ATOMS AND THEIR STRUCTURE

A basic understanding of the fundamental concepts of current and voltage requires a degree of familiarity with the atom and its structure. The simplest of all atoms is the hydrogen atom, made up of two basic particles, the **proton** and the **electron,** in the relative positions shown in Fig. 1(a). The **nucleus** of the hydrogen atom is the proton, a positively charged particle. *The orbiting electron carries a negative charge that is equal in magnitude to the positive charge of the proton.* In all other

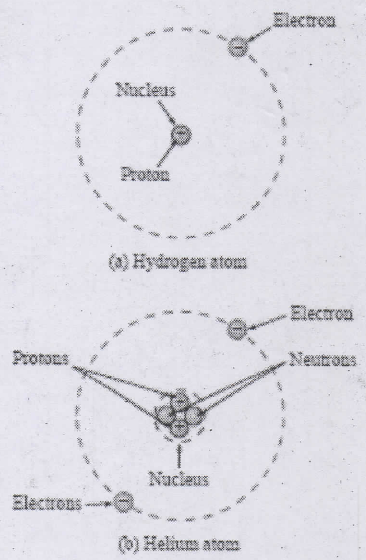


Fig.1

elements, the nucleus also contains **neutrons,** which are slightly heavier than protons and have no electrical charge. The helium atom, for example, has two neutrons in addition to two electrons and two protons, as shown in Fig. 1(b). *In all neutral atoms the number of electrons is equal to the number of protons.* The mass of the electron is $9.11 * 10^{-28}$ g, and that of the proton and neutron is $1.672 * 10^{-24}$ g. The mass of the proton (or neutron) is therefore approximately 1836 times that of the electron. The radii of the proton, neutron, and electron are all of the order of magnitude of $2 * 10^{-15}$ m.

For the hydrogen atom, the radius of the smallest orbit followed by the electron is about 5 $*10^{-11}$ m. The radius of this orbit is approximately 25,000 times that of the radius of the electron, proton, or neutron. This is approximately equivalent to a sphere the size of a dime revolving about another sphere of the same size more than a quarter of a mile away. Different atoms will have various numbers of electrons in the concentric shells about the nucleus. The first shell, which is closest to the nucleus, can contain only two electrons. If an atom should have three electrons, the third must go to the next shell. The second shell can contain a maximum of eight electrons; the third, 16; and the fourth, 32; as determined by the equation $2n^2$, where n is the shell number. These shells are usually denoted by a number (n = 1, 2, 3, . . .) or letter (n _ $k, l, m,$ . . .). Each shell is then broken down into subshells, where the first subshell can contain a maximum of two electrons; the second subshell, six electrons; the third, 10 electrons; and the fourth, 14; as shown in Fig. 2. The subshells are usually denoted by the letters s, p, d, and f, in that order, outward from the nucleus.

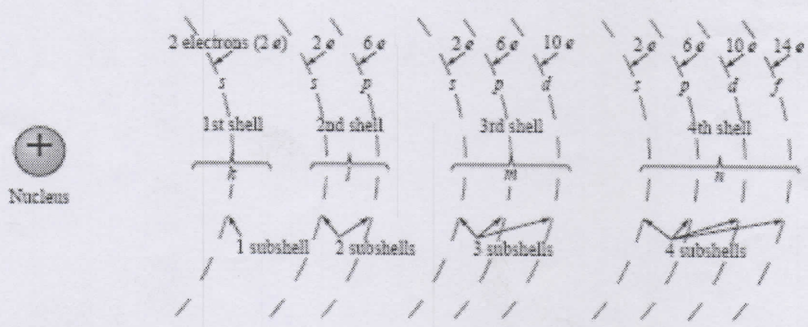


Fig.2

It has been determined by experimentation that *unlike charges attract, and like charges repel.* The force of attraction or repulsion between two charged bodies $Q1$ and $Q2$ can be determined by **Coulomb's law:**

$$\boxed{F \text{ (attraction or repulsion)} = \frac{kQ_1Q_2}{r^2}} \quad \text{(newtons, N)}$$

Where F is in newton, k = a constant = $9.0 * 10^9$ N·m^2/C^2, $Q1$ and $Q2$ are the charges in coulombs , and r is the distance in meters between the two charges. In particular, note the squared r term in the denominator, resulting in rapidly decreasing levels of F for increasing values of r.

In the atom, therefore, electrons will repel each other, and protons and electrons will attract each other. Since the nucleus consists of many positive charges (protons), a strong attractive force exists for the electrons in orbits close to the nucleus [note the effects of a large charge Q and a small distance r in above Eq.] . As the distance between the nucleus and the orbital electrons increases, the binding force diminishes until it reaches its lowest level at the outermost subshell (largest r). Due to the weaker binding forces, less energy must be expended to remove an electron from an outer subshell than from an inner subshell. Also, it is generally true that electrons are more readily removed from atoms having outer subshells that are incomplete *and,* in addition, possess few electrons. These properties of the atom that permit the removal of electrons under certain conditions are essential if motion of charge is to be created. Without this motion, this text could venture no further—our basic quantities rely on it.

CONDUCTORS, INSULATORS and SAEMICONDUCTORS

Different wires placed across the same two battery terminals will allow different amounts of charge to flow between the terminals. Many factors, such as the density, mobility, and stability characteristics of a material, account for these variations in charge flow. In general, however, **conductors** ***are those materials that permit a generous flow of electrons with very little external force (voltage) applied.***

In addition,

good conductors typically have only one electron in the valence (most distant from the nucleus) ring.

Since **copper** is used most frequently, it serves as the standard of comparison for the relative conductivity in Table 1. Note that aluminum, which has seen some commercial use, has only 61% of the conductivity level of copper, but keep in mind that this must be weighed against the cost and weight factors.

Insulators ***are those materials that have very few free electrons and require a large applied potential (voltage) to establish a measurable current level.***

Table 1

Relative conductivity of various materials.

Metal	Relative Conductivity (%)
Silver	105
Copper	100
Gold	70.5
Aluminum	61
Tungsten	31.2
Nickel	22.1
Iron	14
Constantan	3.52
Nichrome	1.73
Calorite	1.44

It must be pointed out, however, that even the best insulator will break down (permit charge to flow through it) if a sufficiently large potential is applied across it. The breakdown strengths of some common insulators are listed in Table 2. According to this table, for insulators with the same geometric shape, it would require 270/30 = 9 times as much potential to pass current through rubber compared to air and approximately 67 times as much voltage to pass current through mica as through air.

Table 2

Breakdown strength of some common insulators.

Material	**Average Breakdown Strength (kV/cm)**
Air	30
Porcelain	70
Oils	140
Bakelite	150
Rubber	270
Paper (paraffin-coated)	500
Teflon	600
Glass	900
Mica	2000

Semiconductors ***are a specific group of elements that exhibit characteristics between those of insulators and conductors.***

The prefix *semi,* included in the terminology, has the dictionary definition of *half, partial,* or *between,* as defined by its use. The entire electronics industry is dependent on this class of materials since electronic devices and integrated circuits (ICs) are constructed of semiconductor materials. Although *silicon* (Si) is the most extensively employed material, *germanium* (Ge) and *gallium arsenide* (GaAs) are also used in many important devices.

Semiconductor materials typically have four electrons in the outermost valence ring.

Semiconductors are further characterized as being photoconductive and having a negative temperature coefficient. Photoconductivity is a phenomenon where the photons (small packages of energy) from incident light can increase the carrier density in the material and thereby the charge flow level. A negative temperature coefficient reveals that the

resistance will decrease with an increase in temperature (opposite to that of most conductors).

