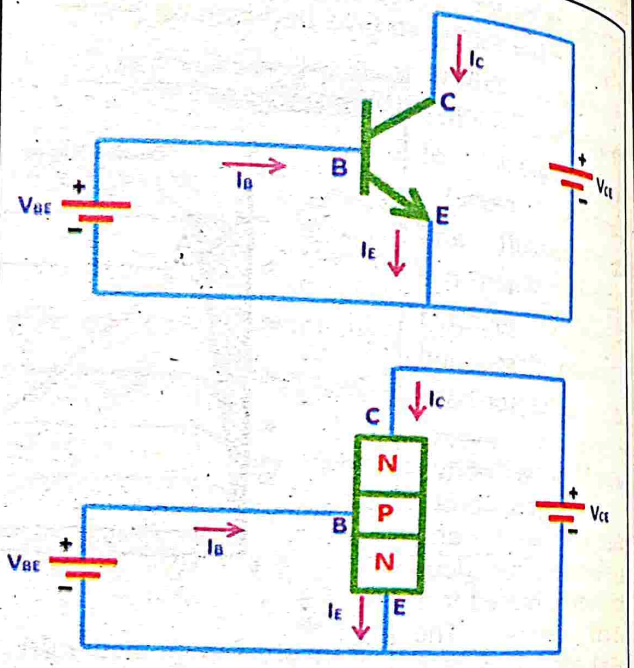
17.7.2 COMMON EMITTER CONFIGURATION

The configuration in which the emitter is connected between the collector and base is known as a common emitter configuration. Thus, the emitter is common to both the input and the output circuit hence it is named as common emitter configuration. In common emitter configuration, base is the input terminal, collector is the output terminal and emitter is the common terminal for both input and output. That means the base terminal and common emitter terminal are known as input terminals whereas collector terminal and common emitter terminal are known as output terminals. In common emitter configuration, the emitter terminal is grounded so the common emitter configuration is also known as grounded emitter configuration.

NOT FOR SALE

Sometimes common emitter configuration is also referred to as CE configuration, common emitter amplifier, or CE amplifier. The common emitter (CE) configuration is the most widely used transistor configuration. The common emitter (CE) amplifiers are used when large current gain is needed. The supply voltage between base and emitter is denoted by V_{BE} while the supply voltage between collector and emitter is denoted by V_{CE}. In common emitter (CE) configuration, input current or base current is denoted by I_B and output current or collector current is denoted by I_C.

FIGURE 17.16



Transistors in CE mode: (a) circuit

ALPHA FACTOR:. The ratio of I_C and I_E is called as alpha factor. It is an amplification factor.

Since $I_C \approx I_E$, $\alpha \approx 1$. Therefore,

$$\alpha_{static} = \frac{I_C}{I_E} \qquad \ldots(17.3)$$

and

$$\alpha_{dynamic} = \frac{\Delta I_C}{\Delta I_E}$$

BETA FACTOR: The ratio of collector current I_c and base current I_B is called as beta factor.

NOT FOR SALE

That is:

$$\beta_{static} = \frac{I_C}{I_B} \qquad \ldots(17.4)$$

and

$$\beta_{dynamic} = \frac{\Delta I_C}{\Delta I_B}$$

The beta factor is called as current gain or current amplification factor. Generally it ranges from 50 to 400. We can write;

$$\beta = \frac{I_C}{I_B} \qquad \ldots(17.5)$$

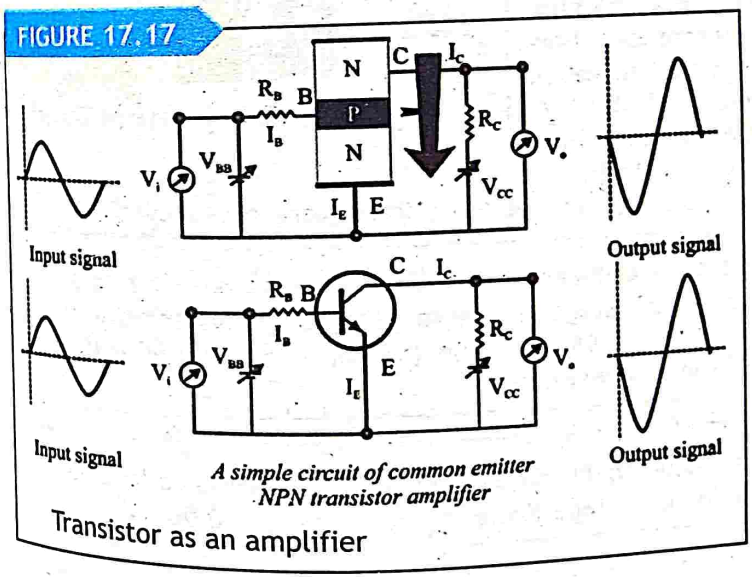
$$= \frac{I_C}{I_E - I_C} = \frac{I_C / I_E}{1 - I_C / I_E}$$

$$\beta = \frac{\alpha}{1-\alpha} \qquad \ldots(17.6)$$

17.7.3 TRANSISTOR AS AN AMPLIFIER

Amplification is the process of increasing the strength of a signal. A signal is just a general term used to refer to any particular current, voltage, or power in a circuit. An amplifier is the device that provides amplification (the increase in current, voltage, or power of a signal) without changing the original signal.

FIGURE 17.17



A simple circuit of common emitter NPN transistor amplifier

Transistor as an amplifier

NOT FOR SALE

An electrical signal can be amplified by using a device which allows a small current or voltage to control the flow of a much larger current from a DC power source. Transistors are the basic device providing control of this kind. The basic configurations of transistor amplifier circuits are the common base, the common emitter, and the common collector. All these configurations can be used as transistor amplifier. Because the common-emitter circuit configurations the most often used, it is described in Fig 17.17 here. The same principles apply to the common-base and common-collector circuits.

17.7.4 TRANSISTOR AS A SWITCH

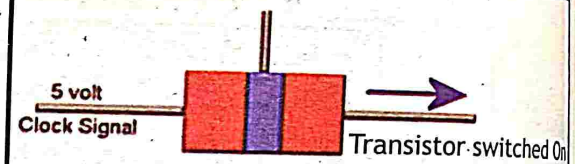
Transistor is used in a great variety of circuits. Transistor switches form the basis of all electronic computers. With the switch closed, base current flow causing collector to flow.

The output voltage is $V_{CE} = 0$ V (Fig 17.18. a). The battery voltage is dropped across the load causing the collector voltage to fall to a very low value.

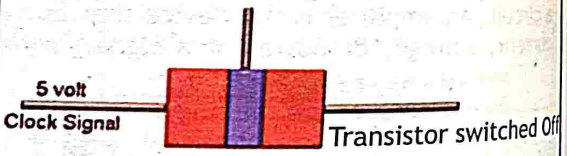
The transistor is said to be saturated. With the switch open no base current flow, therefore no collector current can flow. The transistor is said to be cut off. $V_{CE} \approx +V$ (Fig 17.18 b).

These two states are described as 0 and 1, or low and high.

FIGURE 17.18



(a) No signal to centre of Transistor



(b) Signal to centre of Transistor

Transistor ON-OFF switch

EXAMPLE 17.1

A transistor is connected in a CE configuration. The collector supply voltage is 10V and the voltage drop across the 500Ω connected in the collector circuit is 0.6V. If α = 0.96, find the (a) collector-emitter voltage (b) base current, and (c) the emitter current.

GIVEN

collector supply voltage V= 10V , resistance R= 500Ω
collector voltage V_c= 0.6V, α = 0.96,

NOT FOR SALE

REQUIRED

(a) collector-emitter voltage V_{CE} =?
(b) base current I_B =? , and (c) the emitter current I_E =?

SOLUTION

To collector current, $I_C = \frac{V_c}{R_c} = \frac{0.6}{500} = 1.2$ mA

(1) Collector-emitter voltage $V_{CE} = V_{CC} - V_C = 10\text{-}0.6$
=9.4V

(2) $\alpha = \frac{I_c}{I_E}$ or $I_E = \frac{I_C}{\alpha} = \frac{1.2}{0.96} = 1.25$mA

(3) $I_E = I_B + I_C$ or
$I_B = I_E - I_C = 1.25 - 1.2 = .05$mA

EXAMPLE 17.2

The constant α of a transistor is 0.95. What would be the change in the collector current corresponding to a change of 0.4mA in the base current in a common-emitter arrangement?

GIVEN

current-gain α =0.95, base current I_B = 0.4mA

REQUIRED

change in the collector current I_C = ?

SOLUTION

The current gain of a transistor in common-emitter arrangement is β, which is related to its current-gain α in common-base arrangement

$$\beta = \frac{\alpha}{1-\alpha}$$

$$\beta = \frac{0.95}{1-0.95} = 19$$

But, β is the ratio of change in collector current to the change in base current.

$$\beta = \frac{\Delta I_c}{\Delta I_b} \text{ or } \Delta I_c = \beta \times \Delta I_b = 19 \times 0.4 \times 10^{-3} \text{A} = 7.6\text{mA}$$

NOT FOR SALE

KEY POINTS

Semiconductors : those materials whose conductivity lying in between conductors and insulators i.e, silicon and germinium.

Intrinsic semiconductor: Chemically pure semiconductors.

Carrier in pure semiconductor: Majority charge carrier in N-type are electrons and in P-type are holes.

An N-type semiconductor: when a pure semiconductor is doped with a pentavalent impurity

A P-type semiconductor: when a pure semiconductor is doped with a trivalent impurity.

Rectification: the conversion of AC into DC.

Rectifier: a device used for rectification.

Transistor types : PNP or NPN transistor.

Amplification : an increase in voltage or current level.

NOT FOR SALE

EXERCISE

Choose the best possible answer

1. In an N-type silicon, which of the following statement is true
   (a) Electrons are majority carriers and trivalent atoms are the dopants.
   (b) Electrons are minority carriers and pentavalent atoms are the dopants.
   (c) Holes are minority carriers and pentavalent atoms are the dopants.
   (d) Holes are majority carriers and trivalent atoms are the dopants.

2. The barrier potential of silicon diode at room temperature is.
   (a) 0.3V (b) 0.7V (c) 0.9V (d) 1.0V

3. The width of depletion region of a junction
   (a) Increases under forward bias
   (b) Is independent of applied voltage
   (c) Increases under reverse bias
   (d) Remains same

4. For common emitter configuration of NPN transistor, current gain is given by
   (a) I_C/I_B (b) I_C/I_E (c) I_E/I_B (d) I_B/I_E

5. The reverse saturation current in a PN junction diode is only due to
   (a) majority carriers (b) minority carriers
   (c) acceptor ions (d) donor ions

6. PN junction when reversed biased act as:
   (a) Capacitor (b) ON switch (c) Inductor (d) OFF Switch

7. Improper biasing of a transistor circuit produces
   (a) Heavy loading of emitter current
   (b) Distortion in the output signal
   (c) Excessive heat at collector terminal
   (d) Faulty location of load line

8. When transistors are used in digital circuits they usually operate in the:
   (a) Active region
   (b) Breakdown region
   (c) Saturation and cutoff regions
   (d) linear region

NOT FOR SALE

MULTIPLE CHOICE

9. Most of the electrons in the base of an NPN transistor flow:
   (a) out of the base lead (b) into the collector
   (c) into the emitter (d) into the base supply

10. In a transistor, collector current is controlled by:
   (a)Collector voltage (b)base current
   (c)Collector resistance (d)all of the above

11. The minimum number of diode required for full wave rectification are
   (a) 3 (b) 4 (c) 2 (d) 1

12. In a transistor both collector-base and base-emitter junctions are reverse biased then it is
   (a) Active region (b) Cutoff region
   (c) Saturation region (d) Q-point

CONCEPTUAL QUESTIONS

1. Why in a transistor (a) the base is thin lightly doped and (b) the collector is large in size.
2. Why the base current is weak as compared to collector current?
3. Why the emitter base junction is forward biased and collector base junction is reverse biased?
4. How NPN and PNP transistors works.
5. Distinguish between N-type semiconductors and P-type semiconductors.
6. A P-type semiconductor has a large member of holes but still it is electrically neutral. Why?
7. Why CE configuration is widely used in amplifier circuits?
8. Why transistor is called current amplification device?
9. A doped semiconductor has 10^{10} silicon atoms and 10 trivalent atoms. If the temperature is 25C°, how many free electrons and holes are there inside the semiconductor?

COMPREHENSIVE QUESTIONS

1. Describe the energy band structure of insulator, semiconductor and conductor.

NOT FOR SALE

2. Explain the significance of depletion layer in an equilibrium state in a PN-junction. Give energy band diagram.
3. Explain how PN-junction acts as a half-wave rectifier.
4. Explain the working of transistor as an amplifier?
5. Draw the circuit for a half wave rectifier and full wave rectifier.
6. Compare the advantages and disadvantages of full wave rectifier and half wave rectifier.
7. Deduce the relation between α and β of a transistor.
8. Discuss the conductivity of extrinsic semiconductor and its band gap energy.

NUMERICAL PROBLEMS

1. In a certain circuit, the transistor has a collector current of 10 mA and a base current of 40 μA. What is the current gain of the transistor?
   Answer (250)

2. The current flowing into the base of a transistor is 100 μA. Find its collector current I_C, its emitter current I_E, and the ratio I_C / I_E if the value of current gain β is 100.
   Answer (10 mA, 10.1mA, 0.99)

3. A transistor is connected in CE configuration. The voltage drop across the load resistance (R_C) 3 k Ω is 6 V. Find the base current. The current gain α of the transistor is 0.97.
   Answer (2.06×10^{-3} A)

4. In a common base circuit, the current gain is 0.96. If the collector current is 60 μ A. Find the emitter current.
   Answer (62.5 μA)

5. In transistor, the emitter current (I_E) is 3.5 A and collector current (I_C) is 2.35 A find the base current.
   Answer (1.15 A)

NOT FOR SALE

Unit

18

DAWN OF THE MODERN PHYSICS



Tardigrade (water bear) only grow up to 1.5 mm. How are such high resolution images possible for such small creatures?

LEARNING OUTCOMES

After studying this unit the students will be able to

- distinguish between inertial and non-inertial frames of reference.
- describe the significance of Einstein's assumption of the constancy of the speed of
- light.
- identify that if c is constant then space and time become relative.
- explain qualitatively and quantitatively the consequence of special relativity in relation to:
  - the relativity of simultaneity
  - the equivalence between mass and energy
  - length contraction
  - time dilation
  - mass increase
  - explain the implications of mass increase, time dilation and length contraction for space travel.

NOT FOR SALE

LEARNING OUTCOMES

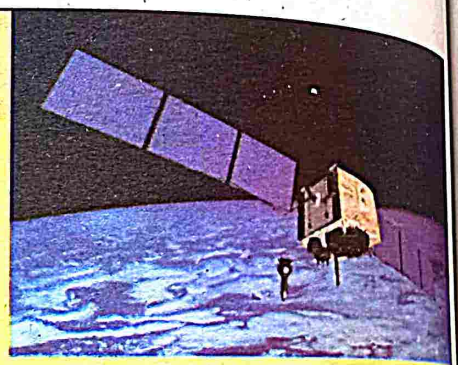
- describe the concept of black body radiation.
- describe how energy is distributed over the wavelength range for several values of source temperature.
- describe the Planck's hypothesis that radiation emitted and absorbed by the walls of a black body cavity is quantised.
- elaborate the particle nature of electromagnetic radiation.
- describe the phenomenon of photoelectric effect.
- solve problems and analyse information using: $E = hf$ and $c = f\lambda$.
- identify data sources, gather, process and present information to summarise the use of the photoelectric effect in solar cells & photocells.
- describe the confirmation of de Broglie's proposal by Davisson and Germer.
- experiment in which the diffraction of electrons by the surface layers of a crystal lattice was observed.
- describe the impact of de Broglie's proposal that any kind of particle has both wave and particle properties.
- explain the particle model of light in terms of photons with particular energy and frequency.
- describe Compton effect qualitatively.
- explain the phenomena of pair production and pair annihilation.
- explain how the very short wavelength of electrons, and the ability to use electrons and magnetic fields to focus them, allows electron microscope to achieve very high resolution.
- describe uncertainty principle.

At the end of the 19th century, scientists thought that they had discovered nearly everything about physics. Newton's laws of motion and his theory of universal gravitation, Maxwell's theoretical work in combining electricity and magnetism, and the laws of thermodynamics effectively explain all the known physics.

NOT FOR SALE

However, at the turn of the 20th century, two major concepts improved our understanding of nature. In 1900 Planck provided the basic ideas that led to the quantum theory, and in 1905 Einstein formulated his special theory of relativity. These theories inspired new developments and theories in the fields of atomic, nuclear, and condensed-matter physics.

For your information **GPS**



According to relativity theory, a moving clock appears to run slow with respect to a similar clock that is at rest. The satellites are constantly moving relative to observers on the Earth which causes them to run at slightly faster rate than clocks on the Earth's surface.

A calculation using General Relativity predicts that the clocks in each GPS satellite should get ahead of ground-based clocks by 45 microseconds per day. So the role of special theory of relativity is important in GPS.

18.1 REFERENCE FRAMES

A coordinate system in which an experimenter makes position and time measurements of physical events is called a reference frame.

In the theory of special relativity, an event, is a physical "happening" that occurs at a certain place and time. To record the event, experimenter uses a reference frame that consists of a set of x, y, z axes (called a coordinate system) and time measuring device such as a clock. Reference frames are used to specify the relationship between a moving observer and the event. However, in some physical situations, it is impractical to choose a reference system with a fixed origin.

NOT FOR SALE

Consider, for example, a jet plane landing on an aircraft carrier that is going forward at full throttle at the same time as shown in figure 18.1. You want to describe the plane's motion in a coordinate system fixed to the carrier, even though the carrier is moving. The reason why this is important is that the plane needs to come to rest relative to the carrier at some fixed location on the deck.

FIGURE 18.1

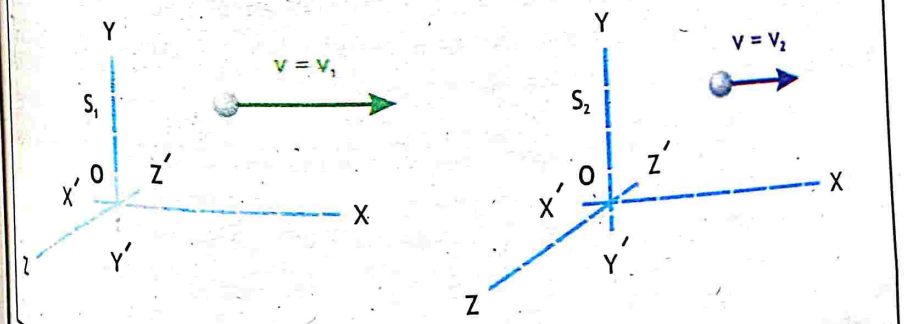


Jet landing on aircraft carrier

A. Inertial Reference Frame

An inertial frame is one in which an object subjected to no forces moves in a straight line at constant speed.

FIGURE 18.2



Velocities observed in different reference frames

B. Non-inertial Reference Frame

An accelerating frame of reference is called a non-inertial frame of reference.

Any frame or system moving with constant velocity with respect to an inertial system must also be an inertial, thus there is no single, preferred inertial frame, as shown in figure 18.2

The earth-based reference frame is not exactly an inertial reference frame because it is subjected to centripetal acceleration as the earth spins on its axis and revolves around the sun. In most situations, the effects of these accelerations are small, and we can neglect them. Therefore the earth's surface can be considered as inertial reference frame in many situations.

For example, when analyzing the motion of a cricket ball, the fact that Earth rotates about its axis does not have much effect. But if we want to analyze the motion of a meteor falling from a great distance toward Earth, Earth's rotation must be considered.

18.2 SPECIAL THEORY OF RELATIVITY

In 1905 Albert Einstein proposed a theory that completely changed our views of space and time. He based his special theory of relativity on two postulates

1. The principle of relativity: The laws of physics are the same in all inertial reference frames.

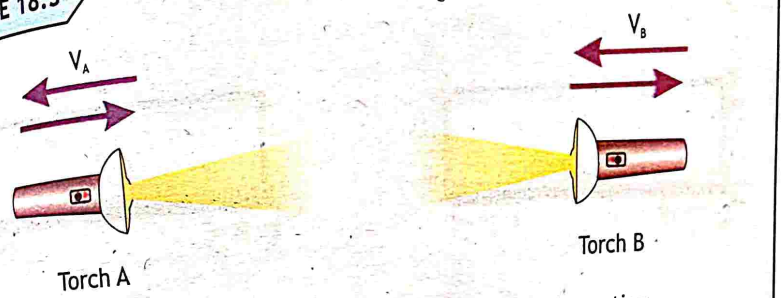
The first postulate declares that the laws of physics are absolute, universal, and the same for all inertial observers. Laws that hold for one inertial observer cannot be violated for any inertial observer. Einstein's principle of relativity means that any kind of experiment—mechanical, thermal, optical, or electrical—performed in a laboratory at rest must give the same result when performed in a laboratory moving at a constant speed past the first one.

For example the pouring of tea in an aeroplane moving with constant speed is same as that on earth.

2. The principle of constancy of the speed of light: The speed of light in a vacuum has the same value, $c = 2.997\ 924\ 58 \times 10^8$ m/s, in all inertial reference frames, regardless of the velocity of the observer or the velocity of the source emitting the light.

The second postulate is more difficult to accept because it seems to go against our 'common sense,' which we observe in everyday experiences.

FIGURE 18.3



Speed of light is constant and independent of relative motion.

Consider two experimenters one at torch A and the other at torch B as shown in figure 18.3. Both these experimenters, regardless of if they are at rest or move with respect to each other finds that in every situation light travel with the same speed as $c = 3 \times 10^8$ m/s.

18.3 CONSEQUENCES OF SPECIAL THEORY OF RELATIVITY

As we examine some of the consequences of relativity, we will find that they contradict some basic concepts.

A. SIMULTANEITY

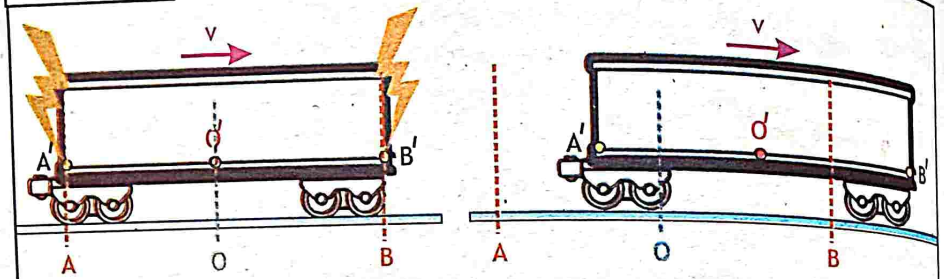
Two events that are simultaneous in one frame are in general not simultaneous in a second frame moving with respect to the first. That is, simultaneity (the occurrence of two or more events at the same time) is not an absolute concept, but a relative concept that depends on the state of motion of the observer.

Einstein devised the following **thought experiment** to illustrate this point. A box car moves with uniform velocity, and two lightning bolts strike the ends of the box car, as shown in Figure 18.4, leaving marks on the boxcar and ground. The marks left on the box car are labeled A′ and B′; those on the ground are labeled A and B.

NOT FOR SALE

An observer at O moving with the box car is midway between A′ and B′, and a ground observer at O is midway between A and B. The events recorded by the observers are the light signals from the lightning bolts.

FIGURE 18.4



The lightning bolts striking the moving box car at front and back

The two light signals reach the observer at O at the same time. This observer realizes that the light signals have traveled at the same speed over equal distances. Thus, observer O concludes that the events at A and B occurred simultaneously. Now consider the same events as viewed by the observer on the box car at O′. By the time the light has reached observer O′, observer O′ has moved. Thus, the light signal from B′ has already swept past O′, but the light from A′ has not yet reached O′.

According to Einstein, observer O′ must find that light travels at the same speed as that measured by observer O. Therefore, observer O′ concludes that the lightning struck the front of the box car before it struck the back. This thought experiment clearly demonstrates that the two events, which appear to O to be simultaneous, do not appear to be simultaneous to O′ as well.

B. TIME DILATION

The time taken for an event to occur within its rest frame is called proper time Δt_p. Observers in different frames in relative motion will always judge the time to be longer called time dilation Δt.

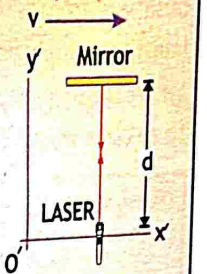
$$\Delta t = \frac{\Delta t_p}{\sqrt{1-\frac{v^2}{c^2}}} \qquad 18.1$$

NOT FOR SALE

For your information

MATHEMATICAL PROOF OF TIME DILATION

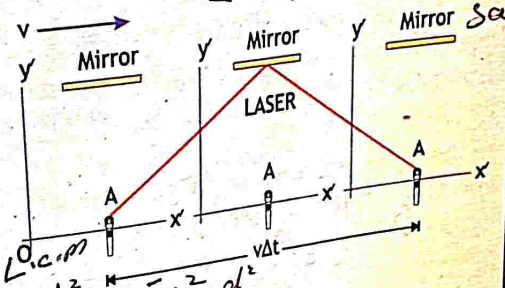
Consider a vehicle moving to the right with a speed 'v' as in Figure. A mirror is fixed to the ceiling of the vehicle, and a laser at distance 'd' below the mirror' emits a pulse of light directed toward the mirror, and at some later time after reflecting from the mirror, the pulse arrives back at the laser. Observer O′ at rest with the system measure the time interval Δt_p between these two events as



$$\Delta t_p = \frac{2d}{c} \qquad (1)$$

Now consider the same set of events as viewed by O in a second frame. According to this observer, the mirror and laser are moving to the right with a speed 'v', and, as a result, the sequence of events appears different.

By the time the light from the laser reaches the mirror, the mirror has moved to the right a distance 'vΔt/2', where Δt is the time it takes the light pulse to travel from point A to the mirror and back to point A as measured by 'O'. The Pythagorean theorem gives



$$\left(\frac{c\Delta t}{2}\right)^2 = \left(\frac{v\Delta t}{2}\right)^2 + d^2$$

$$\text{or } \Delta t = \frac{2d}{\sqrt{c^2-v^2}}$$

$$\Delta t = \frac{2d}{c\sqrt{1-\frac{v^2}{c^2}}} \qquad (2)$$

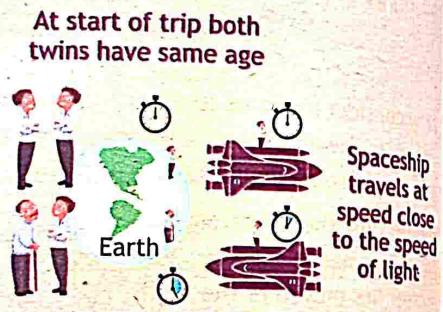
putting equation1 in equation 2 we get $\Delta t = \frac{\Delta t_p}{\sqrt{1-\frac{v^2}{c^2}}}$ (B)

NOT FOR SALE

'A moving clock runs slower than a clock at rest'. We can say that all physical processes, including chemical reactions and biological processes, slow down when observed from a reference frame in which they are moving. For example, the heartbeat of an astronaut moving through space would keep time with a clock inside the spaceship, but both the astronaut's clock and her heartbeat appear slow to an observer, with another clock, in any other reference frame.

Science Tidbits **Twin Paradox**

Suppose one of a pair of 20-year-old twins takes off in a spaceship traveling at very high speed to a distant star and back again, while the other twin remains on Earth. According to the Earth twin, the astronaut twin will age less.



E Thought experement Good idea

NOT FOR SALE

C. LENGTH CONTRACTION

The length of an object measured within its rest frame is called proper length ΔL_p. Observers in different frames in relative motion will always measure the length to be shorter called length contraction ΔL.

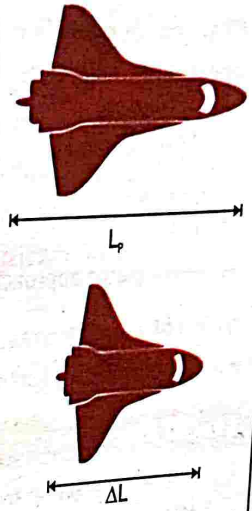
$$\Delta L = \Delta L_p \sqrt{1 - \frac{v^2}{c^2}} \qquad 18.2$$

D. RELATIVISTIC MASS

The mass of an object measured within its rest frame is called rest mass Δm_o. Observers in different frames in relative motion will always measure the mass to be greater called relativistic mass Δm.

$$\Delta m = \frac{\Delta m_o}{\sqrt{1 - \frac{v^2}{c^2}}} \qquad 18.3$$

FIGURE 18.5



The length contraction takes place only along the direction of motion..

E. MASS ENERGY EQUIVALENCE

The mass of an object is equivalent to certain quantity of energy, Thus mass can be converted into energy and conversely energy can be converted into mass. By the Einstein's famous equation

$$E = \Delta m c^2 \qquad 18.4$$

In pair production of particle and antiparticle energy is converted into mass, whereas in particle annihilation with antiparticle the entire mass is converted into energy.

F. SPEED LIMIT

Calculation of expanded times and contracted lengths involve the expression

$$\sqrt{1 - \frac{v^2}{c^2}}$$

Since times and lengths are real measurements, they must be represented by real numbers, so the value under the square root must be a positive real number. For this to be true,

$$\frac{v^2}{c^2} < 1 \qquad \frac{v_2^2}{c^2} < 1$$

This implies that v < c. Consider what happens to Δt when v approaches c in (v = c):

$$\Delta t = \frac{\Delta t_p}{\sqrt{1-\frac{v^2}{c^2}}} \quad \text{or} \quad \Delta t = \frac{\Delta t_p}{\sqrt{1-\frac{c^2}{c^2}}} \quad \text{or} \quad \Delta t = \frac{\Delta t_p}{\sqrt{1-1}}$$

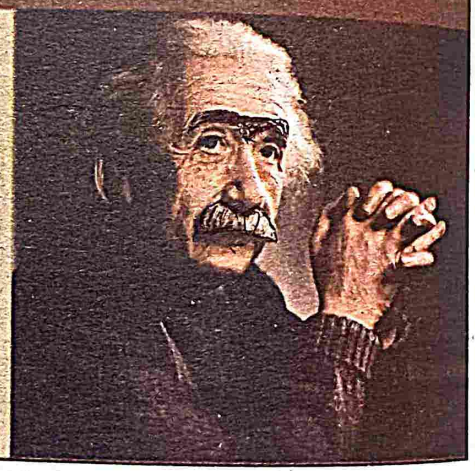
The denominator approaches zero, therefore $\Delta t = \infty$

SPEED LIMIT
3×10^8 m/s

Division of a non-zero real number by zero is undefined so an object's speed must be less than the speed of light. This speed limit applies only to material objects.

ALBERT EINSTEIN (1879-1955)

Albert Einstein was born on March 14, 1879 in Germany. In 1905, Einstein published three papers. The first was his explanation of the photoelectric effect. The second was on mathematical interpretation of Brownian motion. The third set out special relativity, revising our conceptions of time, length and energy. In 1933, he accepted a post at the Institute for Advanced Studies at Princeton (USA), where he stayed until his death on April 18, 1955.



APPLICATION OF TIME DILATION AND LENGTH CONTRACTION FOR SPACE TRAVEL

The special theory of relativity suggest that due to time dilation and length contraction effects our journey to distant places in universe will take less time. For example if a star is 8 light years away and we move to it in a spaceship with half the speed of light. From the point of view of spaceship-crew the length of the journey will be contracted.

SPACE TRAVEL

EXAMPLE 18.1

Alpha Centauri is nearest star to our sun. It is at 4.37 light years from earth, it means that it takes 4.37 years for light to reach from earth to Alpha Centauri. If a spaceship is sent to Alpha Centauri with a speed of v = 0.96 c. How much time would have passed for the passengers, when they reach it? Assume that the earth and Alpha Centauri are stationary with respect to one another.

GIVEN

time for light to travel 't' = 4.37 years, Speed 'v' = 0.96 c

REQUIRED

Proper time 't_p' = ?

SOLUTION

The dilated time for person on earth is $\Delta t = \frac{4.37\,years}{0.96} = 4.55\,years$

The passenger on ship measures the proper time as $\Delta t_p = \Delta t \times \sqrt{1-\frac{v^2}{c^2}}$

putting values $\Delta t_p = 4.55\,years \times \sqrt{1-\frac{(0.96c)^2}{c^2}} = 4.55\,years \times \sqrt{1-\frac{0.92c^2}{c^2}}$

therefore $\Delta t_p = 1.29\,years$ **Answer**

Thus, the passengers in spaceship will have aged only 1.29 years when they reach Alpha Centauri, and not the 4.55 years an observer on earth has calculated.

