

Introduction:-

Acoustics is the Science of Sound and deals with the origin, propagation and auditory sensation of sound.

An auditorium or a hall is said to be acoustically good if the following conditions are satisfied

- * The speech or music whatever is performed on the stage should be audible in the entire hall or theatre either direct or with the amplifier system as the case may be.
- * The quality of sound should be uniform throughout hall or theatre
- * The syllables ought to be clear without overlapping
- * The quality of speech or music heard should be the same whether the hall is full with audience or not.
- * There must not be any pockets of maxima or minima sounds due to interference or reflection
- * The loudness of the sound should be uniform throughout the hall.
- * No echo should be present.
- * The hall should have proper reverberation time about 1.1-1.5 second
- * The sounds from the outside must not disturb the proceedings inside.
- * No resonance effect should be present.

When a sound wave strikes a surface, part of its energy is absorbed, part of it is transmitted and the remaining part is reflected. The property of a surface by which sound energy is converted into other form of energy is known as absorption.

Coefficient :- The effectiveness of a surface in absorbing sound energy is expressed with the absorption coefficient. The coefficient of absorption 'a' of a material is defined as the ratio of sound energy absorbed by its surface to that of the total sound energy incident on the surface.

$$\therefore a = \frac{\text{Sound energy absorbed by the surface}}{\text{Total sound energy incident on the surface.}}$$

(or)

Def 2:- The absorption coefficient of a material can also be defined as the ratio of sound energy absorbed by a certain area of the surface to that of an open window of same area.

(or)

Def (3):-

The absorption coefficient of a surface is defined as the reciprocal of its area which absorbs the same sound energy as absorbed at a unit area of an open window

Reverberation time:-

Sound produced in an enclosure continues to be heard for some time. A sound produced in a room undergoes multiple reflections from the walls, floor and ceiling before it becomes inaudible. A person in the room continues to receive the successive reflections of progressively diminishing intensity, as part of energy is lost.

The reverberation can be defined as the prolonged reflection of sound from the walls, floor and ceiling of a hall.

(or)

Persistence of audible sound after the source has stopped to emit sound. The duration for which the sound persists is called reverberation time.

This time is measured from the instant the source stops emitting sound. The "reverberation time is also defined as the time taken for the sound to fall below the minimum audibility measured from the instant when the source stopped sounding."

According to Sabine's law, the reverberation time T in seconds is

expressed as
$$T = \frac{0.165 V}{\Sigma a S}$$

where V is the volume of the hall in m^3 and $\Sigma a S$ is given by

$$\Sigma a S = a_1 S_1 + a_2 S_2 + \dots + a_n S_n$$

Here $a_1, a_2, \dots, a_n$ are the absorption coefficients of the material in the hall whose surface areas exposed to sound are $S_1, S_2, \dots, S_n$ respectively measured in m^2 .

The average value of absorption coefficient $\bar{a}$ is given by

$$\bar{a} = \frac{a_1 S_1 + a_2 S_2 + \dots + a_n S_n}{S_1 + S_2 + \dots + S_n} = \frac{\Sigma a S}{S}$$

$$\Rightarrow \Sigma a S = \bar{a} S \rightarrow (1)$$

By statistical method Jaeger showed that sound travels a distance $4V/s$ on an average, between two successive reflections. This is known as mean free path.

Time taken b/w two successive reflections = $\frac{4V}{Sv}$ where v is the velocity of sound, V is the Volume of the room.

Number of reflections per sec = $\frac{Sv}{4V}$

The avg number of reflection in time $t = \frac{Sv}{4V} \times t = \frac{Svt}{4V}$

Let $\bar{a}$ be the fraction of sound absorbed at a single reflection. Then fraction of sound reflected is $(1 - \bar{a})$. After two reflections, the fraction of sound reflected is $(1 - \bar{a})^2$. Similarly, after a time

the fraction of sound reflected will be (4)

$$(1-\bar{\alpha})^{\left(\frac{svt}{4V}\right)}$$

Let I_0 be the initial intensity of sound and I_t be intensity after time t , then $I_t = I_0 (1-\bar{\alpha})^{\frac{svt}{4V}}$

When $t = T$ reverberation time $\frac{I_T}{I_0} = 10^{-6} = (1-\bar{\alpha})^{\left(\frac{svT}{4V}\right)}$

Taking natural logarithms of both sides of above eqn.

$$\log(10^{-6}) = \left(\frac{svT}{4V}\right) \log_e(1-\bar{\alpha})$$

$$\Rightarrow T = \log_e(10^{-6}) \left[\frac{4V}{sv \log_e(1-\bar{\alpha})} \right]$$

$$\Rightarrow T = 2.3026 \log_{10}(10^{-6}) \left[\frac{4V}{sv \log_e(1-\bar{\alpha})} \right]$$

$$\Rightarrow = \frac{2.3026 \times (-6) \times 4V}{5 \times 330 \times \log_e(1-\bar{\alpha})} \quad \left(\begin{array}{l} \text{velocity of sound} \\ v = 330 \text{ m/sec} \end{array} \right)$$

$$\Rightarrow = \frac{-55.26V}{330 \times 5 \times \log_e(1-\bar{\alpha})}$$

$$T = \frac{-0.165V}{S(-\bar{\alpha})} \quad \therefore \log(1-\bar{\alpha}) \approx -\bar{\alpha}$$

from eqn (1) $S\bar{\alpha} = \epsilon a S$

Substitute in above eqn

$$\therefore T = \frac{0.165V}{\epsilon a S}$$

his equation is in good agreement with the experimental values obtained by Sabine.

From Sabine's formula

reverberation time is

- (i) directly proportional to the volume of the auditorium.
- (ii) Inversely proportional to the areas of sound absorbing surfaces such as ceiling, walls, floor and other materials present inside the hall and
- (iii) inversely proportional to the total absorption.

Reverberation Time:- The prolongation of sound inside a room or hall even after the source producing the sound is turned off is called reverberation.

The reverberation time for a room is the time required for the intensity to drop to one millionth (10^{-6}) of its initial value.

Reverberation time can be expressed in terms of (dB) sound level rather than intensity. If the initial intensity I_0 and the final intensity I_t

or I_f then
$$dB_i = 10 \log I_0 / I$$

$$dB_f = 10 \log I_t / I$$

$$dB_i - dB_f = 10 \log (I_0 / I_t)$$

Since $I_0 / I_t = 10^6 \Rightarrow dB_i - dB_f = 10 \log 10^6$
 $= 6 \times 10 = 60$

The reverberation time is the time required for the intensity to drop by 60 decibels.

Introduction:- The sound waves having frequency more than 20kHz are known as Ultrasonics or Supersonics. Ultrasonic waves move with velocity of sound. Hence, ultrasonic waves are acoustic in nature with shorter wavelength and higher frequency.

Most of the applications of the ultrasonic waves have been possible on account of their smaller wavelength. Ultrasonic waves can be used in non-destructive testing (NDT).

Production of Ultrasonics:-

1. Magnetostriction method:- this method

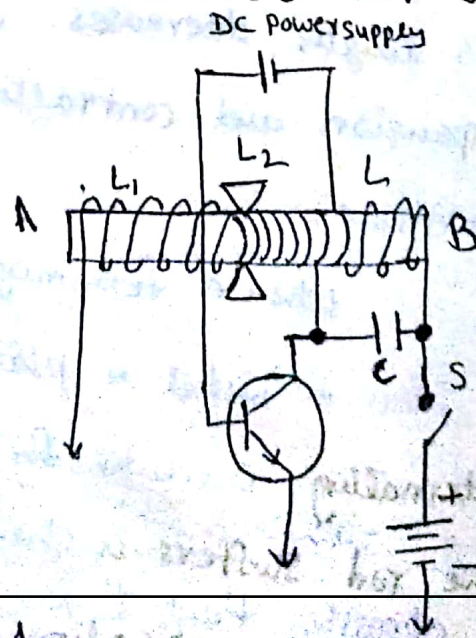
Principle: The phenomenon of magnetostriction is involved in the generation of ultrasonic waves. When a magnetic material is magnetised, its length increases and when it is demagnetised its length decreases. In this way a magnetic material undergoes expansion and contraction of its length and set into vibrating condition.

When a ferromagnetic rod made of material such as iron or nickel is placed inside a magnetic coil carrying alternating current, for each half cycle of alternating current the rod suffers a change in its length due to magnetisation and demagnetisation. Hence, the rod is set into vibrations.

amplitude of vibration is usually small, but if the frequency of the AC coincides with the natural frequency of the rod, then resonance occurs and the amplitude of vibration is considerably increased. Sound waves are now emitted from the ends of the rod. If the applied frequency is of the order of ultrasonic frequency, the rod sends out ultrasonic waves.

Construction:- A short nickel rod AB which is clamped at the centre, is permanently magnetised in the beginning by passing a direct current in the coil L_2 which is wrapped at the centre of the rod. Another two coils L_1 and L are wrapped at the ends of the rod. The coil L is connected to the collector of the transistor and the coil L_1 is connected to the base of the transistor. The collector current can be adjusted using the variable condenser C and the current can be noted by a millimeter connected across the coil L . The frequency of the oscillatory circuit is $\left(\frac{1}{2\pi\sqrt{LC}}\right)$. The necessary biasing between emitter and collector, that is, emitter is forward biased and collector is reverse biased can be achieved by the connected battery.

working:- when the battery is switched on, the collector current is passed through the coil L . When this current is changed



Change in the magnetisation of the rod. The rod suffers change in its length and the rod starts vibrating due to magnetostriction effect. The vibrations in the length causes a variation of magnetic flux linked with the coil L_1 connected to the base, which in turn changes the e.m.f developed across L_1 . This e.m.f acts on the base and produces an amplified current change in the collector circuit, that is, in the coil L . In this way, the plate current build up to large amplitude with a frequency determined by the frequency of the longitudinal vibration of the rod. When the frequency of the circuit becomes equal to the frequency of the rod, resonance occurs and the sound waves of maximum amplitude are generated. By adjusting the length of the rod and the capacity of the condenser, ultrasonic waves with different frequencies can be obtained.