In the isolated atomic structure there are discrete (individual) energy levels associated with each orbiting electron, as shown in Fig. 3a. Each material will, in fact, have its own set of permissible energy levels for the electrons in its atomic structure.

The more distant the electron from the nucleus, the higher the energy state, and any electron that has left its parent atom has a higher energy state than any electron in the atomic structure.

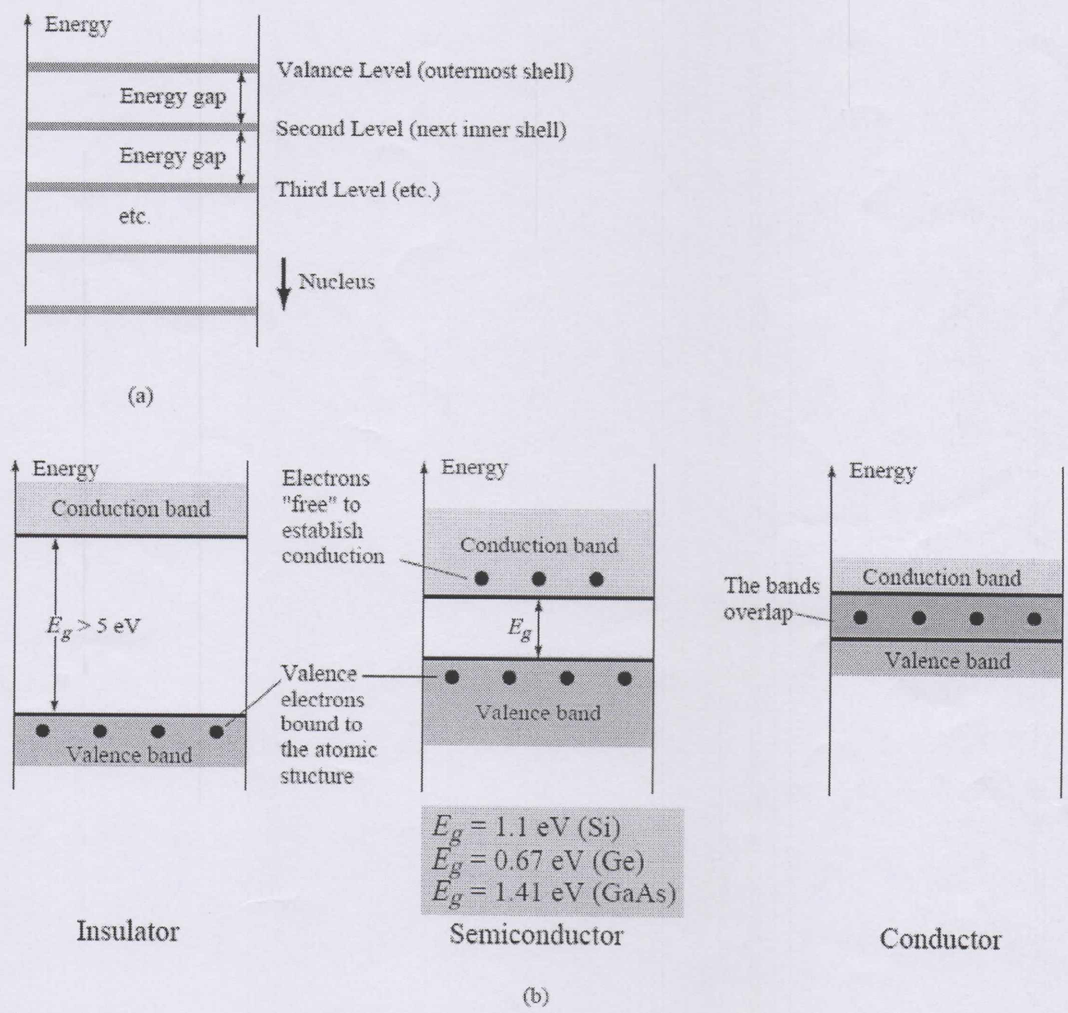


Figure 3 Energy levels: (a) discrete levels in isolated atomic structures; (b) conduction and valence bands of an insulator, semiconductor, and conductor.

Between the discrete energy levels are gaps in which no electrons in the isolated atomic structure can appear. As the atoms of a material are

brought closer together to form the crystal lattice structure, there is an interaction between atoms that will result in the electrons in a particular orbit of one atom having slightly different energy levels from electrons in the same orbit of an adjoining atom. The net result is an expansion of the discrete levels of possible energy states for the valence electrons to that of bands as shown in Fig. 3b. Note that there are boundary levels and maximum energy states in which any electron in the atomic lattice can find itself, and there remains a *forbidden region* between the valence band and the ionization level. Recall that ionization is the mechanism whereby an electron can absorb sufficient energy to break away from the atomic structure and enter the conduction band.

Coulomb's Law :-

The electrostatic interaction for two charged particles is given by Coulomb's law, as follows: The electrostatic interaction between two charged particles is proportional to their charge and to the inverse of the square of the distance between them, and its direction is along the line joining the two charges.

This may be expressed mathematically by

$$F = K_e \frac{qq'}{r^2} \quad \text{---- (1)}$$

where r is the distance between the two charge q and q', F is the force acting on either charge and K_e is a constant to be determine by our choice of units. For ~~par~~ practical and Computational resone it is more convenient to express K_e in the form.

$$K_e = \frac{1}{4\pi\epsilon_0}$$

where ϵ_0 is called the vacuum permittivity.

$$\therefore \quad F = \frac{q q'}{4\pi \epsilon_0 r^2} \qquad \text{(coulomb's Law)} \ldots \text{(c)}$$

we must include the charges q and q' with their signs. A negative value of F corresponds to attraction and a positive value corresponds to repulsion.

The value of K_e is $\Longrightarrow K_e = 9 * 10^9$,

~~while ϵ_0 = to~~

The unit of charge is Coulomb and is designated by symbol C, may establish the following definition:

The Coulomb is that charge which, when it is palced one meter from an ~~$10^{-7} c^2$ or 8.987×10^9 newtons.~~ equal charge in vacuum, repels it with a force of $10^{-7} c^2$ or $8.9874 * 10^9$ newtons.

while $\epsilon_0 = \frac{10^7}{4\pi c^2} = 8.854 * 10^{-12} \ N^{-1} m^{-2} C^2$

or $m^{-3} kg^{-1} s^2 C^2$

Ex: given the charge arrangement of Fig. 1, where $q_1 = +15 * 10^{-3}$ C $q_2 = -0.5 * 10^{-3}$ C, $q_3 = 0.2 * 10^{-3}$ C, and AC = 1.2 m, BC = 0.5 m, find the resultant force on charge q_3.