METER ROD

ASSIGNMENT 18.1

How fast must a meter stick be moving if its length is observed to shrink to one-half of a meter? (Answer: 2.60×10^8 m/s)

18.4 BLACK BODY RADIATION

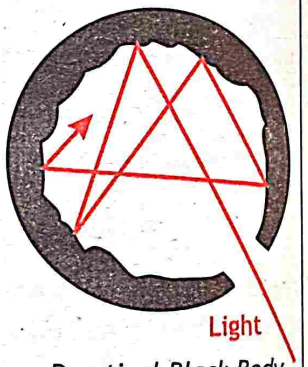
The electromagnetic radiation emitted by objects because of their temperature are called thermal radiation.

All bodies, no matter how hot or cold, continuously radiate electromagnetic waves. For example, we see the glow of very hot objects because they emit electromagnetic waves in the visible region of the spectrum. Our sun, which has a surface temperature of about 6000 K, appears yellow, while the cooler star Betelgeuse has a red-orange appearance due to its lower surface temperature of 2900 K. However, at relatively low temperatures, cooler objects emit visible light waves only weakly and, as a result, do not appear to be glowing. The human body, at only 310 K, does not emit enough visible light to be seen in the dark. However the human body does emit electromagnetic waves in the infrared region of the spectrum, and these can be detected with infrared-sensitive devices.

A perfect black-body at a constant temperature absorbs and re-emits all the electromagnetic radiation that falls on it.

A blackbody or perfect absorber is also an ideal radiator. In practice, a small opening in any heated cavity, behaves like a blackbody because such an opening traps all incident radiation. If the direction of the radiation is reversed in figure 18.6, the light emitted by a small opening is in thermal equilibrium with the walls, because it has been absorbed and re-emitted many times. The radiations emitted by black body are called **black body radiations.**

FIGURE 18.6



Practical Black Body

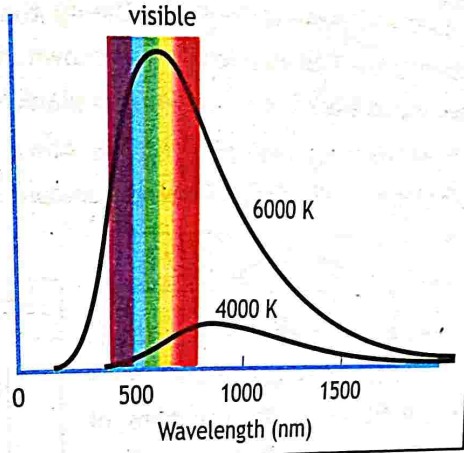
Science Tidbits **Glowing bolt**

The glowing bolt in this picture radiates primarily in the infrared part of the spectrum, but it is hot enough (a few thousand kelvin) so that a significant portion of its radiation falls within the red end of the visible region. The other bolts are too cool to radiate any detectable amount of visible light.



FIGURE 18.6

The nature of the radiation from the cavity hole of black body depends upon the cavity walls. Experimental data for the distribution of energy of the black body at two different temperatures is shown in the figure. The radiation emitted (the area under the curve) increases by increasing temperature.



A. WEIN'S DISPLACEMENT LAW

With the increase in the wavelength the peak of distribution shifts toward shorter wavelength as in figure 18.6. This shift is found to obey Wien's displacement Law. If 'λ_{max}' is the wavelength at which the curve peak and 'T' is absolute temperature then

$$\lambda_{max} \propto \frac{1}{T} \quad \text{or} \quad \lambda_{max} = \frac{\text{Constant}}{T} \quad \text{or} \quad \boxed{\lambda_{max} T = \text{Constant}} \quad (18.5)$$

Where constant = 0.2898×10^{-2} m K.

B. STEPHEN-BOLTSMANN LAW

The area under the curve represents the total energy radiated per second per square metre over all wavelengths at particular temperature. It is found that area is directly proportional to the fourth power of absolute temperature.

$$E \propto T^4 \quad \text{or} \quad \boxed{E = \sigma T^4} \quad (18.6)$$

Where the constant $\sigma = 5.67 \times 10^{-8}$ $Wm^{-2}K^{-4}$ is called Stephen constant. And the relation 18.6 is called as Stephen-Boltsmann Law.

Several attempts were made to completely explain the black body spectrum, but all of them failed due to one reason or another. For example Raleigh-Jean presented a theory that could predict long wavelengths but was unable to predict short wavelengths. Similarly Wein presented a theory that explained short wavelengths but failed at longer wavelengths.

NOT FOR SALE

18.5 QUANTUM THEORY OF RADIATION (PLANCK'S THEORY)

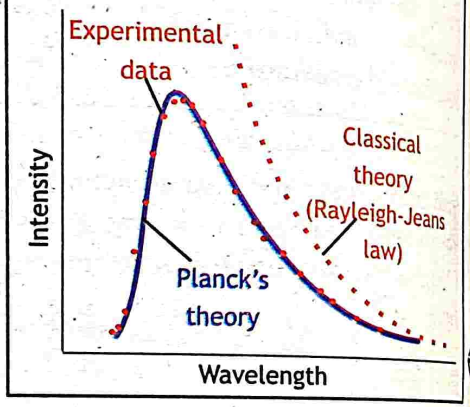
In 1900 Max plank presented a theory that was in complete agreement with experiments at all wavelengths, as shown in figure 18.7. In order to explain the spectrum of black-body radiation max plank made the two assumptions:

1. The vibrating molecules of the black body cavity which emitted these radiations were having only discrete amount of energy E_n, given by

$$E_n = nhf \qquad 18.7$$

Where n is the positive integer (n =1, 2, 3, ...) called quantum number. f is the frequency of oscillations of molecules and h = 6.626×10^{-34} J s is the plank's constant. It means that atoms or molecules cannot emit or absorb radiation in all possible ways, but an oscillating atom or molecule can absorb or emit energy only in discrete bundles. This discreat unit of energy is called quanta or photon.

FIGURE 18.7

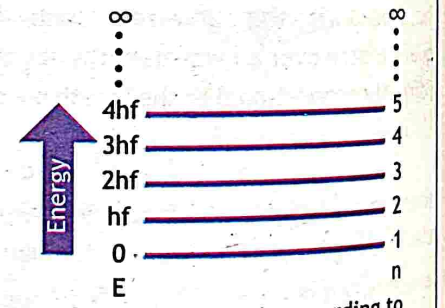


2. Atoms or molecules emit or absorb radiation when they jump from one quantum state to another. Hence the energy of one quantum (that is the difference between two adjecent energy levels) is

$$E = hf$$

Atoms or molecules will emit or absorb energy only when it changes states if it remain in one quantum state no energy is emitted or absorbed.

FIGURE 18.8



Allowed energy levels according to Planck's original hypothesis for an oscillator with frequency f.

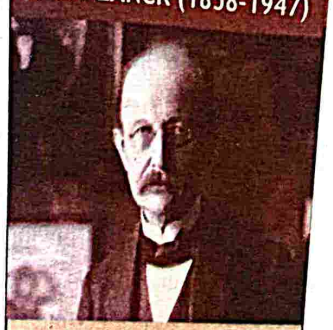
NOT FOR SALE

Thus the resonator can change its energy only by the difference ΔE, as

$$\Delta E = hf \qquad 18.8$$

That is, it cannot lose just any amount of its total energy, but only a finite amount, hf, called quantum of energy.

MAX PLANCK (1858-1947)



Max Planck (Germany). His work on the spectral distribution of radiation, which led to the quantum theory, was honored with the 1918 Nobel Prize.

HUMAN BODY RADIATION

EXAMPLE 18.2

The temperature of the human skin is approximately 35 °C. What is the wavelength at which the peak occurs in the radiation emitted from the skin?

GIVEN

Wien's constant = 0.2898×10^{-2} mK

Temperature T = 35 °C = 35 + 273 K = 308 K

REQUIRED

Wavelength λ = ?

SOLUTION

by Wien's displacement Law $\lambda_{max} T = \text{Constant}$ or $\lambda_{max} = \dfrac{\text{Constant}}{T}$

Putting values $\lambda_{max} = \dfrac{0.2898 \times 10^{-2}\ \text{mK}}{308\text{K}}$

therefore $\lambda = 9.409 \times 10^{-6}\ \text{m} = 9.4\mu m$ **Answer**

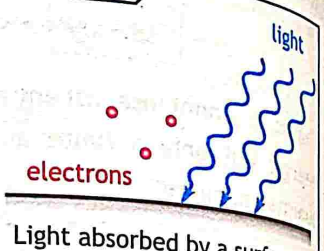
NOT FOR SALE

18.6 PHOTOELECTRIC EFFECT

When light hits the metal surface electrons are emitted, the phenomena is called photoelectric effect and the electrons emitted are called photo-electrons.

When a beam of light having short enough wavelength is directed on a metal surface, the light will eject the electrons from the surface of metal, as shown in figure 18.10.

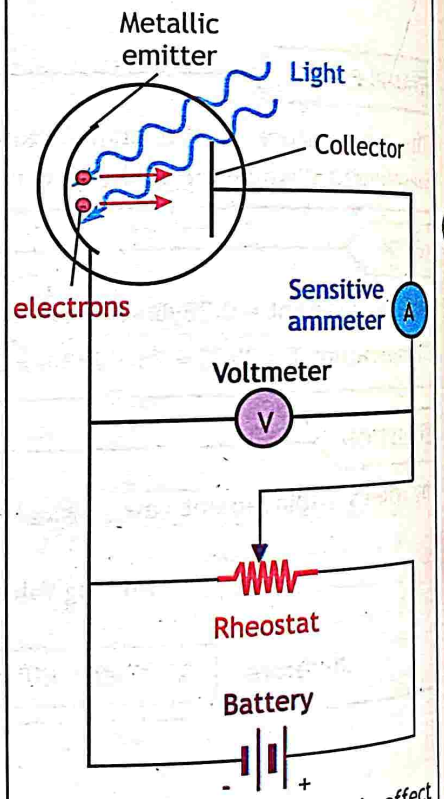
FIGURE 18.9



Light absorbed by a surface causes electrons to be ejected.

This phenomenon, was discovered by Heinrich Hertz in 1887, and Einstein explained it with photon concept of light in 1905. Let us analyze two basic photoelectric experiments, each using the apparatus shown in figure 18.10, in which light of frequency 'f' is directed onto metallic emitter and ejects electrons from it. A potential difference 'V' is maintained between metallic emitter and collector. This arrangement produces a photoelectric current 'I' that is measured with sensitive ammeter 'A'.

FIGURE 18.10



Apparatus for photo electric effect

First Photoelectric Experiment: We adjust the potential difference V by moving the sliding contact in figure 18.10 so that collector is slightly negative with respect to metallic emitter. This potential difference acts to slow down the ejected electrons. We then vary V until it reaches a certain value, called the stopping potential V_o, at which the reading of sensitive ammeter A has just dropped to zero.

NOT FOR SALE

When $V = V_o$, the most energetic ejected electrons are turned back just before reaching the collector. Then 'KE_{max}', the kinetic energy of these most energetic electrons, is

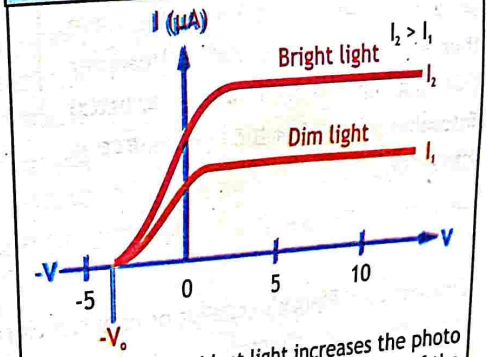
$$KE_{max} = eV_o \quad \text{18.9}$$

where 'e' is the elementary charge and V_o is the stopping potential.

Measurements show that for light of a given frequency, 'KE_{max}' does not depend on the intensity of the light.

The photoelectric current 'I' as a function of the potential difference 'V' for two different values of the intensity of the light is plotted in figure 18.11. When the intensity I is doubled, the current is doubled (twice as many photo-electrons are emitted), but the stopping potential V_o remains the same.

FIGURE 18.11



Brightness of incident light increases the photo current but the maximum Kinetic energy of the ejected photo-electrons remains the same.

This experimental result is a puzzle for classical physics. Classically, the incident light is a sinusoidally oscillating electromagnetic wave. If we increase the amplitude of the wave, the electron should get a more energy as it is being ejected. That is not what happens.

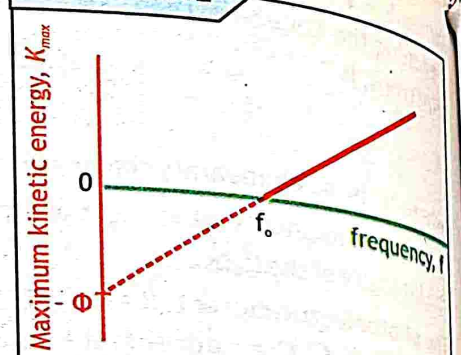
Second Photoelectric Experiment: Now we vary the frequency f of the incident light and measure the associated stopping potential V_o or maximum Kinetic energy KE_{max} of photoelectrons. Figure 18.12 is a plot of KE_{max} versus f. Note that the photoelectric effect does not occur if the frequency is below a certain threshold frequency f_o (or equivalently, if the wavelength is greater than the corresponding threshold wavelength $\lambda_o = c/f_o$).

NOT FOR SALE

This is another puzzle for classical physics. If we view light as an electromagnetic wave, we must expect that no matter how low the frequency may be, electrons can always be ejected by incident light if you supply them with enough energy—that is, if you use a light source that is bright enough. That is not what happens.

There is a third puzzle for classical physics in both experiments the wave theory predicts a time delay. However the first photoelectrons are emitted instantaneously after the light source is turned on.

FIGURE 18.12



Kinetic energy of the ejected photo-electron depends upon frequency, f

EINSTEIN EXPLANATION OF PHOTOELECTRIC EFFECT (PHOTON THEORY OF LIGHT)

Einstein used Planck's concept of quantization of energy. Einstein proposed that the energy of electromagnetic radiation is not continuously distributed over the wave front, but instead is concentrated in localized bundles or quanta (also known as photons). The energy of a photon associated with an electromagnetic wave of frequency '*f*' is

$$E = hf$$

Einstein's picture was that a light quantum was so localized that it gave all its energy '*hf*' directly to a single electron in the metal. Therefore, according to Einstein, the maximum kinetic energy for emitted electrons is

$$KE_{max} = hf - \varphi \qquad 18.10$$

where φ is the **work function** of the metal, which corresponds to the minimum energy with which an electron is bound in the metal. Table 18.1 lists values of work functions measured for different metals.

NOT FOR SALE

Equation 18.10 beautifully explain the puzzling independence of KE_{max} and intensity. For a fixed light frequency f, an increase in light intensity means more photons and more photoelectrons per second, although KE_{max} remains unchanged.

In addition, Equation 18.10 explain the phenomenon of threshold frequency f_o. Light of threshold frequency f_o, which has just enough energy to knock an electron out of the metal surface, causes the electron to be released with zero kinetic energy as shown in figure 18.13. Setting $KE_{max} = 0$ then $f = f_o$ and Equation 18.10 gives

$$0 = hf_o - \varphi \quad \text{or} \quad hf_o = \varphi$$

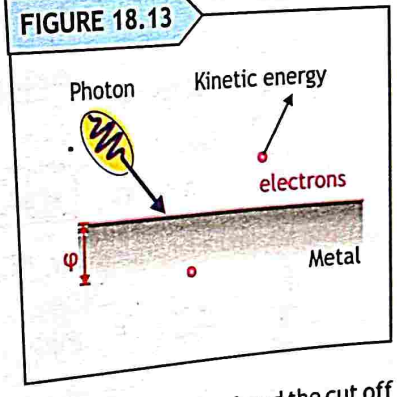
$$\text{hence} \quad f_o = \frac{\varphi}{h} \qquad (3)$$

Thus the energy quantization used by Planck in solving the blackbody radiation problem was, in fact, a universal characteristic of light.

Table: 18.1 Work Functions of Selected Metals

Metal	Work Function, Φ, (in eV)
Na	2.28
Al	4.08
Cu	4.70
Zn	4.31
Ag	4.73
Pt	6.35
Pb	4.14
Fe	4.50

FIGURE 18.13



The general wave equation $v = f\lambda$ in terms of threshold frequency f_o and the cut off wavelength λ_c can be written as

$$c = f_o\lambda_c \quad \text{or} \quad \lambda_c = \frac{c}{f_o} \qquad (4)$$

Putting equation 3 in equation 4, we get $\lambda_c = \frac{hc}{\varphi}$

NOT FOR SALE

EXAMPLE 18.3

TUNGSTEN METAL

The work function for tungsten metal is 4.52 eV. (a) What is the cutoff wavelength λ_c for tungsten? (b) What is the maximum kinetic energy of the electrons when radiation of wavelength 198 nm is used? (c) What is the stopping potential in this case?

GIVEN

Work Function 'φ' = 4.52 eV

$\varphi = 4.52\,eV \times 1.6 \times 10^{-19}\,C = 7.232 \times 10^{-19}\,J$

Wavelength 'λ'= 198 nm

REQUIRED

Cutoff wavelength λ_c = ?

Maximum kinetic energy 'KE_{max}' = ?

Stopping potential 'V_o' = ?

SOLUTION

(a) The cutoff wavelength λ_c is $\lambda_c = \dfrac{hc}{\varphi}$

Putting values $\lambda_c = \dfrac{6.626 \times 10^{-34}\,Js \times 2.998 \times 10^{8}\,ms^{-1}}{7.232 \times 10^{-19}\,J}$

therefore $\lambda_c = 275\,nm$ — Answer

(b) The Maximum kinetic energy 'KE_{max}' at shorter wavelength 'λ' is

$KE_{max} = hf - \varphi$ or $KE_{max} = \dfrac{hc}{\lambda} - \varphi$

Putting values $KE_{max} = \dfrac{6.626 \times 10^{-34}\,Js \times 2.998 \times 10^{8}\,ms^{-1}}{198 \times 10^{-9}\,m} - 7.232 \times 10^{-19}\,J$

therefore $KE_{max} = 2.79 \times 10^{-19}\,J$ — Answer

(c) The stopping potential 'V_o' $V_o = \dfrac{KE_{max}}{e}$

Putting values $V_o = \dfrac{2.79 \times 10^{-19}\,J}{1.6 \times 10^{-19}\,C}$

NOT FOR SALE

therefore $V_o = 1.74\,V$ — Answer

ASSIGNMENT 18.2

SODIUM METAL

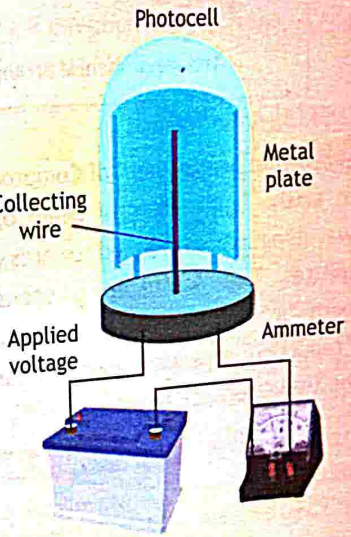
A sodium surface is illuminated with light of wavelength 300 nm. The work function for sodium is 2.46eV. Find (a) the K.E of the ejected electrons and (b) The cut-off wavelength for sodium.

(Answer: (a) 2.7×10^{-19} J (or 1.68 eV); (b) 5.05×10^{-7} m (or 505 nm)

Science Tidbits — Photocell

A device in which the photoelectric effect or photoconductivity is used to produce a current or voltage when exposed to light or other electromagnetic radiation.

A simple photocell is shown in the figure. It consist of evacuated glass tube with thin anode rod and cathode of appropriate surface. The material of cathode is selected whose work function suit the frequency of incident radiation on which the photocell is operated. When this surface is exposed to light electrons are emitted which are collected at cathode. As a result current flows in the external circuit. This current increases with intensity and stops when light beam is interrupted.



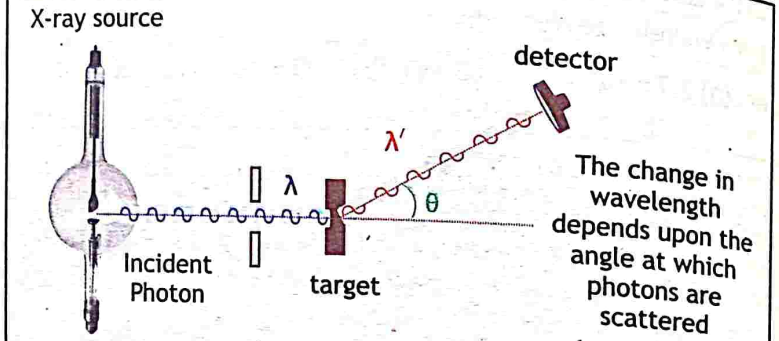
Burglar alarms and automatic doors often make use of the photocell circuit. When a person interrupts the beam of light, the sudden drop in current in the circuit activates a switch which operates a bell or opens the door. Photocells are used in many other devices, such as absorption spectrophotometers, to measure light intensity.

NOT FOR SALE

18.7 COMPTON EFFECT

The scattering of high frequency photon strikes a stationary electron the frequency of photon is decreased after collision. This phenomenon is referred to as Compton's effect.

FIGURE 18.14



The experimental arrangement of Compton effect

EXPERIMENTAL ARRANGEMENT

The experimental arrangement of Compton effect is shown in the figure 18.14. A beam of X-rays having wavelength 'λ' is directed towards a target of graphite. The scattered photons have wavelength 'λ'' slightly longer, the amount of energy reduction depended upon the angle at which the X-rays were scattered.

The change in wavelength $\Delta\lambda$, between the scattered X-ray photon of wavelength λ' and incident X-ray photon of wavelength λ is called **Compton Shift.**

The X-ray photon of frequency 'f' is incident on a stationary electron.

COMPTON (1892-1962)

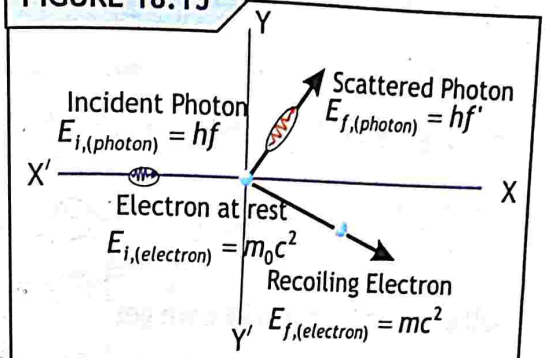


Arthur H. Compton (America). His work on X-ray scattering verified Einstein's photon theory and earned him the 1927 Nobel Prize.

NOT FOR SALE

The initial energy of photon by Plancks theory is 'hf' and initial rest energy for electron by Eienstein equation is 'm_oc^2'. After collision the energy of photon reduce to hf' and electron is recoiled with total energy 'mc^2' as shown in figure 18.15.

FIGURE 18.15



Conservation of energy in Compton Scattering

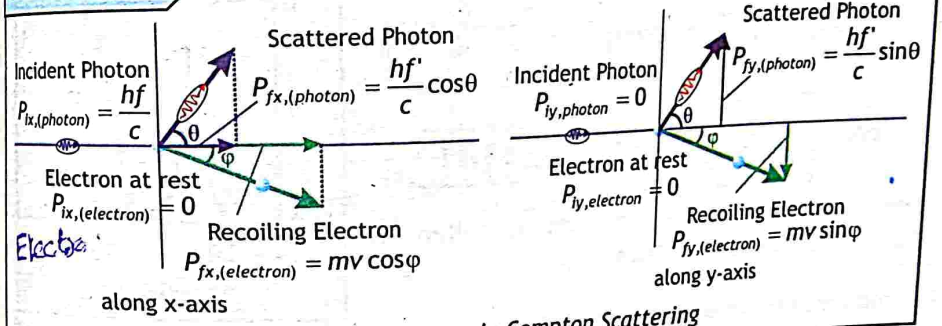
By law of conservation of energy

$$E_{i,(photon)} + E_{i,(electron)} = E_{f,(photon)} + E_{f,(electron)}$$

substituting values $hf + m_0c^2 = hf' + mc^2$ ——— (1)

The initial momentum of photon is 'hf/c' and since electron is considered at rest therefore it have zero momentum. After collision the momentum of photon is 'hf'/c' making an angle 'θ' with its original direction and electron is recoiled with momentum 'mv' making an angle φ, as shown in figure 18.16.

FIGURE 18.16



Conservation of momentum in Compton Scattering

By law of conservation of momentum

Along x-axis $P_{ix,(photon)} + P_{ix,(electron)} = P_{fx,(photon)} + P_{fx,(electron)}$

substituting values $\frac{hf}{c} + 0 = \frac{hf'}{c}\cos\theta + mv\cos\varphi$

or $\frac{hf}{c} = \frac{hf'}{c}\cos\theta + mv\cos\varphi$ ——— (2)

By law of conservation of momentum

$P_{iy,(electron)} = P_{fy,(photon)} + P_{fy,(electron)}$

substituting values $0 + 0 = \frac{hf'}{c}\sin\theta - mv\sin\varphi$

or $0 = \frac{hf'}{c}\sin\theta - mv\sin\varphi$ ——— (3)

Solving equation 1, equation 2 and equation 3, simultaneously we get

$$\frac{1}{f'} = \frac{1}{f} + \frac{h}{m_o c^2}(1-\cos\theta) \quad \text{——— (4)}$$

multiplying equation 4 by c we get

$$\frac{c}{f'} = \frac{c}{f} + \frac{h\not{c}}{m_o c^{\not{2}}}(1-\cos\theta)$$

or $\frac{c}{f'} = \frac{c}{f} + \frac{h}{m_o c}(1-\cos\theta)$

here $\frac{c}{f'} = \lambda'$ and $\frac{c}{f} = \lambda$

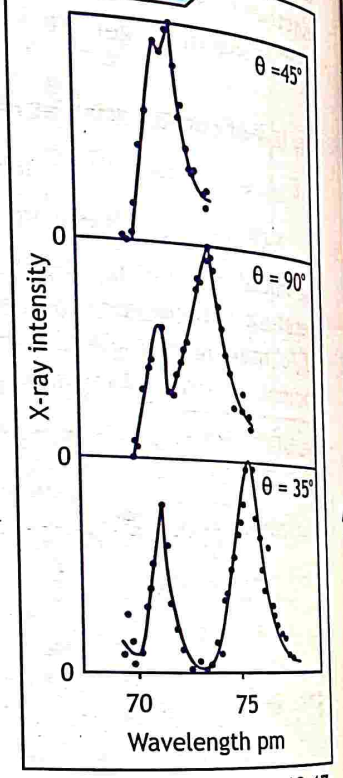
Therefore $\lambda' = \lambda + \frac{h}{m_o c}(1-\cos\theta)$

or $\lambda' - \lambda = \frac{h}{m_o c}(1-\cos\theta)$

hence $\Delta\lambda = \frac{h}{m_o c}(1-\cos\theta)$ **18.11**

The quantity $h/m_o c$ is constant is called as Compton wavelength 2.43×10^{-12} m.

FIGURE 18.17



Compton's results for scattering of X rays with λ = 71 pm is shown in figure 18.17. Right-hand peak shows the wavelength shift of the Compton effect. The un-shifted left-hand peak is from photons scattering off tightly bound atomic electrons, which don't absorb significant energy. Solid curves are theoretical predictions. These results shows that the Compton's theoretical approach agrees with the experimental observations hence the photon concept is a valid concept.

Today, Compton scattering with gamma rays is a widely used technique for studying the structure of matter.

EXAMPLE 18.4 — **CARBON SCATTERING**

X-ray of wavelength λ = 0.20 nm are scattered from a block of carbon. The scattered X-rays are observed at an angle of 45° to the incident beam. Calculate the wavelength of the scattered X-ray at this angle.

GIVEN

Angle θ = 45°

Plank's constant h = 6.626×10^{-34} Js

rest mass of electron m_o = 9.11×10^{-31} kg

speed of light c = 3×10^{8} ms^{-1}

wavelength λ = 0.20 nm = 0.20×10^{-9} m

REQUIRED

wavelength after scattering λ′ = ?

SOLUTION

By Compton's scattering formula we have $\lambda' = \lambda + \frac{h}{m_o c}(1-\cos\theta)$

Putting values $\lambda' = 0.20\times10^{-9}m + \frac{6.626\times10^{-34}\,Js}{9.11\times10^{-31}\,kg\times3\times10^{8}\,ms^{-1}}(1-\cos45^{\circ})$

or $\lambda' = 0.20\times10^{-9}m + 7.11\times10^{-13}m$

therefore $\lambda' = 2.00711\times10^{-8}m = 0.200711nm$ **Answer**

ASSIGNMENT 18.3 — **CARBON SCATTERING**

X-rays of wavelength 0.140 nm are scattered from a very thin slice of carbon. What will be the wavelengths of X-rays scattered at (a) 0°, (b) 90°, (c) 180°?

(Answer: (a) 0.140 nm. (b) 0.142 nm (c) 0.145 nm.)

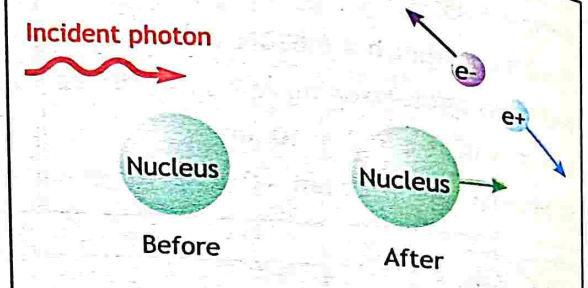
18.8 PAIR PRODUCTION

The creation of an elementary particle and its antiparticle, usually when a photon (or another neutral boson) interacts with a nucleus an electron and its antiparticle, the positron, may be created is called pair production.

$$\gamma \rightarrow e^+ + e^-$$

Pair production is the process in which a photon is converted into matter in accordance with Einstein equation $E = mc^2$. A photon when passes near a nucleus it disintegrates into electron and positron pair as shown in figure 18.18. Positron has the same mass as electron but opposite charge.

FIGURE 18.18



Pair Production in presence of nucleus

A photon cannot create an electron alone, because this would violate law of conservation of charge. Thus to conserve charge a positron is created.

In pair production for any energy of incident photon an additional massive object (such as atomic nucleus) is required to carry some of momentum. Therefore to conserve momentum the presence of nucleus is required.

In order to create an electron positron pair a minimal of $2m_oc^2$ is needed, the surplus energy is taken by electron and positron as their Kinetic energies.

$$hf = 2m_0c^2 + (KE)_{-e} + (KE)_{+e} \quad \text{18.12}$$

For minimum energy the electron and positron will not carry any additional energy as their kinetic energies. Thus $(KE)_{-e}$ and $(KE)_{+e}$ must be zero, therefore the minimum energy is

$$hf = 2m_0c^2$$

The rest mass of electron $m_o = 9.11 \times 10^{-31}$ kg and speed of light $c = 3 \times 10^8$ m/s

$$hf = 2(9.11\times10^{-31}kg)(3\times10^8 m/s)^2 = 16.38\times10^{-14} J$$

$$hf = \frac{16.38\times10^{-14} J}{1.6\times19^{-19} C} = 1.023\times10^6 eV = 1.02 MeV$$

Pair production requires at least 1.02 MeV energy photon. The photon in pair production will have a very short wavelength and very high frequency (as with X-ray and gamma-ray photons).

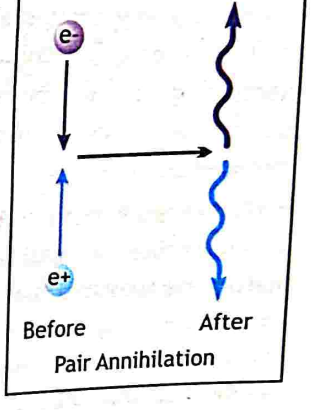
18.9 PAIR ANNIHILATION

When an electron (e–) and a positron (e+) collide two gamma ray photons are produced and the phenomenon is called pair annihilation.

$$e^+ + e^- \rightarrow \gamma + \gamma$$

When a positron and an electron combine together they annihilates as shown in figure 18.19. Both particles disappear, and two (or occasionally three) photons can appear, with total energy of at least. Decay into a single photon is impossible because such a process could not conserve both energy and momentum.

FIGURE 18.19



Pair Annihilation

$$2hf = 2m_oc^2 \quad \text{18.13}$$

So each photon produced must have energy

$$hf = m_oc^2$$

The rest mass of electron $m_o = 9.11\ 10^{-31}$ kg and speed of light $c = 3\ 10^8$ m/s

$$hf = (9.11\times10^{-31}kg)(3\times10^8 m/s)^2 = 8.19\times10^{-14} J$$

$$hf = \frac{8.19\times10^{-14} J}{1.6\times10^{-19} C} = 0.51\times10^6 eV = 0.51 MeV$$

As with any two charged objects, electrons and positrons may also interact with each other without annihilating, in general by elastic scattering.