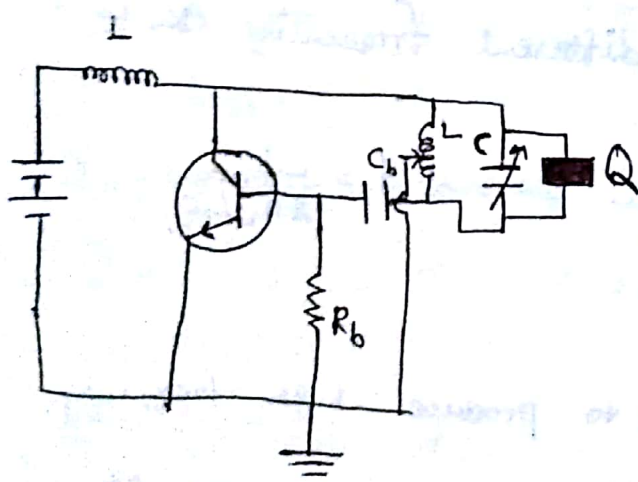
Frequency of ultrasonic wave is $f = \frac{1}{2\pi\sqrt{LC}}$

Piezoelectric Method:-

Principle:- This method is used to produce high frequency ultrasonic waves, when pressure or compression is applied on certain crystals like quartz, Rochelle salt, tourmalines etc. along certain axis, then charges are produced on a set of opposite faces those create an electric potential difference between the faces. This is known as piezoelectric effect and

If the frequency of electric field is same as natural frequency of the crystal, resonance occurs and then amplitude of crystal oscillations is quite large. If the applied frequency is of the order of ultrasonic frequency, the piezoelectric crystal sends out ultrasonic waves.

2. Construction:-



The high frequency alternating voltage which is applied to crystal is obtained by Hartley oscillatory circuit. The Hartley circuit consists of a tuned oscillatory circuit. One end of the tuned circuit is connected to the base of NPN transistor. The coil L is tapped

near the centre and joined to the emitter. The quartz crystal Q is connected in parallel to the variable condenser C . The proper

biasing and feedback can be achieved by the base resistor R_b & base condenser

when battery is switched on, the proper base biasing

is obtained and the current rush through the tank circuit and the capacitor is charged, after fully charged no current passes through the same. Then the capacitor starts discharging through the inductor and hence the electric energy is in the form of electric and magnetic fields associated with the capacitor and the inductor, respectively.

The Piezo electric crystal is set into vibrations. The feed back achieved by means of base resistor R_b and base condenser C_b keep continuous electrical oscillations. Hence, the crystal is set into sustained vibrations. The capacity of the variable condenser C is adjusted so that the frequency of the oscillating circuit is tuned to the natural frequency of the crystal. Now the quartz crystal is set into mechanical vibrations and ultrasonic waves are produced. The ultrasonic waves up to a frequency of 500 kHz with a moderate size crystal can be produced by this method. However, frequency up to $15 \times 10^7\text{ Hz}$ can be produced by ~~the~~ tourmaline crystal.

Ultrasonic transducer:-

A transducer is a device that generally, converts one form of energy to another form. In the case of ultrasonic testing the transducer converts sound energy to electrical energy and vice-versa.

defects, structures of a material without causing any damage to the NDT.

Types of Transducers:-

- a) Contact Transducers:- Contact transducers are used in direct contact with the test specimen. They send sound energy perpendicular to the surface. They are used for locating voids, porosity and cracks or delamination parallel to the other surface of the specimen.
- b) Angle Beam Transducers:- They are used in conjunction with plastic or epoxy wedges to send shear waves or longitudinal waves into the test piece at a particular angle with respect to the surface. Angle beam transducers are commonly used in the inspection of weldings.
- c) Delay line Transducers:- The delay line transducers incorporate a short plastic wave guide or delay line between the active element and the test piece. They are used to improve near surface resolution. Also in high temperature testing the delay line protects the active element from thermal damage.
- d) Immersion Transducers:- The immersion transducers are designed to couple sound energy to the test piece through a water bath. They are used in automated scanning applications and also in situations where a sharply focused beam is needed to improve the resolution of flaws.

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This type of transducers utilize separate transmitter and receiver elements in a single assembly or system. They are used in the applications which involve rough surfaces, coarse grained materials, direction of pitting etc. They also offer good, high temperature tolerance.

Ultrasonic Scanning:-

Scanning is a kind of reviewing the imagery details, generally applied to diagnose the internal organs of the human body or internal parts of pre-fabricated objects. The ultrasound source (transducer) sends a pulse into the body, which is reflected by an organ in its path. The intensity of the reflected signal and the corresponding time delay are the defining parameters of the image built up. Ultrasonic scanning is broadly classified as A-scan, B-scan and C-scan imaging.

1. **A-scan:-** In A-scan imaging amplitude of the ultrasonic echo is a function of distance. Amplitude of the echo represents the strength of the echo. The time delay between the pulse and echo helps to locate the reflecting organ and to estimate its location. Using A-scan, diagnosis and localization of malignant tumours, placental localizations, fetal cephalometry can be done.

2. B-Scan:- In B-scan imaging, an oscillating ultrasonic beam is introduced into the test piece, through probe. The beam is reflected back to the probe. These echoes are displayed as a series of dots that form an image. The brightness of the dots is determined by the strength of the echo which in turn allows to determine the density of the tissue under testing.

3. C-Scan:- In C-scan imaging, cross sectional details inside the specimen are scanned. Suppose, we select a cross-section inside the specimen, which is at a specific depth. The frequency of the ultrasonic beam is so adjusted that it scans the selected cross-section. If the ultrasonic probe is connected to X-Y recorder and moved over the surface of the specimen, the intensity of the echo reflected from the cross-section appears as shading. The probe may be moved in zig-zag fashion or parallel to itself. The C-scan image may be with variation of 'I' or a shading in the defective cross-section. The position as well as the cross section area of the defective cross-section can be simultaneously studied. We get 2D observations in this method.

C-Scan testing is automatic. Generally, C-scan systems generate images which are parallel to the surface of the skin and records 2 dimensional plane images at different

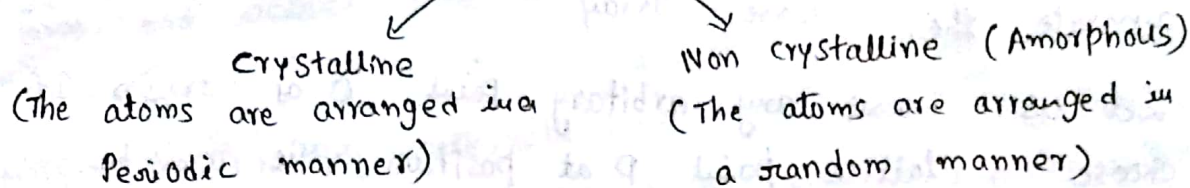
The ultrasonic testings are performed for the detection and sizing of internal defects, flaws, weld inspection, rail inspection, material analysis, landing gear inspection, inspection in foundry industry, Corrosion testing, underwater measurement, concrete inspection etc.

Applications of Ultrasonic waves:-

1. Ultrasonic transducers are used for drilling non-circular holes on brittle materials such as glass and ceramics
2. Ultrasonics are used for welding of lighter materials like aluminium
3. Ultrasonics are used to mix non-miscible liquids like oil and water.
4. Sound Navigation and Ranging (SONAR) Uses Ultrasonics.
5. Twins can be recognised on the screen of ultrasonic scan in the form of contours of the two fetal heads appear side by side.
6. Ultrasonics are used to form alloys from high density elements which uniform composition.

Introduction:-

Solids



Single Crystal

The entire solid consists of only one crystal

Polycrystalline

It is an aggregate of many small crystals separated by well defined boundaries

Non crystalline substances:- It is also called amorphous and they have no directional properties and therefore they are called "isotropic" substances. They do not possess any regular shape and they have wide range of melting point.

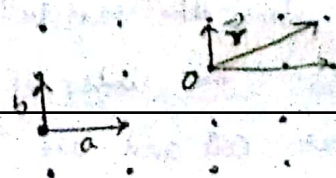
Crystalline substances:- A crystal has regular shape and when it is broken all broken pieces have the same regular shape. A crystal has sharp melting point. Since the crystals may have different periodic arrangements in all three directions, the physical properties vary with direction and they are called "anisotropic" substances.

Space lattice:- A space lattice is defined as an infinite array of points in three dimensions in which every point has surroundings identical to that of every other point in the array.

(or)
A space lattice represents the geometrical pattern of crystal in which the surroundings of each lattice point is the same.

Let us consider the two dimensional square array of points.

By repeated translation of the two



Two vectors a and b in the plane of the paper, we can generate the square array. The magnitude of a and b are equal and can be taken to be unity. The angle between them is 90° . a and b are called the fundamental translational vectors, that generate the square array.

Let us choose any arbitrary point O as origin. If we choose a lattice point P at position r it can be represented by translational vector as

$$\vec{r} = l\vec{a} + m\vec{b}$$

where l and m are integers.

For a three dimensional lattice $\vec{r} = l\vec{a} + m\vec{b} + n\vec{c}$

The unit cell:- The unit cell is the smallest unit which, when repeated in space indefinitely, generates the space lattice.
(or)

The smallest geometric figure, which on repetition in three dimensional space gives the actual Crystal Structure called a unit cell.

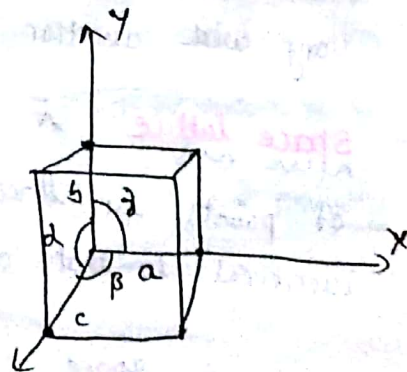
Basis:- A group of atoms or molecules identical in composition is called the basis (or) pattern. The basis provides the number of atoms per lattice point, their types mutual orientations and distances of separation.

$\therefore$ Lattice + basis $\longrightarrow$ Crystal Structure.