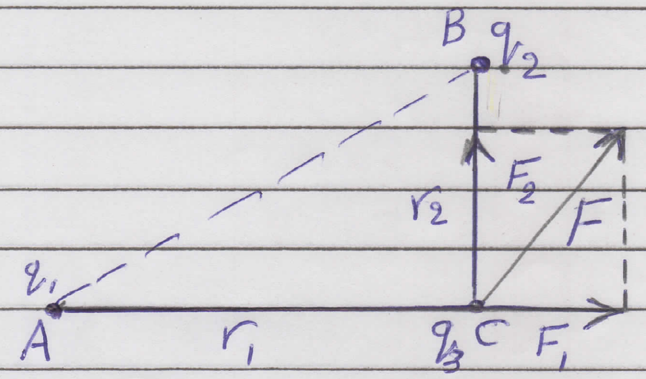


Fig. 1

Solution:

The force F_1 between q_1 and q_3 is repulsive, while the force F_2 between q_2 and q_3 is attractive. their respective values when used Coulomb's law

$$F_1 = \frac{q_1 q_3}{4\pi \epsilon_o^2 r_1^2} = 1.9 * 10^3 \text{ N}$$

$$F_2 = \frac{q_2 q_3}{4\pi \epsilon_o r_2^2} = -3.6 * 10^3 \text{ N}$$

therefore the resultant force is

$$F = \sqrt{F_1^2 + F_2^2}$$

$$= 4.1 * 10^3 \text{ N}$$

Electric Field :-

In any region where an electric charge experiences a force we say there is an electric field. The force is due to the presence of other charge in that region. For example, a charge q placed in a region where there are other charge q_1, q_2, q_3, etc. (Fig. 2) experiences a force

$$F = F_1 + F_2 + F_3 \text{ ---- ---- } \quad (3)$$

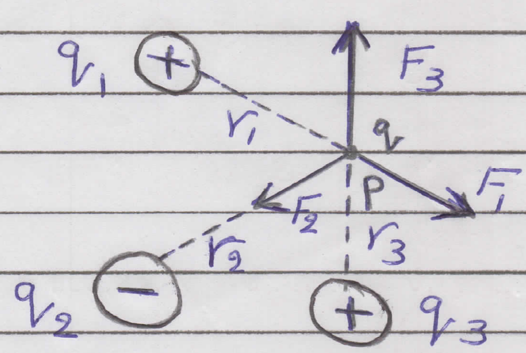


Fig. 2

and we say that there is an electric field produced by the charge q_1, q_2, q_3 ... (The charge q of course also exerts forces on q_1, q_2, q_3 ..., but we are not concerned with them now). Since the force that each charge q_1, q_2, q_3 ... produces on the charge q is proportional to q. Thus the force on a particle placed in an electric

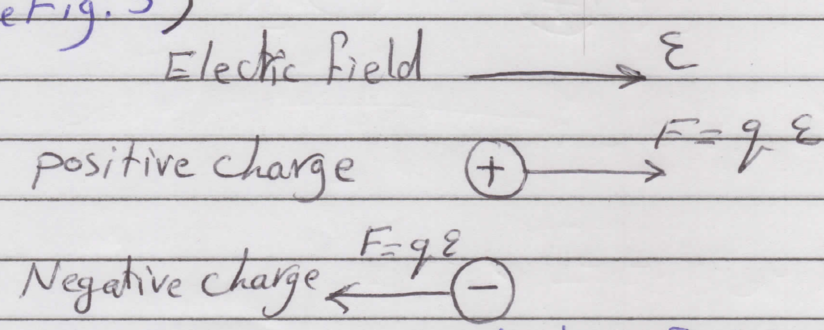
field is proportional to the charge of the particle.

The intensity of the electric field at a point is equal to the force per unit charge placed at that point. The symbol is $\mathcal{E}$. Therefore

$$\mathcal{E} = \frac{F}{q} \quad \text{or} \quad F = q\,\mathcal{E} \quad \ldots (4)$$

The electric field intensity $\mathcal{E}$ is expressed in newtons/coulomb or N/C, or using fundamental units $m\ Kg\ s^{-2}\ C^{-1}$.

If q is positive, the force F acting on the charge has the same direction as the field $\mathcal{E}$, but if q is negative, the force F has the direction opposite to $\mathcal{E}$ (see Fig. 3)



Fig(3)

Therefore if we apply an electric field to a region where positive and negative particles or ions are present, the field will tend to move the positively and negatively

charged bodies in opposite directions resulting in a charge separation, an effect sometimes called polarization.

A uniform electric field has the same intensity and direction everywhere. Obviously a uniform field is represented by parallel lines of force (see fig. 4). The best way of producing a uniform electric field is by charging, with equal and opposite charges two parallel metal plates. Symmetry indicates that the field is uniform.

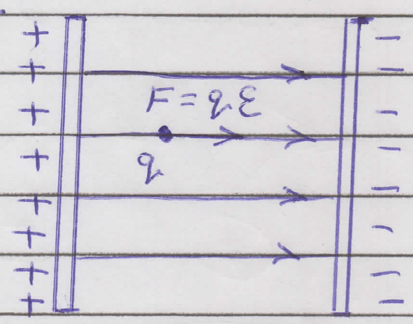


Fig. 4

when $F = q'\left(\frac{q}{4\pi\epsilon_0 r^2}\right)$

$F = q'\mathcal{E}$

$$\therefore \quad \mathcal{E} = \frac{q}{4\pi\epsilon_0 r^2} \quad \text{------} \quad (5)$$

on the vector form $\mathcal{E} = \frac{q}{4\pi\epsilon_0 r^2} u_r$ ------ (6)

where u_r is the unit vector in the radial direction, away from the charge q, since F is along this direction

equ (6) is valid for both positive and negative charges with the direction of $\mathcal{E}$ relative to u_r given by the sign of q. Thus $\mathcal{E}$ is directed away from a positive charge and toward a negative charge. Fig (5) indicate the electric field at points near a positive and negative charges.

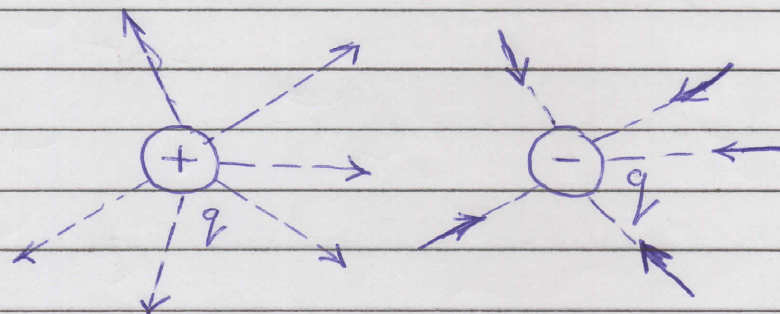
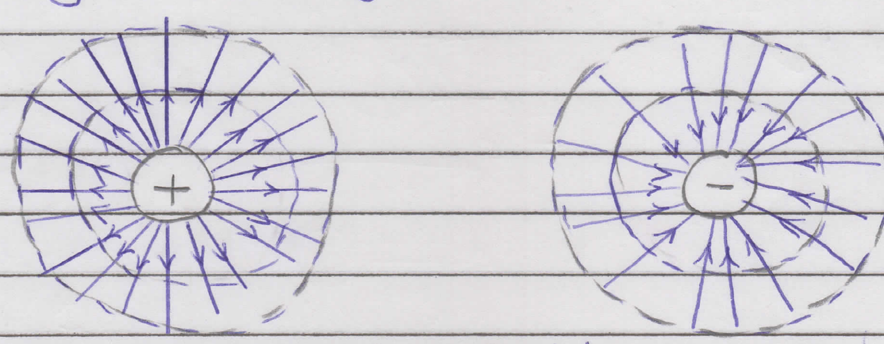


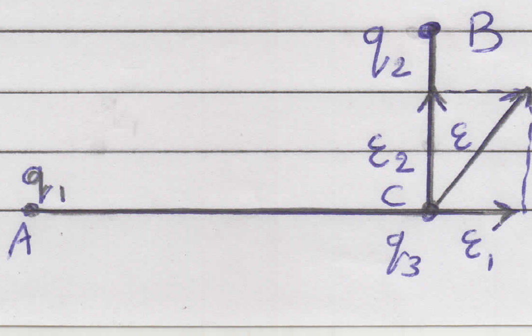
Fig (5)

The lines of force of the electric field of a positive and of a negative charge are shown in fig (6). They are straight lines passing through the charge.

fig (6)



Ex :- determine the electric field produce by charges q_1 and q_2 at C in fig below when $q_1 = +1.5 \times 10^{-3}$ C , $q_2 = -0.5 \times 10^{-3}$ C , $q_3 = 0.2 \times 10^{-3}$ C and AC = 1.2 m BC = 0.5 m