The electron-positron annihilation process is the physical phenomenon relied on as the basis of positron emission tomography (PET) and positron annihilation spectroscopy (PAS). It is also used as a method of measuring the Fermi surface and band structure in metals.

18.10 WAVE NATURE OF PARTICLES

Wave-particle duality is a theory that proposes that all matter exhibits the properties of not only particles, but also waves, which transfer energy.

Light and other electromagnetic radiation act sometimes like waves and sometimes like particles. Interference and diffraction demonstrate wave behavior, whereas in this chapter we saw considerable evidence for the photon theory of light as well, where electromagnetic waves consisted of photons, particle-like pulses that have energy and momentum.



Louis de-Broglie *(France). A member of an aristocratic family, his work contributed substantially to the early development of the quantum theory.*

In 1924 a French physicist, Louis de-Broglie, made a remarkable proposal about the nature of matter. He reasoned that as light is dualistic in nature, behaving in some situations like waves and in others like particles. If nature is symmetric, this duality should also hold for matter. Electrons and protons, which we usually think of as particles, may in some situations behave like waves.

If a particle acts like a wave, it should have a wavelength and a frequency. De-Broglie postulated that a free particle with rest mass 'm', moving with non-relativistic speed 'v' should have a wavelength 'λ' related to its momentum 'p= mv' in exactly the same way as for a photon.

The energy of photon having frequency f by plancks theory is

$$E = hf \quad \text{——(1)}$$

According to Einstein mass energy relation $E = mc^2$ ——(2)

comparing equation 1 and equation 2 we get $hf = mc^2$ ——(3)

Dividing equation 3 by c we get $\frac{hf}{c} = \frac{mc^2}{c}$ or $\frac{hf}{c} = mc$

Since momentum 'P = mv' for photon can be written for speed of light 'c' as 'P = mc' therefore

$$\frac{hf}{c} = P \qquad 18.14$$

Equation 18.14 gives momentum of photon in terms of frequency, by general wave equation for light we also know that 'c = fλ', therefore equation 18.14 can be written as

$\frac{hf}{f\lambda} = P$ or $\frac{h}{\lambda} = P$ hence $\lambda = \frac{h}{P}$ 18.15

Equation 18.15 gives momentum of photon in terms of wavelength.

De-Broglie argued that we can also assign wavelength to a particle of mass 'm' moving with velocity 'v' in the same way by putting 'p = mv'

$$\lambda = \frac{h}{mv} \quad \text{——(4)}$$

If the particle's speed is an appreciable fraction of the speed of light 'c', we can replace 'mv' in Equation 4 with

$$mv = \frac{m_o v}{\sqrt{1-\frac{v^2}{c^2}}} \qquad 18.16$$

Thus in de-Broglie's hypothesis, the relationships of wavelength to momentum and of frequency to energy are exactly the same for free particles as for photons.

DAVISSON AND GERMER EXPERIMENT

The Davisson-Germer experiment demonstrated the wave nature of the electron, confirming de-Broglie hypothesis.

An electron diffraction experiment gave the first experimental confirmation of the wave nature of particles (and the quantitative confirmation of the de-Broglie relationship λ = h/p).

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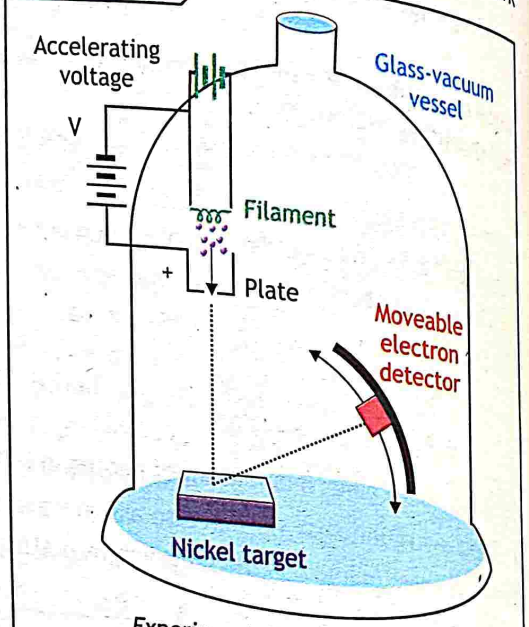
This experimental proof was provided by American physicists Clinton J. Davisson (1881-1958) and Lester H. Germer (1896-1971) at the Bell Laboratories in New York in 1927.

They designed a vacuum apparatus for measuring the energies of electrons scattered. The electron beam was accelerated towards nickel target, which could be rotated to observe angular dependence of the scattered electrons as shown in the figure 18.20. At certain angles there was a peak in the intensity of the scattered electron beam. This peak indicated wave behavior for the electrons, and could be interpreted by the Bragg law to give values for the lattice spacing in the nickel crystal.

The results obtained from the experiment were explained by treating electrons as waves of wavelength given by de Broglie's equation.

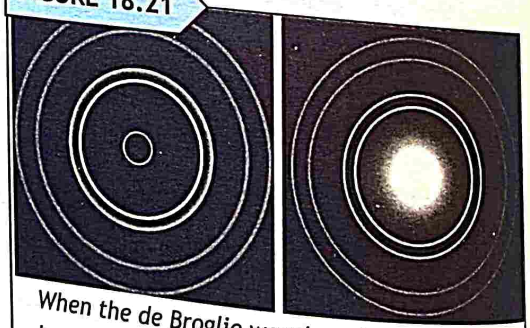
The diffraction pattern of electrons from the nickel crystal was found similar to that of X-ray diffraction as shown in figure 18.21.

FIGURE 18.20



Experimental arrangement by Davisson and Germer

FIGURE 18.21



When the de Broglie wavelength of an electron beam equals the wavelength of the X-rays. The diffraction patterns of thin beam of X-rays and electrons passing through a thin foil are similar as shown in simulation.

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A similar demonstration of the wave nature of relativistic electrons was provided in the same year by G. P. Thomson, who observed the transmission of electrons with energies in the range of 10 to 40 keV through thin metallic foils (G. P. Thomson, the son of J. J. Thomson, shared the Nobel Prize in Physics in 1937 with Davisson).

The wave properties of particles like protons, neutrons, other atoms and even molecules has also been observed. In all cases the measured wavelengths agree with de Broglie's prediction, proving that all matter has wavelike as well as particle like properties.

EXAMPLE 18.5 — **ELECTRON WAVELENGTH**

Determine the wavelength of electron that has been accelerated through a potential difference of (a) 50 V (b) 200 V.

GIVEN

Potential Difference $\Delta V_1 = 50$ V

Potential Difference $\Delta V_2 = 200$ V

rest mass of electron $m_e = 9.11 \times 10^{-31}$ kg

Charge on electron $q_e = 1.602 \times 10^{-19}$ C

Plank's constant $h = 6.626 \times 10^{-34}$ Js

REQUIRED

wavelength $\lambda_1 = ?$

wavelength $\lambda_2 = ?$

SOLUTION

The de-Broglie wave length λ is $\lambda = \frac{h}{m_e v}$ ——(1)

the speed of electron can be determined by its kinetic energy gained through the potential difference.

$$\frac{1}{2} m_e v^2 = q_e \Delta V \quad \text{or} \quad v^2 = \frac{2 q_e \Delta V}{m_e}$$

Taking square root on both sides $v = \sqrt{\frac{2 q_e \Delta V}{m_e}}$ ——(2)

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Putting equation 2 in equation 1 we get $\lambda = \dfrac{h}{m_e\sqrt{\dfrac{2q_e\,\Delta V}{m_e}}}$

rearranging $\lambda = \dfrac{h}{\sqrt{2m_e q_e\,\Delta V}}$

(a) $\lambda_1 = \dfrac{h}{\sqrt{2m_e q_e\,\Delta V_1}}$ Putting values $\lambda_1 = \dfrac{h}{\sqrt{2m_e q_e\,\Delta V_1}}$

Putting values $\lambda_1 = \dfrac{6.626\times10^{-34}\,Js}{\sqrt{2\times9.11\times10^{-31}kg\times1.602\times10^{-19}C\times50V}}$

therefore $\lambda_1 = 0.173\times10^{-9}m = 0.173\,nm$ Answer

(b) $\lambda_2 = \dfrac{h}{\sqrt{2m_e q_e\,\Delta V_2}}$ Putting values $\lambda_2 = \dfrac{h}{\sqrt{2m_e q_e\,\Delta V_2}}$

Putting values $\lambda_2 = \dfrac{6.626\times10^{-34}\,Js}{\sqrt{2\times9.11\times10^{-31}kg\times1.602\times10^{-19}C\times200V}}$

therefore $\lambda_2 = 0.087\times10^{-9}m = 0.087\,nm$ Answer

ASSIGNMENT 18.4 — **COMPARING DE BROGLIE WAVELENGTH**

Compute the de Broglie wavelength of the following: (a) A cricket ball of mass 160 g, traveling at 45 m/s (b) A smoke particle of mass 10^{-9} g moving at 1 cm/s. (c) An electron moving with a typical speed of 10^6 m/s.

[Answer: (a) 9.2×10^{-25} m, (b) 6.6×10^{-20} m, and (c) 7.3×10^{-10} m]

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18.11 ELECTRON MICROSCOPE

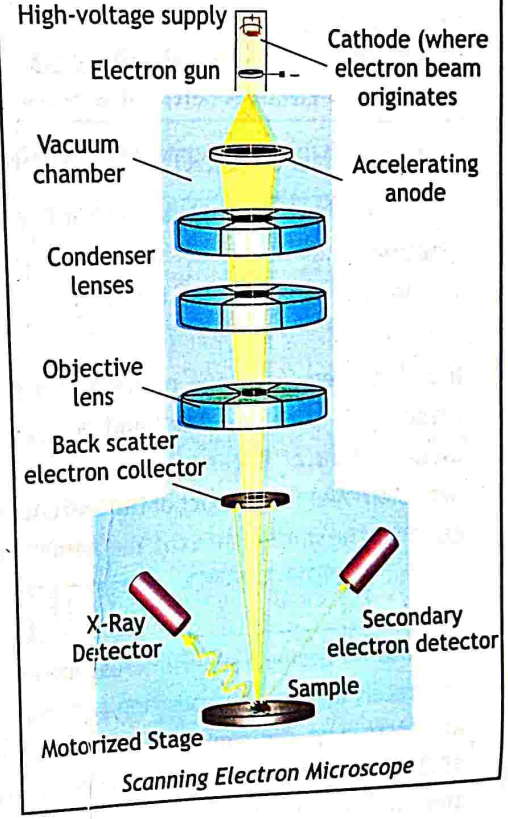
An electron microscope (EM) is a type of microscope that uses an electron beam with its wave like properties to illuminate a specimen and produce a magnified image. Electron Microscope is based on the wave characteristics of electrons.

The resolving power of EM is greater than optical microscope because electrons have wavelengths about 100,000 times shorter than visible light photons. They can achieve better than 50 pm resolution and magnifications of up to about 10,000,000x (whereas ordinary, light microscopes are limited by diffraction to about 200 nm resolution and useful magnifications below 2000x).

The scanning electron microscope is shown in the figure 18.22, it produces images with a three-dimensional quality. The electron beam produced by an electron gun, is accelerated by an anode. The condenser lenses (electromagnetic coils) controls and defines the size of the electron beam (which set the resolution). The objective lens focus the beam onto the sample.

Two types of electrons used for imaging are Back Scattered Electrons (BSE) and Secondary Electrons (SE), which are collected by corresponding detectors. The X-rays generated from the electron-matter interaction is also collected through a detector. Computer is used to compile data from all the detectors and a magnified image of the object is obtained, as shown in figure 18.23.

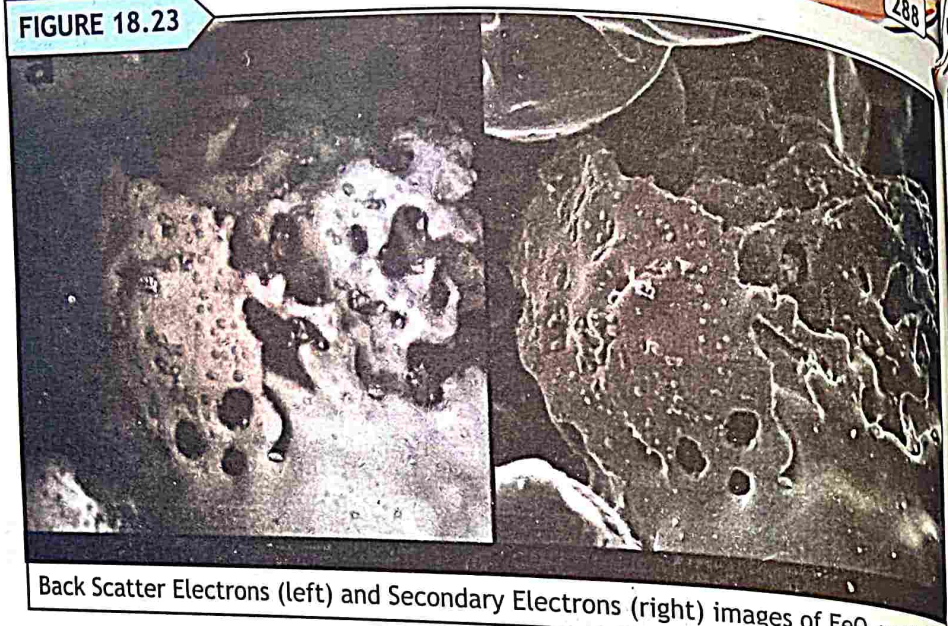
FIGURE 18.22



Scanning Electron Microscope

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FIGURE 18.23



Back Scatter Electrons (left) and Secondary Electrons (right) images of FeO_2 particles.

18.12 THE UNCERTAINTY PRINCIPLE

This principle states that **'the more precisely the position is determined, the less precisely the momentum is known in this instant, and vice versa'.**

If a measurement of the position of a particle is made with precision 'Δx' and a simultaneous measurement of linear momentum is made with precision 'ΔP_x' the product of the two uncertainties can never be smaller than 'h', mathematically

$$\Delta x \bullet \Delta P_x \approx h \qquad 18.17$$

Suppose we design a super microscope and want to accurately measure the position and momentum of an electron at the same time as shown in figure 18.24. As objects can be seen to a precision of about the wavelength of the radiation used due for diffraction.

Heisenberg (1901-1976)

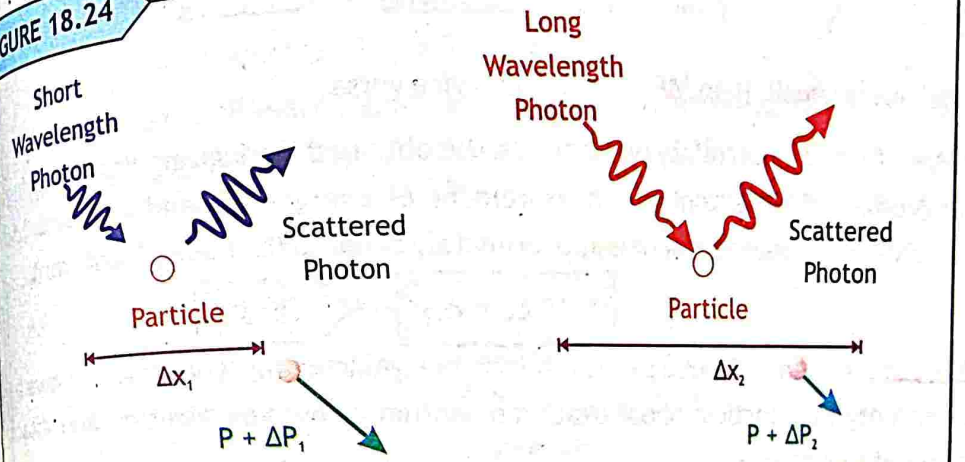


Werner Heisenberg (Germany). Best known for the uncertainty principle, he also developed a complete formulation of the quantum theory based on matrices.

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for us to see the electron and determine its location, at least one photon of light must strike the electron, however, the photon transfers some unknown amount of its momentum to the electron.

FIGURE 18.24



If 'Δx' is very small, then 'ΔP_x' is large, and vice-versa.

The incoming photon has momentum h/λ, in collision, the photon can transfer part (or all) of its momentum to the electron (along the x-axis). Therefore, the uncertainty in the electron's momentum after the collision is as great as the momentum of the incoming photon, mathematically

$$\Delta P_x \approx \frac{h}{\lambda} \qquad (1)$$

Further, because the photon also has wave properties, we expect to be able to determine the electron's position to within one wavelength of the light being used to view it, so

$$\Delta x \approx \lambda \qquad (2)$$

multiplying equation 1 and equation 2 we get $\Delta x \bullet \Delta P_x \approx \lambda \times \frac{h}{\lambda}$

and $\Delta x \bullet \Delta P_x \approx h$

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The value 'h' represents the minimum in the product of the uncertainties. Because the uncertainty can always be greater than this minimum, we have

$$\Delta x \bullet \Delta P_x \geq h \qquad 18.18$$

If 'Δx' is very small, then 'ΔP_x' is large, and vice versa.

Another form of uncertainty principle can be obtained through similar reasoning. The product of uncertainty in measurement of energy 'ΔE' and the time 'Δt' available for the measurement is approximately equal to the Planck's constant.

$$\Delta E\ \Delta t \approx h. \qquad 18.19$$

Thus our knowledge about a particle is inherently uncertain. There will always be uncertainty in a particle about exact momentum at a given position and exact energy at a given time.

EXAMPLE 18.6 — **UNCERTAINTY IN POSITION**

An electron moves in a straight line with a constant speed 6.61×10^6 m/s which has been measured to a precision of 0.10 %. What is the maximum precision with which its position could be simultaneously measured?

GIVEN

speed 'v' = 6.61×10^6 m/s

mass of electron 'm' = 9.11×10^{-31} kg

precision percentage '$\%\Delta v$' = 0.10 %

Plank's constant $h = 6.626 \times 10^{-34}$ Js

REQUIRED

position precision 'Δx' = ?

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SOLUTION

The momentum 'P' of the electron is $P = mv$

Putting values $P = 9.11 \times 10^{-31}\ \text{kg} \times 6.61 \times 10^6\ m/s$

therefore $P = 6.02 \times 10^{-24}\ \text{kg}\ m/s$

The momentum is '$P = mv$', and the uncertainty in momentum '$\%\Delta P$' is also = 10% which is $\Delta P = 0.0010 \times P$.

$\Delta P = 0.0010 \times 6.02 \times 10^{-24}\ \text{kg}\ m/s$ or $\Delta P = 6.02 \times 10^{-27}\ \text{kg}\ m/s$

From the uncertainty principle, the best simultaneous position measurement will have an uncertainty of

$$\Delta x \bullet \Delta P \approx h$$

or $\Delta x \approx \dfrac{h}{\Delta P}$ Putting values $\Delta x \approx \dfrac{6.626 \times 10^{-34}\ Js}{6.02 \times 10^{-27}\ \text{kg}\ m/s}$

therefore $\Delta x \approx 1.10 \times 10^{-7}\ m$ — **Answer**

This is about 1000 times the diameter of an atom.

ASSIGNMENT 18.5 — **UNCERTAINTY IN ENERGY**

The life time of electron in the excited state is about 10^{-8} s. What is the uncertainty in energy during this time? (Answer: 6.626×10^{-26} m)

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KEY POINTS

Inertial reference frame: a reference frame moving with constant velocity.

Non-inertial reference frame: a frame of reference that is accelerating.

Relativity: the study of how different observers measure the same event

Postulates os Special theory of relativity: the two postulates are

- The laws of physics are the same in all inertial frames.
- The speed of light in free space has the same value for all observers, regardless of their state of motion

Black body: an ideal radiator, which can radiate equally well at all wavelengths

Quantized: the fact that certain physical entities exist only with particular discrete values and not every conceivable value

Plank's Constant: $h = 6.626 \times 10^{-34}$ Js

Photon: a quantum, or particle, of electromagnetic radiation

Photo electric effect: the phenomenon whereby some materials eject electrons when light is shined on them

Compton effect: the phenomenon whereby x rays scattered from materials have decreased energy

Pair Production: the change of very high energy photon into electron -positron pair.

Annihilation of matter: when a positron comes close to an electron, they annihilate and produce two photons

de Broglie wavelength: the wavelength possessed by a particle of matter

Wave -particle duality: both radiation and matter exhibit particle as well as wave like properties

Heisenberg uncertainty principle: fundamental limit to the precision with which pairs of quantities (momentum and position, and energy and time) can be measured

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Exercise

MULTIPLE CHOICE QUESTIONS

Choose the best possible answer

1. Triplets A and B board spaceships and head away from Earth in opposite directions, each traveling the same distance at the same speed before returning to Earth. Triplet C remains on Earth. Which expression describes the triplets' relative ages once they're reunited on Earth?

   A. A < B < C B. A = B > C C. A = B < C D. A = B = C

2. If a spaceship travels from Earth to a planet in the Alpha Centauri star system, which observer measures the proper time for the trip?

   A. an observer on Earth

   B. an observer on the planet in the Alpha Centauri star system

   C. an observer on the spaceship

   D. an observer deep in space far from the planet and Earth

3. When you compress a spring between your fingers, its mass

   A. increase B. decrease C. stay the same D. turns negative

4. By doubling the absolute temperature of black-body, the total energy radiated will change by a factor of

   A. 0.5 B. 2 C. 4 D. 16

5. According to Einstein, increasing the brightness of a beam of light without changing its color will increase:

   A. the number of photons. B. the energy of each photon.

   C. the speed of the photons. D. the frequency of the photons.

6. Sources of red, blue, and yellow light each emit light with a power of 50 mW. The source which emit more photons is

   A. red B. blue C. yellow

7. D. They all emit the same number per second.

7. Of the following energies for photons, which is the least energy that could result in photoelectron production if the work function is 3.00 eV?

   A. 1.50 eV B. 2.90 eV C. 3.50 eV D. 6.01 eV

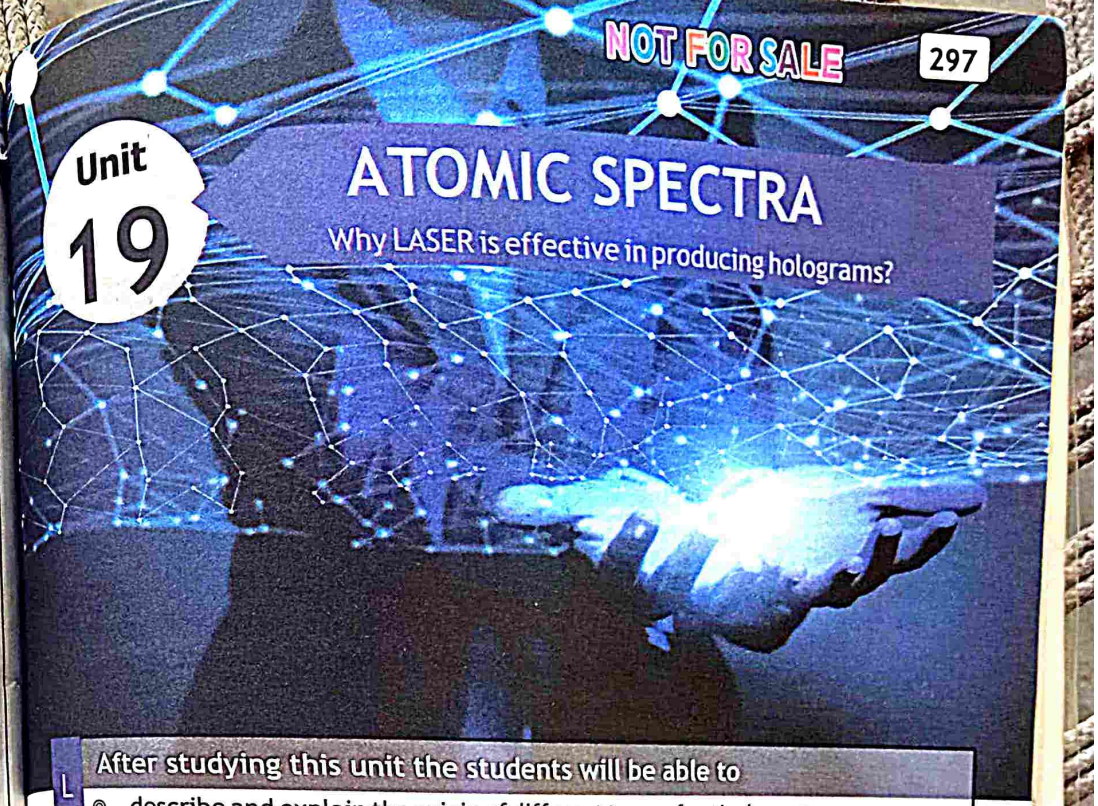
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MULTIPLE CHOICE QUESTIONS

8. In a Compton scattering experiment at which angle the electron carry maximum energy? (Assume that initially the target electron is at rest).
   A. 0° B. 90° C. 135° D. 180°
9. If X-rays are scattered from protons instead of electrons, the change in its wavelength for a given angle of scattering
   A. increases B. decreases C. is unchanged D. is one radian
10. Pair production cannot take place in vacuum because.
   A. Mass is not conserved B. Momentum is not conserved
   C. Energy is not conserved D. Charge is not conserved
11. According to de-broglie equation which one has the smallest wavelength associated with it
   A. proton B. neutron C. α - particle D. electron
12. An electron and a proton have the same de-broglie wavelength. Then the kinetic energy of the electron is
   A. Zero B. infinity
   C. equal to the kinetic energy of the proton
   D. greater than the kinetic energy of the proton
13. In Electron microscope, light source is replaced by a beam of very fast moving
   A. electron B. neutron C. proton D. photon
14. According to Heisenberg, as the uncertainty in the measurement of a particle's momentum is reduced by a factor of 2, by what factor is the uncertainty in that same particle's position changed?
   A. 1/2 B. 1 C. 2 D. 4

life is very important of the world

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Unit 19

ATOMIC SPECTRA

Why LASER is effective in producing holograms?

LEARNING OUTCOMES

After studying this unit the students will be able to

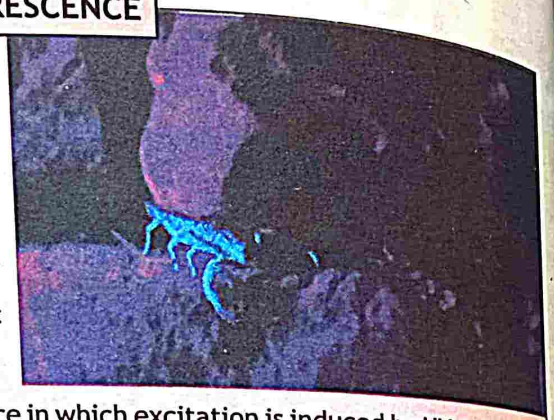
- describe and explain the origin of different types of optical spectra.
- show an understanding of the existence of discrete electron energy levels in isolated atoms (e.g. atomic hydrogen) and deduce how this leads to spectral lines.
- explain how the uniqueness of the spectra of elements can be used to identify an element.
- analyse the significance of the hydrogen spectrum in the development of Bohr's model of the atom.
- explain hydrogen atom in terms of energy levels on the basis of Bohr Model.
- determine the ionization energy and various excitation energies of an atom using an energy level diagram.
- Solve problems and analyse information using $1/\lambda = R_H [1/p^2 - 1/n^2]$.
- understand that inner shell transitions in heavy elements result into emission of characteristic X-rays.
- explain the terms spontaneous emission, stimulated emission, meta stable states, population inversion and laser action.
- describe the structure and purpose of the main components of a He-Ne gas laser.

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When an atomic gas or vapours kept at less than atmospheric pressure is suitably excited, the emitted radiation has a spectrum which contains certain specific wavelengths only.

For your information **FLUORESCENCE**

Objects glow in the visible spectrum when illuminated by an ultraviolet light. Emissions are characteristic of the mineral involved, since they are related to its energy levels. In the case of scorpions, proteins near the surface of their skin give off the characteristic blue glow.



This is a colorful example of fluorescence in which excitation is induced by UV radiation while de-excitation occurs in the form of visible light.

19.1 ATOMIC SPECTRA

The spectrum of frequencies of electromagnetic radiation emitted or absorbed during transitions of electrons between energy levels within an atom is called atomic spectra. Each element has a characteristic spectrum by which it can be recognized.

All the matter when heated produces light. Solids, liquids, and very dense gases give light with a spectrum showing continuous (not discrete) changes in intensity referred as a continuous spectrum.

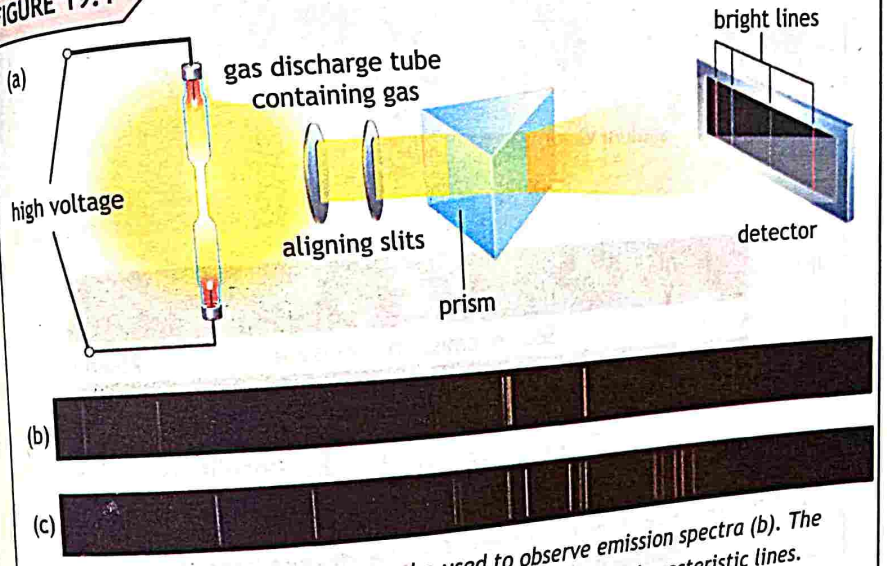
A. LINE EMISSION SPECTRUM

The radiations from electrically 'excited' gases are discrete rather than continuous (an excited gas gives off only specific frequencies of light). When this light is passed through a spectroscope, a bright-line emission spectrum is observed, containing lines of light of the various frequencies given off by that gas.

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Consider an evacuated glass tube filled with a gas (such as helium, neon, mercury or barium) as shown in figure 19.1. If the potential difference is applied to the electrodes, the tube will emit light. If emitted light is passed through aligning slits and then through a spectroscope (such as prism) a series of discrete line is observed, each line corresponds to different wavelength, termed as line emission spectrum. Since each element has its unique set of lines, therefore spectrum can be used to identify a substance.

FIGURE 19.1



(a). A prism spectroscope can be used to observe emission spectra (b). The emission spectra of mercury and (c). barium show characteristic lines.

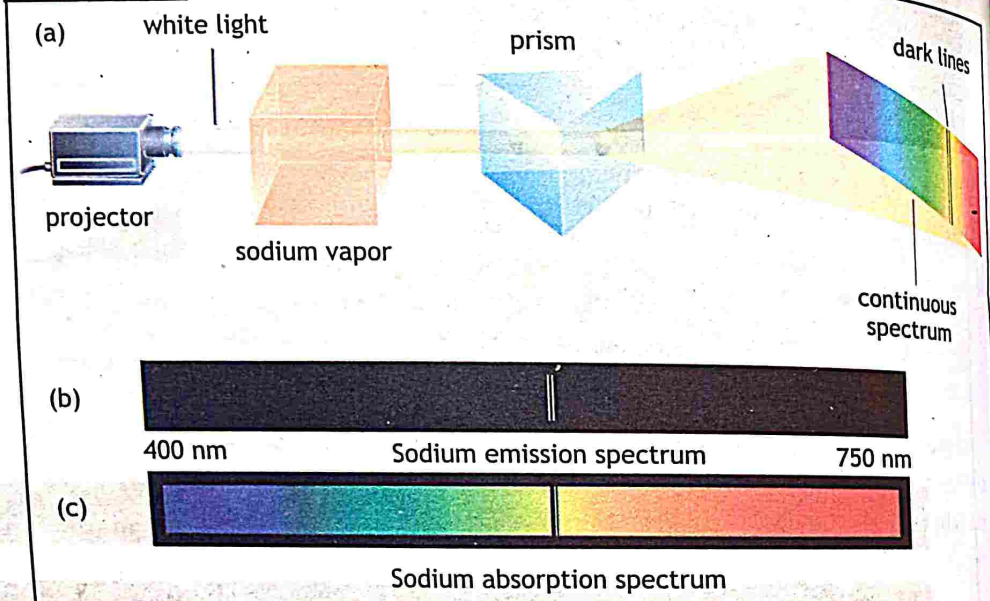
B. LINE ABSORPTION SPECTRUM

If a beam of white light passes through a sample of the substance. Photons absorbed by the atoms are missing from the transmitted light, causing dark lines (gaps) to appear in the continuous spectrum called line absorption spectrum.