Lattice parameters:-

The lines drawn parallel to the lines of intersection of any three faces of the unit cell which do not lie in the same plane are called crystallographic axes.

The three translational vectors a, b and c lie along the crystallographic axes.



The intercepts a, b and c define the dimensions of an

unit cell and are known as its primitives.



The angles between a and b is α , the angle between a and c is β , and that between b and c is γ . The angle between a and b is α , the angle between a and c is β , and that between b and c is γ .

The primitives a, b and c and interfacial angles α, β, γ are the basic lattice parameters. Because they determine the form and actual size of the unit cell. The unit cell formed by the primitives a, b and c is called primitive cell.

NOTE:- A primitive cell, will have only one lattice point. If there are two or more lattice points, then it is not a primitive cell. Most of the unit cells of various crystal lattice contain two or more lattice points and hence it is not necessary that the unit cell should be a primitive cell.

Bravais Lattice:- Three dimensional space lattice is generated by repeated translation of three noncoplanar vectors a, b and c . There are only fourteen distinguishable ways of arranging points in three dimensional space. These 14 space lattices are known as Bravais lattices. They belong to seven crystal systems.

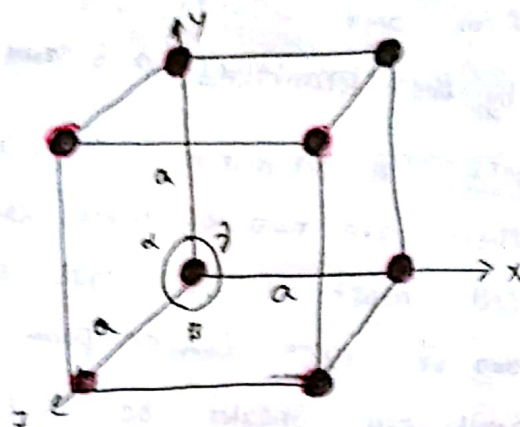
Crystal System	Unit vector	Angles	Bravais lattices	Symbols
Cubic	$a = b = c$	$\alpha = \beta = \gamma = 90^\circ$	Simple Body centered Face centered	P I F
Tetragonal	$a = b \neq c$	$\alpha = \beta = \gamma = 90^\circ$	Simple Body centered	P I
Orthorhombic	$a \neq b \neq c$	$\alpha = \beta = \gamma = 90^\circ$	Simple Base-centered Body centered Face centered	P I I F
Mono clinic	$a \neq b \neq c$	$\alpha = \beta = 90^\circ \neq \gamma$	Simple Base-centered	P C
Trigonal Triclinic	$a \neq b \neq c$	$\alpha \neq \beta \neq \gamma \neq 90^\circ$	Simple	P
Trigonal	$a = b = c$	$\alpha = \beta = \gamma \neq 90^\circ$	Simple	P
Hexagonal	$a = b \neq c$	$\alpha = \beta = 90^\circ, \gamma = 120^\circ$	Simple	P

In this Crystal System, all the unit cell edge lengths are equal and are at right angles $a=b=c$ & $\alpha=\beta=\gamma=90^\circ$. In cubic system there are three Bravais lattices; they are simple, body centred and face centred.

Simple Cubic:- Lattice points are

(or) atoms are present at the corners of the cube.

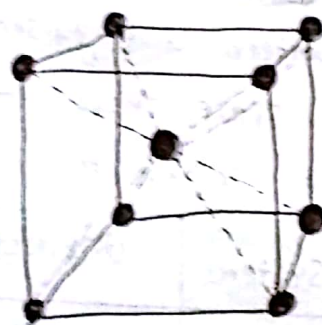
The no. of atoms per unit cell is $= \frac{1}{8} \times 8 = 1$



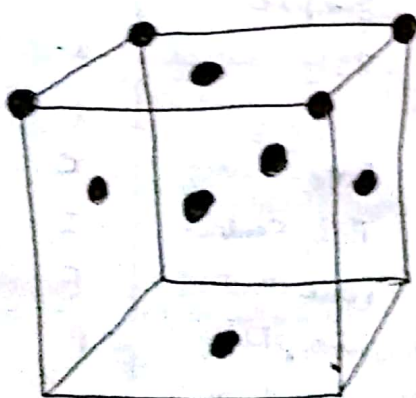
[Corner atom is shared by eight unit cells. So that contribution of a corner atom to a unit cell is $\frac{1}{8}$]

Body Centred Cubic:-

Lattice points are or atoms are present at the corners and one atom is completely present at the centre of the cube.



Face Centred Cubic:-



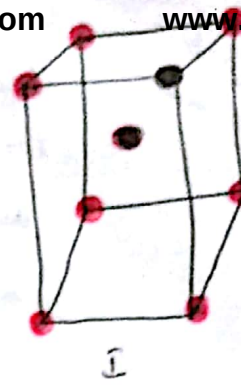
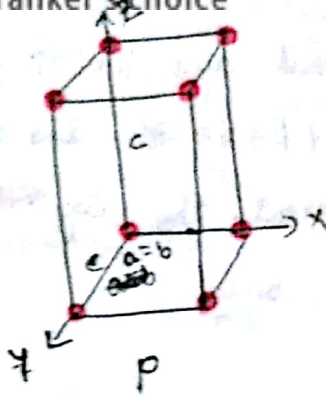
Lattice points or atoms

are present at the corners and at the centre of all faces of cube.

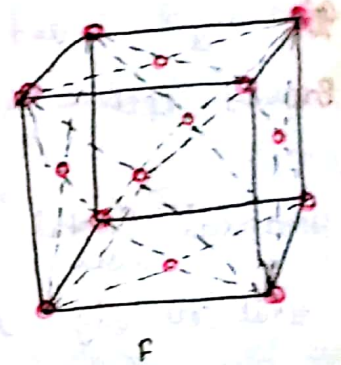
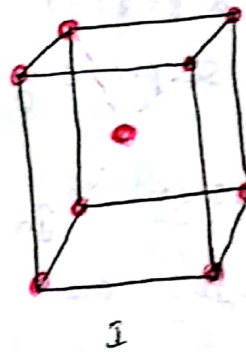
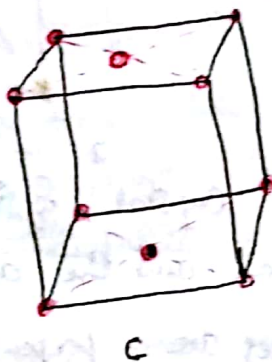
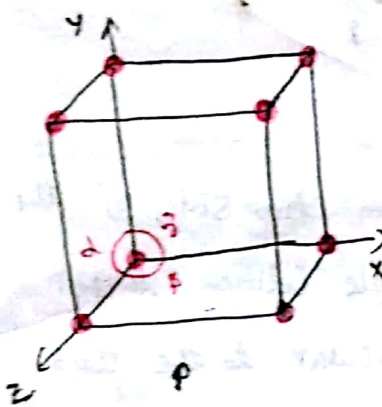
(Each face centred atom shared by two unit cells. So that contribution of a corner atom to a unit cell is $\frac{1}{2}$)

Tetragonal Crystal System:-

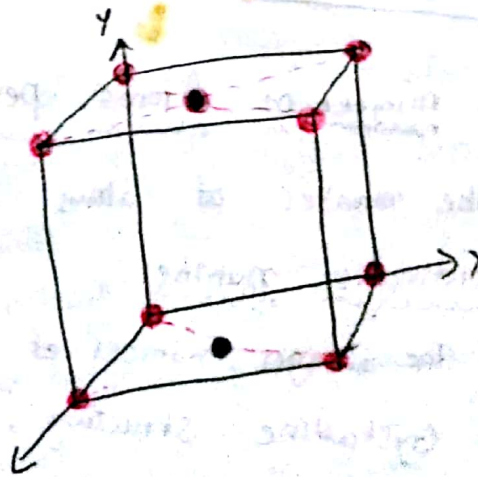
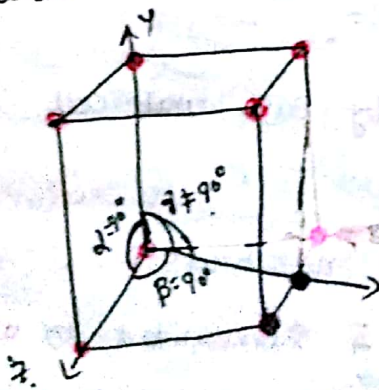
In this Crystal System, two lengths of the unit cell edges are equal whereas the third length is different. The three edges are perpendicular to one another i.e. $a=b \neq c$ and $\alpha=\beta=\gamma=90^\circ$. In tetragonal system, there are two Bravais lattices; they are simple and body centred.

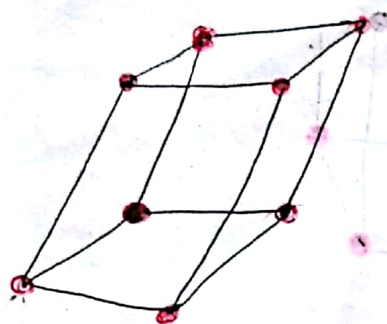


Orthorhombic Crystal System:- In this Crystal System, unit cell edge lengths are different and they are perpendicular to one another i.e. $a \neq b \neq c$ and $\alpha = \beta = \gamma = 90^\circ$. There are four Bravais lattices in this System. They are Simple, face Centred, body Centred and base Centred.



Monoclinic Crystal System:- In this Crystal System, the unit cell edge lengths are different. Two unit cell edges are not perpendicular but they are perpendicular to the third edge. i.e. $a \neq b \neq c$; $\alpha = \beta = 90^\circ \neq \gamma$. This Crystal System has two Bravais lattices; they are Simple and base Centred.

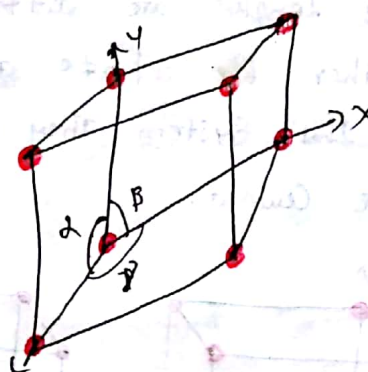




In this Crystal System, the unit cell edge lengths are different and are not perpendicular i.e. $a \neq b \neq c$ and $\alpha \neq \beta \neq \gamma \neq 90^\circ$ and all the angles are different. This Crystal exists in primitive Cell only.