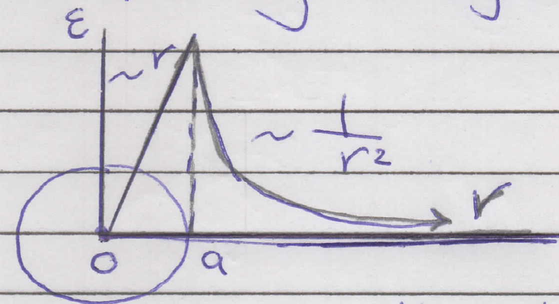
$$\mathcal{E}_1 = \frac{q_1}{4\pi\epsilon_0 r_1^2} = 0.94 * 10^7 \ N \ C^{-1}$$

$$\mathcal{E}_2 = \frac{q_2}{4\pi\epsilon_0 r_2^2} = 1.8 * 10^7 \ N \ C^{-1}$$

therefore the resultant field is

$$\mathcal{E} = \sqrt{\mathcal{E}_1^2 + \mathcal{E}_2^2} = 2.03 * 10^7 \ N \ C^{-1}$$

The electric field of a uniformly charged ~~sphere~~ sphere



The field of a sphere of radius a with a charge Q uniformly distributed throughout all its volume is given at all exterior points $(r > a)$ by

$$\mathcal{E} = \frac{Q}{4\pi\epsilon_0 r^2} \qquad r > a \qquad \text{----} \ (7)$$

$$\mathcal{E} = \frac{Qr}{4\pi\epsilon_0 a^3} \qquad r < a \qquad \text{----} \ (8)$$

Electric potential :

A charge particle placed in an electric field has potential energy because of its interaction with the field. The electric potential at a point is defined as the potential energy per unit charge place at the point. Designating the electric potential by V and the potential energy of a charge q by E_p, we have

$$V = \frac{E_p}{q} \quad \text{or} \quad E_p = qV \quad \text{---} \ (9)$$

The electric potential is measured in Joules/Coulomb or JC^{-1}, a unit called a volt abbreviated V.

If a charge q moves from one point P_1 to another point P_2 along any path, the work done by the electic field

$$W = E_{p_1} - E_{p_2} = q\,(V_1 - V_2)$$

which gives the different in potential between point P_1 and P_2

$$(V_1 - V_2) = \frac{W}{q} \quad \text{---} \ (10)$$

Thus we may define the electric potential different

between two points as the work done by the electric field in moving the unit charge from one point to the other. For example, there is a potential difference of one volt between two points if the electric field does a work of one Joule in moving a charge of one Coulomb from one point to the other. A new unit of energy called the electron volt, abbreviated eV. An electron volt is equal to the work done on a particle of charge e when it moves through a potential difference of one volt. $eV = (1.6021 * 10^{-19} C)(1V) = 1.6021 * 10^{-19} J$.

The component $\mathcal{E}_s$ of the electric field along the direction corresponding to a displacement ds is given by

$$\mathcal{E}_s = -\frac{dV}{ds} \quad \text{-----} \quad (11)$$

the negative sign shows that the electric field points in the direction in which the electric potential decreases. Equation (11) indicates that the electric field can also be expressed in Volt/meter, a unit which is equivalent

to newton/Coulomb given before. This can be seen in the following way

$$\frac{\text{volt}}{\text{meter}} = \frac{\text{Joule}}{\text{Coulomb-meter}} = \frac{\text{newton-meter}}{\text{Coulomb-meter}} = \frac{\text{newton}}{\text{coulomb}}$$

By Common usage, the term volt/meter, abbreviated Vm^{-1}, is preferred to NC^{-1}.

eq. (11) is used to find the electric potential V when the field $\mathcal{E}$ is known, and Conversely. We shall illustrate the method in two simple Cases.

(a) Uniform Field

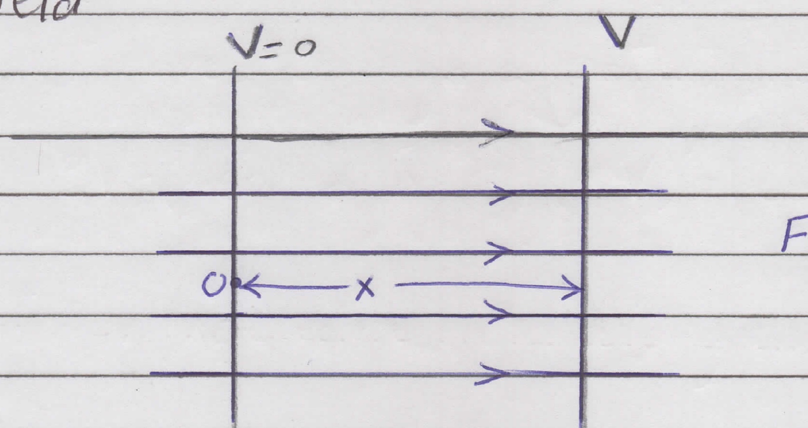


Fig (7)

placing the X-axis parallel to the uniform field (Fig 7)

$$\mathcal{E} = -\frac{dV}{dx}$$

Since $\mathcal{E}$ is constant, and we assume V=0 at x=0 by integration we have

$$\int_0^V dV = -\int_0^x \mathcal{E}\, dx = -\mathcal{E}\int_0^x dx \quad \text{or} \quad V = -\mathcal{E}x \quad \ldots (12)$$

we may note that because of the negative sign in eq. (12) the electric field points in the direction in which the electric potential decrease. when we consider two points X_1 and X_2, Eq. 12 gives

$V_1 = -\mathcal{E} X_1$ and $V_2 = -\mathcal{E} X_2$

subtracting we have

$V_2 - V_1 = -\mathcal{E}(X_2 - X_1)$

or calling $d = x_2 - x_1$

$$\mathcal{E} = -\frac{V_2 - V_1}{d} \quad \text{or} \quad \mathcal{E} = \frac{V_1 - V_2}{d}$$

Although this relation is valid only for uniform electric fields, it can be used to estimate the electric field between two points separated a distance d if the potential difference $V_1 - V_2$ between them is known. If the potential difference $V_1 - V_2$ is positive the field points in the direction from X_1 to X_2, and if it is negative the field points in the opposite direction.

Electric potential of a point charge To obtain the electric potential due to a point charge, we use Eq. (11) with s replaced by the distance r, since the electric field it produces is along the radius that is

$$\mathcal{E} = -\frac{dV}{dr}$$

when $\mathcal{E} = \frac{q}{4\pi \epsilon_0 r^2}$

$$\therefore \frac{1}{4\pi\epsilon_0}\frac{q}{r^2} = -\frac{dV}{dr}$$

Integrating and assuming $V=0$ for $r=\infty$

$$\int_0^V dV = \frac{-q}{4\pi\epsilon_0}\int_\infty^r \frac{dr}{r^2}$$

The result of these integration is

$$V = \frac{q}{4\pi\epsilon_0 r}$$

The electric potential V is positive or negative depending on the sign of the charge q.