NOT FOR SALE

When white light is incident on sodium vapor some part of light will be absorbed in the sodium and the rest will be transmitted as shown in figure 19.2. If transmitted light is passed through a spectroscope (such as prism) a continuous spectrum is observed, with dark lines (gaps) at different wavelength, termed as line absorption spectrum.

FIGURE 19.2



(a). This apparatus is used to produce the absorption spectrum of sodium. (b). The emission spectrum of sodium consists of several distinct lines. (c). whereas the absorption spectrum of sodium is nearly continuous.

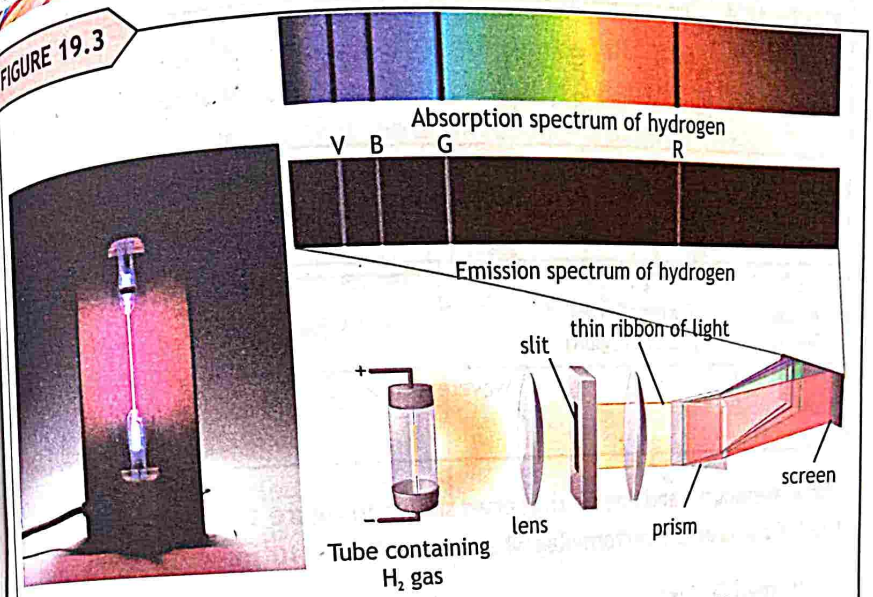
19.2 SPECTRUM OF HYDROGEN ATOM

The simplest line spectrum is that of atomic hydrogen, and much effort has been devoted to understanding the pattern of wavelengths that it contains.

When hydrogen gas is placed in a discharge tube, and high voltage is applied across the tube, the gas becomes luminous and give off bluish red light as shown in figure 19.3.

NOT FOR SALE

FIGURE 19.3



The emission spectrum of hydrogen in the visible range has four lines.

BALMER SERIES

The line spectrum of hydrogen in the visible region is shown in the figure 19.4. Balmer in 1885, showed that the wavelengths of these lines is predicted accurately by empirical formula:

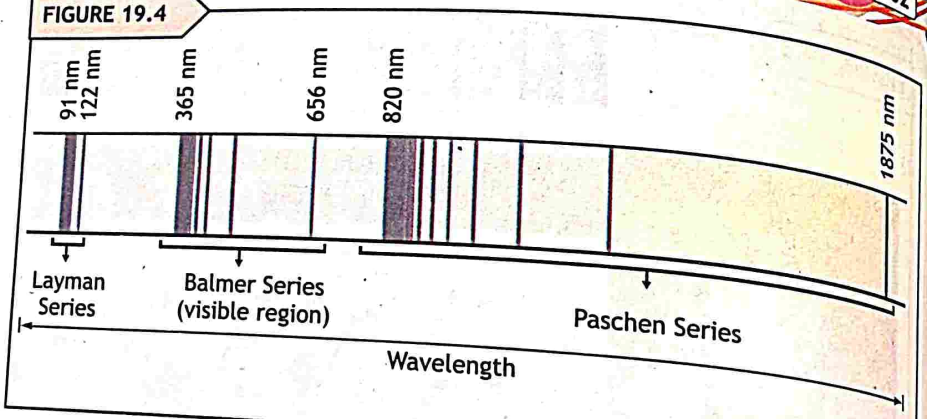
$$\frac{1}{\lambda_n} = R_H\left(\frac{1}{2^2} - \frac{1}{n^2}\right) \qquad 19.1$$

In equation 19.1 n = 3, 4, 5, ... and R_H is **Rydberg constant** ($R_H = 1.0974 \times 10^7\ m^{-1}$). The longest wavelength corresponds to n = 3, and its predicted wavelength is 656.2 nm. Similarly the wavelengths for the second and third lines are 486.1 nm and 434.1 nm, which matched with the experimental results.

Balmer's formulation predicted that series of other lines might also exist. Within few years spectra from other regions beyond visible were obtained, which is divided into different groups, each named after their discoverer.

NOT FOR SALE

FIGURE 19.4



The wavelengths and lines in the series shown in figure 19.4 can be calculated by the following empirical formulae where $R_H = 1.0974 \times 10^7$ m.

(Lyman Series)
Ultraviolet region $\frac{1}{\lambda_n} = R_H\left(\frac{1}{1^2} - \frac{1}{n^2}\right)$ Where n = 2, 3, 4, ...

(Balmer Series)
Visible region $\frac{1}{\lambda_n} = R_H\left(\frac{1}{2^2} - \frac{1}{n^2}\right)$ Where n = 3, 4, 5, ...

(Paschen Series)
Infrared region $\frac{1}{\lambda_n} = R_H\left(\frac{1}{3^2} - \frac{1}{n^2}\right)$ Where n = 4, 5, 6, ...

(Brackett Series)
Infrared region $\frac{1}{\lambda_n} = R_H\left(\frac{1}{4^2} - \frac{1}{n^2}\right)$ Where n = 5, 6, 7, ...

The general mathematical form is called the **Rydberg formula** and is given as

$$\frac{1}{\lambda_n} = R_H\left(\frac{1}{p^2} - \frac{1}{n^2}\right) \qquad 19.2$$

In equation 19.2 p = 1, 2, 3, 4, ... and n = p + 1, p + 2, p +3, ...

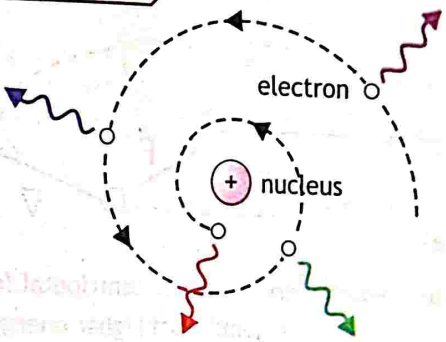
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19.3 BOHR MODEL OF HYDROGEN ATOM

Following Rutherford's proposal that the mass and positive charge are concentrated in a very small region at the center of the atom, the Danish physicist Niels Bohr in 1913 suggested that the atom resembled planetary system, with the electrons circulating about the nucleus like planets orbiting the Sun.

Classical physics requires that an accelerated electric charge, such as orbiting electron, must continuously radiate electromagnetic energy. As it radiates this energy, its total energy would decrease, the electron would spiral in toward the nucleus, and the atom would collapse as shown in figure 19.5. To overcome this difficulty, Bohr proposed that there are certain special states of motion, called *stationary states*, in which the electron may exist without radiating electromagnetic energy.

FIGURE 19.5



According to Maxwell's equations, the orbiting electron should continuously radiate energy and spiral into the nucleus.

In these states, the angular momentum 'L' of the electron takes values that are integral multiples of 'h'. In stationary states, the angular momentum of the electron may have magnitude only of h, 2h, 3h, . . ., but never such values as 2.5h or 3.1h. This is called the quantization of angular momentum.

Bohr Model is Based on the following Postulates

Postulate 1: The electron moves around the nucleus in a circular orbit. The centripetal force required to keep the electron in the circular orbit is provided by the coulomb force between the positively charged nucleus and negatively charged electron. Mathematically

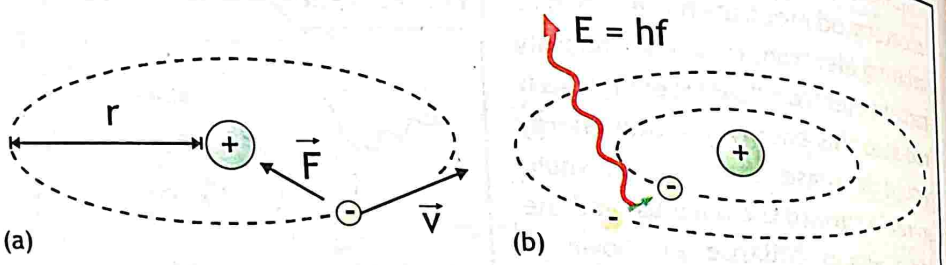
$$F_{centripetal} = F_{coulomb} \qquad \text{hence} \qquad \frac{mv^2}{r} = k\frac{e^2}{r^2} \quad \text{---(1)}$$

NOT FOR SALE

Postulate 2: An electron cannot revolve around the nucleus in any arbitrary circular orbit. Only those orbits are possible for which the angular momentum is the integral multiple of $h/2\pi$. Mathematically

$$L = n\frac{h}{2\pi} \quad \text{or} \quad mvr = n\frac{h}{2\pi} \qquad \text{---(2)}$$

FIGURE 19.6



(a) Coulomb force provides centripetal force and (b) atom radiate energy only when it jump from higher energy level to lower energy level.

Postulate 3: An electron in stable orbit does not radiate energy. Atom radiates energy only when it jumps from an allowed orbit of higher energy E_n to one of lower energy E_p. The difference in energy appears as photon of energy $E = hf$.

$$hf = E_n - E_P \qquad \text{---(3)}$$

A. RADII OF QUANTIZED ORBITS

Bohr's model of the hydrogen atom states that electrons can orbit the nucleus only at certain specific distances from the nucleus. These distances are multiples of the radius of the smallest permitted orbit. Thus, the orbits in an atom are quantized.

From Bohr's first postulate $\frac{mv^2}{r_n} = k\frac{e^2}{r_n^2}$ or $mv^2 = k\frac{e^2}{r_n}$ ---(4)

From Bohr's second postulate $mvr_n = n\frac{h}{2\pi}$ or $v = n\frac{h}{2\pi mr_n}$ ---(5)

putting equation 5 in equation 4 we get $m\left(n\frac{h}{2\pi mr_n}\right)^2 = k\frac{e^2}{r_n}$

NOT FOR SALE

or $m^2n^2\frac{h^2}{4\pi^2m^2r_n^2} = k\frac{e^2}{r_n}$

therefore $n^2\frac{h^2}{4\pi^2mr_n} = ke^2$

Isolating r_n we get

$$r_n = n^2\frac{h^2}{4\pi^2mke^2} \qquad 19.3$$

Here $h = 6.626 \times 10^{-34}$ J s, $\pi = 3.14$, $m = 9.109 \times 10^{-31}$ kg, $k = 8.988 \times 10^9$ Nm^2/C^2, and $e = 1.602 \times 10^{-19}$ C, are all constants collectively termed as r_o and can be calculated as

$$r_0 = \frac{h^2}{4\pi^2mke^2}$$

putting values

$$r_0 = \frac{(6.63\times10^{-34}\,Js)^2}{4(3.14)^2(9.11\times10^{-31}kg)(8.99\times10^9\,Nm^2/C^2)(1.67\times10^{-19}C)^2}$$

or $r_0 = 0.53\times10^{-10}m$

Expression for the radius of the nth circular allowed orbit in the hydrogen atom can be written as

$$r_n = n^2r_0 = n^2(0.53\times10^{-10}m) \qquad 19.4$$

The Bohr orbit with the smallest radius, is known as the Bohr radius, other radii can be calculated from this Bohr radius as

$$r_1 = (1)^2r_0 = 0.53\times10^{-10}m$$
$$r_2 = (2)^2r_0 = 2.12\times10^{-10}m$$
$$r_3 = (3)^2r_0 = 4.77\times10^{-10}m$$
$$\vdots \quad \vdots \quad \vdots$$

NIELS BOHR (1885-1962)



Niels Henrik David Bohr (Denmark) recieved 1922 Nobel prize in physics for the investigation of the structure of atoms and of the radiation emanating from them.

NOT FOR SALE

B. ENERGY OF ELECTRON IN QUANTIZED ORBITS

Both the kinetic energy and the electric potential energy of an electron in orbit around a nucleus depend on the electron's distance from the nucleus. So, the energy of an electron in an atom is also quantized. Each orbit corresponds to a particular energy level for the electron.

The total energy E_n for an electron in an orbit is sum of its kinetic energy (K.E) and potential energy (P.E)

$$E_n = K.E + P.E \quad \text{——— (6)}$$

Since kinetic energy can be written as $K.E = \frac{1}{2}mv^2$ ——— (7)

putting value of mv^2 from equation 4 in equation 7 we get

$$K.E = \frac{1}{2}k\frac{e^2}{r_n} \quad \text{——— (8)}$$

The electrostatic potential energy is $P.E = -k\frac{e^2}{r_n}$ ——— (9)

putting equation 8 and equation 9 in equation 6 we get

$$E_n = \frac{1}{2}k\frac{e^2}{r_n} - k\frac{e^2}{r_n} \quad \text{or} \quad E_n = -\frac{1}{2}k\frac{e^2}{r_n} \quad \text{——— (10)}$$

substituting the value of r_n from equation 19.3 in equation 10 we get

$$E_n = -\frac{1}{2}k\frac{e^2}{\left(n^2\frac{h^2}{4\pi^2 mke^2}\right)} \quad \text{or} \quad E_n = -\frac{1}{2}\times\frac{2\pi^2 mk^2e^4}{n^2h^2}$$

hence

$$E_n = -\frac{1}{n^2}\times\frac{2\pi^2 mk^2e^4}{h^2} \qquad \textbf{19.5}$$

Here $\pi = 3.14$, $m = 9.109 \times 10^{-31}$ kg, $k = 8.988 \times 10^9$ Nm^2/C^2, $e = 1.602 \times 10^{-19}$ C and $h = 6.626 \times 10^{-34}$ J s, are all constants and collectively termed as E_o can be calculated as

NOT FOR SALE

$$E_0 = \frac{2\pi^2 mk^2e^4}{h^2}$$

putting values $E_0 = \frac{2(3.14)^2(9.11\times10^{-31}kg)(8.99\times10^9 Nm^2/C^2)^2(1.67\times10^{-19}C)^4}{(6.63\times10^{-34}Js)^2}$

or $E_0 = 2.17\times10^{-18}J = 13.6eV$

Expression for the Energy of the nth allowed orbit in the hydrogen atom can be written as

$$E_n = -\frac{E_0}{n^2} = -\frac{2.17\times10^{-18}J}{n^2} = -\frac{13.6eV}{n^2} \qquad \textbf{19.6}$$

The negative in 19.6 sign shows that the electron is bound to the nucleus. The lowest possible energy level is called **ground state**: other allowed energy levels can be calculated from this ground state or stationary state as

$$E_1 = -\frac{E_0}{(1)^2} = -2.17\times10^{-18}J = -13.6eV$$

$$E_2 = -\frac{E_0}{(2)^2} = -0.54\times10^{-18}J = -3.4eV$$

$$E_3 = -\frac{E_0}{(3)^2} = -0.24\times10^{-18}J = -1.51eV$$

⋮ ⋮ ⋮ ⋮

C. HYDROGEN EMISSION SPECTRUM

According to Bohr's theory the emission line spectrum of an element tells us that atoms of that element emit photons with only certain specific frequencies '*f*' and hence certain specific energies '$E = hf$'. During the emission of a photon, the internal energy of the atom changes by an amount equal to the energy of the photon.

Each atom has a set of possible energy levels. An atom can have an amount of internal energy equal to any one of these levels, but it cannot have an energy intermediate between two levels. All isolated atoms of a given element have the same set of energy levels, but atoms of different elements have different sets.

Suppose an atom is raised, or excited, to a high energy level. (In a hot gas this happens when fast-moving atoms undergo inelastic collisions with each other or with the walls of the gas container.) According to Bohr, an excited atom can make a transition from one energy level to a lower level by emitting a photon with energy equal to the energy difference between the initial and final levels. If E_p is the initial energy of the atom before such a transition and E_n is its final energy after the transition the photon's energy is

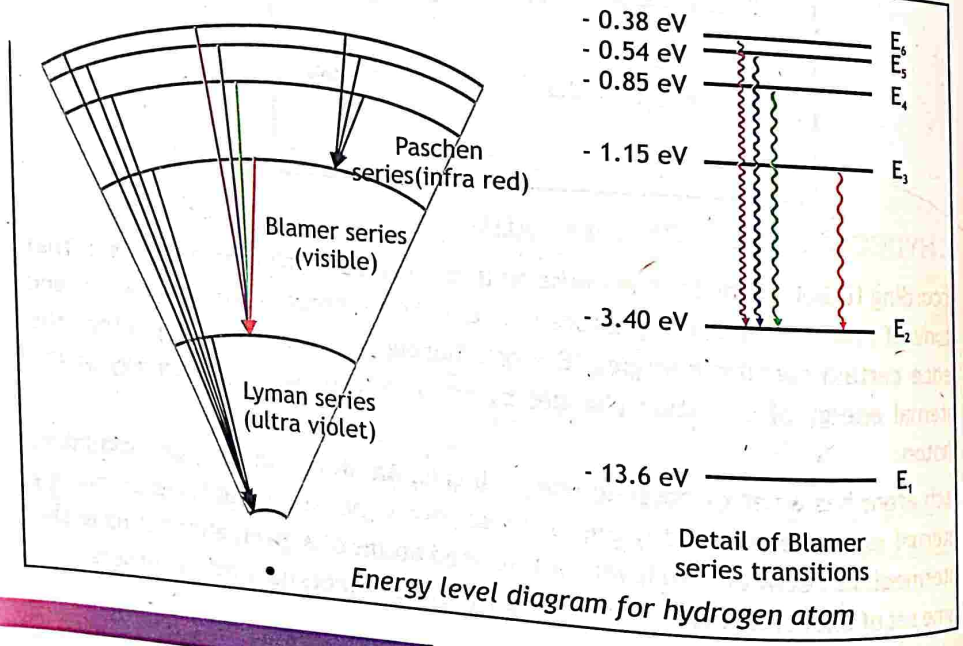
$$hf = E_n - E_P \qquad \text{—— (1)}$$

From energy of electron in quantized orbits $E_n = -\frac{E_0}{n^2}$ and $E_p = -\frac{E_0}{p^2}$

Equation 1 can be written as $hf = \left(-\frac{E_0}{n^2}\right) - \left(-\frac{E_0}{p^2}\right)$ since $f = \frac{c}{\lambda}$

therefore $\frac{hc}{\lambda} = \frac{E_0}{p^2} - \frac{E_0}{n^2}$ or $\frac{1}{\lambda} = \frac{E_0}{hc}\left(\frac{1}{p^2} - \frac{1}{n^2}\right)$

FIGURE 19.7



Energy level diagram for hydrogen atom

$$\frac{E_0}{hc} = \frac{(2.17\times10^{-18}\,J)}{6.63\times10^{-34}\,Js\times3\times10^{8}\,m/s} \quad \text{hence} \quad \frac{E_0}{hc} = 1.0974\times10^{7}\,m^{-1}$$

but $R_H = 1.0974\times10^{7}\,m^{-1}$ so $R_H = \frac{E_0}{hc}$

therefore $\boxed{\frac{1}{\lambda} = R_H\left(\frac{1}{p^2} - \frac{1}{n^2}\right)}$ 19.7

Since the value of R_H in Bohr theory is in agreement with the value determined empirical by Balmer. The equation resembles the general form of the spectral formula for the hydrogen atom. Therefore Bohr model can be used to compute energies or the wavelengths in Hydrogen spectra.

D. EXCITATION AND IONIZATION POTENTIAL

The Bohr model predicts that the total energy of electron in an atom is quantized. The allowed energy states are given by the equation

$$E_n = -\frac{E_0}{n^2} \qquad \text{—— (1)}$$

where n = 1, 2, 3, ... The state n =1 is called ground state and n = 2, 3, 4, ... are called excited states.

The energy required to move an electron from its ground state (n = 1) to the excited state (n = 2, 3, 4, ...) is called excitation energy.

The energy required to move an electron must be equal to the difference in the energy levels. Thus the first excitation energy that is, an electron making transition from E_1 to E_2, in hydrogen atom by Bohr formula is

$$E_2 - E_1 = -\frac{E_0}{2^2} - \left(-\frac{E_0}{1^2}\right) \quad \text{or} \quad E_2 - E_1 = -\frac{E_0}{4} + E_0$$

or $E_2 - E_1 = \left(-\frac{1}{4} + 1\right)E_0$ hence $E_2 - E_1 = \left(\frac{-1+4}{4}\right)E_0$

or $E_2 - E_1 = \frac{3}{4}E_0$ since $E_0 = 2.17\times10^{-18}\,J = 13.6eV$

therefore $E_2 - E_1 = -\frac{3}{4}E_0 = 1.62\times10^{-18}\,J = 10.2eV$

NOT FOR SALE

Thus in hydrogen atom 10.2 eV energy is required for an electron to jump from ground state (n =1) to first allowed state (n= 2). Similarly the second excitation energy is that is, an electron making transition from E_1 to E_3.

$$E_3 - E_1 = -\frac{E_0}{3^2} - \left(-\frac{E_0}{1^2}\right) \quad \text{or} \quad E_3 - E_1 = \left(-\frac{1}{9} + 1\right)E_0$$

$$\text{or} \quad E_3 - E_1 = \frac{8}{9}E_0$$

$$\text{therefore} \quad E_3 = E_1 - 12.1eV$$

Hence 12.1 eV energy is required for an electron to jump from ground state (n =1) to allowed state (n= 3) in hydrogen atom.

The potential difference required to move an electron from its ground state (n = 1) to the excited state (n = 2, 3, 4, ...) is called **excitation potential.**

The excitation energy required to move an electron must be equal to the excitation potential. Therefore the first and second excitation potential for hydrogen atom are 10.2 eV and 12.1 eV respectively.

The minimum energy required to remove an electron from the atom in its ground state (n = 1) is called **ionization energy.**

When an atom absorbs sufficient amount of energy an atom may be raised to a level of $n = \infty$. The electron then become free from the attractive force of the nucleus. An atom which have lost one or more electrons is said to be ionized. Thus the ionization energy that is, an electron making transition from E_1 to E_∞, in hydrogen atom by Bohr formula is

$$E_\infty - E_1 = -\frac{E_0}{\infty^2} - \left(-\frac{E_0}{1^2}\right) \quad \text{since} \quad \frac{1}{\infty} = 0$$

$$\text{hence} \quad E_\infty - E_1 = 0 + E_0$$

$$\text{or} \quad E_\infty - E_1 = E_0 = 2.17 \times 10^{-18} J = 13.6eV$$

Thus ionization energy for hydrogen atom is 13.6 eV. This means that ionization energy of an atom is numerically equivalent to ground state energy of an atom.

NOT FOR SALE

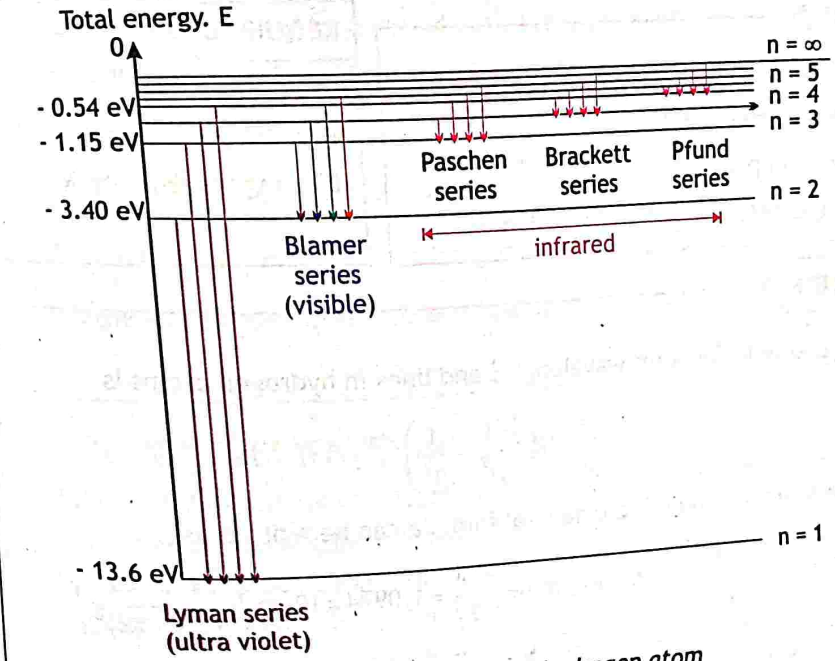
The minimum potential difference required to remove an electron from the atom in its ground state (n = 1) is called **ionization potential.**

The ionization energy required to remove an electron from an atom must be equal to the ionization potential. Therefore ionization potential for hydrogen atom is also 13.6 eV.

E. ENERGY LEVEL DIAGRAMS

It is useful to represent the energy values given by Equation 19.7 on an energy level diagram as shown in figure 19.8. In this diagram, which applies to the hydrogen atom (Z = 1), the highest energy level corresponds to $n = \infty$ and has an energy of 0 eV. This is the energy of the atom when the electron is completely removed ($r = \infty$) from the nucleus and is at rest. In contrast, the lowest energy level corresponds to n = 1 and has a value of - 13.6 eV.

FIGURE 19.8



Energy level diagram for hydrogen atom

The lowest energy level is called the ground state, to distinguish it from the higher levels, which are called excited states.

The various lines in the hydrogen atom spectrum are produced when electrons change from higher to lower energy levels and photons are emitted. Electrons can also make transitions in the reverse direction, from lower to higher levels. In this case, an atom absorbs a photon that has precisely the energy needed to produce the transition. Thus, if photons with a continuous range of wavelengths pass through a gas and then are analyzed with a grating spectroscope, a series of dark absorption lines appears in the continuous spectrum. Thus the dark lines indicate the wavelengths removed by the absorption process.

EXAMPLE 19.1 — **BALMER SERIES**

The Balmer series for hydrogen atom corresponds to electronic transitions that terminate in the state of quantum number n = 2. Find the (a) shortest and (b) longest wavelength of photon emitted in the Balmer's series of hydrogen atom?

GIVEN

(a) Energy level $n_s = \infty$

(b) Energy level $n_L = 3$

Energy level $p = 2$

Rydberg constant $R_H = 1.0974 \times 10^7$ m

REQUIRED

(a) short wavelength $\lambda_s = ?$

(b) Long wavelength $\lambda_L = ?$

SOLUTION

The general formula for wavelengths and lines in hydrogen atoms is

$$\frac{1}{\lambda} = R_H\left(\frac{1}{p^2} - \frac{1}{n^2}\right)$$

(a) For short wavelength the general formula can be written as

$$\frac{1}{\lambda_s} = R_H\left(\frac{1}{p^2} - \frac{1}{n_s^2}\right) \quad \text{Putting values} \quad \frac{1}{\lambda_s} = 1.0974\times10^7\, m^{-1}\left(\frac{1}{(2)^2} - \frac{1}{(\infty)^2}\right)$$

Since $\frac{1}{\infty} = 0$ so $\frac{1}{\lambda_s} = 0.27435\times10^7\, m^{-1}$

$$\lambda_L = \frac{1}{0.27435\times10^7} m = 3.645\times10^{-7} m$$

therefore $\lambda_S = 364.5\times10^{-9} m = 654.5 nm$ — **Answer**

(b) For long wavelength the general formula can be written as

$$\frac{1}{\lambda_L} = R_H\left(\frac{1}{p^2} - \frac{1}{n_L^2}\right) \quad \text{Putting values} \quad \frac{1}{\lambda_L} = 1.0974\times10^7\, m^{-1}\left(\frac{1}{(2)^2} - \frac{1}{(3)^2}\right)$$

$$\frac{1}{\lambda_L} = 0.152417\times10^7\, m^{-1} \quad \text{or} \quad \lambda_L = \frac{1}{0.152417\times10^7} m = 6.560947\times10^{-7} m$$

therefore $\lambda_L = 656.09\times10^{-9} m = 656.1 nm$ — **Answer**

ASSIGNMENT 19.1 — **LAYMAN SERIES**

The Layman series for hydrogen atom corresponds to electronic transitions that terminate in the state of quantum number n = 1. Find the (a) shortest and (b) longest wavelength of photon emitted in the Layman's series of hydrogen atom?

[Answer: (a) 91 nm, (b) 121.5 nm]

ASSIGNMENT 19.2 — **PASCHEN SERIES**

What is the wavelength of the second line of paschen series?

(Answer: 1281.43 nm)

19.4 DE-BROGLIE WAVES AND HYDROGEN ATOM

Of all the postulates of Bohr Model of the hydrogen atom, the most puzzling is the assumption about the angular momentum that an electron cannot revolve around the nucleus in any arbitrary circular orbit. Only those orbits are possible for which the angular momentum is the integral multiple of $h/2\pi$.

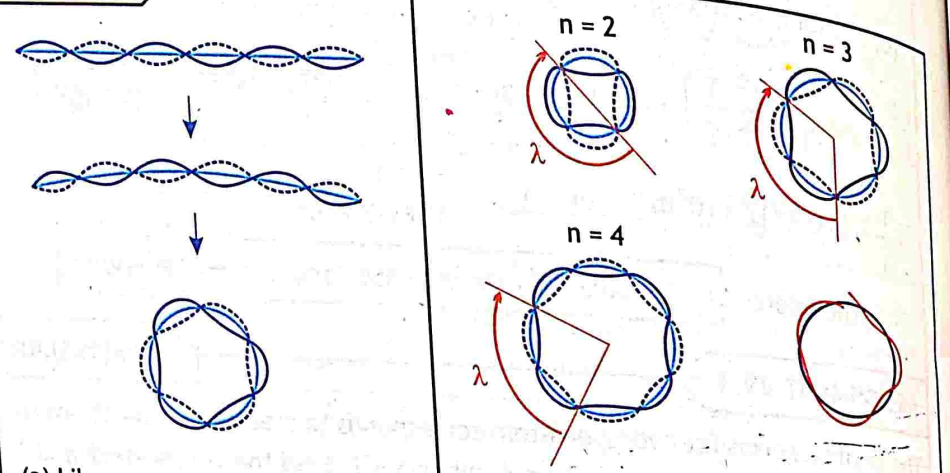
In 1923, ten years after Bohr's work, de Broglie pointed out that his own theory for the wavelength of a moving particle could provide an answer to this question.

NOT FOR SALE

According to de Broglie $\lambda = \frac{h}{p} = \frac{h}{mv}$ ——— (1)

The electron in its circular Bohr orbit must be pictured as a particle wave as shown in figure 19.9 (a).

FIGURE 19.9



(a) Like waves traveling on a string, particle waves can lead to standing waves under resonant conditions.

(b) Bohr orbits are shown for which $2\pi r = 2\lambda$, $2\pi r = 3\lambda$ and $2\pi r = 4\lambda$, these state are possible for electrons orbiting the nucleus all the intermediate stages are not possible.

$2\pi r = n\lambda$ or $\lambda = \frac{2\pi r}{n}$ ——— (2)

Comparing equation 1 and equation 2 we get $\frac{h}{mv} = \frac{2\pi r}{n}$

or $mvr = \frac{nh}{2\pi}$ **19.8**

which is just what Bohr assumed for the angular momentum of the electron. As an example, Figure19.9 (b) illustrates the standing particle wave on a Bohr orbit for which $2\pi r = 3\lambda$. Whereas those orbits are not possible where this condition is not met.

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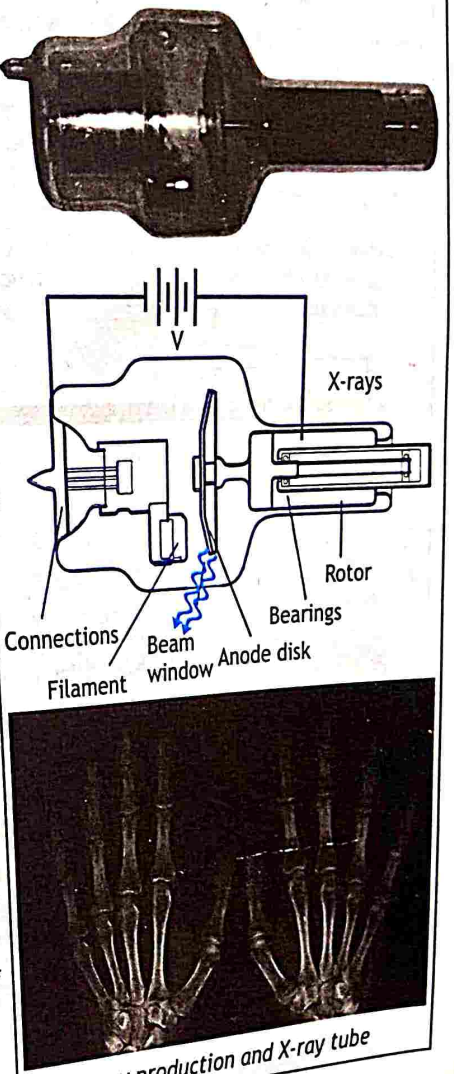
19.5 X-RAYS

X-rays are electromagnetic waves with wavelengths in the region of an Angstrom Å (10^{-10}m).