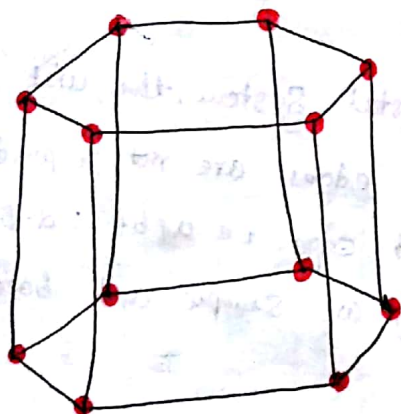
Rhombohedral (Trigonal) Crystal System:-

In this Crystal System, all the edges are equal. The angle between the axes are equal but other than 90° . $a = b = c$ and $\alpha = \beta = \gamma \neq 90^\circ$. The Bravais lattice is simple only.



Hexagonal Crystal System:-

In this Crystal System two sides of the unit cell edge lengths are equal and the angle between these edges are perpendicular to the third edge, and not equal in length i.e. $a \neq b$ $a = b \neq c$ and $\alpha = \beta = 90^\circ, \gamma = 120^\circ$. The Bravais lattice is primitive only.



Effective number of Atoms per unit cell:-

The number of atoms possessed by each unit cell.

Co.ordination number:-

The integer number of its nearest neighbours.

In a Crystalline structure, every atom is surrounded by other atoms. Co.ordination number gives the number of equidistant neighbours that an atom has in contact with surrounding atoms in the given structure.

Atomic packing factor:- The fraction of the space occupied by atoms in a unit cell.

It is the ratio of the total volume occupied by the atoms in the unit cell (V_a) to the total available volume by the unit cell (V)

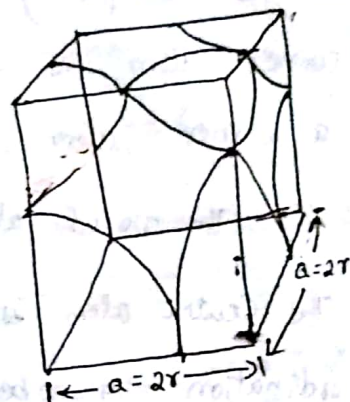
$$\text{Packing fraction} = \frac{V_a}{V}$$

Simple Cube:-

Atomic radius:- It is defined as half the distance between the nearest neighbouring atoms in a crystal.

Nearest neighbour distance ($2r$):-

The distance between the centres of two nearest neighbouring atoms is called nearest neighbour distance. If 'r' is the radius of the atom, nearest neighbour distance is $2r$.



Simple Cube:- Atoms are present only at the corners of this unit cell. A corner atom is shared by eight unit cells, so that the contribution of a corner of this unit cell atom to a unit cell is $\frac{1}{8}$. The cube has eight corners, hence the contribution of eight corner atoms to a unit cell is $\frac{1}{8} \times 8 = 1$ or the number of atoms per unit cell = $\frac{1}{8} \times 8 = 1$.

Let 'r' be the radius of an atom. The surfaces of the atoms touch along the cube edges. So, the distance between the centres of two neighbouring atoms or the nearest neighbour distance ($2r$) is equal to the lattice constant 'a'.

In a simple cubic cell, the number of nearest neighbour atoms to an atom is six.

The volume occupied by atoms in the unit cell is $= 1 \times \frac{4}{3} \pi r^3$

$$= \frac{\pi}{6} = 0.52 \text{ (or) } 52\%$$

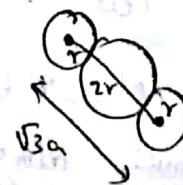
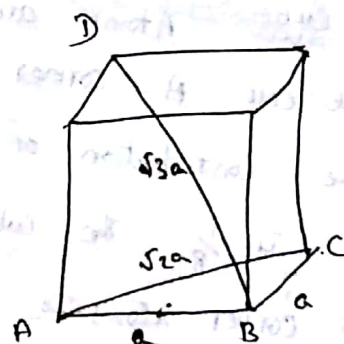
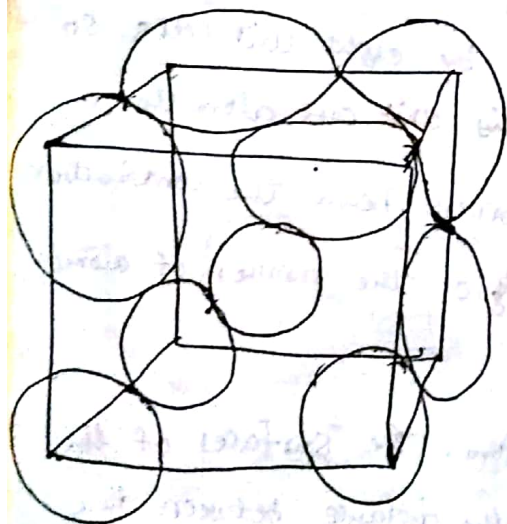
This structure is a loosely packed.

Body Centred Cubic Structure:-

Atoms are present at the corners of the cube and one atom is completely present at the Centre of the unit cell. A corner atom is shared by eight unit cells so that the contribution of a corner atom to a unit cell is $\frac{1}{8}$.

$$\therefore \text{The no. of atoms per unit cell} = \frac{1}{8} \times 8 + 1 = 2.$$

The Centre atom is surrounded by eight corner atoms, So the Coordination number is 8. The surfaces of unit cell corner atoms may not touch, but they are in contact with the centre atom. i.e. the surfaces of atoms are in contact along a body diagonal of the unit cell.



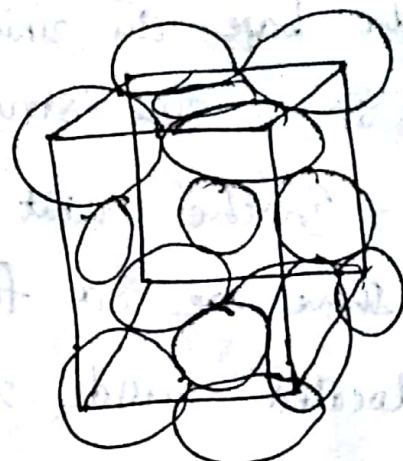
$$\text{Packing factor} = \frac{2 \times \frac{4}{3} \pi r^3}{a^3}$$

From a figure. $\sqrt{3}a = 4r \Rightarrow a = \frac{4r}{\sqrt{3}}$

$$\therefore \text{Packing factor} = \frac{2 \times \frac{4}{3} \pi r^3}{\left(\frac{4r}{\sqrt{3}}\right)^3} = 0.68 = 68\%$$

Face Centred Cubic Structure (FCC):-

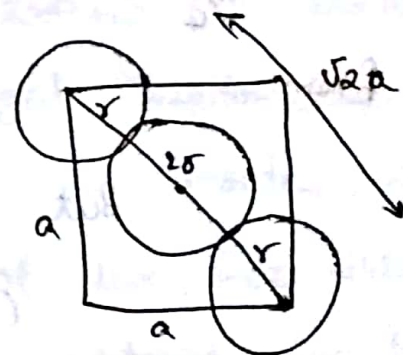
Atoms are present at the corners and at the face centres of this cubic structure. The intersection of face diagonals represent face centre of the cube. A corner atom is shared by



eight unit cells and a face centred atom is shared by two unit cells. The cube has eight corners and bounded by six faces. So the number of atoms per unit cell = $\frac{1}{8} \times 8 + \frac{1}{2} \times 6 = 4$.

Let r be the radius of an atom. The surfaces of atoms do not touch along unit cell edges but the surfaces of atoms along face diagonals of this structure are in contact. Half of the nearest neighbour distance along the face diagonal is equal to radius of an atom.

From figure $4r = \sqrt{2}a \Rightarrow a = \frac{4}{\sqrt{2}}r$



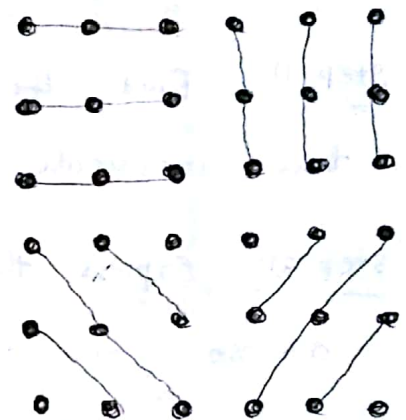
$$\therefore \text{Packing factor} = \frac{4 \times \frac{4}{3} \pi r^3}{a^3}$$

$$= \frac{16 \pi r^3}{3 \times 8 \times 2\sqrt{2}^3}$$

$$= \frac{\pi}{3\sqrt{2}} = 0.74 \text{ or } 74\%$$

Introduction:- In the Crystals the atoms or molecules will be oriented in highly systematic manner such that every atom consists the same type of environment. If a row of atoms is taken, it looks as the atoms are arranged on a line, it is 1D view of a crystal. If all the rows of atoms in a plane which are parallel to each other are taken, it is 2D view of a crystal and is called crystal plane.

Crystal planes are defined as some imaginary planes inside a crystal in which large concentration of atoms are present. Inside the crystal, there exists certain directions along which large concentration of atoms exist. These directions are called crystal directions.



Miller indices:- Crystal planes and directions can be represented by a set of three small integers called "Miller indices".