If we have Several charges $q_1, q_2, q_3 \ldots$ the electric potential at known point is

$$V = \frac{q_1}{4\pi\epsilon_0 r_1} + \frac{q_2}{4\pi\epsilon_0 r_2} + \frac{q_3}{4\pi\epsilon_0 r_3} + \cdots = \frac{1}{4\pi\epsilon_0}\sum_i \frac{q_i}{r_i}$$

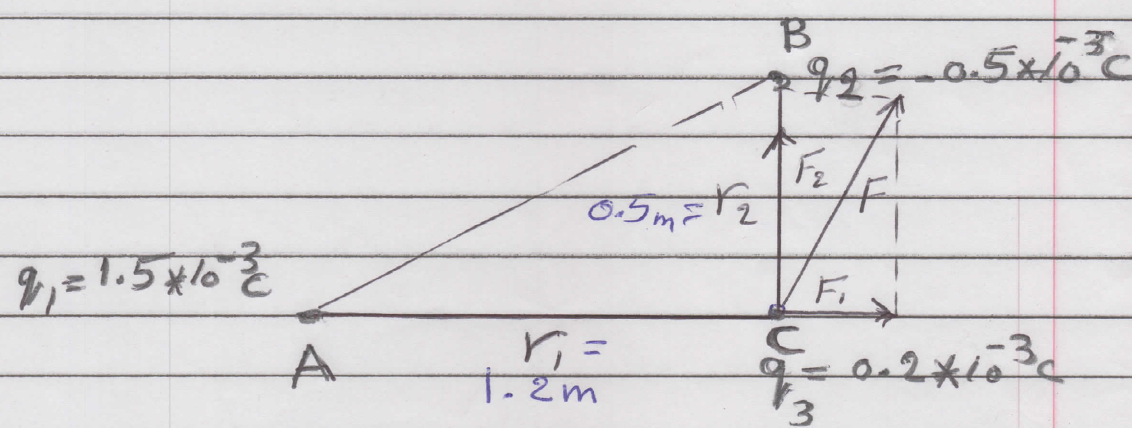
If we place a charge q' at a distance r from a charge q, the potential energy of the system is $E_p = qV$

$$E_p = \frac{qq'}{4\pi\epsilon_0 r}$$

and the potential energy of a system of charge is

$$E_p = \sum_{\substack{all \\ pairs}} \frac{qq'}{4\pi\epsilon_0 r}$$

Ex: Find the electric potential energy of charge q_3 for below Fig.



The electric potential produced at C by charge q_1 and q_2 at A and B are respectively.

$$V_1 = \frac{q_1}{4\pi\epsilon_0 r_1} = 11.2 \times 10^6 \ V$$

$$V_2 = \frac{q_2}{4\pi\epsilon_0 r_2} = -9 \times 10^6 \ V$$

the total electric potential

$$V = V_1 + V_2 = 2.2 \times 10^6 \ V$$

The potential energy of charge q_3 is

$$E_p = q_3 V = 0.2 \times 10^{-3} \times 2.2 \times 10^6 = 4.4 \times 10^2 \ J$$

Energy Relation in an Electric Field :-

The total energy of a charged particle or ion of mass m and charge q moving in an electric field is

$$E = E_K + E_p = \frac{1}{2} m v^2 + q V \quad \text{---} (13)$$

when the ion moves from position P_1 (where the electric potential is V_1) to position P_2 (where the potential is V_2), Eq. (13) Combined with the principle of Conservation of energy, gives.

$$\frac{1}{2} m v_1^2 + q V_1 = \frac{1}{2} m V_2^2 + q V_2$$

$$\therefore \quad \frac{1}{2} m V_2^2 - \frac{1}{2} m v_1^2 = q (V_1 - V_2) \quad \text{---} (14)$$

Note from Eq. (14) that a positively charged particle ($q > 0$) gains kinetic energy when moving from a Larger to a smaller potential ($V_1 > V_2$), while a negatively charged particle ($q < 0$), to gain energy, has to move from a lower to a higher potential ($V_1 < V_2$)

If we choose the zero of electric potential at P_2 ($V_2 = 0$) and arrange our experiment so that at P_1 the ions have zero velocity ($v_1 = 0$) Eq. (14) becomes (dropping the subscripts)

$$\frac{1}{2} m v^2 = q V$$

an expression that gives the kinetic energy acquired by a charged particle when it moves through an electric potential difference V.

Electric Current

The intensity of an electric current is defined as the electric charge passing per unit time through a section of the region where it flows, such as a section of an accelerator tube or of a metallic wire. Therefore if, in time t, N charged particles, each carrying a charge q, pass through a section of the conducting medium, the total charge passing being.

$$Q = Nq \quad \text{--- (15)}$$

the intensity of the current is

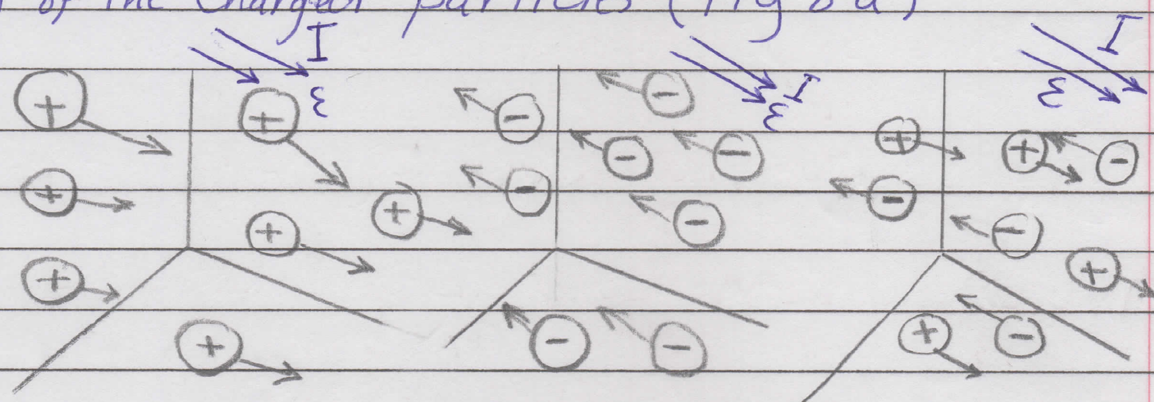
$$I = \frac{Q}{t} \quad \text{--- (16)}$$

Actually the above expression gives the average current in time t; the instantaneous current is

$$I = \frac{dQ}{dt} \quad \text{--- (17)}$$

The electric current is expressed in coulombs/second or $C s^{-1}$, a unit called the ampere (abbreviated A)

The direction of an electric current is assumed to be that of the motion of the positively charged particles. It is the same direction as that of the applied electric field or of the potential drop which produces the motion of the charged particles (Fig 8 a)



(a) positive charge (b) Negative charge (c) positive and negative charges

Fig (8) motion of positive and negative ions resulting in an electric current I produced by an electric field ε.

Therefor if a current is due to the motion of negatively charged particles, such as electrons, the direction of the current is opposite to the actual motion of the electrons (fig 8 b). Maintaining an electric current requires energy because the moving ions are accelerated by the electric field. Suppose that in time t there are N ions each with

charge q, which move through a potential difference V. Each ion gains an energy qV, and the total energy they gain is

$$\text{Energy gained} = NqV = QV \quad \text{--- (18)}$$

The energy per unit time, or the power required to maintain the current, is then

$$P = \frac{QV}{t} = VI \quad \text{--- (19)}$$

Eq. (19) which is of general validity, gives the power required to maintain an electric current I through a potential difference V applied to two points of any conducting media.

$$\text{Volts} \times \text{amperes} = \frac{\text{Joules}}{\text{Coulomb}} \times \frac{\text{Coulombs}}{\text{second}}$$

$$= \frac{\text{Joules}}{\text{second}} = \text{watts}$$

Example :- The accelerating potential in a Van der Graaff accelerator is 4×10^6 V. The particles are protons (or hydrogen ions). The ion current is 10^{-4} A. Find

ⓐ the velocity of the proton when striking the target

ⓑ the power required to drive the accelerator

$\frac{1}{2} m v^2 = q V$

$v = \sqrt{2 q V / m}$

q/m for proton is 9.579×10^7

$\therefore \quad v = 2.77 \times 10^7 \ m\, s^{-1}$

b The power

$P = 4 \times 10^6 \times 10^{-4} = 400 \ W$

Ch3 Mutual Magnetic And Electric Effects:

Motion of charge in electric field :-

The equation of motion of an electric charge in an uniform electric field ($\vec{\mathcal{E}}$) is given by equations

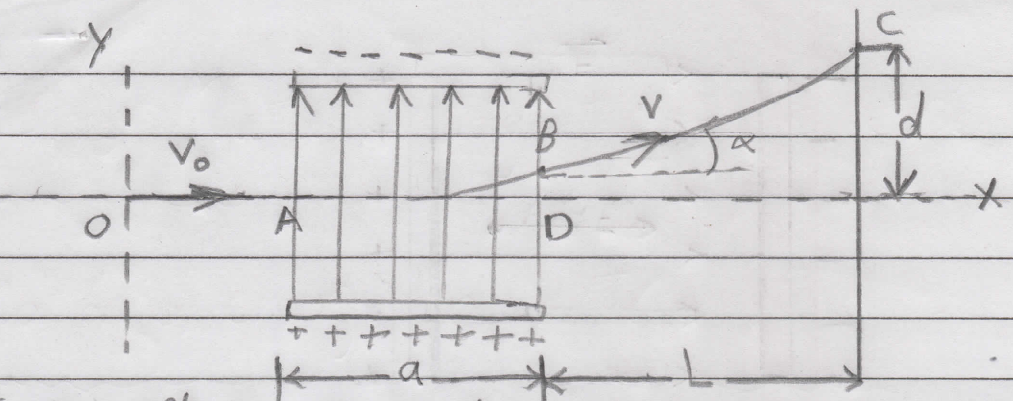
$m\vec{a} = \vec{F}$ and $\vec{F} = q\vec{\mathcal{E}}$

$\therefore m\vec{a} = q\vec{\mathcal{E}}$ or $\vec{a} = \frac{q}{m}\vec{\mathcal{E}}$ ---- (3-1)

where, m is the mass of the charged particle, and $\vec{a}$ is its acceleration, q is the charge of the charged particle.

The acceleration of a body in an electric field depends therefore on the ratio q/m. Since this ratio is in general different for different charged particles or ions, their acceleration is an electric field are also different.

The figure (3-1) is illustrate the charged particles which passing through an electric field. we assume that the initial velocity v_o of the particle when it enters the field is perpendicular to the direction of the electric field.



Fig(3-1) Deflection of a positive charge by a uniform electric field

From the equation of motion in mechanic, we have

$$X = v_0 t \quad \text{and} \quad y = \frac{1}{2} a t^2 \quad \text{---} (3\text{-}2)$$

Eliminating the tim t, by using Eq (3.1) in Eq.(3.2) we obtain

$$y = \frac{1}{2}\left(\frac{q}{m}\right)\left(\frac{\mathcal{E}}{v_0^2}\right) x^2 \quad \text{---} (3.3)$$

thus verifying that its a parabola. We obtain the deflection α by Calculating the slop dy/dx of the path at $x = a$.
The result is

$$\tan\alpha = \left(\frac{dy}{dx}\right)_{x=a} = \frac{q\mathcal{E}a}{m v_0^2}$$

If we place a screen S at distance L, the particle with given q/m and velocity v_0 will reach a point c on the screen. Noting that $\tan\alpha$ is also approximately equal to d/L because the vertical displacement BD is small compared with d if L is Large. we have.

$$\frac{q\mathcal{E}a}{m v_0^2} = \frac{d}{L} \quad \text{----} (3\text{-}4)$$

By measuring d, L, a, and $\mathcal{E}$, we may obtain the velocity v_0 (or the kinetic energy) if we know the ratio q/m or, conversely, we may obtain q/m if we know v_0. Therefore when a stream of particles, all having the same ratio q/m, passes through the electric field, they are deflected according to their velocities or energies

MAGNETISM:-

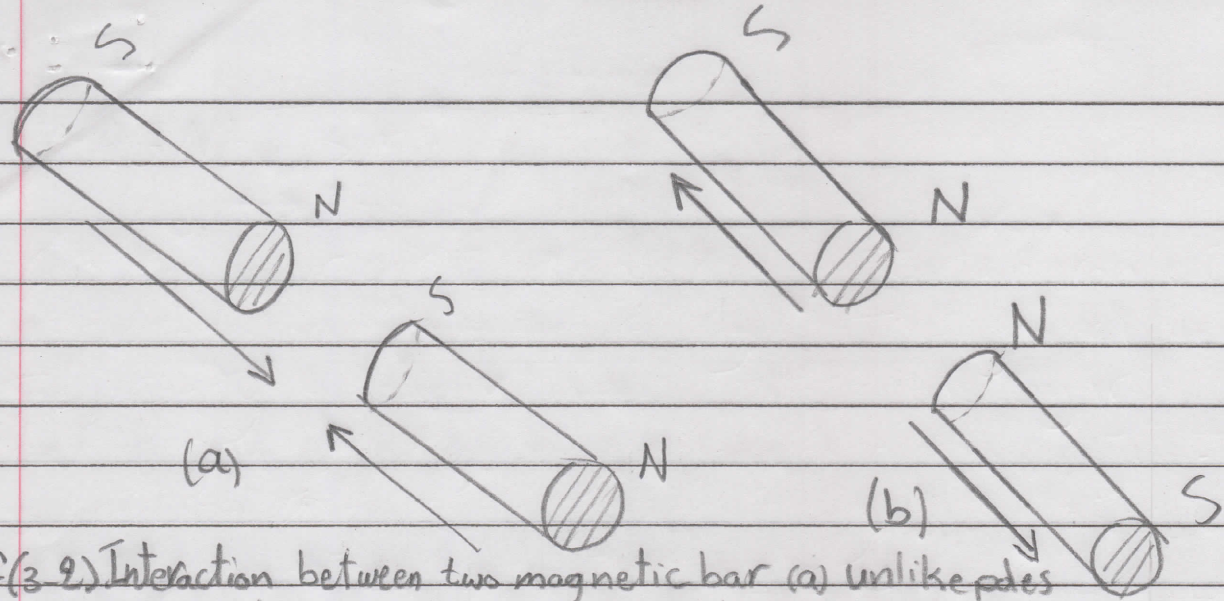
Centuries befor christ, men observed that certain iron ores, such as the lodestone, have the property of attracting small pieces of iron. The property is exhibited in the natural state by iron, Cobalt, and manganese, and by many compounds of these metals. This property is unrelated to gravitation, since not only dose it fail to be exhibited naturally by all bodies, but it appears to be concentrated at certain spots in the mineral ore. It is also apparently unrelated to the electric interaction, because neither cork balls nor pieces of paper are attracted at all by these minerals. Therefore a new name "magnetism" was given to this physical property. The regions of a body where the magnetism appears to be concentrated are called "magnetic poles". A magnetized body is called magnet.

The earth itself is a huge magnet. For example, if we suspend a magnetized rod at any point on the earth's surface and allow it to rotate freely about the vertical, the rod orients itself so that the same end always points toward the north geographic pole. This result shows that the earth is exerting an additional force on the magnetized rod which it dose not exert on unmagnetized rods.

This experiment also suggest that there are two kinds of magnetic poles. which we may designate by the signs (+) and (-), or by the letters (N) and (S), corresponding to the north-seeking and south-seeking poles, respectively. If we take two magnetized bars and place them as shown in fig. (3.2), the bars will either repel or attract each other depending on whether we place like or unlike poles facing each other.

Thus we conclude from our experiment that;

"The interaction between like magnetic poles is repulsive and the interaction between unlike magnetic poles is attractive"



f(3-2) Interaction between two magnetic bar (a) unlike poles attract each other. (b) like poles repel each other.