A. PRODUCTION OF X-RAYS

Figure 19.10 shows an arrangement of producing X-rays. An X-ray tube is a vacuum tube that produces X-rays. It consist of filament heated by current supplied from battery, which emits electrons. These electrons are accelerated towards rotating anode, anode is rotated to reduce overheating. A high voltage power source, for example 30 to 150 kilovolts (kV), is connected across cathode and anode to accelerate the electrons. When such high energy electrons are suddenly stopped by target, an intense beam of X-rays are produced. The X-ray spectrum depends on the anode material and the accelerating voltage. The range of photon energies emitted by the system can be adjusted by changing the applied voltage, and installing aluminum filters of varying thicknesses.

FIGURE 19.10

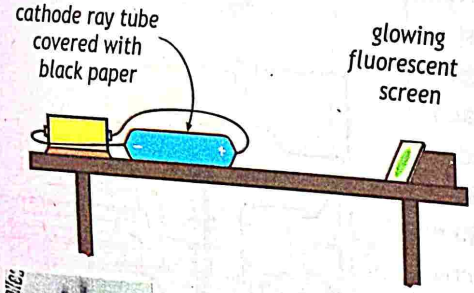


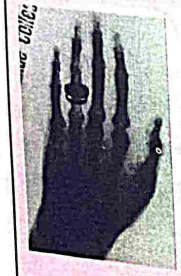
X-ray production and X-ray tube

NOT FOR SALE

For your information **X-RAYS DISCOVERY**

Röntgen discovered X-rays in November 1895 in his laboratory at the University of Wurzburg, Germany. Röntgen was investigating cathode rays using a fluorescent screen painted with barium platinocyanide and a Crookes tube which he had wrapped in black cardboard. He noticed that when the tube was switched on some invisible rays coming from it were passing through the cardboard to make the screen glow which was placed about 1 meter away.





Röntgen studied them throughly and investigated nearly all the properties associated with them. He is also gave them the name "X-rays" (signifying an unknown quantity).

RÖNTGEN (1845-1923)



Wilhelm Conrad Rontgen (Germany). In recognition of the extraordinary services he has rendered by the discovery of X rays he was awarded with Nobel Prize for Physics in 1901

It should be noted that about 1% of the energy generated is emitted/radiated, usually perpendicular to the path of the electron beam, as X-rays, the rest is converted into heat. The target becomes very hot and therefore should have high melting point. Typical target materials are a tungsten-rhenium target on a molybdenum core.

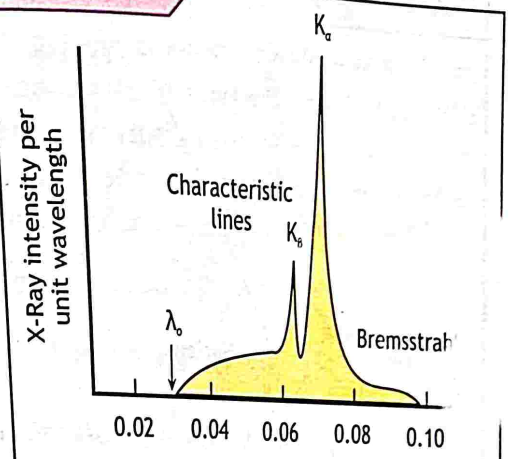
B. X-RAY SPECTRUM

We can understand X-rays by studying the spectrum of radiation emitted. It consist of two parts i.e. characteristic X-rays and continuous X-rays.

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A typical example of X-ray spectrum is shown in the figure 19.11. If we look at the spectrum of wavelengths emitted by an X-ray tube, we see that the spectrum consists of two parts: one is series of peaks (K_α, K_β, ...); characteristic X-rays and the second is Bremsstrahlung; continuous X-rays with a cutoff wavelength λ_o.

FIGURE 19.11



Typical X-ray spectrum

C. CHARACTERISTIC OR INNER SHELL TRANSITION X-RAYS

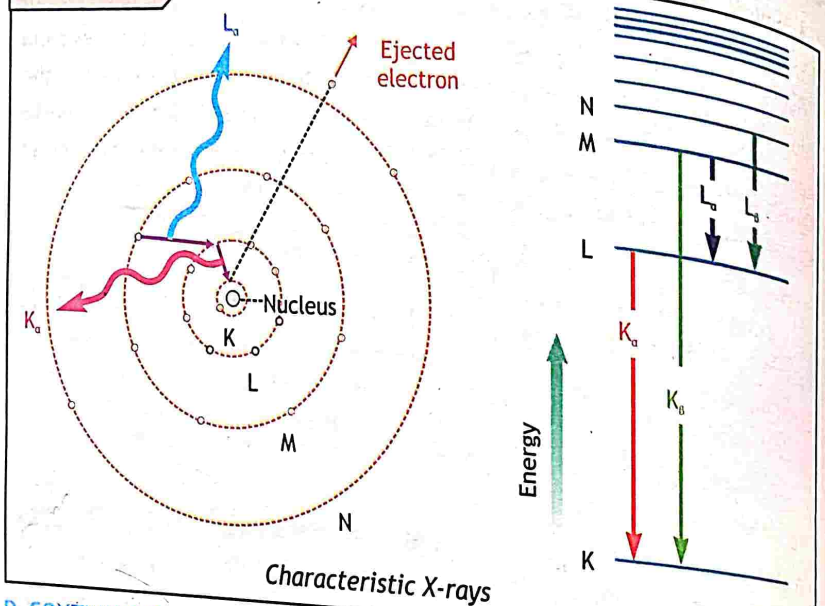
In atoms having many electrons (like molybdenum target in X-ray tube), the electrons are arranged in different orbitals or shells as K, L, M ... . When an incoming beam of electrons strike the atom it may remove an inner shell electron from the atom (such as ejecting a K-shell electron). Now an electron from K, L, M shell will rapidly make a transition to fill that vacancy, emitting an X-ray photon in the process. Thus we can explain these characteristic X-rays (the peaks in Figure 19.11) as photons emitted when an electron in an upper state drops down to fill the lower state.

The K lines; K_α, K_β, ... result from transitions into the K shell from L, M, ... shells respectively. Whereas L lines; L_α, L_β, ... result from transitions into the L shell from M, N, ... shells respectively as shown in figure 19.12.

In a similar manner, we label the other X-ray series by M,N, and so forth.

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FIGURE 19.12



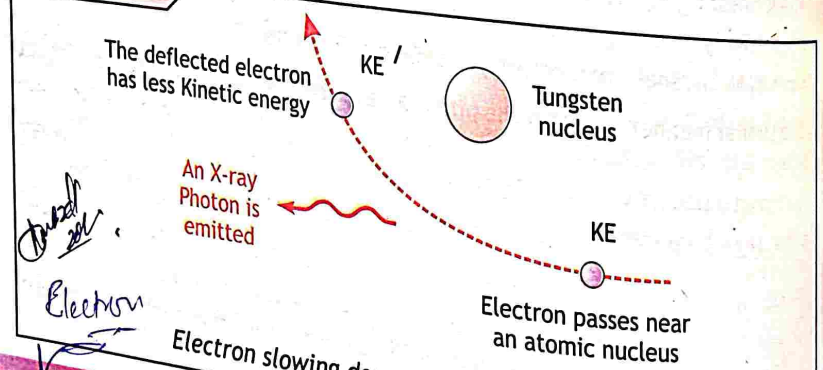
Characteristic X-rays

D. CONTINUOUS X-RAYS

An electron by interaction with atoms of the target slows down and thus emits radiation, and in this case it is called bremsstrahlung (German for "braking radiation") as shown in figure 19.13. Because energy is conserved, the energy of the emitted photon hf, equals the loss of kinetic energy of the electron as

$$KE - KE' = hf \quad \text{——} (1)$$

FIGURE 19.13



Electron slowing down near a nucleus of an atom

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An electron may lose all or a part of its energy in such a collision. Since different electrons are slowed down differently in target and thus varying amounts of energies are lost by the electrons in the form of X-rays. Therefore the spectrum obtained is continuous X-ray spectrum. The shortest-wavelength X-ray (the highest frequency) must be due to an electron that gives up all its kinetic energy to produce one photon in a single collision. Since the initial kinetic energy of an electron is equal to the energy given it by the accelerating voltage, V, then

$$KE = q_e V \quad \text{——} (2)$$

In a single collision in which the electron is brought to rest $KE' = 0$ —— (3)

putting values from equation 2 and equation 3 in equation 1

$$q_e V - 0 = hf \quad \text{or} \quad q_e V = hf \quad \text{since} \quad f = \frac{c}{\lambda}$$

$$\text{therefore} \quad q_e V = h\frac{c}{\lambda} \quad \text{hence} \quad \boxed{\lambda = \frac{hc}{q_e V}} \quad 19.9$$

The equation 19.9 agrees with experimentally observed values. This result is further evidence that X-rays are a form of electromagnetic radiation (light) and that the photon theory of light is valid.

E. APPLICATIONS OF X-RAYS

The important practical applications of X-rays can be divided into three categories

A. Scientific Applications: The diffraction pattern of X-rays by different crystals give information about internal structure of crystals. The spacing and dispositions of the atoms of crystals can be determined.

B. Industrial Applications: X-rays penetrating ability can be used to detect defects in Rial roads, bridges and large machinery. The structure of rubber and plastics can be analyzed. It is also used at airports to check customers and baggage and by art historians to see if a picture has been painted on top of an older one.

C. Medical Applications: Since bore is more opaque to X-rays than flesh, therefore if X-rays are allowed to pass through the human body a shadow of bone can be obtained on photographic film. The X-ray film reveal the fractures of bones and presence of foreign bodies.

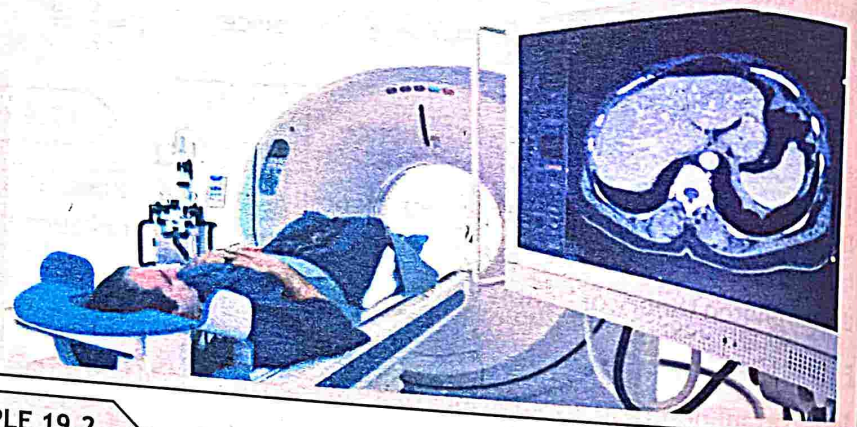
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High energetic X-rays can be used for therapeutic purposes as well.

For your information **CT SCANNER**

The acronym CAT stands for Computerized Axial Tomography or in short CT (Computerized Tomography).

In CT scan machine there are large number of X-ray detectors. The source and detectors are arranged on a large ring shape structure. In this technique a number of X-ray beams pass simultaneously through the patient. The source and detector are rotated to get views from different directions. Large number of images are obtained and are combined by a computer to get detailed 3D images of the patient. In effect, the CAT scanning technique makes it possible to take an X-ray picture of a cross-sectional 'slice' that is perpendicular to the body's long axis.



EXAMPLE 19.2 **CUTOFF WAVELENGTH**

A tungsten target is struck by electrons that have been accelerated from rest through a 40.0-kV potential difference. Find the shortest wavelength of the radiation emitted.

GIVEN

Applied voltage 'V' = 40.0-kV = 40.0×10^3 V

Plank's constant 'h' = 6.626×10^{-34} Js

charge on electron 'q_e' = 1.6×10^{-19} C

speed of light 'c' = 3×10^8 ms^{-1}

REQUIRED

Shortest wavelength 'λ' = ?

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SOLUTION

For electrons accelerated through a potential difference of 40.0 kV, starting from rest, the kinetic energy is KE = e(ΔV) = e(40.0 kV) = 40.0 keV. When these electrons strike the tungsten target, the shortest wavelength possible is produced when the electron loses all its kinetic energy and is brought to rest in a single collision, producing a single photon. The wavelength of the photon produced is

$$\lambda_{min} = \frac{hc}{q_e V}$$

Putting values $$\lambda_{min} = \frac{6.626 \times 10^{-34}\, Js \times 3 \times 10^8\, ms^{-1}}{1.6 \times 10^{-19}\, C \times 40.0 \times 10^3\, V}$$

therefore $\lambda_{min} = 3.11 \times 10^{-11} m = 0.0311 nm$ **Answer**

ASSIGNMENT 19.3 **MINIMUM WAVELENGTH**

Electrons in an x -ray tube are accelerated through a potential difference of 3000 V. if these electrons were slowed down in a target, what will be the minimum wavelength of X -rays produced? **(Answer: 0.414 nm)**

19.6 LASER

A LASER is a device that emits light through a process of optical amplification based on the stimulated emission of electromagnetic radiation. Intense, monochromatic and coherent beam of light is emitted from LASER source.

The term LASER is abbreviation of Light Amplification by Stimulated Emission of Radiation. Light denotes electromagnetic radiation of any frequency, not only visible light. Therefore LASER operating at microwaves and radio-frequency is called MASER.

To understand how a laser works the terms stimulated emission and population inversion must be understood first.

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A. SPONTANEOUS AND STIMULATED EMISSIONS

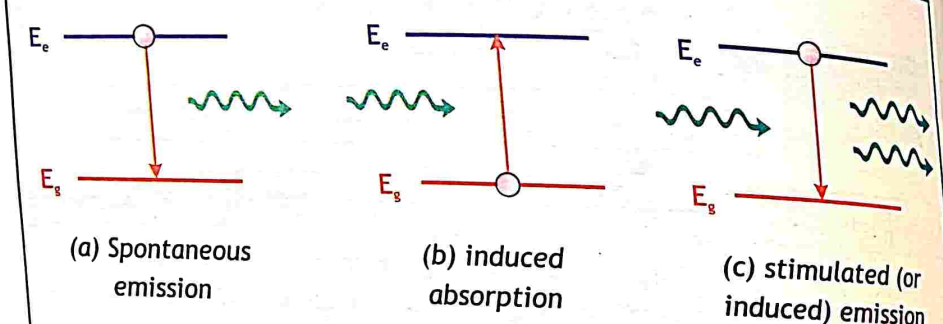
There are three means by which radiation can interact with the energy levels of atoms.

i. Spontaneous emission: In the first kind of interaction, an atom in an excited state makes a transition to a lower state, with the emission of a photon.

$$atom^* \rightarrow atom + photon$$

where the asterisk (*) indicates an excited state.

FIGURE 19.14



(a) Spontaneous emission (b) induced absorption (c) stimulated (or induced) emission

Spontaneous and Stimulated Emissions

ii. Induced Absorption: The second interaction, induced absorption, is responsible for absorption spectra and resonance absorption. An atom in the ground state absorbs a photon (of the proper energy) and makes a transition to an excited state.

$$atom + photon \rightarrow atom^*$$

iii. Stimulated emission: The third interaction, which is responsible for the operation of the laser, is stimulated (or induced) emission. In this process, an atom is initially in an excited state. A passing photon of just the right energy (again, equal to the energy difference of the two levels) induces the atom to emit a photon and make a transition to the lower or ground state.

$$atom^* + photon \rightarrow atom + 2\,photon$$

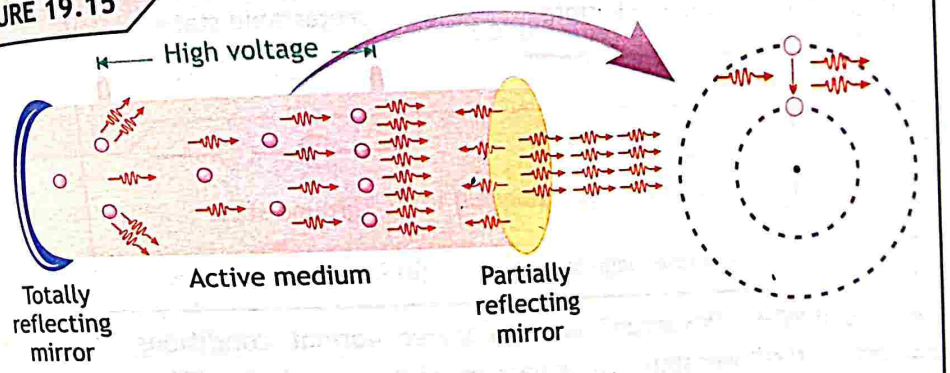
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The two photons that emerge are travel in exactly the same direction with same energy, and the associated electromagnetic waves are perfectly in phase (coherent).

B. LASER ACTION

Suppose we have collection of atoms and potential difference is applied to excite the atoms to the same energy level as shown in figure 19.15. These atoms are confined in a cylinder one side of which is having a totally reflecting mirror and the other is partially reflecting to allow the beam of light to escape.

FIGURE 19.15



LASER construction and working

A photon passes the first atom, causing induced emission and resulting in two photons. This process continues, doubling the number of photons at each step, until building up an intense beam of photons, all coherent and moving in the same direction is emitted from partially reflecting mirror.

However there are few difficulties with this model.

First, it is difficult to keep a collection of atoms in their excited states until they are stimulated to emit the photon. Secondly all the atoms must be in the same excited sate otherwise atoms that happen to be in their ground state undergo absorption and thus remove photons from the beam as it builds up.

These problems can be solved by considering the following situations.

C. META-STABLE STATE

The excited states in atom in which electrons stays for slightly longer period of time before spontaneously falling to ground state are called meta-stable state.

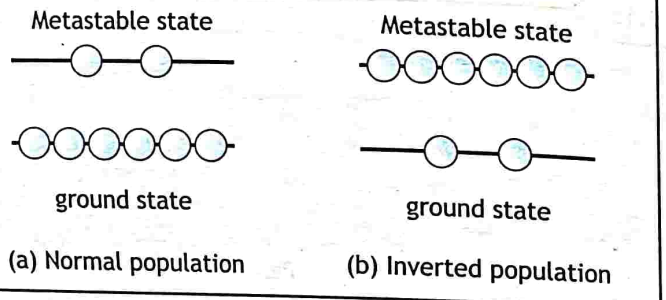
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The excited state decays very rapidly (about 10^{-8} s by spontaneous emission) to a lower excited state. Meta-stable state is the state in which the electrons stay for longer duration (about 10^{-3} s). These states make the stimulated emission possible as more time is provided to photons to pass atoms in meta-stable state.

D. POPULATION INVERSION

In a collection of atoms, when there are more atoms in the excited state than in the ground state is called population inversion as shown in figure 19.16.

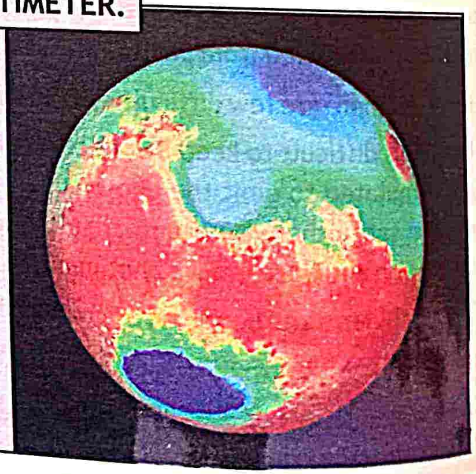
FIGURE 19.16



This is called an "inversion" because under normal conditions at thermal equilibrium, the lower state always has the greater population. The 'inversion' is thus an unnatural situation that must be achieved by artificial means, because it is essential for the operation of the laser.

For your information **LASER ALTIMETER.**

Figure shows an impressive example of how a laser can be used to measure distances accurately. The photograph in the figure is a three-dimensional map of the Martian topography that was obtained by the Mars Orbiter Laser Altimeter (MOLA) on the Mars Global Surveyor spacecraft. The map was constructed from 27 million height measurements, each made by sending laser pulses to the Martian surface and measuring their return times.



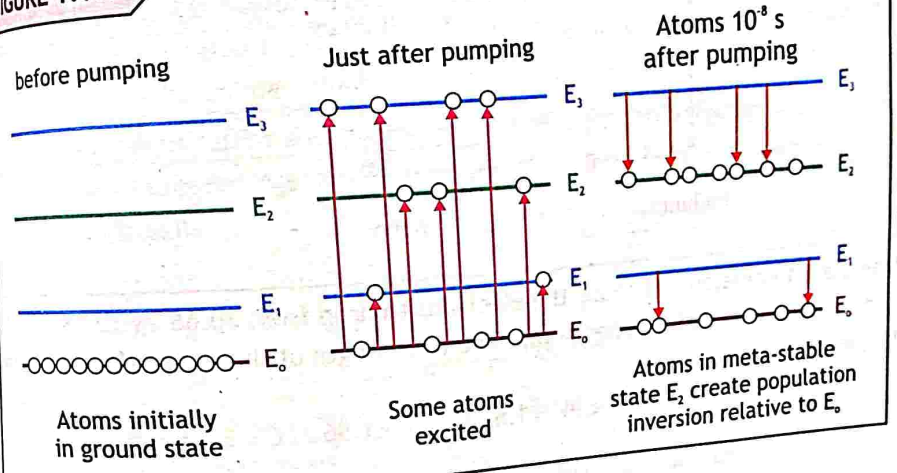
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E. LASER PUMPING

The act of energy transfer from an external source, producing excited states in its atoms is called Laser pumping. The pump energy is usually provided in the form of light (optical pumping) or electric current (electrical pumping).

Let us consider a material whose atoms can reside in four different states. The ground state E_o, two excited states with short life times E_1 and E_3 and meta-stable excited state with long life time E_2 as shown in figure 19.17. When laser pumping is provided atoms are excited to different energy levels. The atoms excited to meta-stable state will stay there longer and after 10^{-8} s, electrons in excited state E_3 will jump to meta-stable state E_2, this increase the number of atoms in meta-stable state E_2 with respect to ground state E_o. Thus population inversion is achieved.

FIGURE 19.17

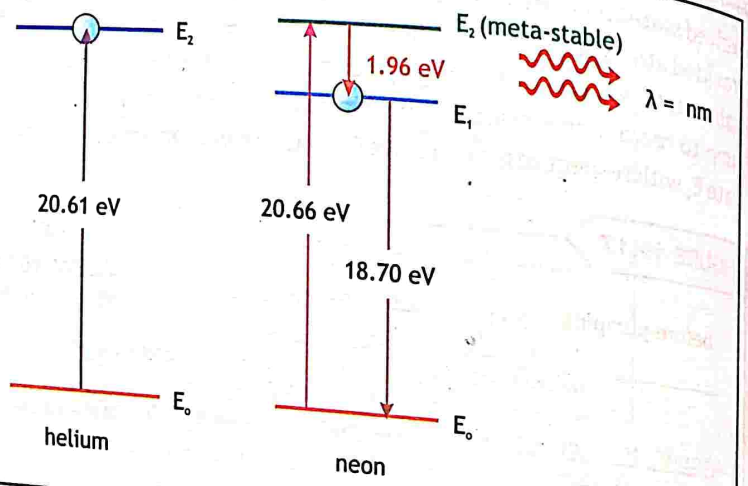


F. HELIUM NEON LASER

It is the most common type of gas Laser. A tube with partially reflecting mirrors is filled with helium 85 % and neon 15%. The neon is the lasing or active medium in this tube. Helium and Neon have identical meta-stable states located at 20.61eV and 20.66 eV respectively. The high voltage electric discharge excites the electrons in some of the helium atoms to 20.61 eV meta-stable state.

These excited helium atoms collide with neon atoms. During the collision helium atoms de-excite to round state by giving the excitation energy of 20.61 eV and some 0.05 eV energy due to its kinetic energy to excite the neon atoms to 20.66 eV meta-stable state. Thus population inversion is achieved in neon in state E_2 relative to E_1 as shown in the figure 19.18.

FIGURE 19.18



Stimulated emission will cause the electrons to drop from 20.66 eV to 18.70 eV, corresponding to 1.96 eV energy gap. The wavelength of the emitted photon can be calculated as

$$E = E_2 - E_1 = 1.96\,eV = 1.6\times10^{-19}\,C \times 1.96\,J/C = 3.14\times10^{-19}\,J$$

since $E = hf$ but $f = \frac{c}{\lambda}$ hence $E = h\frac{c}{\lambda}$

or $\lambda = \frac{hc}{E}$ ——— (1)

here $E = 3.136\times10^{-19}\,J$ $h = 6.63\times10^{-34}\,Js$ $c = 3\times10^{8}\,m/s$

putting values $\lambda = \frac{(6.63\times10^{-34}\,Js)\times(3\times10^{8}\,ms^{-1})}{3.14\times10^{-19}\,J} = 6.334\times10^{-7}\,m$

The value is $\lambda = 6.334 \times 10^{-7}$ m = 633.4 nm, which corresponds to red color in electromagnetic spectrum.

G. LASER AND ORDINARY LIGHT

Laser light, like the light from an ordinary lightbulb, is emitted when atoms make a transition from higher quantum state to a lower one. However, in a lightbulb the emissions are random, both in time and direction, and in a laser they are coordinated so that the emissions are at the same time and in the same direction.

i. Laser light is highly monochromatic. Light from an ordinary incandescent lightbulb is spread over a continuous range of wavelengths and is not monochromatic.

ii. Laser light is highly coherent. Individual long waves (wave trains) for laser light can be several hundred kilometers long. When two separated beams that have traveled such distances over separate paths are recombined, they are able to form a pattern of interference fringes.

iii. Laser light is highly directional. A laser beam spreads very little; it departs from strict parallelism only because of diffraction at the exit aperture of the laser. Whereas ordinary light spreads.

iv. Laser light can be sharply focused. Laser light can be focused to the smaller spot with greater intensity (power per unit area) at that spot as compared to ordinary light.

H. APPLICATIONS OF LASER

Lasers have wide applications some of them are listed below.

i. Lasers in the Medical Field: Lasers have perhaps found the most beneficial and useful applications in the field of medicine. These uses include eye surgery, ulcer removal and disease prevention.

ii. Compact Disks (CDs): Compact disks have digital information (video, music) stored on them, which is read inside the CD player, thus enabling you to hear music. All CD players contain a tiny laser, the job of which is to read the digital codes of information and translate them into music.

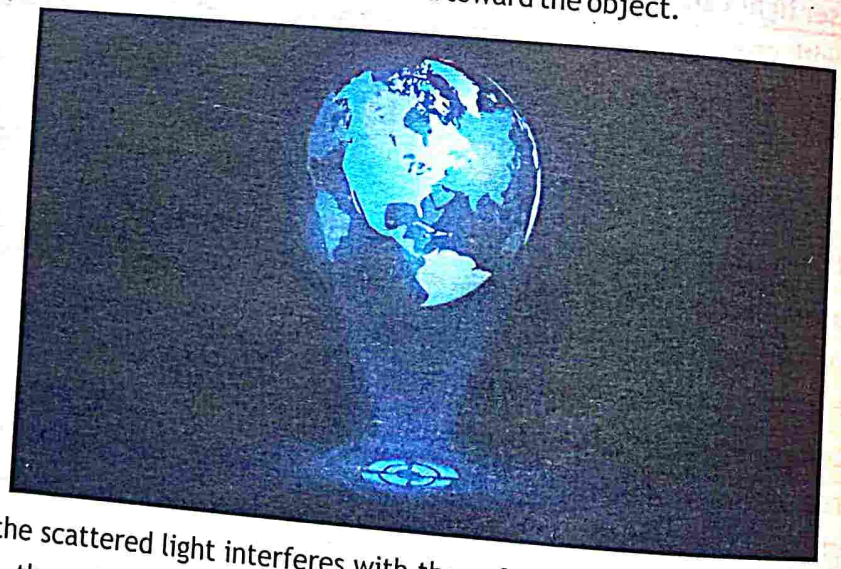
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iii. Supermarket Scanners: The purchases in the supermarket are scanned by a device, for pricing and other information. These scanners contain a laser, which reads the information on the barcode of the product.

iv. Other Uses: Laser fiber optics used by computers and the internet for transferring information and data. Lasers can be used for very accurate and precise cutting, blasting, and welding with the help of intense laser beams. Lasers are used for measuring distances. Lasers can be used to reveal hidden finger prints.

Science Tidbits **HOLOGRAPHY**

Holography is a method of using interference to record both the phase and intensity of an object and therefore use it to reproduce an accurate 3-dimensional representation of that object. There is a wide variety of holography techniques, but all of them follow the same primary process where holography lasers are split into two different beams and one is directed to the recording media and the other is directed toward the object.



When the scattered light interferes with the reference beam at the recording media, the resultant interference pattern contains both the phase and amplitude of the object. Therefore we do not get just illusion of depth but we generate truly three-dimensional images.

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KEY POINTS

Spectrum: The separation of electromagnetic radiation into its component colors or wavelengths

Rydberg formula: The general mathematical form for wavelengths of spectral lines, which is given as

$$\frac{1}{\lambda_n} = R_H\left(\frac{1}{p^2} - \frac{1}{n^2}\right)$$

Rydberg constant: $R_H = 1.0974 \times 10^7\ m^{-1}$

Postulates of Bohr's model of H -atom: Three postulates are

- An electron bound to the nucleus in an atom, can move around the nucleus in certain circular orbits without radiating. These orbits are called the discrete stationary states of the atom.
- Only those stationary states are allowed for which orbital angular momentum is, equal to an integral multiple of 'h' i.e, $mvr = nh/2\pi$
- Whenever an electron makes a transition, i.e, jumps from high energy state E_n to a lower energy state E_p, a photon of energy hf is emitted such that $E_n - E_p = hf$

Characteristics X-rays: The X-rays emitted in inner shell transition

Continuous X-rays: The X-rays that are emitted in all directions and with a continuous range of frequencies

LASER: Light Amplification by Stimulated Emission of Radiation.