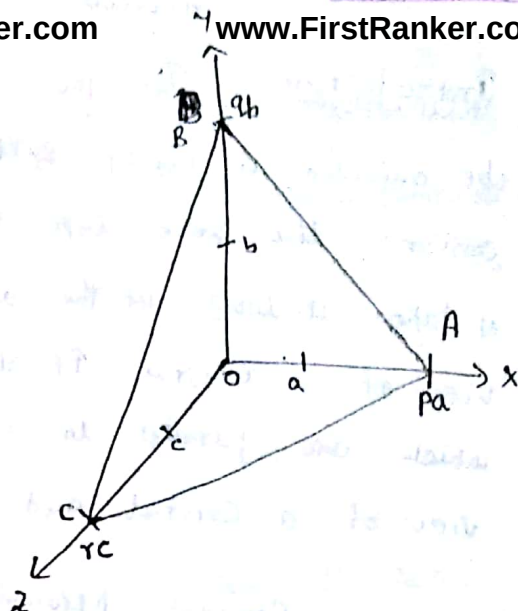
In a crystal orientation of planes or faces can be described in terms of their intercepts on the three crystallographic axes. Miller suggested a method of indicating the orientation of a plane by reducing the reciprocal of the intercepts into smallest whole number. These indices are called Miller indices. Generally represented by (hkl) .

* All equally spaced parallel planes have the same Miller indices
Note: The integers h, k, l are enclosed in round brackets (hkl) then it represents a plane. If they are enclosed in square brackets $[hkl]$ then it represents crystal direction perpendicular to the plane.

Procedure for finding Miller indices

The unit cell translational distances or lattice constants along x, y and z directions are a, b and c.

Let a crystal plane ABC intersect these three axes at p, q, r.



Step 1:- Find the intercepts of the desired plane on the three coordinate axes. Let these be (p, q, r)

Step 2:- Express the intercepts as multiples of the unit cell dimensions or lattice parameters. i.e. (p, q, r)

Step 3:- Take the ratio of reciprocals of these numbers.

$$\text{i.e. } \frac{1}{p} : \frac{1}{q} : \frac{1}{r}$$

Step 4:- Convert these reciprocals into whole numbers by multiplying each with their L.C.M to get the smallest whole number.

This gives the Miller indices ~~plane~~ (hkl) of the plane.

Important features of Miller indices:-

(1) When a plane is parallel to any axis, the intercept of the plane on that axis is infinity. Hence its Miller index for that axis is zero.

(2) All equally spaced parallel planes have the same index number (hkl)

Eg: (8 4 4) and (4 2 2) or (2 1 1) are parallel planes.

(3) When the intercept of a plane on any axis is negative

a bar is put on the corresponding miller index.

(4) If (hkl) are the miller indices of a plane, then the plane divides the lattice constant a along x-axis into h equal parts, b along y-axis into k equal parts and c along z-axis into l equal parts.

(5) If a plane passes through origin, it is defined in terms of parallel plane having non-zero intercept.

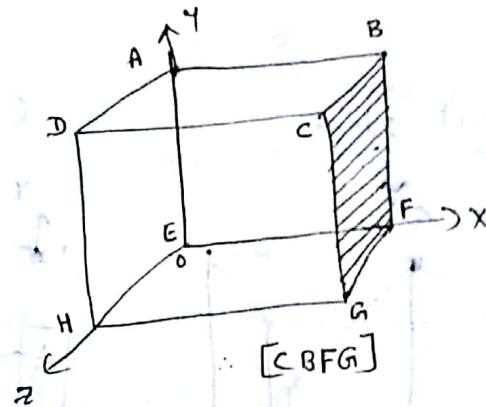
Crystal planes and directions in a Cubic Crystal:-

(100) plane €

miller indices (1 0 0)

→ Reciprocals $\frac{1}{1}, \frac{1}{0}, \frac{1}{0}$

→ intercepts [1 ∞ ∞]

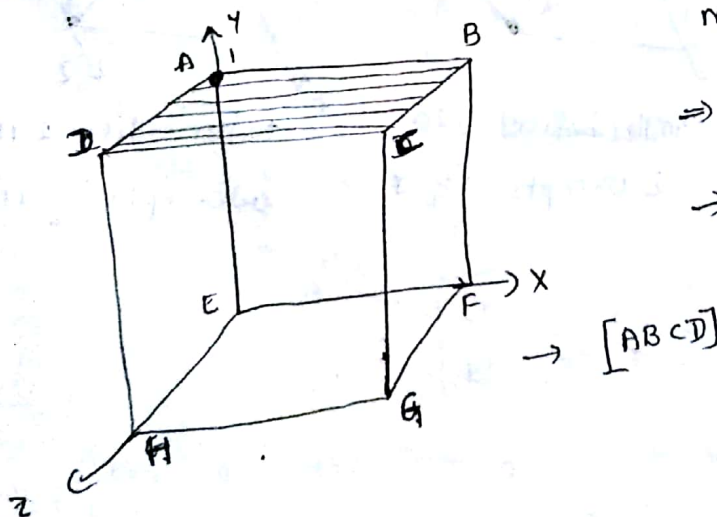


(010) plane:

miller indices (0 1 0)

⇒ Reciprocals $\frac{1}{0}, \frac{1}{1}, \frac{1}{0}$

→ intercepts [∞ 1 ∞]

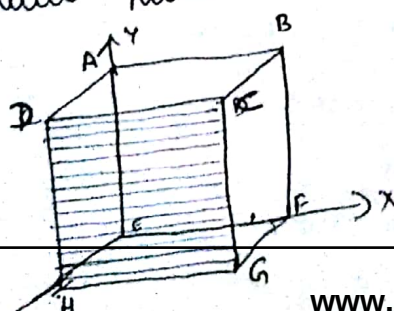


(001) plane:

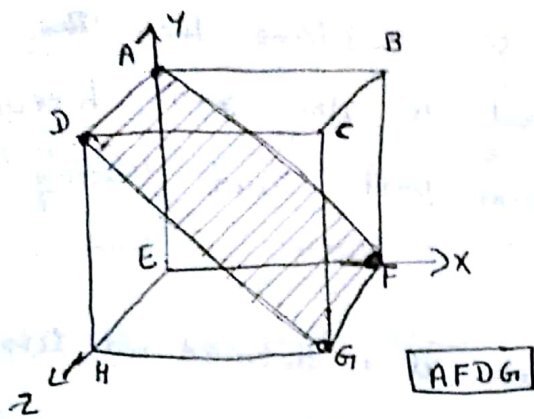
miller indices (0 0 1)

→ Reciprocals $\frac{1}{0}, \frac{1}{0}, \frac{1}{1}$

→ intercepts [∞ ∞ 1]



(110) Plane

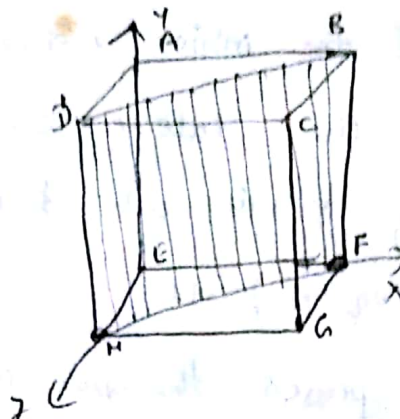


Miller indices 110

intercepts 1 1 ∞

AFDG

(101) Plane

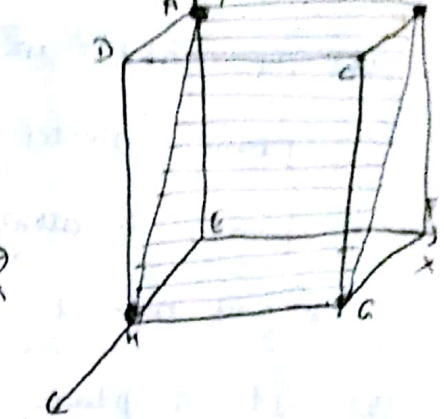


Miller indices 101

intercepts 1 ∞ 1

DBHF

(011) Plane

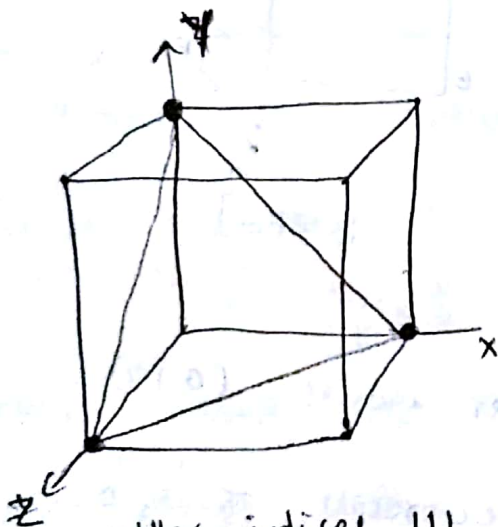


Miller indices 011

intercepts ∞ 1 1

ABGH

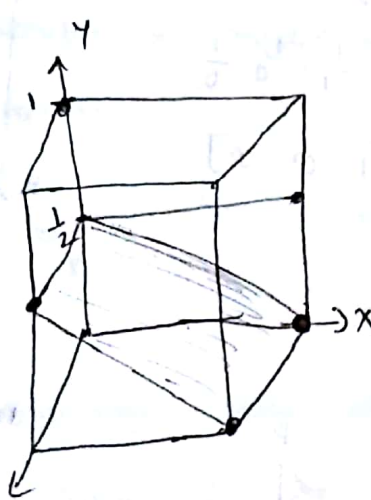
(111) Plane



Miller indices 111

intercepts 1 1 1

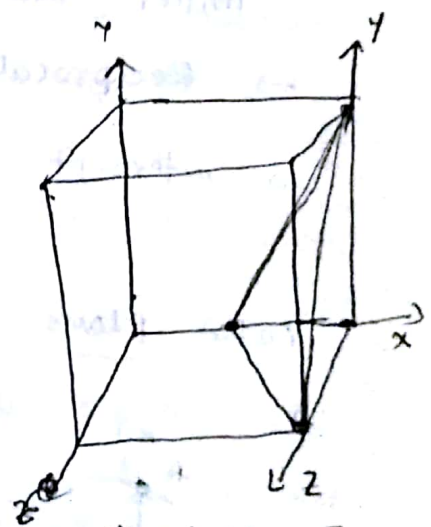
(120) Plane



Miller indices 120

intercepts 1 1/2 ∞

(2̄ 11) Plane

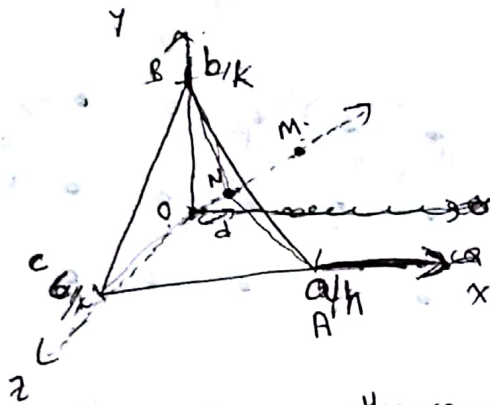
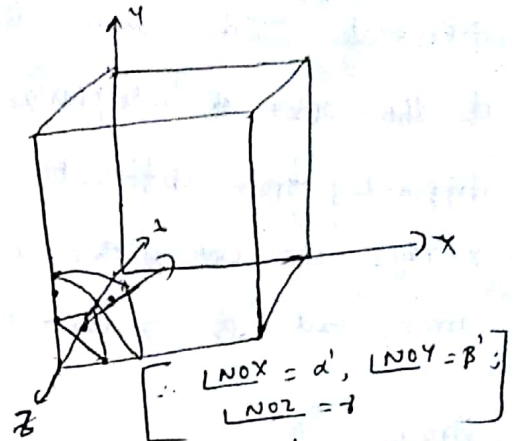