Magnetized bodies always exhibit poles in pairs, equal and opposite, and the notions of magnetic pole and magnetic mass have been found unnecessary for the description of magnetism. Electric and magnetic interaction are very closely related and in fact are only two different aspects of one property of matter its electric charge, 'magnetism is a manifestation of electric charges in motion'. Electric and magnetic interaction must be considered together under the more general name of "electromagnetic interaction'

The Magnetic Field:-

Since there is an interaction between magnetized bodies, we may say in analogy with the electrical case, that a magnetized body produced a 'magnetic field' in the space around it. When we place an electric charge at rest in a magnetic field, no special force is observed on the charge. But when an electric charge moves in a region where there is a magnetic field, a force is observed on the charge in addition to this force due to its electric interaction. By measuring at the same point in a magnetic field, the force experienced by different charges moving in different ways, we may obtain a relation between the force, the charge, and its velocity. In this we conclude that "The force exerted by a magnetic field on a moving charge is proportional to the electric charge and

to its velocity, and the direction of the force is perpendicular to the velocity of the charge"

we may write the force ($\vec{F}$) on a charge (q) moving with velocity (V) in a magnetic field as the vector product.

$$\vec{F} = q\,\vec{V} \times \vec{B} \quad \text{(magnetic force)} \; \text{---} \; (3\text{-}5)$$

Here ($\vec{B}$) is a vector found at each point by comparing the observed value of ($\vec{F}$) at the point with those of (q) and ($\vec{V}$).

The vector ($\vec{B}$) may vary from point to point in a magnetic field but at each point it is found experimentally to be the same for all charges and velocities. Therefore ($\vec{B}$) as define by Eq. (3.5), describes a property that is characteristic of the magnetic field, and we shall call it the "magnetic field strength".

when the particle moves in a region where there are an electric and magnetic force ($q\vec{V} \times \vec{B}$) That is

$$\vec{F} = q(\vec{E} + \vec{V} \times \vec{B}) \; \text{.....} \; (3\text{-}6)$$

This expression is called the "lorentz force"

Because of the propety of the vector product, Eq (3.5) gives a force perpendicular to the velocity ($\vec{V}$), but also perpendicular to the magnetic field ($\vec{B}$). Eq. (3.5) also implies that when ($\vec{V}$) is parallel to ($\vec{B}$), the force ($\vec{F}$) is zero. In fig (3-3) the relation between the three vectors $\vec{V}$, $\vec{B}$, and $\vec{F}$ is illustrated for both a positive and a negative charge. The figure shows the right-hand rule for determining the direction of the force. If (α) is the angle between $\vec{V}$ and $\vec{B}$, the magnitude of F is

$$F = qVB \sin\alpha \; \text{----} \; (3\text{-}7)$$

The maximum force occure when $\alpha = \pi/2$ or $\vec{V}$ is perpendicular to $\vec{B}$, resulting in

$$F = qVB \; \text{---} \; (3\text{-}8)$$

The force is zero when $\alpha = 0$ or when $\vec{V}$ is parallel to $\vec{B}$.

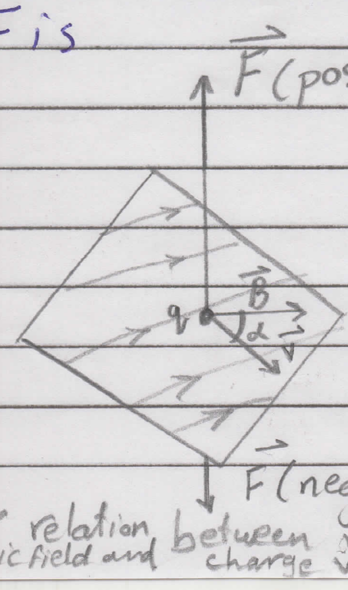


Fig. (3-3) vector relation between magnetic force, magnetic field and charge velocity

~~Ex~~ From Eq (3.5), we may define the unit of magnetic field as $N/C\,m\,s^{-1}$ or $(kg\,s^{-1}C^{-1})$. This unit is called a tesla, abbreviated (T). That is $T = kg\,s^{-1}C^{-1}$.

Tessla = "one tesla corresponds to the magnetic field that produces a force of one newton on a charge of one Coulomb moving perpendicular to the field at one meter per second"

Because the magnetic force $\vec{F} = q\vec{V} \times \vec{B}$ is perpendicular to the velocity, its work is Zero, and therefore it does not produce any change in the kinitic energy of the particle.

Ex: Force exerted on a Cosmic-ray proton which enters the magnetic field of the earth. Suppose the proton moves in a direction perpendicular to the field with a velocity equal to $10^7\,m\,s^{-1}$. The intensity of magnetic field near the earth's surface at the equator is about $B = 1.3 * 10^{-5}\,T$. The electric charge on the proton is $q = +e = 1.6 * 10^{-19}\,c$.

Solution: The force on the proton i

$$F = qVB = 1.6 * 10^{-19}\,c * 10^{7}\,m\,s^{-1} * 1.3 * 10^{-5}\,T$$

$$= 2.1 * 10^{-17}\,N$$

which is about 10^9 times larger than the force due to gravity.

$$F = m_p g = 1.6725 * 10^{-27}\,kg * 9.78\,m\,s^{-1} \simeq 1.6 * 10^{-25}\,N$$

The acceleration due to the magnetic force.

$$F = qVB \;,\; F = m_p a$$

$$a = F/m_p = qVB/m_p = \frac{2.1 * 10^{-17}\,N}{1.67 * 10^{-27}\,kg} = 1.2 * 10^{10}\,m\,s^{-2}$$

Thus the magnetic acceleration of the proton is also 10^9 times larger than the acceleration of gravity.

Motion of a Charged particle in a Uniform Magnetic field :-

Consider the motion of a charge particle in a uniform magnetic field; i.e a magnetic field having the same intensity and direction at all its points. The magnetic force which is given by Eq.(3-8) is perpendicular to the velocity, its effect is to change the direction of the velocity without changing its magnitude, resulting in a uniform circular motion, Fig.(3-4). The acceleration is then centripetal, and using the equation of motion, we have

$$F = \frac{mv^2}{r} \text{ (centripetal force)}$$

and then

$$\frac{mv^2}{r} = qvB$$

from which we obtain

$$r = \frac{mv}{qB} \quad \text{.....} \quad (3\text{-}9)$$

wich gives the radius of circle described by the charged particle of mass (m).

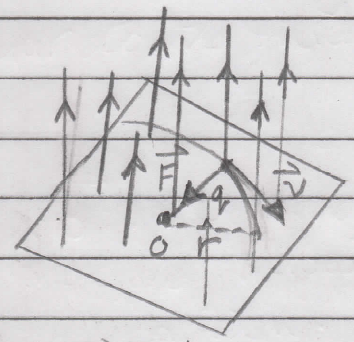


Fig.(3-4) A charge moving perpendicular to a uniform magnetic field follows a circular path.

Eq.(3-9) tells us that the curvature of the path of a charged particle in magnetic field depends on the energy of the particle. The longer the energy (or the momentum $p = mv$), the larger the radius of the path and the smaller the curvature.

By writing $v = \omega r$ in eq.(3-9) where ω is the angular velocity of the particle, we have

$$\omega = \frac{q}{m} B \quad \text{-----} \quad (3\text{-}10)$$

therefore the angular velocity is independent of the linear velocity V and depends only on the radio q/m and the field $\vec{B}$.