Stimulated or Induced emission: When the incident photon of energy hf = $E_f - E_i$ induce the atom to decay by emitting a photon that travels in the direction of the incident photon

Population inversion: In a collection of atoms, when there are more atoms in the excited state than in the ground state

Meta-stable state: The excited states in atom in which electrons stays for slightly longer period of time before spontaneously falling to ground state

Laser pumping: The act of energy transfer from an external source, producing excited states in its atoms

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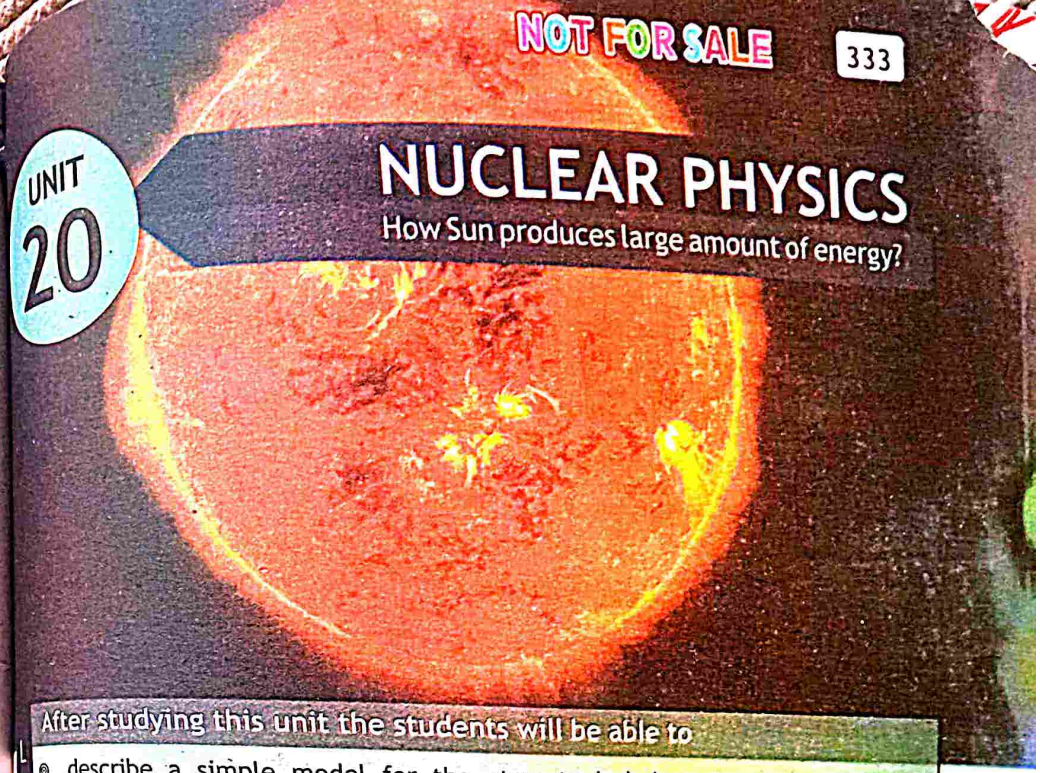
Exercise

MULTIPLE CHOICE QUESTIONS

Choose the best possible answer

1. Which of the following series of hydrogen spectra lies in the visible region of the spectrum
   A. Layman B. Balmer C. Pashen D. Brachett
2. The longest wavelength in Balmer's series with wavelength is 656.2 nm corresponds to
   A. n = 3 B. n = 4 C . n = 5 D . n = ∞
3. If 13.6eV energy is required to ionize the hydrogen atom, then the required energy to remove an electron from n = 2 is
   A. 10.2eV B. 0 eV C. 3.4 eV D. 6.8 eV
4. If an atom exists in excited state n = 5, the maximum number of transitions that take place is
   A. 3 B. 5 C. 10 D. 25
5. The energy of the electron in the excited state n = 4 in hydrogen atom is
   A. - 13.6 eV B. - 3.4 eV C. - 0.85 eV D. - 1.5 eV
6. The radius of third Bohr orbit is greater than the radius of first Bohr orbit (Bohr's radius) by factor of
   A. 3 B. 6 C. 9 D. 16
7. The reverse process of X-ray production can be related to
   A. Compton Effect B. photoelectric effect
   C. Pair Production D. Pair Annihilation
8. The duration of meta-stable state is approximately
   A. 10^{-3} s B. 10^{-6} s C. 10^{-8} s D. 10^{-10} s
9. Helium-Neon Laser beam emitted from a discharge tube has a color
   A. Blue B. Green C. Red D. White
10. In He-Ne LASER, the discharged tube is filled with
    A. 50 % He & 50 % Ne B. 15 % He & 85 % Ne
    C. 85 % He & 15 % Ne D. 99 % He & 1 % Ne

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UNIT 20

NUCLEAR PHYSICS

How Sun produces large amount of energy?

LEARNING OUTCOMES

After studying this unit the students will be able to

- describe a simple model for the atom to include protons, neutrons and electrons.
- Determine the number of protons, neutrons and nucleons it contains for the specification of a nucleus in the form ${}^{A}_{Z}X$.
- explain that an element can exist in various isotopic forms each with a different number of neutrons.
- explain the use of mass spectrograph to demonstrate the existence of isotopes and to measure their relative abundance.
- define the terms unified mass scale, mass defect and calculate binding energy using Einstein's equation.
- illustrate graphically the variation of binding energy per nucleon with the mass number.
- explain the relevance of binding energy per nucleon to nuclear fusion and to nuclear fission.
- identify that some nuclei are unstable, give out radiation to get rid of excess energy and are said to be radioactive.
- describe that an element may change into another element when radioactivity occurs.

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LEARNING OUTCOMES

- identify the spontaneous and random nature of nuclear decay.
- describe the term half life and solve problems using the equation $\lambda = 0.693/T_{1/2}$.
- determine the release of energy from different nuclear reactions.
- explain that atomic number and mass number conserve in nuclear reactions.
- describe energy and mass conservation in simple reactions and in radioactive decay.
- describe the phenomena of nuclear fission and fusion.
- describe the fission chain reaction.
- describe the function of various components of a nuclear reactor.
- describe the interaction of nuclear radiation with matter.
- describe the use of Geiger Muller counter and solid state detectors to detect the radiations.
- describe the basic forces of nature.
- describe the key features and components of the standard model of matter including hadrons, leptons and quarks.

An atom has a nucleus. The nucleus is positively charged. The overall dimensions of a nucleus are much smaller than those of an atom. The radius of a nucleus is 10^4 times smaller than the radius of an atom. This means the volume of a nucleus is about 10^{12} times the smaller than volume of the atom. For an analogy, if an atom is enlarged to the size of a classroom, the nucleus would just be about the size of pinhead. In other words, an atom is almost empty, as (more than 99.9%) of the mass of an atom is concentrated at the nucleus.

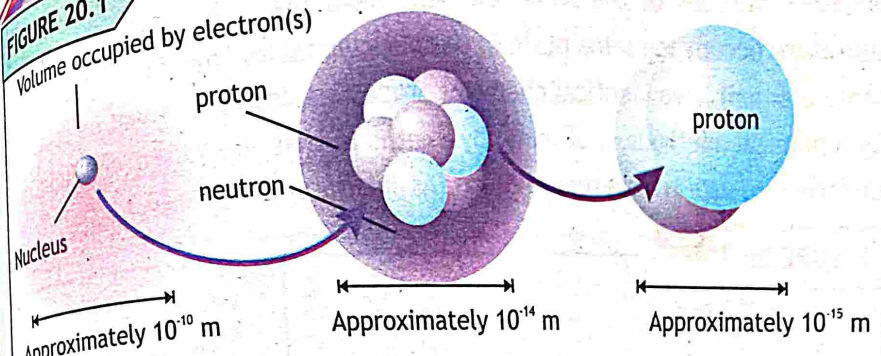
Does the nucleus have a structure, just like atoms? Yes there are many similarities between atomic structure and nuclear structure, which makes our study of the properties of the nucleus easier.

20.1 COMPOSITION OF ATOMIC NUCLEI

In an atom the atomic nucleus is several thousand times more massive than the electrons and occupies only a tiny fraction of the atom's volume (about 1 part in 10^{12} or less). The nucleus is a bound collection of protons and neutrons. Together, protons and neutrons are referred to as nucleons (particles found inside the nucleus).

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FIGURE 20.1



Composition of atomic nucleus

In describing the atomic nucleus, we use the following quantities

- The atomic number **'Z'** (sometimes called the charge number), which is the **number of protons** in the nucleus.
- The neutron number **'N'** which is the **number of neutrons** in the nucleus.
- The mass number **'A'** which is the **number of nucleons** in the nucleus (A = Z + N).

In representing nuclei, it is convenient to have a system of symbols to show how many protons and neutrons are present. The symbol used is ${}^{A}_{Z}X$, where X represents the chemical symbol for the element, Z represents the number of protons and A represents the number of nucleons (i.e number of protons and neutrons) as shown in figure 20.2.

FIGURE 20.2

Number of nucleons

$^{A}_{Z}X$ Symbol for element $^{24}_{12}Mg$

Number of protons or electrons

Symbolic representation of magnesium

Because the atomic number can also be obtained through the element symbol, therefore we state only the mass number in the superscript and leave out the atomic number subscript, for example ^{12}C, ^{24}Mg and ^{35}Cl.

20.2 ISOTOPES

The atoms of an element having the same number of protons, or the same atomic number, but having different numbers of neutrons, or different atomic weights is called an isotope.

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The term isotope comes from the Greek isos-topos, which means same place, because isotopes of the same element have the same atomic number and therefore occupy the same place in the periodic table. Therefore isotopes of the same element have identical chemical properties. Isotopes cannot be separated by chemical methods, but only by methods that are based on their mass differences, such as mass spectrometry. As illustrated in figure 20.3

FIGURE 20.3



Chlorine 35	*Chlorine* 36	*Chlorine* 37	*Chlorine* 39
17 Protons	17 Protons	17 Protons	17 Protons
18 Neutrons	19 Neutrons	20 Neutrons	22 Neutrons
17 Electrons	17 Electrons	17 Electrons	17 Electrons

(a) Three natural isotopes of chlorine, choline 36 is unstable and is found in trace amounts

(b) The most stable artificial isotope of chlorine

Over 3,000 isotopes either exist in nature or have been made artificially in particle accelerators, out of which only 257 are stable. The remaining isotopes are unstable and are termed as radioisotopes.

20.3 MASS SPECTROGRAPH

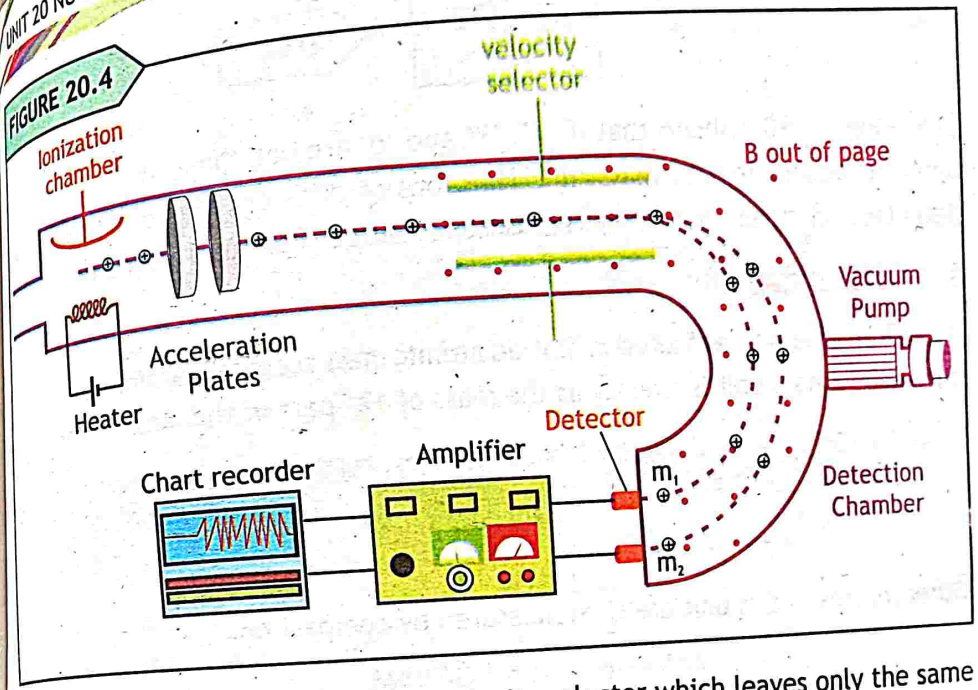
A device which is used to determine the mass of charged particles is called mass spectrograph. This device can also be used to separate isotopes of chemical element and to determine their relative abundance .

A mass spectrograph is based upon the principle that a beam of ions moving through electric and magnetic fields is deflected, and this deflection depends upon the charge and mass of ions.

A mass spectrometer can be used to separate a mixture of ions having different masses. A schematic view of mass spectrograph is shown in the figure 20.4. The atoms or molecules understudy in vapor form are pushed into ionization chamber. Where an electron is removed from them leaving them with a net positive charge.

The charged particles are accelerated through acceleration plates through potential difference 'V' applied.

FIGURE 20.4



The beam is then passed through a velocity selector which leaves only the same velocity particles. Thus by leaving the velocity selector the kinetic energy of single charge ion will be given by the equation

$$\frac{1}{2}mv^2 = qV \quad \text{or} \quad v = \sqrt{\frac{2qV}{m}} \qquad \text{——(1)}$$

These ions are then subjected to perpendicular and uniform magnetic field 'B', in the vacuum chamber, where they are deflected in semicircular path towards the detector. The centripetal force is provided by the magnetic force

$$\frac{mv^2}{r} = qvB \quad \text{or} \quad v = \frac{qB}{m} \times r \qquad \text{——(2)}$$

Comparing equation 1 and equation 2 $\frac{qB}{m} \times r = \sqrt{\frac{2qV}{m}}$

Squaring both sides $\frac{q^2B^2r^2}{m^2} \times = \frac{2qV}{m}$ Solving for m we get $m = \frac{r^2B^2q}{2V}$

So we can obtain the mass if r, B, q and V are known. By rearranging the above equation we can also write

NOT FOR SALE

$$r = \sqrt{\frac{2Vm}{B^2 q}} \qquad 20.1$$

This equation 20.1 shows that if 'V', 'B' and 'q' are not changed the 'r' depends upon the square root of mass 'm'. Thus ions of different masses will strike the detector at different points thus the isotopes can be separated from each other.

20.4 NUCLEAR MASSES

Nuclear masses are measured in unified atomic mass scale. According to this scale one atomic mass unit is exactly as the mass of 12th part of the mass of carbon 12 atom.

$$1u = \frac{mass\ of\ one\ ^{12}C\ atom}{12}$$

Other masses in this unit are then measured by comparison.

A. UNIFIED ATOMIC MASS UNIT IN KILOGRAM

As we know that 1 kg mole of any element contain Avogadro's number of atoms. Thus

$$\text{Mass of } 6.023 \times 10^{26} \text{ atoms of } ^{12}C = 12\text{kg}$$

or $$\text{Mass of 1 atoms of } ^{12}C = \frac{12}{6.023 \times 10^{26}}\text{kg}$$

and $$\text{Mass of } \frac{1}{12} \text{ atoms of } ^{12}C = \frac{1}{12} \times \frac{12}{6.023 \times 10^{26}}\text{kg}$$

therefore $$1u = 1.660 \times 10^{-27}\text{kg} \qquad 20.2$$

B. UNIFIED ATOMIC MASS UNIT IN JOULES

In nuclear physics we sometime also give the masses in energy units. As by Einstein mass energy relation we have

$$\Delta E_0 = (\Delta m)c^2 = (1.6605 \times 10^{-27}\text{kg})(2.9979 \times 10^8 \text{m/s})^2$$

therefore $$1u = 1.4924 \times 10^{-10}\text{J} \qquad 20.3$$

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C. UNIFIED ATOMIC MASS UNIT IN ELECTRON VOLTS

Also in nuclear physics we sometime also give the masses in energy units as electron volts, as

$$1u = (1.4924 \times 10^{-10}\text{ J})\left(\frac{1\text{eV}}{1.6022 \times 10^{-19}\text{ J}}\right) = 9.315 \times 10^8\text{ eV}$$

therefore $$1u = 931.5\text{ MeV} \qquad 20.4$$

All the masses of different particles can be converted into this scale as shown in the table 20.1.

Table 20.1 Rest masses in Kilograms, Unified Atomic Mass Units and MeV

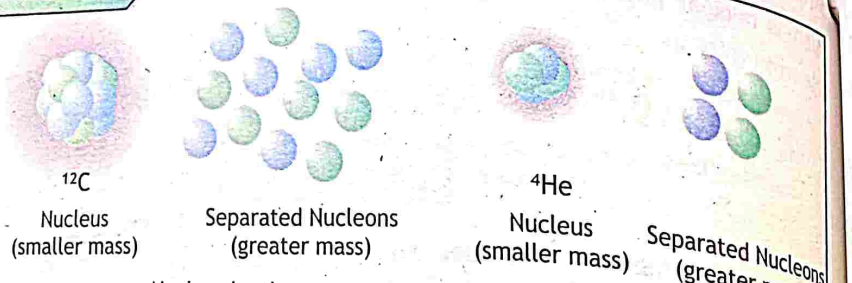
Particle	kg	u	MeV/c²
Electron	9.1164×10^{-31}	0.0005485	0.511
Proton	1.67262×10^{-27}	1.007276	938.27
Neutron	1.67493×10^{-27}	1.008665	939.57
Hydrogen	1.67353×10^{-27}	1.007825	938.78
Deuterium	3.34449×10^{-27}	2.014102	1876.12
Tritium	5.00827×10^{-27}	3.016049	2809.43
Helium	6.64648×10^{-27}	4.002603	3728.40
Carbon	1.99265×10^{-27}	12.000000	11177.9

20.5 MASS DEFECT AND BINDING ENERGY

The total mass of a nucleus is less than the sum of the masses of its individual nucleons. For example as shown in the table 20.1 six protons and six neutrons, each having a mass larger than 1 u, combined with six electrons to form a carbon-12 atom having a mass of exactly 12 u. The bound system of ^{12}C has a lower rest energy than that of six separate protons and six separate neutrons. Similarly the mass of helium nucleus which consist of two protons and two neutrons is 0.8% less than the mass of two protons and two neutrons separated from each other.

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FIGURE 20.5



Nucleus has lower energy than its constituent nuclei

The amount by which the mass of an atomic nucleus is less than the sum of the masses of its constituent particles is called **mass deficit or mass defect.**

The energy that holds a nucleus together is called **binding Energy,** *this amount of energy will be required to break the nucleus into separate parts.*

The binding energy is equal to the mass defect of the nucleus. Since the nucleus is a bound system, its total energy is less than the energy of Z protons and N neutrons that are far apart and at rest.

E_B = (total energy of Z protons and N neutrons) – (total energy of nucleus)

If M is the mass of the nucleus, M_p is the mass of proton and M_N is the mass of Neutron, the Binding energy of the nucleus will be:

$$E_B = (ZM_p + NM_N - M)c^2 \qquad 20.5$$

Where Z is the number of protons and N is the number of neutron in the nucleus. The mass defect or mass deficit (Δm) is given by the relation

$$\Delta m = ZM_p + NM_N - M \qquad 20.6$$

The binding energy per nucleon of a nucleus is called **packing fraction.** If 'A = N + Z' is the mass number (number of nucleons), then the packing fraction '*f*' is

$$f = \frac{E_B}{A} = \frac{(ZM_p + NM_N - M)c^2}{A} \qquad 20.7$$

The packing fraction (binding fraction) is the measure of stability of a nucleus. The greater the binding energy per nucleon, the more stable the nucleus is.

For your information **STRONG NUCLEAR FORCE**

Since very large repulsive Coulomb forces exists between the close-packed protons in a nucleus, and this force should cause the nucleus to fly apart. Because that does not happen, there must be a counteracting attractive force, this force is called **strong nuclear force.** The strong nuclear force is a very short range (about 2 fm) attractive force that acts between all nuclear particles. The protons attract each other by means of the nuclear force, and, at the same time, they repel each other through the Coulomb force. The nuclear force also acts between pairs of neutrons and between neutrons and protons. The nuclear force dominates the Coulomb repulsive force within the nucleus (at short ranges), so stable nuclei can exist.

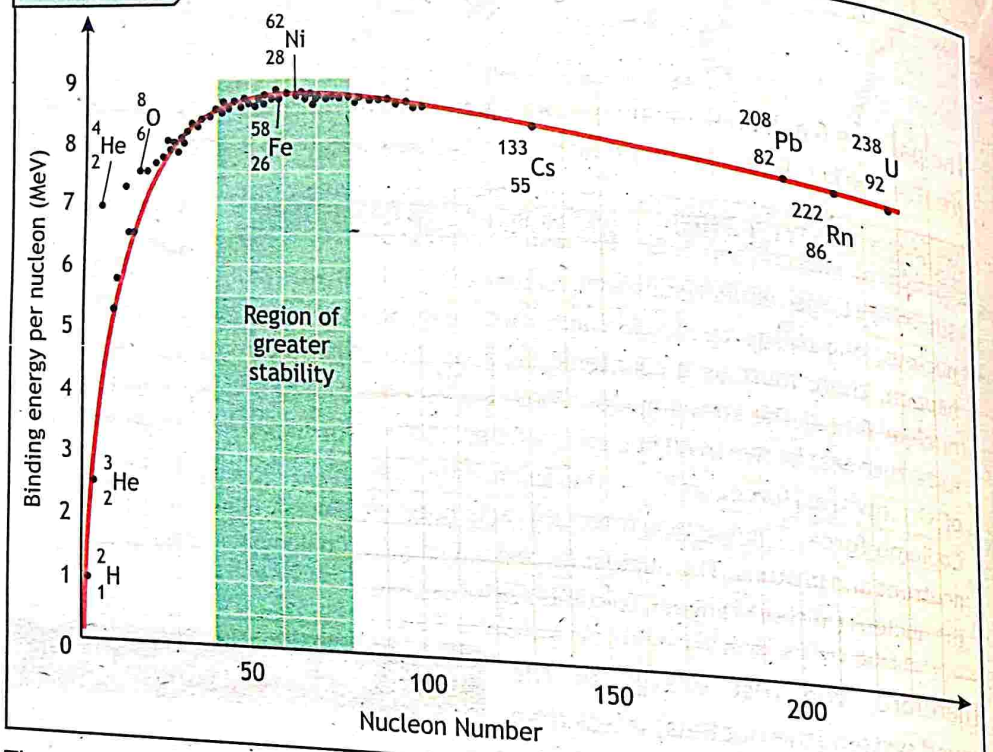
Therefore, the rest energy of the bound system (the nucleus) is less than the combined rest energy of the separated nucleons. To separate the protons and neutron from a nucleus work would need to be done to overcome nuclear force, called binding energy. Binding energy is also equal to the energy liberated when a nucleus is created from other nucleons or nuclei. This nuclear binding energy is derived from the nuclear force and is the energy required to disassemble a nucleus into the same number of free, unbound neutrons and protons it is composed.

TABLE 20.2 SOME BINDING ENERGIES

Nucleus	Total binding energy (MeV)	Binding energy per nucleon (MeV / nucleon)
^{2}H	2.23	1.1
^{4}He	28.3	7.1
^{12}C	92.1	7.7
^{16}O	127.5	8.0
^{56}Fe	492.3	8.8
^{63}Cu	552.1	8.8
^{238}U	1803	7.6

NOT FOR SALE

FIGURE 20.6



The graph of binding energy per nucleon in MeV to the nucleon number is shown in the figure 20.6.

i. Intermediate Nuclei: The most stable nuclei lie in the region of greater stability and about A = 50 to 60 this is where binding energy per nucleon is greatest almost of 8.7 MeV called intermediate size nuclei. (e. g $^{62}_{28}$Ni and $^{58}_{26}$Fe)

ii. Small Nuclei: The decrease in Packing fraction 'f' for small 'A' is due to surface effect. The particles at or near the surface are less strongly bond than the nucleons at the interior. The smaller the nucleus the larger the percentage of constituents at the nuclear surface. (e. g $^{4}_{2}$He and $^{16}_{8}$O)

iii. Large Nuclei: The decrease in 'f' for large nuclei is because of large number of protons. The coulomb repulsion between protons opposes the binding effect of nuclear force. Therefore nuclei with large 'A' are unstable. (e. g $^{222}_{86}$Rn and $^{238}_{92}$U). The instability shows why a nuclear fission results in large nuclei such as $^{235}_{92}$U. The fission fragments of the nuclei undergoing fission lie in the region of greater stability. The binding energy increases from 7.5 MeV to nearly 8.5 MeV. This difference is the energy liberated in a nuclear fission process.

EXAMPLE 20.1 — **SODIUM NUCLEUS**

Sodium ^{23}Na has an atomic mass of 22.989,769 u. Find the (a) mass defect (b) binding energy and (c) binding energy per nucleon for this nucleus.

GIVEN

Number of protons 'Z' = 11

Mass of proton 'M_p' = 1.007276 u

Number of neutrons 'N' = 12

Mass of neutron 'M_n' = 1.008665 u

Mass of Sodium nucleus M = 22.989769 u

REQUIRED

Mass defect 'Δm' = ?

Binding Energy 'E_B' = ?

Binding energy per nucleon 'f' = ?

SOLUTION

(a) The mass defect is given by $\Delta m = ZM_P + NM_N - M$

Putting values $\Delta m = 11(1.007825\,u) + 12(1.008665\,u) - 22.989769\,u$

or $\Delta m = 11.086075\,u + 12.10398\,u - 22.989769\,u$

therefore $\Delta m = 0.200286\,u$ — **Answer**

(b) The Binding energy is given by $E_B = \Delta m \times c^2 = \Delta m \times 931.5\,MeV$

Putting values $E_B = 0.200286 \times 931.5\,MeV$

therefore $E_B = 186.566\,MeV$ — **Answer**

(c) The packing fraction (binding fraction).is the binding energy per nucleon, and is given as

$$f = \frac{E_B}{A} \qquad \text{since } A = Z + N = 11 + 12 = 23$$

Putting values $f = \frac{186.566}{23} MeV$

therefore $f = 8.11 MeV$ — Answer

ASSIGNMENT 20.1 — **CARBON NUCLEUS**

Find the mass defect, expressed in kilograms, and the binding energy for a carbon-12 nucleus. (Answer: 0.098 940 u or 1.6429 × 1028 kg, 92.16 MeV)

20.6 RADIOACTIVITY

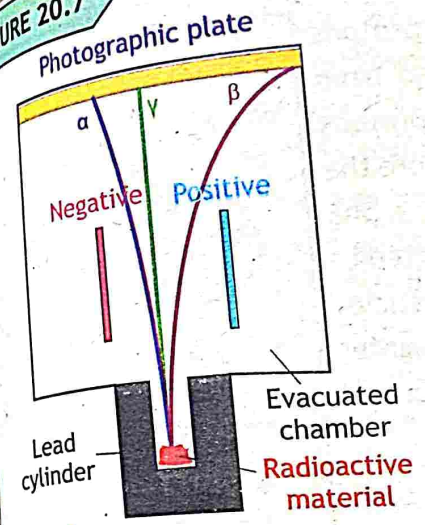
The spontaneous release of subatomic particles or gamma rays by unstable atoms as their nuclei decay to attain stability is called radioactivity. The element which possess such property is called radioactive element.

In order to attain stability element emit three types of radiation: alpha (α), in which the emitted particles are ^4He nuclei; beta (β), in which the emitted particles are either electrons or positrons; and gamma (γ), in which the emitted 'rays' are high-energy photons.

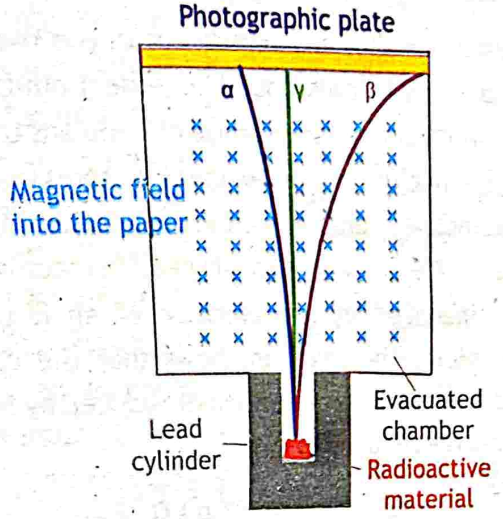
Among about 3000 known nuclides, only 257 are stable. The time scale of these decay processes ranges from a small fraction of a microsecond to billions of years.

When the radiation from a radioactive sample is directed into a region in which there is either an electric or a magnetic field as shown in Figure 20.7, we can separate it into three forms of radiation alpha (α), beta (β) and gamma (γ). Table 20.3 gives properties of these radiations you studied in grade 10.

FIGURE 20.7



(a) Alpha, Beta and Gamma rays in electric field



(b) Alpha, Beta and Gamma rays in magnetic field

TABLE 20.3 RADIOACTIVE EMISSIONS

Emission	Description	Rest mass (in u)	Charge	Penetrating power	Relative ionizing ability
Alpha (α)	Helium nuclei (two protons and two neutrons)	4.002603	+2	Stopped by sheet of paper	highest
Beta (β)	electrons or positrons	0.000594	-1, +1	several millimetres of aluminum	medium
Gamma (γ)	short wavelength electromagnetic radiations	0	0	several centimetres of lead	lowest

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A. ALPHA (α) EMISSION

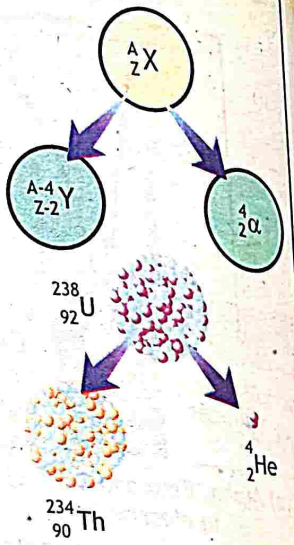
Alpha particles are helium nuclei (i.e two protons and two neutrons bound together) emitted from the nucleus. When the ratio of neutrons to protons in the nucleus is too low, certain atoms restore the balance by emitting alpha particles. In alpha decay, the original (parent) nuclide is converted to a 'daughter' by the emission of an α particle. Balancing the reaction shows that the daughter nuclide has a nucleon number reduced by four and a charge reduced by two.

$$^{A}_{Z}X = ^{A-4}_{Z-2}Y + \alpha + Q$$

$$^{263}_{106}Sg = ^{259}_{104}Rf + ^{4}_{2}He\,(\alpha) + Q$$

The spontaneous emission of an α-particle by some (heavy) nuclei is related to the compactness of the He nucleus whose binding energy is = 7 MeV/nucleon. *Many Nuclei with Z > 83 are radioactive in this mode.* It is manifestation of quantum tunneling through potential barrier.

FIGURE 20.8



$$^{238}_{92}U = ^{234}_{90}Th + ^{4}_{2}He\,(\alpha) + Q$$

The emission of an alpha particle by uranium-238 results in the formation of thorium-234

NOT FOR SALE

B. BETA EMISSION

Beta particle emission occurs when the ratio of neutrons to protons in the nucleus is too high. In this case, an excess neutron transforms into a proton and an electron. The proton stays in the nucleus and the electron is ejected energetically. A neutron by itself is unstable; and on average in 890 s will decay into a proton and an electron. Unlike α-decay, β-decay of a radionuclide does not change the number of nucleons. In essence, β-decay changes a neutron into a proton.

$$^{A}_{Z}X = ^{A}_{Z+1}Y + \beta^{-} + \bar{\upsilon} + Q$$

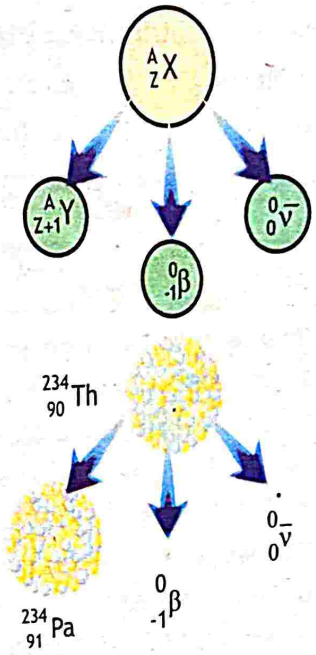
$$^{14}_{6}C = ^{14}_{7}N + \beta^{-} + \bar{\upsilon} + Q$$

Positron Beta emission: Like beta decay β⁻, positron emission β⁺ does not change the number of nucleons. In essence, β⁺ decay changes a proton into a neutron.

$$^{A}_{Z}X = ^{A}_{Z-1}Y + \beta^{+} + \upsilon + Q$$

$$^{18}_{9}F = ^{18}_{8}O + \beta^{+} + \upsilon + Q$$

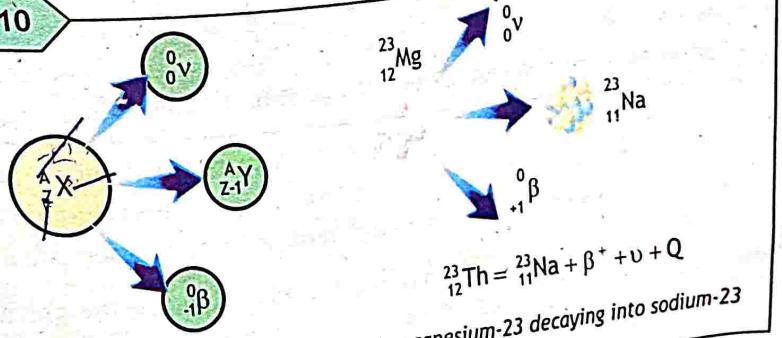
FIGURE 20.9



$$^{234}_{90}Th = ^{234}_{91}Pa + \beta^{-} + \bar{\upsilon} + Q$$

The emission of a beta particle by thorium-234 results in the formation of protactinium-234

FIGURE 20.10



$$^{23}_{12}Th = ^{23}_{11}Na + \beta^{+} + \upsilon + Q$$

The positron emission (β+ decay) is shown with magnesium-23 decaying into sodium-23

NOT FOR SALE

Notice, in electron emission, an electron antineutrino is also emitted. Whereas the positron emission is accompanied by the emission of an electron neutrino. The electron neutrino is a subatomic particle which has no net electric charge. Like all particles, the electron neutrino has a corresponding antiparticle, the electron antineutrino, which differs only in that some of its properties have equal magnitude but opposite sign.

Science Tidbits — **Why a neutrino is emitted in Beta decay?**

Beta decay was a puzzle at first because a continuous spectrum of electron (or positron) kinetic energies was observed. Beta particles are ejected from nucleus at different speeds. In α decay, the definite kinetic energy is same for all particles to conserve energy and momentum. For the same reasons, scientists thought that β particles emitted in a given decay reaction should also be monoenergetic.