Miller indices 2̄ 11

intercepts (1/2) 1 1

Separation between successive (hkl) planes :-

Let (hkl) be the miller indices of the plane ABC. Let $ON = d$ be a normal to the plane passing through the origin O. Let this ON make angles α' , β' and γ' with x, y, and z axes respectively.



$$\text{Then } \cos \alpha' = \frac{d}{OA} = \frac{d}{a/h} = \frac{dh}{a}$$

$$\cos \beta' = \frac{d}{OB} = \frac{d}{b/k} = \frac{dk}{b}$$

$$\cos \gamma' = \frac{d}{OC} = \frac{d}{c/l} = \frac{dl}{c}$$

from cosine theorem

$$\cos^2 \alpha' + \cos^2 \beta' + \cos^2 \gamma' = 1$$

Substituting the values of $\cos \alpha'$, $\cos \beta'$, $\cos \gamma'$.

$$\frac{d^2 h^2}{a^2} + \frac{d^2 k^2}{b^2} + \frac{d^2 l^2}{c^2} = 1$$

$$\Rightarrow d^2 \left[\frac{h^2}{a^2} + \frac{k^2}{b^2} + \frac{l^2}{c^2} \right] = 1$$

$$\therefore d = \frac{1}{\left[\frac{h^2}{a^2} + \frac{k^2}{b^2} + \frac{l^2}{c^2} \right]}$$

For a cubic crystal $a = b = c$

$$\therefore d = \frac{a}{\sqrt{h^2 + k^2 + l^2}}$$

$$\therefore d_{hkl} = \frac{a}{\sqrt{h^2 + k^2 + l^2}}$$

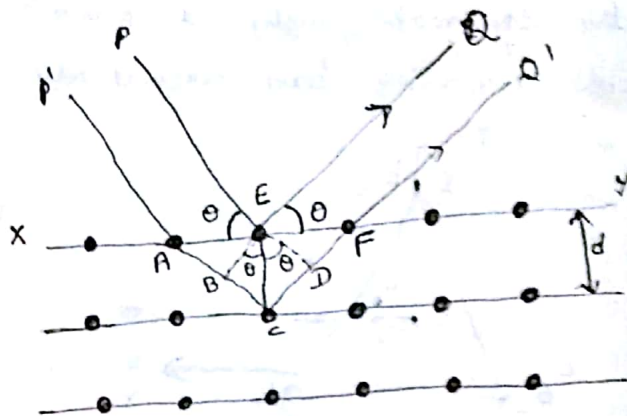
Note: Formula is applicable only to Cubic, orthorhombic and tetragonal System.

X-Ray diffraction:-

As we know that the x-rays can penetrate solids. Since the wavelength of the x-rays ($\sim 1\text{\AA}$) is of the order of interplanar spacing, these rays get strongly diffracted from different crystal planes. By analysing the diffracted x-rays, we can gather information about the internal atomic arrangement of a crystal.

Bragg's law:-

• W.L. Bragg first derived a relation between interplanar spacing and angle of reflection.



Let us consider a crystal made up of equidistant parallel planes of atoms with the interplanar spacing d . Let wavefront of a monochromatic x-ray beam of wavelength λ fall at an angle θ on these atomic planes. Each atom scatters the x-rays in all directions. In certain direction these scattered radiations are in phase i.e. they interfere constructively.

Let us consider the x-rays PE and P'A inclined at angle θ with the top of the crystal plane XY. They are scattered along EQ and CQ' at angle θ with the top of the crystal plane XY. Let us draw normals EB and ED to AC and CF. If EB and ED are parallel to the incident beam and reflected wavefronts then the path difference between the incident and reflected waves is given by $\Delta = BC + CD$.

In $\triangle BEC$ $\sin \theta = \frac{BC}{EC} = \frac{BC}{d} \therefore BC = d \sin \theta$

In $\triangle DEC$ $\sin \theta = \frac{DC}{EC} = \frac{DC}{d} \therefore DC = d \sin \theta$

$\therefore$ path difference $= 2d \sin \theta$

If the two consecutive planes scatter wave in phase with each other, then the path difference must be an integral multiple of wavelength $n \cdot \lambda = n \lambda$, where $n = 0, 1, 2, 3, \dots$ is the order of reflection

$$2d \sin \theta = n \lambda$$

Bragg's law states that x-rays reflected from different parallel planes of a crystal interfere constructively when the path difference is integral multiple of the wavelength of x-rays.

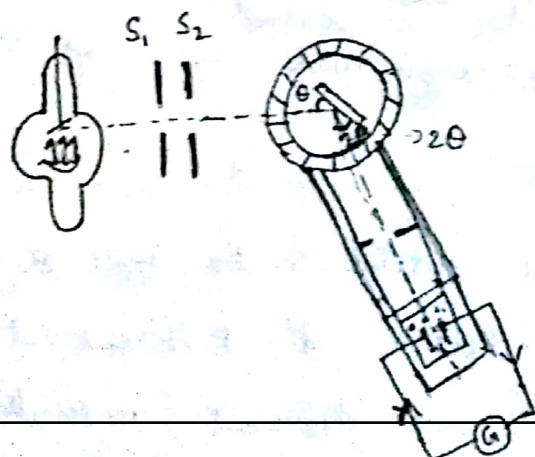
1. maximum possible value for θ is 1

$$\therefore \frac{n \lambda}{2d} \leq 1$$

Bragg's Spectrometer:-

Bragg devised an apparatus used to study the glancing angle θ and the intensities of diffracted x-rays for a given sample.

A monochromatic x-ray beam from the source is passed through two slits, S_1 and S_2 which collimate



it into a fine narrow beam. This x-ray beam is then allowed to fall on the crystal sample C mounted at the centre of a turn table.

A movable arm is also attached

Introduction:- J. J Thomson first proposed the structure of atoms.

Rutherford α -ray scattering experiment revealed the feauting of the structure of an atom. It was an evidence that the atom consists of positive charge which is concentrated in a very small volume at its centre known as nucleus. Marsden and Geiger α -particle scattering experiment supported this experiment. Heisenberg uncertainty principle as well as measurements of nuclear spin and nuclear magnetic moment had been the evidence for absence of negative - charged particles in the nucleus, hence nucleus contains only positive - charged particles. 1

The positive charged particle was named as proton whereas negative - charged particle was named as electron. In 1932, Chadwick discovered a neutral particle in the nucleus, approximately equal to proton mass known as neutron. In a nucleus, the nuclear forces keep the neutrons and protons together. The lighter nuclei are more stable and heavier nuclei are unstable.

The heavier nuclei undergo disintegration until to form stable nuclides. This process is known as radioactivity. The natural radioactivity can be effectively used in determination of ages of both organic and inorganic ~~material~~ materials. The artificial radioactivity is useful in several ways like power generation and also in the research activity to study different physiochemical properties of materials.

An atom consists of positive charged protons as long with neutral charged neutrons occupied in a small volume at its centre known as nucleus. The nucleus is surrounded by negative charged electrons moving in different orbitals. The protons and neutrons in the nucleus are collectively referred as nucleons. The atomic nucleus is described by the following quantities.

- Atomic number (or) charge number (Z):- The no. of protons in the nucleus or the no. of electrons.
- Neutron number (N):- The number of neutrons in the nucleus.
- Mass Number (A):- The number of nucleons in the nucleus.

∴ The total number of neutrons in the nucleus $N = A - Z$.

An atomic nucleus is symbolically represented by ${}^A_Z X$ in which X is chemical symbol of an element.

Classification of Nuclei:-

Isotopes:- The nuclides having same atomic number (Z) but different mass number (A).

Ex:- 1_1H , 2_1H & 3_1H ; • ${}^{11}_6C$, ${}^{12}_6C$, ${}^{13}_6C$ are isotopes of Hydrogen and Carbon respectively.

Isobars:- The nuclides with same mass number (A) but different atomic number (Z).

ex: ${}^{18}_8O$, ${}^{14}_7N$ and ${}^{40}_{20}Ca$, ${}^{40}_{18}Ar$ and ${}^{16}_6C$, ${}^{16}_7N$, ${}^{16}_8O$ and ${}^{16}_9F$ are isobars.

Isotones:- The nuclides of different elements having same number of neutrons ($N = A - Z$)

Ex:- $^{37}_{17}\text{Cl}$ & $^{39}_{19}\text{K}$; $^{14}_6\text{C}$, $^{15}_7\text{N}$, $^{16}_8\text{O}$ are ~~isotopes~~ isotones

Isomers:- Nuclides with same atomic number and same mass number but with different nuclear energy states and exhibit difference in their internal structure are called isomers. These nuclei are distinguished by their different life times and their magnetic moments.

Ex:- $^{80m}_{35}\text{Br}$; $^{80g}_{35}\text{Br}$ where m denotes metastable and g denotes ground state.