Expression (3-10) gives the magnitude of ω but not its direction. We recall the acceleration in a uniform circular motion may be written in vector form as

$$\vec{a} = \vec{\omega} \times \vec{V} \quad \text{----} \quad (3\text{-}11)$$

There the equation of motion $\vec{F} = m\vec{a}$ becomes

$$m\vec{\omega} \times \vec{V} = q\vec{V} \times \vec{B}$$

or, reversing the vector product on the right-hand side and dividing by (m), we get

$$\vec{\omega} \times \vec{V} = -(q/m)\vec{B} \quad \ldots\ (3.12)$$

which gives $\vec{\omega}$ both in magnitude and direction. The minus sign indicates that $\vec{\omega}$ has the opposite to $\vec{B}$ for a positive charge and the same direction for a negative charge. we call $\vec{\omega}$ the "cyclotron frequency".

It is customary to represent a field perpendicular to the paper by a dot (•) if it is directed toward the reader and by across (x) if it is directed into the page. Fig. (3-5) represent the path of a positive and negative charge moving perpendicularly to a uniform magnetic field perpendicular to the page. In (a) ω is directed into the page and in (b) toward the reader.

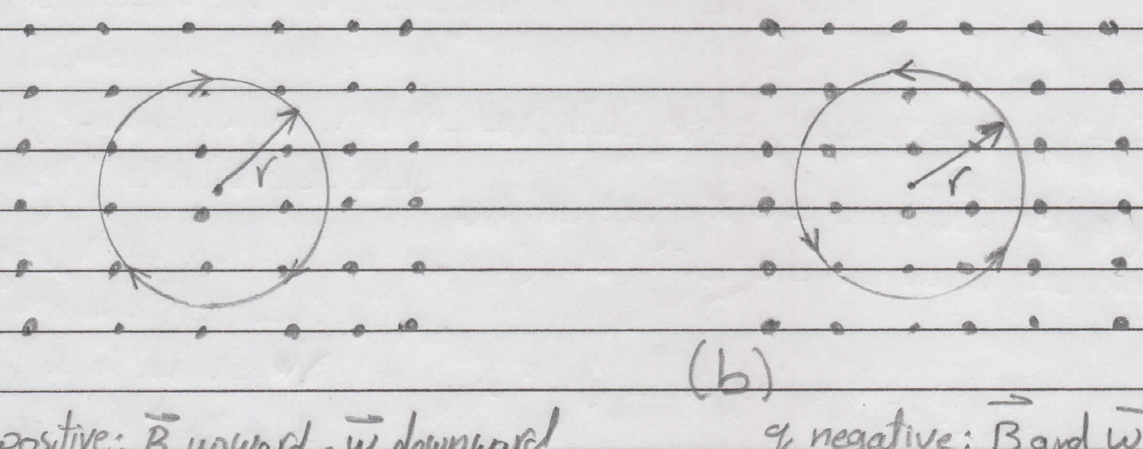
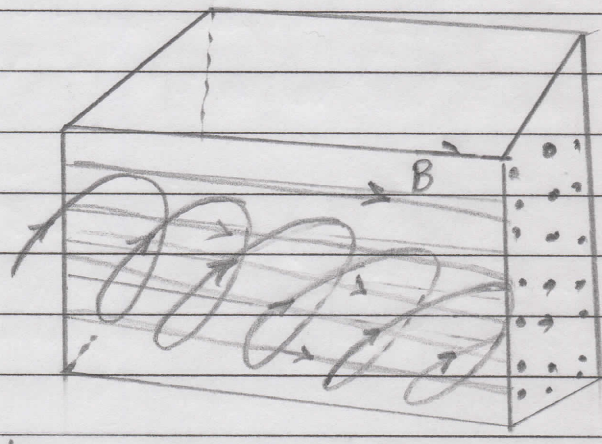


fig (3.5) Circular path of positive and negative charges in a uniform magnetic field.

If a charged particle moves initially in a direction that is not perpendicular to the magnetic field, we may separate the velocity into its parallel and perpendicular components relative to the magnetic field. The parallel component remain unaffected and the perpendicular component changes continuosly in direction but not in magnitude. The motion is then the resultant of a uniform motion parallel to the field and a circular motion around the field with angular velocity given by Eq. (3-10). The path is a helix, as

shown in fig. (3-6) for a positive ion.



F(3-6) Helical path of a positive ion moving obliquely to a uniform magnetic field.

Motion of A charged Particle in A nonuniform Magnetic Field:

we shall now consider the case when a particle moves in a magnetic field which is not uniform. we learn from Eq. (3-9), $r = mv/qB$, that the larger the magnetic field, the smaller the radius of the path of the charged particle. Therefore, if the magnetic field is not uniform, the path is not circular. Fig. (3-7) shows a magnetic field directed from left to right with its strength increasing in that direction. Thus a charged particle injected at the left-hand side of the field describes a helix whose radius decreases continuously. A more detailed analysis, which we must omit here, would show that the component of the velocity parallel to the field does not remain constant but decreases (and therefore the pitch of the helix also decreases) as the particle moves in the direction of increasing field strength.

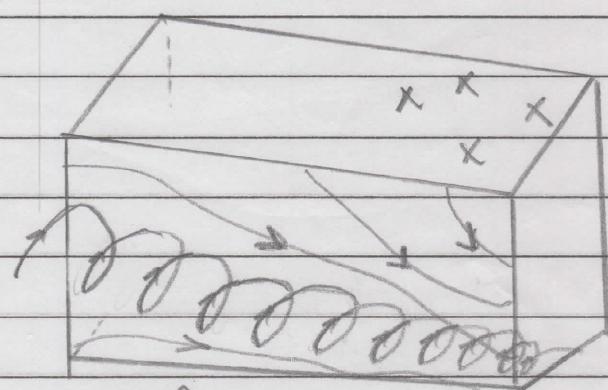


fig (3-7) path of a positive ion in a nonuniform magnetic field.

Ex :- A proton is moving in a circular orbit of radius 14 cm in a uniform 0.35 T magnetic field perpendicular to the velocity of the proton. Find the linear speed of the proton.

Solution :- $r = mv/qB$ we have

$$V = \frac{qBr}{m_p} = \frac{(1.6 * 10^{-19} c)(0.35T)(0.14m)}{1.67 * 10^{-27} \text{ Kg}}$$

$$= 4.7 * 10^{6} \text{ m s}^{-1}$$

Ex A particle with charge $q = 3.2 * 10^{-19}$ C, mass $m = 3 * 10^{-27}$ kg and velocity $\vec{V} = 5 * 10^{5} (\hat{i})$ m s^{-1}, enter a region of uniform magnetic field $\vec{B} = 1.6 (\hat{j})$ T.

(a) Compute the magnitude and direction of the magnetic field.

(b) Compute the radius of the resulting charge circular orbit.

Solution

(a) $$F = q\vec{V} \times \vec{B} = 3.2 * 10^{-19} c [5 \times 10^{5} (\hat{i}) \text{ m s}^{-1}] \times [1.6 (\hat{j}) T]$$

$$= 3.2 \times 10^{-19} * 5 \times 10^{5} * 1.6 (\hat{i} \times \hat{j})$$

$$= 2.56 \times 10^{-13} (\hat{K}) \text{ N}$$

(b) $$r = \frac{mV}{qB} = \frac{3 * 10^{-27} \text{ kg} * 5 * 10^{5} \text{ m s}^{-1}}{3.2 * 10^{-19} \text{ c} * 1.6 \text{ T}} = 2.93 * 10^{-3} \text{ m}$$

$$w = \frac{V}{r} = \frac{5 * 10^{5} \text{ m s}^{-1}}{2.93 * 10^{-3} \text{ m}} = 14.24 * 10^{7} \text{ rad s}^{-1}$$

$$f = \frac{w}{2\pi} = \frac{14.24 * 10^{7}}{2\pi} = 22 * 10^{6} \text{ s}^{-1}$$