Wolfgang Pauli suggested that not one, but two particles were being emitted in beta decay an electron/positron and neutrino/antineutrino. If a nucleus emits two particles instead of one, then they can conserve both energy and momentum while splitting up the kinetic energy in every possible way. Two momentum vectors that add to zero must be equal in magnitude and opposite in direction, but three momentum vectors can add to zero in an infinite number of ways and still share the same total kinetic energy. The neutrino has the following properties:

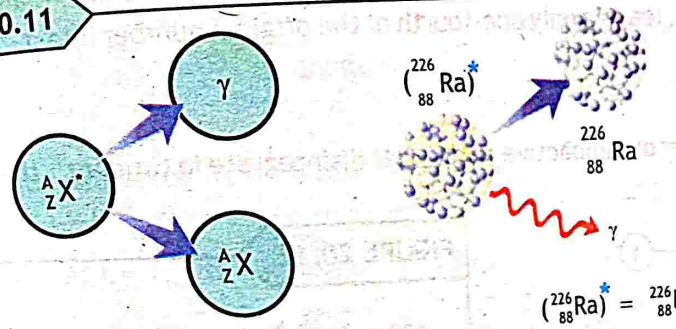
- Zero electric charge
- A mass much smaller than that of the electron, but probably not zero.
- (Recent experiments suggest that the neutrino definitely has mass, but the value is uncertain, perhaps less than 1 eV/c^2.)
- A spin of 1/2
- Very weak interaction with matter, making it difficult to detect

GAMMA EMISSION

Gamma rays are electromagnetic radiation emitted from the nucleus. Gamma radiation emission occurs when the nucleus of a radioactive atom has excess energy. Inside the nucleus the nucleons (like the orbital electrons) exists in discrete energy states or levels. When a nucleus changes from an excited energy state to a lower energy state, a photon is emitted. The photon has a much greater energy and is called a γ ray. In most cases the α or β emission from the nucleus leave it in excited state such nuclei achieve further stability by emitting gamma rays.

$$({}^{A}_{Z}X)^{*} = {}^{A}_{Z}X + \gamma \qquad ({}^{60}_{27}Co)^{*} = {}^{60}_{27}Co + \gamma$$

FIGURE 20.11



The emission of a gamma ray by radium-226 results radium-226 with gamma

20.7 SPONTANEOUS AND RANDOM NUCLEAR DECAY

A process of disintegration that occurs when unstable nuclei decay in an attempt to attain stability is called nuclear decay. This process is both spontaneous and random.

A process without defined pattern, rule or method is called random process. Nuclear decay is unpredictable because precise moment of disintegration is not known for a particular nuclei. Individual disintegrations occur randomly.

A process occurring without apparent external cause is called spontaneous process. Nuclear decay is spontaneous, because the process of radioactive decay cannot be speeded up or slowed down by physical or chemical means.

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20.8 HALF LIFE AND RATE OF DECAY

The time it takes for half of the radioactive nuclei in a sample to decay is called half life.

Individual disintegrations are random, however, the probability of decay for nuclei in a sample has fixed value, which is characteristic of that material.

Thus the amount of radioactive isotope in the sample decrease with time as shown in the figure 20.12 for Half life curve. The number of nuclei present at time t = 0s is N = N_0, and the number present at t = $T_{1/2}$ is N = $N_0/2$. The number present at t = 2 $T_{1/2}$ is N = $N_0/4$, and so on. For example, ^{14}C has a half-life of 15730 years, because it takes this amount of time for one-half of a given quantity of this isotope to disintegrate. In another 15730 years, one-half of the remaining ^{14}C atoms will have disintegrated, leaving only one-fourth of the original number intact.

The rate of decay or activity of radioactive sample is defined as the number of disintegrations that occur per second.

If 'ΔN' is the number of radioactive nuclei that disintegrate in time 'Δt', then

$$\Delta N \propto -N \quad \text{——} (1)$$

and $$\Delta N \propto \Delta t \quad \text{——} (2)$$

Combining equation 1 and equation 2, we get

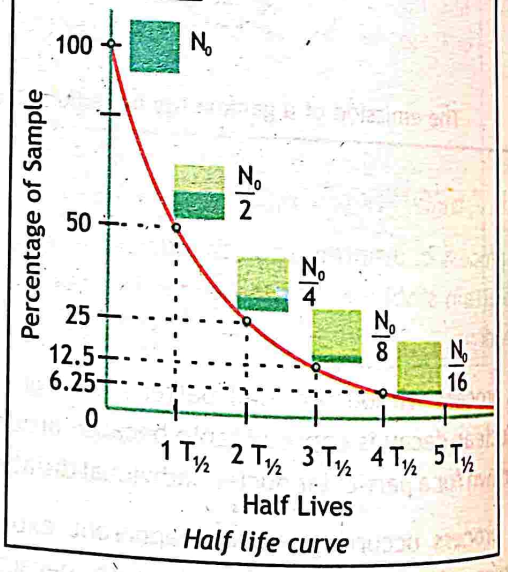
$$\Delta N \propto -N\Delta t$$

and $$\Delta N = -\lambda N\Delta t \quad \text{——} (3)$$

Where 'λ' is the proportionality constant called *decay constant*. The negative sign shows that N decreases with time, the above equation can also be written as

$$\frac{\Delta N}{\Delta t} = -\lambda N \quad \text{——} (4)$$

FIGURE 20.12



Half life curve

NOT FOR SALE

We can show from equation 4 that the number of nuclei present varies with time according to the expression

$$N = N_0 e^{-\lambda t} \quad \text{——} (5)$$

For your information — CALCULUS FOR HALF LIFE CALCULATION

For small change $\frac{\Delta N}{\Delta t} = \frac{dN}{dt}$ so $\frac{dN}{dt} = -\lambda N$ or $\frac{dN}{N} = -\lambda dt$

Integrating both sides $\int \frac{dN}{N} = -\int \lambda\, dt$ or $\ln N = -\lambda t + \text{constant}$

Apply initial conditions, At t = 0, N = N_0 $\ln N_0 = -\lambda(0) + \text{constant}$

constant = $\ln N_0$

therefore $\ln N = -\lambda t + \ln N_0$ or $\ln N = \ln e^{-\lambda t} + \ln N_0$ or $\ln N = \ln N_0 e^{-\lambda t}$

Taking anti natural log on both sides $N = N_0 e^{-\lambda t}$

For half life, At t = $T_{1/2}$, N = $N_0/2$ $\frac{N_0}{2} = N_0 e^{-\lambda T_{1/2}}$ or $\frac{1}{2} = e^{-\lambda T_{1/2}}$

Taking inverse $2 = e^{\lambda T_{1/2}}$ or $\ln 2 = \lambda T_{1/2}$ or $T_{1/2} = \frac{\ln 2}{\lambda}$

The numeric value of ln 2 = 0.693, therefore $T_{1/2} = \frac{0.693}{\lambda}$ **20.8**

This is the relation between decay constant λ and half life $T_{1/2}$. The value of half-life is constant for each radioactive element and it is possible to characterize the element by using its half -life value. The half -life is a measurement of stability of radioactive elements. The rate of radioactive decay is directly proportional to the stability of the isotope.

(i) ACTIVITY

Activity, in radioactive-decay processes is the number of disintegrations per unit time, or the number of unstable atomic nuclei that decay per unit time in a given sample. (i)

NOT FOR SALE

Table 20.4 DECAY TYPES AND HALF LIVES OF SOME RADIOISOTOPES

Radioisotope	Decay type	Half Life
beryllium - 8	α	2.0×10^{-10} seconds
carbon-14	β^-	5.73×10^3 years
oxygen - 15	β^+	122.24 seconds
cobalt - 60	β^-	5.3 years
iodine-131	β^-, γ	8.04 days
Lead - 212	β^-, γ	10.6 hours
polonium - 214	α, γ	0.1643 seconds
radium-226	α, γ	1.62×10^3 years
einsteinium-254	α, β^-, γ	275.7 days

The activity 'A' is number of disintegrations per unit time ($\Delta N/\Delta t$) from equation 4 equals the decay constant times the number of radioactive nuclei in the sample as

$$A = -\frac{\Delta N}{\Delta t} = \lambda N \qquad 20.9$$

(ii) Units of Activity: A common unit of activity is the curie, abbreviated Ci, which is defined to be 3.70×10^{10} decays per second. This is approximately equal to the activity of one gram of radium. The SI unit of activity is the becquerel, abbreviated Bq. *One becquerel is one decay per second.*

$$1\ Ci = 3.70 \times 10^{10}\ Bq = 3.70 \times 10^{10}\ decays/s$$

SI unit of activity

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EXAMPLE 20.2 — **RADIUM**

The half-life of the radioactive radium (^{226}Ra) nucleus is 5.0×10^{10} s. A sample contains 3.0×10^{16} nuclei. (a) What is the decay constant for this decay? (b) How many radium nuclei will decay per second?

GIVEN

Half life '$T_{1/2}$' = 5.0×10^{10} s

Number of nuclei 'N' = 3.0×10^{16}

REQUIRED

(a) decay constant 'λ' = ?

(b) Activity 'A' = ?

SOLUTION

(a) The relation between decay constant λ and half life $T_{1/2}$ is $T_{1/2} = \frac{0.693}{\lambda}$

Rearranging $\lambda = \frac{0.693}{T_{1/2}}$ Putting values $\lambda = \frac{0.693}{5 \times 10^{10} s}$

therefore $\lambda = 1.4 \times 10^{-11} s^{-1}$ — **Answer**

(b) The activity is $A = \lambda N$ Putting values $A = 1.4 \times 10^{-11} s^{-1} \times 3 \times 10^{16}$

$$A = 4.2 \times 10^5\ decays/s = 4.2 \times 10^5\ Bq$$

therefore $A = 4.2 \times 10^5\ Bq = 0.42\ MBq$ — **Answer**

In curies this activity can also be written as $1Bq = \frac{1}{3.70 \times 10^{10}} Ci$

Multiplying both sides by 4.2×10^5 we get $4.2 \times 10^5 Bq = \frac{4.2 \times 10^5}{3.70 \times 10^{10}} Ci$

$$4.2 \times 10^5 Bq = 1.135 \times 10^{-5} Ci = 0.11 \mu Ci$$

ASSIGNMENT 20.2 — **CARBON**

The radioisotope of carbon ^{14}C has a half-life of 5730 yr. If a sample contains 1.00×10^{22} carbon-14 nuclei, what is the activity of the sample?

(Answer: 3.83×10^{10} Bq)

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20.9 INTERACTION OF RADIATION WITH MATTER

Interaction of ionizing radiation with matter is divided into three groups.

A. INTERACTION OF CHARGED PARTICLES

Charged particles (electrons (e-), positrons (e+), protons (P), deuterons (d), alphas (α), heavy ions (A > 4)) traveling through matter lose energy in the following ways:

1. In Coulomb interactions with electrons and nuclei
2. By emission of electromagnetic radiation (bremsstrahlung)
3. In nuclear interactions

B. INTERACTION OF PHOTONS

There is a long list of possible interactions of photons (gammas (γ) or X-rays), but only the three most important ones are:

1. The photoelectric effect
2. Compton scattering, and
3. Pair production.

C. INTERACTION OF NEUTRONS

Since a neutron (n) has no charge, it interacts with nuclei only through nuclear forces. When it approaches a nucleus, it does not have to go through a Coulomb barrier. As a result, the probability (cross section) for nuclear interactions is higher for neutrons than for charged particles. The interactions of neutrons with nuclei are divided into two categories:

1. scattering and
2. absorption

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20.10 RADIATION DETECTORS

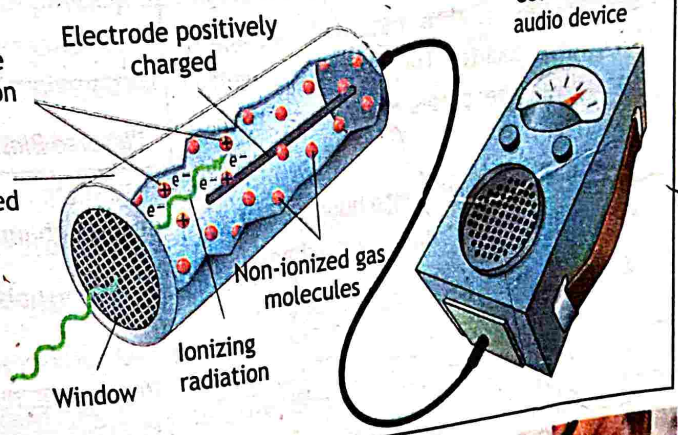
Nuclear radiations are measured with the effect they produce when interacting with matter. The function of the detector is to produce a signal for every particle or photon entering into it. Every detector works by using some interaction of particles with matter. There are many types of radiation detectors, however we would study only two in detail.

1. Geiger-Muller counters
2. Semiconductor detectors

A. GEIGER-MULLER COUNTERS

It is the most widely used device to detect radiation. It consist of cylindrical metal tube filled with gas at low temperature and long wire along the axis of the tube. The wire is maintained at high positive potential with respect to tube. The metal tube is attached with detection system such as counter and audio device as shown in the figure.

FIGURE 20.13



When high energy particle or photon enters the tube trough the thin window at one end some of the atoms of the gas ionizes as shown in figure 20.13. Since the wire is at positive potential the electrons removed from atoms are attracted towards the wire.



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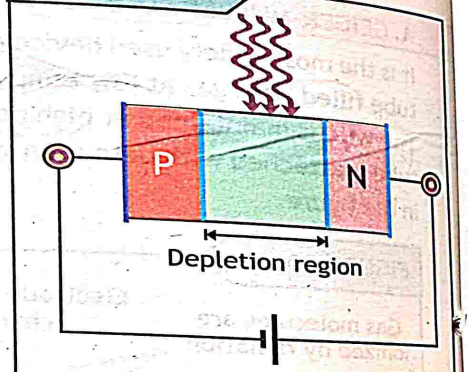
In the process they ionize other atoms in their path. This results in an avalanche of electrons that produces a pulse at the detection system. Which is amplified and counted by counter and sound is produced.

B. SOLID STATE DETECTORS

A solid state detector is a device that uses a semiconductor (usually silicon or germanium) to detect charged particles or photons. A solid state detector is usually a reverse bias PN junction diode, connected to the pulse detection system.

A P-N junction of semiconductor is placed under reverse bias, thus no current flows. When ionizing radiation is allowed to pass through the depleted region it excites electrons into the conduction band. Thus electrons are moved towards positive terminal and holes towards negative terminal of battery, causing a temporary conduction as shown in figure 20.14. This electric pulse is then measured through an electric counter. The electronics used to analyze the pulses does more than counting.

FIGURE 20.14



Reverse Bias PN Junction Diode

It separates the pulses into hundreds of groups called channels. Therefore, the equipment is often called multi-channel analyzer.

20.11 NUCLEAR REACTIONS

A nuclear reaction is said to occur whenever an incident nucleus, particle, or photon causes a change to occur in a target nucleus.

Such a structural change can be brought about in the nucleus by bombarding the target by sufficiently energetic particle such as neutrons, alpha particles etc. As a results the nucleons are added, removed or rearranged within a target nucleus. A process in which nuclear transmutation is done by bombarding target nuclei with energetic light particles is known as induced nuclear reaction. In such nuclear processes the conservation laws must be followed.

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When Nucleus X is bombarded with some light particle a the product nucleus Y and light particle b will be obtained by nuclear reaction. Mathematically

$$a + X \rightarrow Y + b$$

In 1919, Ernest Rutherford observed that when an α particle strikes a nitrogen nucleus, an oxygen nucleus and a proton are produced. This nuclear reaction is written as

$$^{4}_{2}He + ^{14}_{7}N \rightarrow ^{17}_{8}O + ^{1}_{1}H + Q$$

The energy equivalent of the difference between the rest masses of the elements on both sides of nuclear reaction is called nuclear reaction energy 'Q'. If 'Q' is positive energy is released in the reaction, if 'Q' is negative energy is absorbed in the reaction. Few other examples of nuclear reaction are

$$^{1}_{1}H + ^{13}_{6}C \rightarrow ^{14}_{7}N + \gamma \quad \text{and} \quad ^{1}_{0}n + ^{10}_{5}B \rightarrow ^{7}_{3}Li + ^{4}_{2}He$$

CONSERVATION LAWS IN NUCLEAR REACTION

A conservation of physical quantity means that for all the process taking place in a system that particular physical quantity remains constant. The following laws of conservation are obeyed for nuclear processes.

- Conservation of charge
- Conservation of Energy (mass inclusive)
- Conservation of linear and angular momentum
- Conservation of nucleon number

The two conservation laws will be discussed.

A. CONSERVATION OF NUCLEON NUMBER

Before and after the reaction the sum of number of protons and neutrons should remain constant.

Number of nucleons on LHS - Number of nucleons on RHS

For example in the reaction $^{4}_{2}He + ^{14}_{7}N \rightarrow ^{17}_{8}O + ^{1}_{1}H + Q$

We can see that on both sides there are (14 + 4 = 17 + 1 = 18) nucleons.

B. CONSERVATION OF MASS ENERGY

Since the mass number differ from atomic masses and difference provides binding energy to nucleons in the nucleus therefore energy conservation should also hold apart from conservation of nucleon number. This also include energy difference due to change in mass from Einstein mass energy relation.

For example in the reaction $^{4}_{2}He + {}^{14}_{7}N \rightarrow {}^{17}_{8}O + {}^{1}_{1}H + Q$

nuclear reaction energy Q can be calculated as

LHS $^{4}_{2}He = 4.00263\,u$, $^{14}_{7}N = 14.00307\,u$, $= 18.005677\,u$

RHS $^{1}_{1}H = 1.007825\,u$, $^{17}_{8}O = 16.999133\,u$, $= 18.006958\,u$

Since Q is the rest mass difference, therefore Q = 18.005677 u - 18.006958 u

$$Q = -0.001281\ u = -1.192\ MeV$$

As Q is negative therefore α-particle having kinetic energy 1.192 MeV can induce such a reaction.

EXAMPLE 20.3 — **NUCLEAR REACTION**

What is the least energy does the proton have to make the following nuclear reaction possible?

$$^{1}_{1}H + {}^{13}_{6}C \rightarrow {}^{14}_{7}N + {}^{1}_{0}n$$

The mass of hydrogen ^{1}H is 1.007825 u, carbon ^{13}C is 13.003355 u, neutron ^{1}n is 1.008665 u and nitrogen ^{13}N is 13.005739 u.

GIVEN

Mass of hydrogen '^{1}H' = 1.007825 u

Mass of carbon '^{13}C' = 13.003355 u

Mass of neutron '^{1}n' = 1.008665 u

Mass of nitrogen '^{13}N' = 13.005739 u

REQUIRED

Proton energy Q = ?

SOLUTION

nuclear reaction energy Q can be calculated as

LHS $^{1}_{1}H = 1.007825\,u$, $^{13}_{6}C = 13.003355\,u$, $= 14.011180\,u$

RHS $^{13}_{7}N = 13.005739\,u$, $^{1}_{0}n = 1.008665\,u$, $= 14.014404\,u$

Since Q is the rest mass difference, therefore Q = 14.011180 u - 14.014404 u, this means that **Q = - 0.003224 u**, therefore

Q = - 0.003224 u × 931.5 MeV/u = 3.003156 MeV = 3.00 MeV — **Answer**

The negative sign shows that the reaction is endothermic, and proton would require more than 3.00 MeV energy to give excess energy to neutron and nitrogen after formation.

ASSIGNMENT 20.3 — **NUCLEAR REACTION**

The following reaction requires an input of energy equal to 2.438 MeV.

$$^{1}_{1}H + {}^{18}_{8}O \rightarrow {}^{18}_{9}F + {}^{1}_{0}n$$

The mass of hydrogen ^{1}H is 1.007825 u, oxygen ^{18}O is 17.999160 u and neutron ^{1}n is 1.008665 u. **[Answer: 18.000937 u]**

20.12 NUCLEAR FISSION

The process of splitting of nuclei into intermediate size nuclei is called nuclear fission. The fission process often produces free neutrons and photons (in the form of gamma rays), and releases a very large amount of energy.

Nuclear fission of heavy elements was discovered on December 17, 1938 by Otto Hahn and his assistant Fritz Strassmann, and explained theoretically in January 1939 by Lise Meitner and her nephew Otto Robert Frisch. Frisch named the process by analogy with biological fission of living cells.

They found that a uranium nucleus, after absorbing a neutron, splits into two fragments, of intermediate size. The general nuclear reaction of splitting of a massive nucleus into two less massive fragments is given below.

$$^{1}_{0}n + {}^{235}_{92}U \rightarrow (^{235}_{92}U)^{*} \rightarrow X + Y + \text{neutrons}$$

Where $(^{236}U)^*$ is an intermediate excited state that lasts for only about 10^{-12} s before splitting into X and Y. The resulting nuclei X and Y are called fission fragments. There are many combinations of X and Y that satisfy the requirements of conservation of mass-energy, charge, and nucleon number as shown in figure 20.15.

The process results in the production of several neutrons, typically two or three. On the average, about 2.5 neutrons are released per event. A typical reaction of this type is

$$ {}_0^1n + {}_{92}^{235}U \rightarrow ({}_{92}^{235}U)^* \rightarrow {}_{56}^{141}Ba + {}_{36}^{92}Kr + 3\,{}_0^1n + Q $$

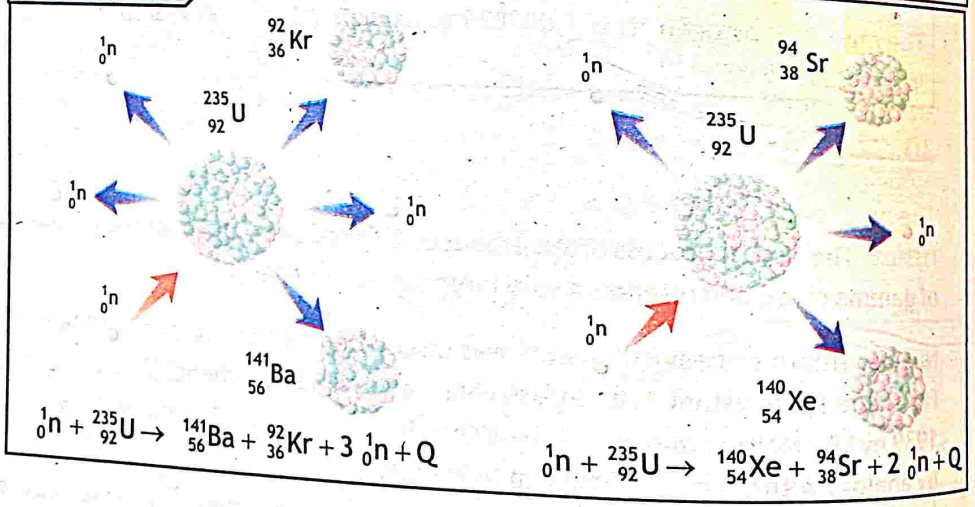
where Q is the nuclear reaction energy.

Lise Meitner (1878 - 1968)



Lise Meitner (Austrian-Swedish) physicist who contributed to the discoveries of the element protactinium and nuclear fission.

FIGURE 20.15



The energy released in this fission can be calculated as

Reactants		Products
		$^{141}_{35}Ba = 140.9139\,u$
$^1_0n = 1.0087\,u$		$^{92}_{36}Kr = 91.8973\,u$
$^{235}_{92}U = 235.439\,u$	+	$3\,{}^1_0n = 3.0261\,u$
$= 236.0526\,u$		$= 235.8373\,u$

Since Q is the rest mass difference Q = 236.0265 u - 235.8373 u

Q = 0.2153 u = 200.44 MeV

When one atom of ^{235}U undergoes this type of fission about 200 MeV energy is released. About 85% of this energy appears in the form of kinetic energy in the heavy fragments. This energy is very large compared to the energy released in chemical processes. For example, the energy released in the combustion of one molecule of octane used in gasoline engines is about one-millionth the energy released in a single uranium fission event.

A. FISSION CHAIN REACTION

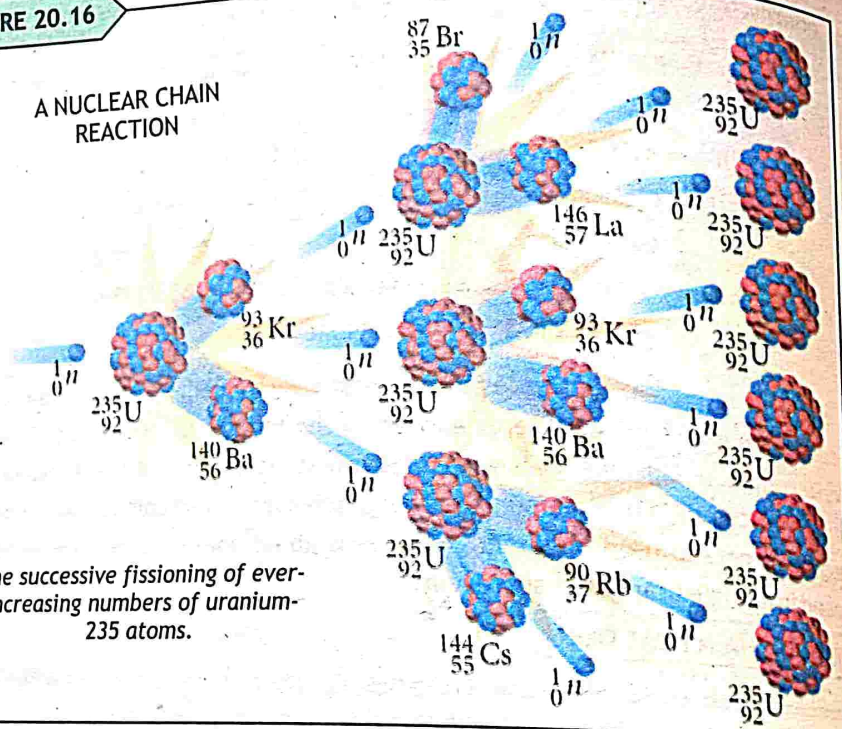
When one nuclear reaction causes an average of one or more nuclear reactions, thus a self-propagating series of these reactions is achieved and is called Fission Chain Reaction.

In a sample of uranium, each of the neutrons emitted in fission can be absorbed by another nucleus of ^{235}U and thus induce another fission process, resulting in the emission of still more neutrons, followed by more fissions, and so forth as shown in figure 20.16.

As long as the average number of neutrons available to produce new fissions is greater than 1 per reaction, the number of fissions grows with time. This series of events is called fission chain reaction, each reaction release about 200MeV. Thus energy released is very high it is found that 1 kg of uranium delivers as much energy as 3000 tons of coal.

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FIGURE 20.16



The successive fissioning of ever-increasing numbers of uranium-235 atoms.

The minimum amount of mass required to sustain a fission chain reaction is called **critical mass.** If the amount of uranium is too small the chain reaction will stop. If a chain reaction is to continue it is necessary that the mass of uranium must be greater or equal to this critical mass.

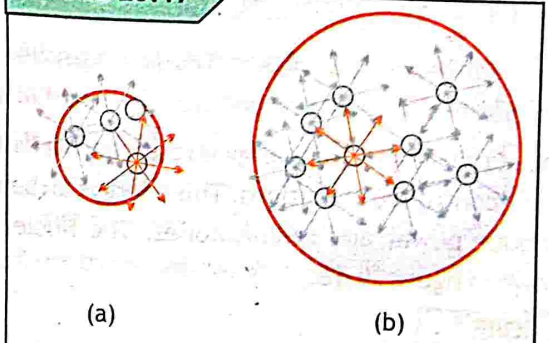
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The mass less than critical mass is called sub-critical and mass greater then critical mass is called super-critical as shown in figure 20.17.

However Natural uranium consists of only about 0.7% of ^{235}U and 99.3% ^{238}U, which means that most of the available uranium nuclei generally do not participate in the fission process but instead remove neutrons from being able to produce other fissions. To overcome this problem it is necessary to use **enriched uranium,** in which the abundance of ^{235}U is increased beyond its natural value of 0.7%.

Fission may take place in any of the heavy nuclei after capture of a neutron. However, low-energy neutrons are able to cause fission only in U-233, U-235, and Pu-239.

FIGURE 20.17



(a) (b)

(a) In a sub-critical mass, too many neutrons escape before colliding (b) in the critical mass, enough neutrons encounter other nuclei to maintain a chain reaction.



Fuel pellets contain enriched uranium-235. Each pellet contains the energy equivalent of I ton of coal.

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20.13 NUCLEAR REACTOR

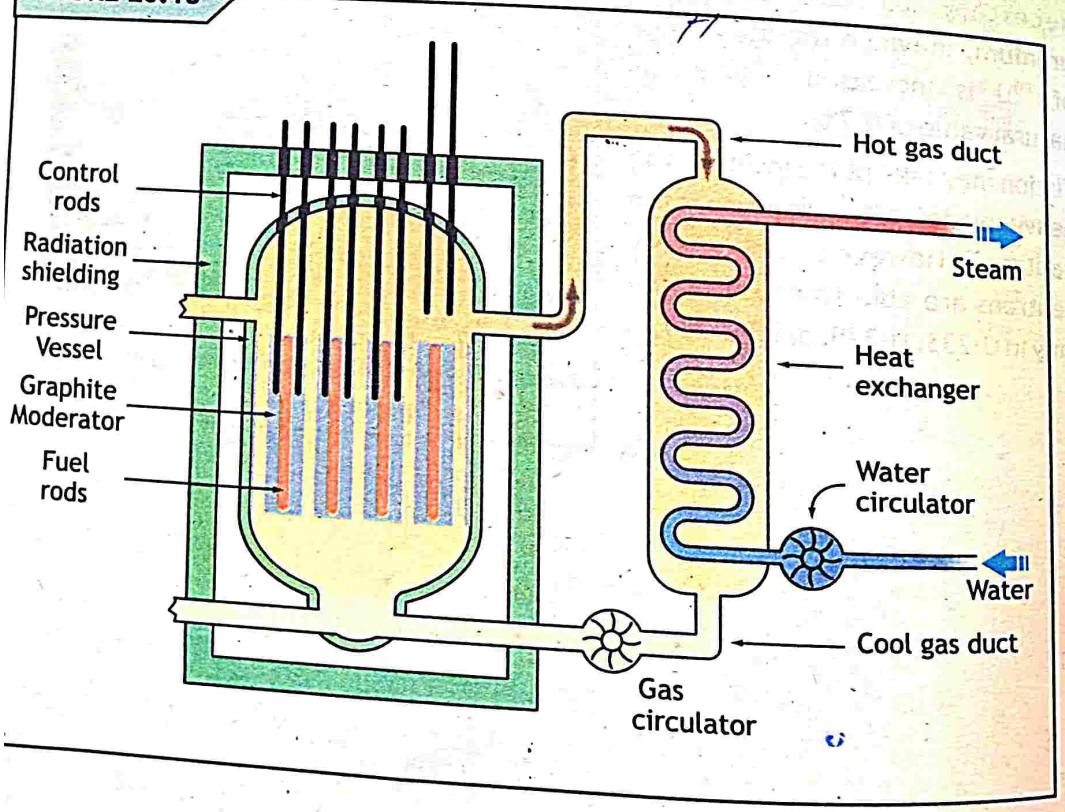
A nuclear reactor is a device that is designed to maintain a self sustaining fission reaction in a controlled manner.

Since large amount of energy is released in a fission process, therefore it is carried under controlled conditions. This energy can be used for useful purposes such as to produce power and radioisotopes. The Nuclear reactor has five main parts as shown in figure 20.18.

A. CORE

The core contain nuclear fuel in which fission is achieved by thermal neutrons, for example, the nuclear fuel may be thin rods about 1 cm in diameter. Uranium ^{235}U is a common reactor fuel. Most commercial reactors use uranium in which the amount of ^{235}U has been enriched to about3%.

FIGURE 20.18



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B. MODERATOR

The material that slows down the neutrons is called a moderator. Neutrons with energies of about 0.025 eV are used in fission of ^{235}U, the neutrons released during the fission process have greater energies of several MeV. Therefore, a nuclear reactor must contain some type of material that decrease or moderate the speed of neutrons so they can fission additional ^{235}U nuclei. The material of moderator should be light and should not absorb neutrons, usually graphite and heavy water are used as moderators.

C. CONTROL RODS

If the output power from a reactor is to remain constant, only one neutron from each fission event must start a new fission. When each fission leads to one additional fission—no more or no less—the reactor is said to be critical. A reactor normally operates in a critical condition.

Science Tidbits — **Sub-critical and Super-critical state of reactors**

What happens when reactor is not operated in critical state?

The reactor is subcritical when, on average, the neutrons from each fission trigger less than one subsequent fission. In a subcritical reactor, the chain reaction is not self-sustaining and eventually stops. When the neutrons from each fission trigger more than one additional fission, the reactor is supercritical. During a supercritical condition, the energy released by a reactor increases. If left unchecked, the increasing energy can lead to a partial or total meltdown of the reactor core.