Atomic Mass Unit:- The mass of $^{12}_6\text{C}$ isotope of Carbon is a base to derive amu. One atomic mass unit is equal $\frac{1}{12}$ th the mass of the $^{12}_6\text{C}$ atom. The atomic mass of Carbon is equal to the mass of Avogadro number of Atoms (6.02×10^{26} / kilo mol)

$$\therefore 1 \text{ amu} = 1.66 \times 10^{-27} \text{ kg}$$

MASS DEFECT:- The atomic nucleus is made up of protons and neutrons. So we expect that the mass of the nucleus is equal to the total mass of its constituent nucleons. But from nuclear mass measurements, we found that the mass of the nucleus is always less than the total mass of its individual nucleons and therefore the mass deficiency of nucleus will occur. The deficit mass of nucleus is converted in the form of an energy which will bind the nucleons together in a nucleus.

mass defect can be expressed in terms of difference in mass of a nucleus (M) and total mass of its constituents (Σm)

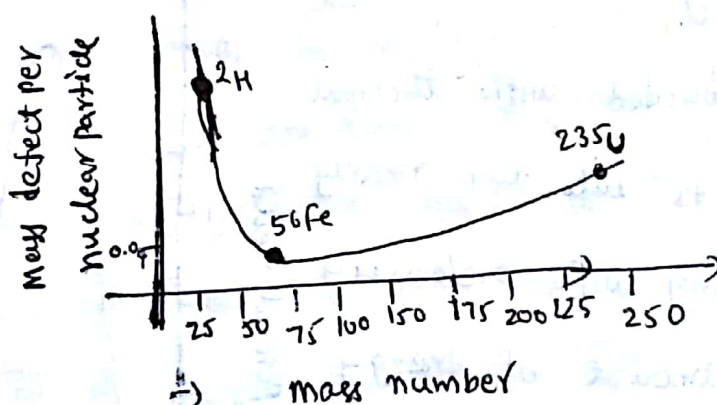
$$\text{mass defect } \Delta M = \Sigma m - M$$

where Σm = Sum of mass of protons and neutrons

$$= Zm_p + (A - Z)m_n$$

$$\therefore \Delta M = [Zm_p + (A - Z)m_n] - M$$

The mass defect is different for different nuclides, the higher mass defect nuclei has more stability. The most stable nuclei are in the atomic range from 30 to 63 and Fe-56 is the most stable nuclei.



Binding Energy:- In a nucleus the nucleons are bind together with nuclear forces. To separate the nucleus into individual nucleons, some amount of energy is required. This energy is known as binding energy of the nucleus. Binding energy is also defined as the energy released when the nucleons are bound together to form a nucleus.

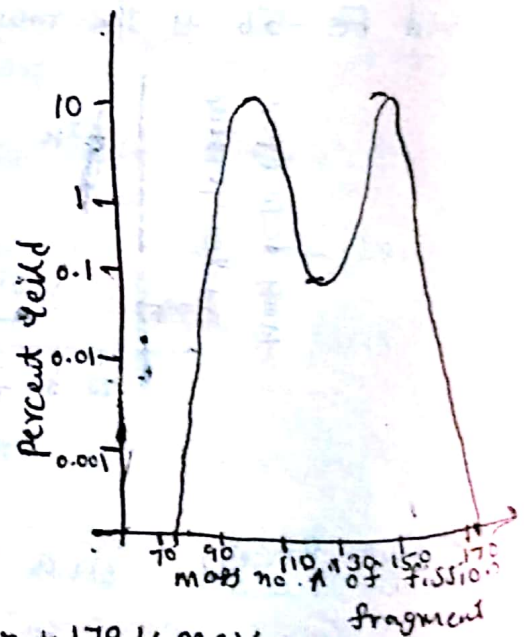
According to law of Conservation energy, the binding energy is the energy equivalent to the mass defect energy

terms of energy is Δmc^2

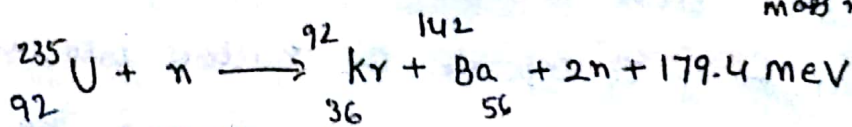
$\therefore$ The binding energy $\Delta E_b = \Delta Mc^2 = \{ [Zm_p + (A-Z)m_n] - m \} c^2$

Nuclear Fission:- The process of subdivision of a heavy unstable nucleus into two approximately equal fragment is known as nuclear fission. This process may take place spontaneously or be induced by the excitation of the nucleus with particles like neutrons, protons, deuterons and α -particles or with electromagnetic radiation in the form of γ -rays.

Ex:- When a heavy unstable nucleus like ${}_{92}^{235}\text{U}$ is bombarded with thermal neutron it splits into two nearly equal parts, along with releasing of considerable amount of energy.



The fission reaction is



We can estimate the total energy released by the fission

is $Q = \text{total final binding energy} - \text{initial binding energy}$

The probability of fission reaction for a particular nucleus depends on the energy of incident neutrons. Nuclei with odd

number of electrons neutrons ${}_{92}^{233}\text{U}$, ${}_{92}^{235}\text{U}$ and ${}_{92}^{239}\text{U}$ undergo fission

slow neutrons ($< 1 \text{ eV}$). The nuclei with even number neutrons $^{238}_{92}\text{U}$, $^{232}_{90}\text{Th}$ require fast neutrons ($> 1 \text{ MeV}$).

Important features of Nuclear fission:-

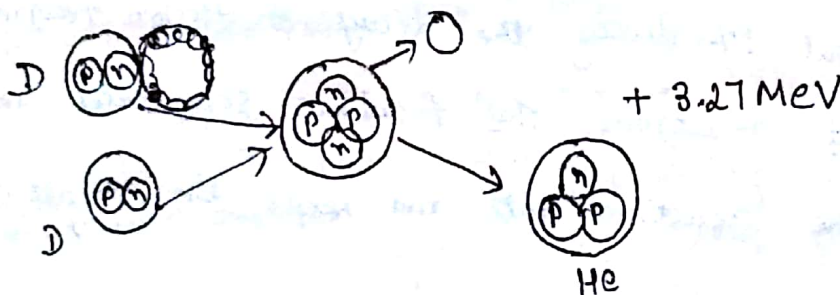
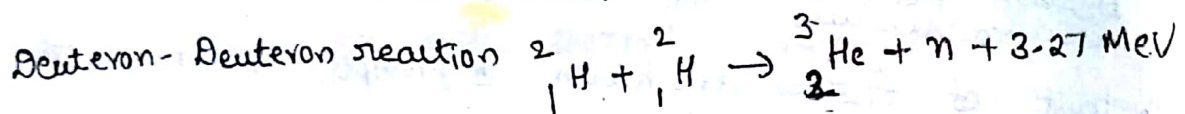
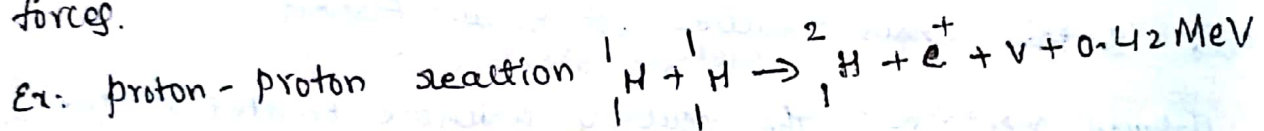
1. Energy emission:- The average amount of energy released in each fission reaction is about 200 MeV per nucleus. To sustain the reaction, most of energy is to be provided for fragments in the form of kinetic energy.
2. Neutron multiplicity:- Nuclear fission process is accompanied by emission of two or more neutrons, which cause the further fission of other nuclei. This feature can be used to build a self-sustaining chain reaction of nuclear fission.
3. Delayed neutrons:- The neutrons which are emitted at the instant of fission are known as prompt neutrons. The neutrons emitted about 1% during the decay of fission fragments are called delayed neutrons. This feature stimulates mechanical control of the reaction rate and keeps the reaction from proceeding too rapidly.

Uses of Nuclear fission:-

1. The high neutron flux is used to study the structure and properties of the materials.
2. The nuclear fission energy is used to dig canals through mountains and hills to construct railway tracks, coal mines, petrol wells, tank etc.
3. It is also used to convert salt water into drinking water.

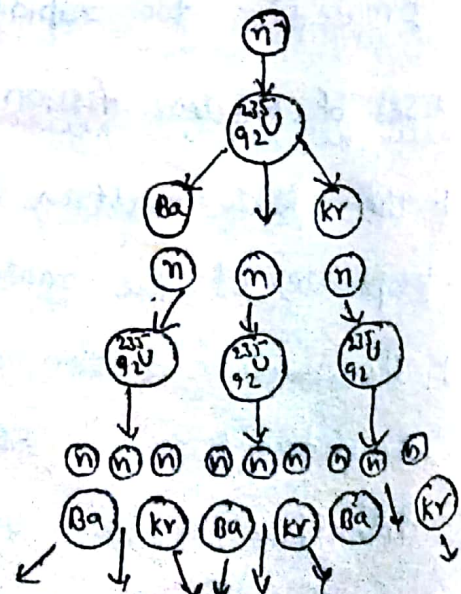
water and detect cracks in heavy water boilers.
4. The nuclear energy is converted into electricity through the thermoelectric effect in semiconductor material like atomic battery, which is used as a source of energy for cardiac pacemakers.

Nuclear Fusion:- where two lighter atoms like hydrogen or protons are fused into a heavier atom like helium, a large amount of energy (28.6 MeV) is released. This phenomenon is called nuclear fusion. ~~The latter~~ Extreme temperature and pressure are required in nuclear fusion reactions to overcome the Coulombic repulsive forces.



Chain Reaction:-

When the fission of ${}^{235}_{92}\text{U}$ starts once, the process continues without any supply of neutrons from outside. In the fission of ${}^{235}_{92}\text{U}$ by thermal neutron, more number of neutrons are produced than they are



summed, hence each neutron triggers another fission. This process is called Chain reaction. The Chain reaction can be either uncontrolled (rapid) or controlled (steady). Controlled Chain reaction in a nuclear reactor is used to produce electrical power. The uncontrolled chain reaction in atomic bomb causes a tremendous explosion.