Therefore, a control mechanism is needed to keep the reactor in its normal, or critical, state. *This control is accomplished by a number of control rods that can be moved into and out of the reactor core.* The control rods contain an element, such as boron, cadmium or hafnium, that absorbs neutrons. These control rods are moved in and out of reactor core to keep reactor in critical state.

D. COOLANT OR HEAT EXCHANGER

The coolant is used to cool the fuel rods and the moderator, and is capable of carrying away heat generated in fission process. Without Heat exchange system the core assembly can melt under enormous heat. The heat generated within the fuel rods is carried away by water that surrounds the rods. The hot water is pumped through a heat exchanger, where heat is transferred to water flowing in a second, closed system.

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The heat carried by coolant can run turbine to generate electricity. After exiting the turbine, the steam is condensed back into water that is returned to the heat exchanger.

E. SHIELDING

Since neutrons and fission fragment in the nuclear reactor produce radiations which are harmful to life and environment. There must be some process of absorbing these radiations. Usually a concrete wall with lead of a few feet thickness is used as shielding.

F. TYPES OF NUCLEAR REACTOR

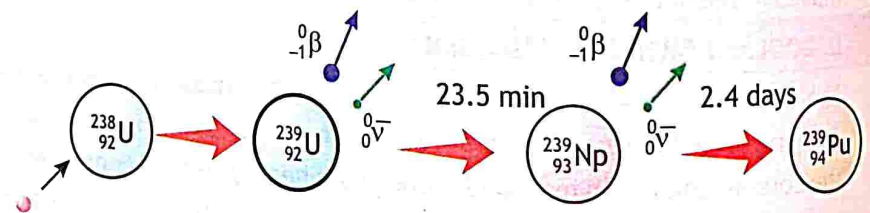
Basically there are two types of nuclear reactors based neutron energy.

I. Thermal reactors: The reactors in which thermal energy neutrons are used are called thermal reactors. There are many designs of thermal reactor. Pressurized Water Reactor (PWR) is most commonly used reactor in the world. In this reactor the water is prevented from boiling at 100°C, by providing high pressure.

ii. Fast Reactors: The reactors in which fast energy neutrons are used are called fast reactors. Fast reactor make use of ^{238}U which is about 99 % in nature. each atom of ^{238}U absorb fast neutron and the following reactions occur.

1. Neutron absorption by uranium - 238 $\quad {}_0^1n + {}_{92}^{238}U \rightarrow {}_{92}^{239}U$
2. Beta decay of uranium - 239 $\quad {}_{92}^{239}U \rightarrow {}_{93}^{239}Np + {}_{-1}^{0}\beta + {}_{0}^{0}\bar{\nu}$
3. Beta decay of neptunium - 239 $\quad {}_{93}^{239}Np \rightarrow {}_{94}^{239}Pu + {}_{-1}^{0}\beta + {}_{0}^{0}\bar{\nu}$

FIGURE 20.19



An induced nuclear reaction is shown in which Uranium - 238 is transmuted into the plutonium-239

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Absorption of a neutron by uranium-238 followed by two beta-decay reactions produces plutonium-239, which can also be used as a fission fuel. Fission can be generated in plutonium-239 by fast neutrons therefore no moderator is required in these reactors. The core of fast reactor consists of mixture of plutonium and uranium dioxide surrounded by ^{238}U blanket. Thus any neutron escaping from the core interact with ^{238}U to produce ^{239}Pu. Thus natural uranium is used to generate more nuclear fuel by the reaction as shown in the figure 20.19.

20.14 NUCLEAR FUSION

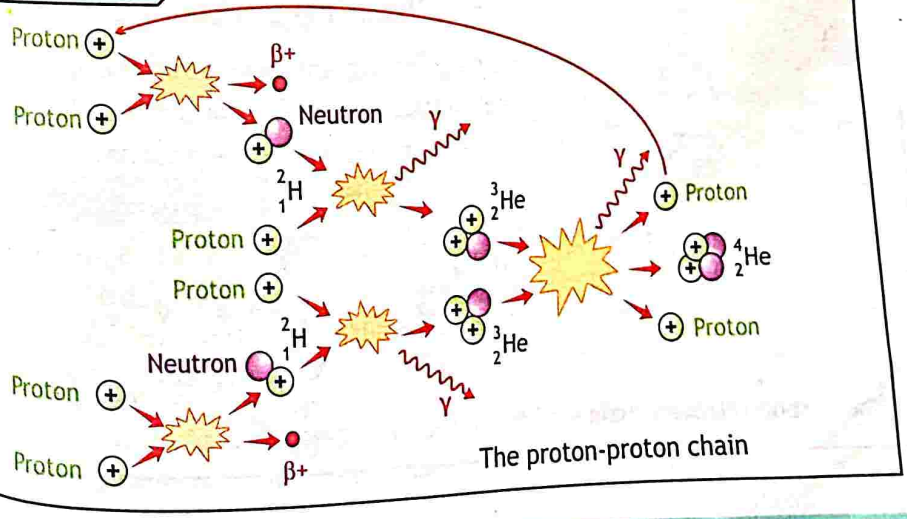
When two light nuclei combine to form a heavy nucleus, the process is called nuclear fusion. When two nuclei form a large nucleus the mass of larger nucleus is less than the mass of nuclei that formed it. This loss in mass appears in the form of energy. A self sustaining fusion reaction is also possible but the energy required is possible only in the environments of stars including sun. This cycle of reactions can be achieved at stars in two series of processes.

A. PROTON CYCLE

In this process the direct collision of protons result in the formation of heavier nuclei whose collision in tern produces helium nuclei as shown in figure 20.20. The initial reaction in proton- proton cycle is

$$ {}_1^1H + {}_1^1H \rightarrow {}_1^2H + \beta^+ + \nu $$

FIGURE 20.20



The proton-proton chain

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A deuteron produced in the above reaction may combine with other proton as

$$_1^1H + _1^2H \rightarrow _2^3He + \gamma$$

Finally, two such reactions can combine to form helium-4 with the release of two protons as

$$_2^3He + _2^3He \rightarrow _2^4He + _1^1H + _1^1H + \gamma$$

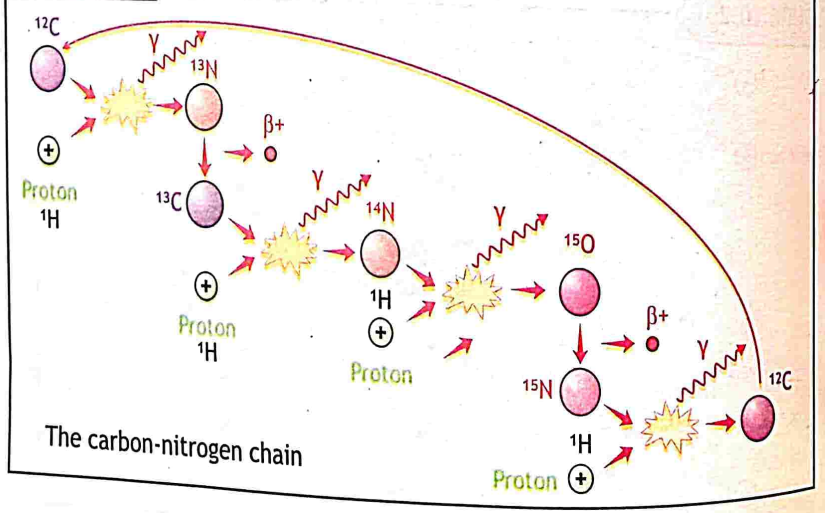
The total energy released in this process is 24.7 MeV which is the difference between the masses of 4 protons and mass of alpha particle plus two positrons.

	Reaction	Energy released
step 1	$_1^1H + _1^1H \rightarrow _1^2H + \beta^+ + \nu$ (twice)	0.42 MeV (twice)
step 2	$_1^1He + _1^2He \rightarrow _2^3He + \gamma$ (twice)	5.49 MeV (twice)
step 3	$_2^3He + _2^3He \rightarrow _2^4He + _1^1H + _1^1H + \gamma$	12.85 MeV
step 4	$_1^0\beta + _{-1}^0\beta \rightarrow 2\gamma$ (twice)	1.02 MeV (twice)
Total	$4\,_1^1H \rightarrow _2^4He + 2_1^0\beta + 2\nu + 7\gamma$	26.71 MeV

B. CARBON CYCLE

The carbon cycle proceeds as shown in figure 20.21.

FIGURE 20.21



The carbon-nitrogen chain

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Since proton-proton cycle is more efficient at low temperature so stars cooler as compared to sun may fuel their energy from proton-proton cycle. Whereas carbon cycle is more efficient at high temperature therefore bright stars at high temperature will favor carbon cycle.

	Reaction	Energy released
step 1	$_1^1H + _6^{12}C \rightarrow _7^{12}N^*$	1.95 MeV
step 2	$_7^{12}N \rightarrow _6^{13}C + \beta^+ + \nu$	1.20 MeV
step 3	$_1^1H + _6^{13}C \rightarrow _7^{14}N + \gamma$	7.54 MeV
step 4	$_1^1H + _7^{14}N \rightarrow _8^{15}O^* + \gamma$	7.35 MeV
step 5	$_8^{15}O \rightarrow _7^{15}N + \beta^+ + \nu$	1.73 MeV
step 6	$_1^1H + _7^{15}N \rightarrow _6^{12}C + _2^4He$	4.96 MeV
step 7	$_1^0\beta + _{-1}^0\beta \rightarrow 2\gamma$ (twice)	1.02 MeV (twice)
Total		26.73 MeV

The energy liberated in fusion of light nuclei into heavier nuclei is called **thermonuclear energy**, especially when it is achieved at earth. However this energy cannot be used in controlled manner in self sustaining cycle. Worldwide effort is underway to harness energy from fusion in laboratory, after the test of first successful Thermonuclear Bomb (hydrogen bomb).

20.15 RADIATION EXPOSURE

All living creatures, from the beginning of time, have been, and are still being, exposed to radiation. when a radiation detector is used it will record these radiations called natural background radiation, it comes from three sources

A. COSMIC RADIATION

The earth, and all living things on it, are constantly bombarded by radiation from space, The dose from cosmic radiation varies in different parts of the world due to differences in elevation and to the effects of the earth's magnetic field.

B. INTERNAL RADIATION

All people also have radioactive potassium-40, carbon-14, lead-210, and other isotopes inside their bodies from birth.

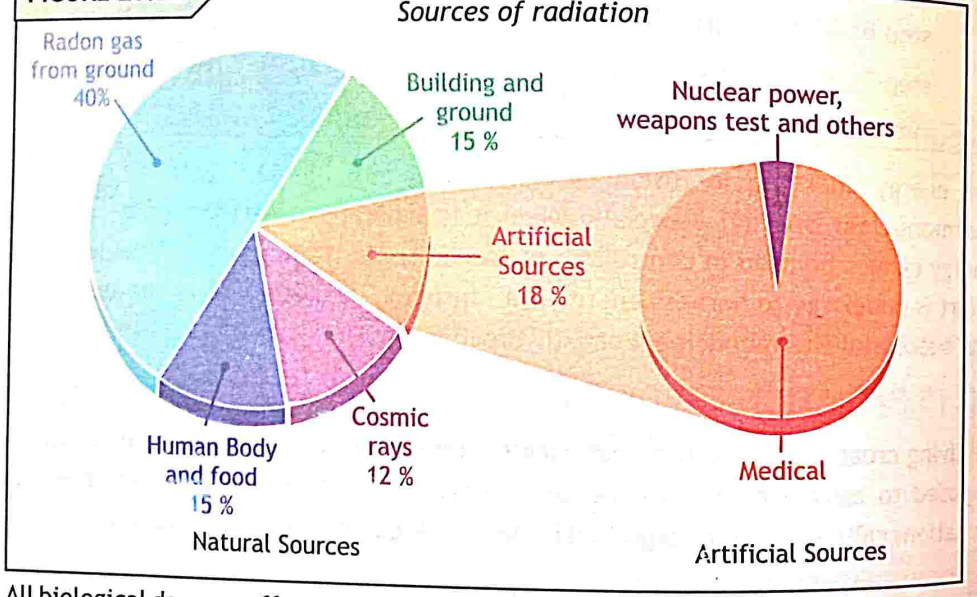
C. TERRESTRIAL RADIATION

Radioactive material is also found throughout nature. It is in the soil, water, and vegetation. The dose from terrestrial sources also varies in different parts of the world.

The major isotopes of concern for terrestrial radiation are uranium and the decay products of uranium, such as thorium, radium, and especially radon. We cannot see it, smell it, or taste it, but radon is the leading source of natural radiation exposure. Building materials and ground always emit these radiations.

Radiation exposure may result from artificial sources (source produced by men), the most significant source of man-made radiation exposure to the public is from medical procedures, such as diagnostic X-rays, nuclear medicine, and radiation therapy, as shown in figure 20.22.

FIGURE 20.22



All biological damage effects begin with the consequence of radiation interactions with the atoms forming the cells. The cell damage may lead to two effects.

i. Somatic Effect: The effects which appears soon after irradiation. Such as skin burns, loss of hair and induction of cancer.

ii. Genetic effects: These effects may not appear in the individual life but damage genes and chromosomes that affect future generations.

20.17 BIOLOGICAL AND MEDICAL USES OF RADIATION

Although scientists have only known about radiation since the 1890s, they have developed a wide variety of uses for this natural force. Today, radiation is used in medicine, academics, and industry.

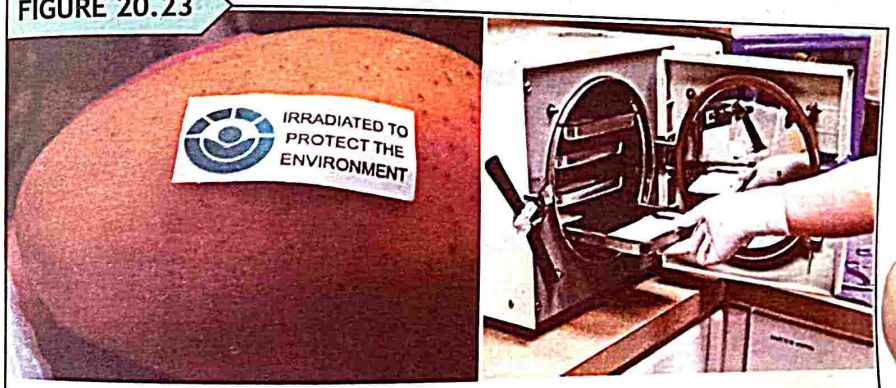
A. BIOLOGICAL USES

Nuclear techniques are used in farming and agricultural communities to combat disease and provide other benefits.

i. Food Preservation: Gamma rays can be used to kill bacteria, mould and insects in food.

ii. Sterilizing: Gamma rays are also used to sterilize hospital equipment, especially plastic syringes that would be damaged if heated.

FIGURE 20.23



Preserving food and sterilization of medical equipment

iii. Insect Control: Controlling insects with chemicals can create environmental problems and result in toxic residues in food. The major way of controlling insects without the use of chemicals is the Sterile Insect Technique.

iv. Chemical Study: The chemical changes in living organism can be studied through tracer method. For example the process of photosynthesis and incorporation of carbon atoms in CO_2 into giant protein or Carbohydrate molecules have been investigated by tracer technique.

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B. MEDICAL USES

One of the most important applications of nuclear physics has been in medicine, for both diagnostic and therapeutic purposes.

i. Medical diagnostics: Radioactive isotopes are used in medical diagnosis as tracers. Radioactive isotopes are introduced in the body in chemical forms that have an affinity for certain organs, such as bone or the thyroid gland. For medical diagnosis, the radionuclide commonly used today is ^{99m}Tc long-lived excited state of technetium-99 (the "m" in the symbol stands for 'metastable' state).

A sensitive detector (called a "gamma-ray camera") can observe the radiations from the isotopes that are concentrated in the organ and can produce an image that shows how the activity is distributed in the patient. These detectors are capable of determining where each gamma-ray photon originates in the patient as shown in figure 20.24.

FIGURE 20.24



Gamma Camera

For your information

POSITRON EMISSION TOMOGRAPHY (PET)

Another technique that reveals information inside the body is positron emission tomography (PET), in which the patient is injected with a positron-emitting isotope that is readily absorbed by the body. Examples of isotopes used are ^{15}O ($t_{1/2}$ = 2 min), ^{13}N ($t_{1/2}$ = 10 min), ^{11}C ($t_{1/2}$ = 20 min), and ^{18}F ($t_{1/2}$ = 110 min). These isotopes are produced with a cyclotron. By surrounding the patient with a ring of detectors, it is possible to determine exactly where the decay occurred, and from a large number of such events, an image is produced that reconstructs the distribution of the radioisotope in the patient.

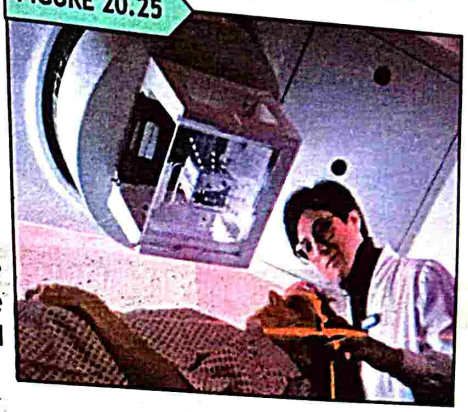
ii. Radiation therapy: Radiation therapy is the use of high-energy radiation to damage cancer cells' DNA and destroy their ability to divide and grow.

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The radioactive source such as cobalt 60 which emit beta particles and high energy gamma rays can also be used to treat various cancers as shown in figure 20.25.

Some radioisotopes are made to absorb by selected organ and radiation is concentrated on the infected tissue. For example cancerous thyroid can be treated with iodine-131.

FIGURE 20.25



20.18 BASIC FORCES OF NATURE (Fundamental Interactions)

All particles in nature are subjected to four fundamental forces, strong force, weak force, electromagnetic force and gravitational force.

A. STRONG FORCE

The strong force is very short range about 10^{-14} m and is responsible for binding of nucleons in the nucleus. It can be considered as an exchange force in which the exchange particles are gluon. It is the strongest of all the forces and have been assigned as relative strength 1.

B. ELECTROMAGNETIC FORCE

Fundamentally, both magnetic and electric forces are manifestations of an exchange force involving the exchange of photons. The electromagnetic force holds atoms and molecules together. It has infinite range and relative strength is 10^{-2}.

C. WEAK FORCE

Weak interaction involves the exchange of the intermediate vector bosons, the W and the Z. The weak interaction changes one flavor of quark into another. It is very short range about 0.1% of diameter of proton i.e 10^{-18} m. It have relative strength of about 10^{-6}.

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D. GRAVITATIONAL FORCE

Gravity is long range force and is the weakest of the four fundamental forces having relative strength of 10^{-43}, yet it is the dominant force in the universe for shaping the large scale structure of galaxies, stars, etc. Viewed as an exchange force, the massless exchange particle is called the graviton (however it is not confirmed yet).

Table 20.5 PARTICLE INTERACTIONS

Force	Particle acted on by force	Relative strength	Typical Lifetimes for decay via given interaction (s)	Force carrying exchange particle
Strong	Quarks, hadrons	1	10^{-20}	gluons
Electromagnetic	Charge particles	10^{-2}	10^{-16}	photons
Weak	Quarks, Leptons	10^{-7}	10^{-10}	$W^{\pm}$ and Z^0 bosons
Gravitational	All particles	10^{-43}	?	gravitons

20.19 BUILDING BLOCKS OF MATTER

Beginning in about 1945, many new particles were discovered in experiments involving high-energy collisions between known particles. Such particles are highly unstable and have very short half-lives, ranging between 10^6 and 10^{23} s. So far, more than 400 of these unstable, temporary particles have been catalogued.

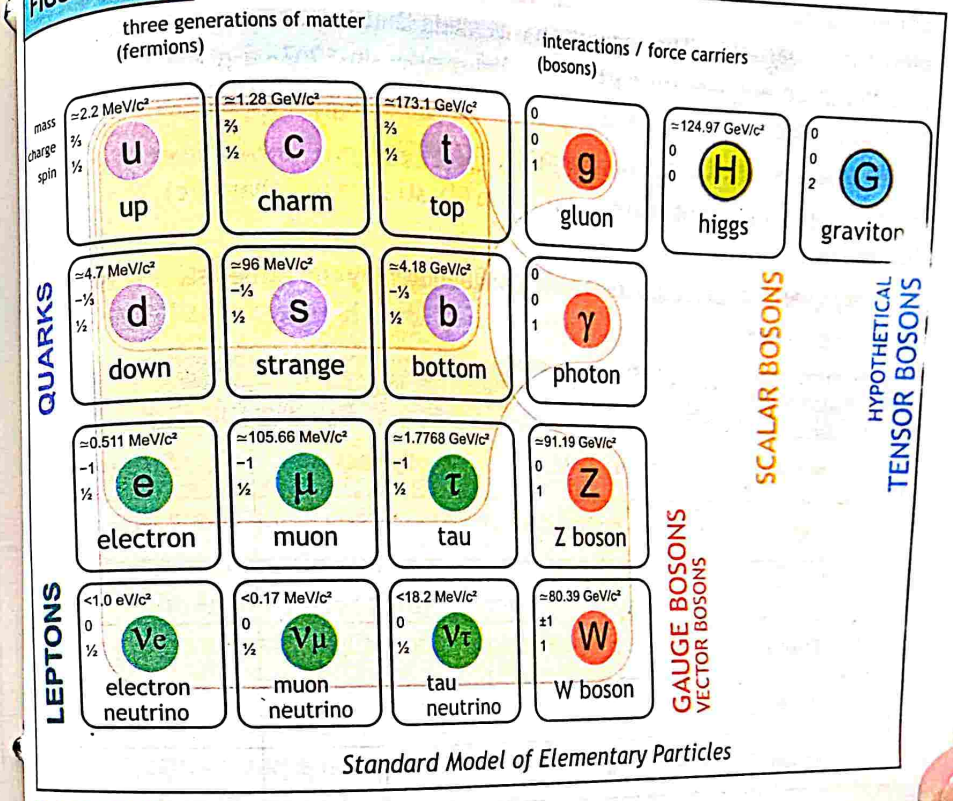
It is useful to group the known particles into three families—the bosons, the leptons, and the hadrons.

A. BOSONS

The boson family is composed of particles that play central roles in nature's fundamental forces. The photon is associated with the electromagnetic force. The W^-, W^+, and Z^0 particles are associated with the weak nuclear force. The gluons are associated with the strong nuclear force, whereas the graviton is thought to be associated with the gravitational force.

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FIGURE 20.26



Standard Model of Elementary Particles

B. LEPTONS

The lepton family consists of particles that interact by means of the weak nuclear force. Leptons can also exert gravitational and (if the leptons are charged) electromagnetic forces on other particles. The four better-known leptons are the electron, the muon, the electron neutrino ν_e, and the muon neutrino ν_μ. Two other leptons have also been discovered, the tau particle τ and its neutrino ν_τ, bringing the number of particles in the lepton family to six. No internal structure for leptons is observed so far, therefore they are considered to be elementary.

C. HADRONS

The hadron family contains the particles that interact by means of both the strong nuclear force and the weak nuclear force. Hadrons can also interact by gravitational and electromagnetic forces, but at short distances the strong nuclear force dominates. Among the hadrons are the proton, the neutron, and the pions. The hadrons are subdivided into two groups, the mesons and the baryons.

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As more and more hadrons were discovered, it became clear that they were not all elementary particles. The suggestion was made that the hadrons are made up of smaller, more elementary particles called quarks. In 1963, a quark theory was initiated independently by M. Gell-Mann (1929-) and G. Zweig (1937-).

Quark Model is based on the following assumptions:

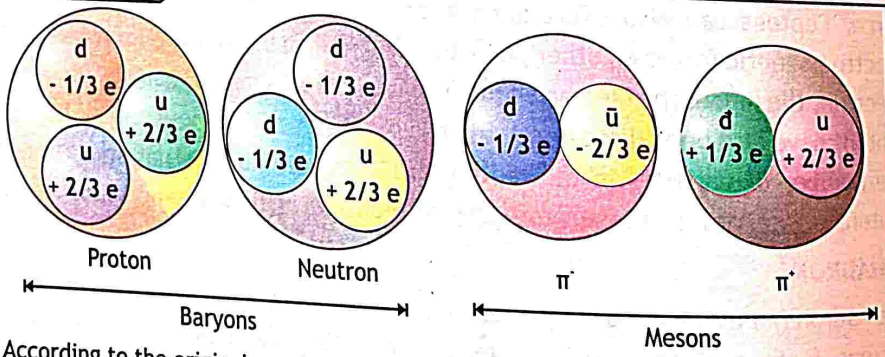
1. There are six types of quark up (u), down (d), strange (s), charm (c), top (t) and bottom (b).

2. Every quark has corresponding antiquark denoted by the same letter with a bar over it.

Table 20.6 QUARKS

Name	Mass (GeV/c²)	Symbol	Charge
up	0.004	u	+ 2/3
down	0.008	d	- 1/3
strange	0.15	s	- 1/3
charm	1.5	c	+ 2/3
bottom	4.7	b	- 1/3
top	176	t	+ 2/3

FIGURE 20.27



According to the original quark model of hadrons, all mesons consist of a quark and an antiquark, whereas baryons contain three quarks.

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3. Quarks combine in three to form baryons (proton, neutron, sigma e.t.c.) and antiquarks combine in three to form anti-baryons (anti-proton, anti-neutron, anti-sigma e.t.c.) as shown in figure 20.27.

4. Quarks combine with antiquarks in twos to form mesons.

D. COLOR CHARGE

Electric charge comes in only one kind (positive) and its opposite (negative), but strong charge comes in three kinds (called red, blue, and green), each of which has an opposite (called antired, antiblue, and antigreen). Color charge has nothing to do with the colors of light that we perceive visually. They are based on an analogy: just as the red, blue, and green dots produced by different phosphors on a TV screen combine to make white, a red quark, blue quark, and green quark combine to form a colorless (white) combination. All free particles have a color charge of zero. A baryon always contains one quark of each color, an antibaryon always contains one antiquark of each anticolor, and a meson always contains a quark of one color and an antiquark of the corresponding anticolor, such as a red quark and an antired antiquark. In each case, the strong force holds quarks together in colorless combinations, similar to the way the electromagnetic force holds negative and positive charges together to form a neutral atom with zero net electric charge.

Red + green + blue = white $\quad r+g+b=0$

Anti-Red (cyan) + Anti-green (magenta) + Anti-blue (yellow) = white

$$\bar{r}+\bar{g}+\bar{b}=0$$

red + anti-red = white, green + anti-green = white, blue + anti-blue = white

$$r+\bar{r}=g+\bar{g}=b+\bar{b}=0$$

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KEY POINTS

Nucleons: The protons and neutrons present in the nucleus

Isotopes: Nuclei of an element that have the same charge number Z, but have different mass number A.

Atomic mass unit (u): the mass of 12^{th} part of the mass of carbon -12 atom.

Binding energy: the energy needed to separate nucleus into individual protons and neutrons. Binding energy per nucleon gives the stability of the nucleus, larger the value more stable the nucleus.

Radioactivity: the emission of rays from the nuclei of atoms

Activity: the number of disintegrations per unit time

Random process: A process without defined pattern, rule or method

Spontaneous process: A process occurring without apparent external cause

becquerel (Bq): SI unit for rate of decay of a radioactive material

Decay constant: quantity that is inversely proportional to the half-life and that is used in equation for number of nuclei as a function of time

Half life: The time in which there is a 50% chance that a nucleus will decay

Nuclear Reaction: an incident nucleus, particle, or photon causes a change to occur in a target nucleus.

Nuclear reaction energy: the energy created in a nuclear reaction

Radiation detector: a device that is used to detect and track the radiation from a radioactive reaction

Nuclear fission: nuclear reaction in which a nucleus splits

Critical mass: minimum amount necessary for self-sustained fission of a given nuclide

Nuclear fusion: a reaction in which two nuclei are combined, or fused, to form a larger nucleus

Quark: an elementary particle and a fundamental constituent of matter

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GLOSSARY

Atria: the heart is divided into four chambers that are connected by heart valves. The upper two heart chambers are called atria.
Alternating Current: the current that changes its direction many times in a second is called alternating current.
Ammeter: a device to measure amperes (current).
Ampere: unit of current.
Alternator: a device that changes mechanical energy into an alternating current (electrical energy) e.g, an AC generator.
Cerebrospinal fluid (CSF): a clear colorless bodily fluid found in the brain and spine.
Conductor: a material that permits a very free exchange/movement of electrons from one atom to another.
Conventional Flow: this theory states that electrons flow from positive (+) to negative (-) potential.
Current: the rate of flow of charge.
Direct Current : unidirectional current is called Direct Current.
Dysfunction: abnormality in the function of an organ or part.
Dynamoelectric machine: a dynamo or generator
Disgorge: taken out from the throat what has been eaten.
Dynamo: from the Greek word dynamis, which means power.
Dynamoelectric: relating to the conversion by induction of mechanical energy into electrical energy or vice versa.
Extra-terrestrial sources: sources that are existing or originating outside the limits of the earth.
Electromagnets : a device consisting of a core of magnetic material surrounded by a coil that create a magnetic field through the application of electricity.
Electromagnetic Induction: the creation of e.m.f. due to relative motion of conductor and magnet.
Electroplaque: these are cells used by electric eels, and other fish for electrogenesis.
Frequency: the number of cycles in one second of alternating current.
Generator: a device that changes mechanical energy into electrical energy.
Insulators: materials that don't readily give up electrons, thereby restricting the flow of current.
Peak inverse voltage (PIV): the maximum voltage V_m the diode can withstand during reverse bias is known as peak inverse voltage (PIV).

Myelin: a white tissue forming an insulating sheath (**myelin sheath**) around certainnerve fibres. Damage to the myelin sheath causes neurological disease, as in multiple sclerosis.
Motor: a device that changes electrical energy into mechanical energy.
Muon: a negatively charged subatomic particle, with the same charge as an electron.
Ohm: unit of resistance.
Ohm's Law: current is directly proportional to voltage and inversely proportional to resistance.
Permanent Magnets: it retain their magnetism after a magnetizing force is removed.
Resistance : the restriction to the flow of electrons.
RMS Value: Root Mean Square Current is also referred to as effective current and is the square root of the average of all the instantaneous currents.
Single-Phase: a continuous single alternating current cycle.
Spectrum: spectrum means set of frequencies absorbed or emitted by a substance.
Terrestrial sources: sources that are existing or originating inside the limits of the earth.
Three-Phase: a continuous series of three overlapping AC cycles offset by 120 degrees.
Transformer: a device used to raise (step up) or lower (step down) a voltage level.
Ventricle: a chamber of the heart that receives blood from an atrium and pumps it to the arteries.
Voltage Drop: voltage value as measured across each resistor or load.
Voltmeter: a device to measure voltage.
Waveform: the shape of the curve obtained by plotting the instantaneous values of voltage or current as ordinate against time as abscissa is called its waveform or wave shape.
Watt: the basic unit of power, indicating the amount of work accomplished when one volt causes one ampere to pass through a circuit.

Authors Profile

Shaukat Ali Taran did his M.Sc in Physics from University of Peshawer in 1988. He also did Master in Education. He is the author and editor of many books of physics. He has 25 years teaching experience in different colleges, including Cadet College, Kohat. Currently, he is working as a Professor in Government Post Graduate College, Timergara (Dir Lower).

Shadab Gul did his M.Sc in Physics from University of Peshawer in 1996. He taught various classes for more than 20 years at school as well as college level. Currently he is working as Assistant Professor in Government Post Graduate College, Lakki Marwat.

Abdul Baseer did his M.Sc in Physics from University of Peshawer in 1990. Currently he is working as a professor in Edwardes College, Peshawer.

Abdur-Rehman did his M.Sc in Physics from University of Peshawer in 2008. He taught Physics in various private and govt institutions. Currently he is working as a Lecturer in Durrani School and College, Peshawer.

Dr. Muhammad Naeem Khalid remained Chairman of Physics Department, Islamia College, Peshawer.

Aamir Ullah Khan has obtained MS - Physics and is currently working as 'Director' at Pakistan Virtual College, Hayatabad Peshawar.
He is the co-author of general science textbooks for grade 6, grade 7 and grade 8 under the National Book Foundation. He is also the co-author of physics textbooks for grade 9, grade 10 and grade 11 of Khyber Pakhtunkhwa Textbook Board, Peshawar.

Hafiz Mehar Elahi did MS/M.Phil Physics from Qurtuba University of Science and Information Technology, Peshawar. Recently honoured with Best Chaperone Award by GIK Institute of Sciences and Information Technology. He got First position in BS-Physics from Govt College Peshawar in 2014 affiliated with UOP.Currently he is working as Lecturer in Physics at Peshawar Model Degree, College.



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