Condition for Chain Reaction:-

1. Fast neutrons must be converted into slow neutrons by allowing them to pass through moderators.
2. At least one thermal neutron should be available to initiate the chain reaction.
3. The state of chain reaction depends on the neutron reproduction factor or multiplication factor k . It is a measure of the growth rate of neutrons in the reactor.

$$k = \frac{\text{Rate of production of neutrons}}{\text{Rate of loss of neutrons}}$$

when $k=1$, the operation of the reactor is said to be critical, the fission reaction is in steady state.

$k > 1$, the system is said to be super-critical, the fission reaction is in accelerated state and uncontrollable.

$k < 1$, the system is said to be sub-critical; the fission is in decelerated state.

Nuclear Reactor:- It is a device which works on the principle of nuclear fission by controlled and self-sustained chain reaction to release the nuclear energy at a constant rate.

- of the nuclear reactor are as follows
1. Nuclear fuel:- Natural abundant uranium contains only $^{235}_{92}\text{U}$, the remaining 99.3% being $^{238}_{92}\text{U}$ is not fissionable by thermal neutrons. Fissionable materials which are enriched uranium U-235, plutonium Pu-239 are mostly used as nuclear fuel. The nuclear fuels in the form of uranium oxide pellets are inserted into metallic tubes which act as fuel rods. The bundle of these rods is surrounded by liquid moderator. This system is collectively known as the nuclear core.
 2. Moderator:- The nuclear fission is induced most effectively by thermal neutrons, not by fast moving neutrons. So in order to slowdown the fast moving neutrons, very lighter materials are used, such materials are called moderators. The moderators do not absorb the neutrons, but by the elastic collisions they slow down the neutron's velocity. The moderators commonly used are water, heavy water, graphite and beryllium.
 3. Reflectors:- The inner surface of the reactor is surrounded by material which reflects the neutrons back into the core are called reflectors. Otherwise the neutrons in fission, will escape from the reactor. To reduce the neutron leakage, the reflectors are mostly made of nickel, thorium, water, graphite, etc.
 4. Control rods:- A series of rods which are used to regulate the rate of reaction in a nuclear reactor are called control rods. These are made with neutron absorbing materials like cadmium (Cd), Boron (B) and Hafnium (Hf). The insertion or withdrawal of the control rods from the reactor core will control the number of neutrons.

In addition to the control rods, the reactors are provided with safety rods. These can be inserted into the reactor when required.

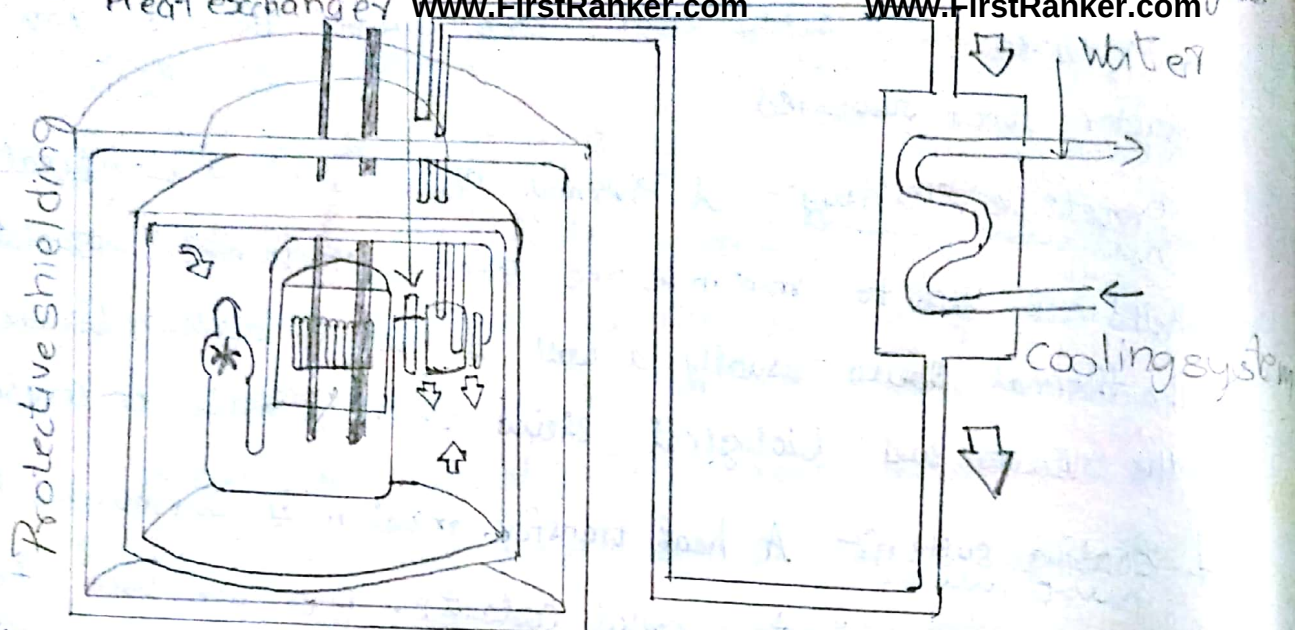
6. Protective Shielding:- A thermal shield and a biological shield are used to minimise the effects of harmful radiation. The thermal shield usually a wall of steel is placed between the reactor and biological shield which is made of concrete.

7. Cooling system:- A heat transfer medium is surrounded by the core and moderators called coolants. These are used to prevent the excess rise in the reactor. The coolant may be water, heavy water or gas like He or CO_2 .

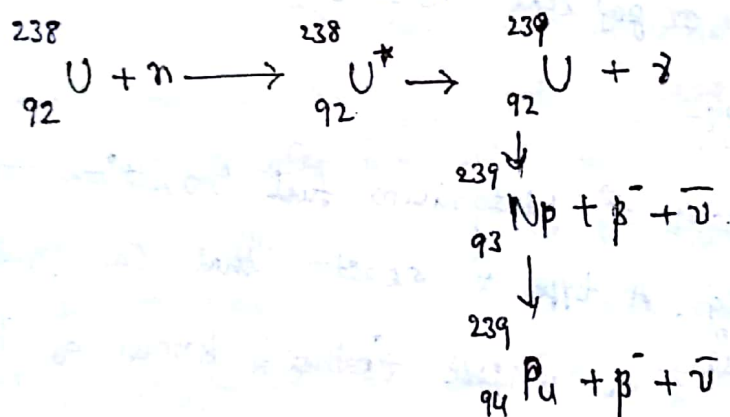
BREEDER REACTOR:-

Principle:- The process of plutonium fuel production from uranium is known as breeding. A type of reactor that can produce more fissionable fuel $^{239}_{94}\text{Pu}$ to utilise further is known as breeder reactor. The plutonium-239 breeder reactor is also known as fast breeder reactor.

Working:- The breeder reactor contains the plutonium isotope Pu-239 as an inner core and that inner core is surrounded by a shield of the uranium isotope U-238 . In these reactors, natural uranium ^{238}U is used as a nuclear fuel because the natural uranium is the most abundant material and contains only 0.7% of ^{235}U the remaining 99.3% being ^{238}U which is not fissionable by thermal neutrons. When Pu-239 is bombarded with neutrons, the plutonium is split into small fragments and produces some heat energy.



Nuclear Reaction:- The production of fissionable ^{239}Pu from ^{238}U is illustrated by the following reaction.



When some neutrons hit the ~~surround~~ surrounding non-fissionable ^{238}U , then ^{239}U is produced with γ -emission. It decays to ^{239}Np followed by β -emission. Now ^{239}Np decays to the nuclide ^{239}Pu with β -emission. When all the surrounding Uranium is converted into plutonium, the fuel is completely regenerated. So during the process, the breeder reactor produces the fuel for itself.

Advantages:-

- * In the fission of ^{239}Pu , fast moving neutrons in addition to slow moving neutrons are obtained, hence a fast breeder reactor

- * A breeder reactor creates 30% more fuel than it consumes.
- * It can generate much more energy than traditional coal power power plants.
- * Natural abundant uranium ^{238}U is used in breeder reactors than enriched uranium ^{235}U which is rare on earth.

Disadvantages:-

- * The operating temperature of a breeder reactor is relatively high and a moderator is not desired; a heat transfer material such as liquid sodium metal is used rather than water.
- * The half-life of time of plutonium is very high (24,000 years) and it is highly toxic, causing lung cancer.
- * These reactors are complex to operate.

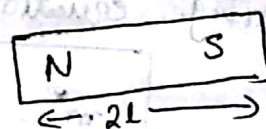
Introduction: Magnetism is a phenomenon by which material

being attractive or repulsive forces on other materials.

magnetic field: A volume of space where there is a change in energy is known as magnetic field. The location where a magnetic field can be detected exiting or entering a material is called a magnetic pole. Magnetic poles have never been detected in isolation but always occur in pairs and thus the name dipole. Dipole is an object that a magnetic pole on one end and a second equal but opposite magnetic pole on the other.

A bar magnet can be considered a dipole with a north pole at one end and south pole at the other. ~~A magnetic field can be created~~ If a magnet is cut in two, two magnets or dipoles are created out of one. This sectioning and creation of dipoles can continue to the atomic level.

Magnetic dipole: It is a system consisting of two equal and opposite magnetic poles separated by a small distance of $2l$ metres.



Magnetic moment of a bar magnet: It is defined as the product of its pole strength (m) and distance between the two poles ($2l$).

$\therefore$ magnetic moment of a dipole $M = 2lm$ units: ampere- m^2 .

Magnetic moment of a current loop (μ): Magnetic dipole may arise when current flows in a conducting wire. It is defined as the product of current passing through the wire and cross-sectional area of the wire.

$\therefore \mu = iA$ units: ampere- m^2

Magnetic induction (or) Magnetic flux density: The number of magnetic lines of force passing perpendicularly through unit area.

$$\therefore B = \frac{\Phi}{A} = \frac{\text{magnetic flux}}{\text{area}} \quad \text{weber}/m^2 \quad (or) \text{ Tesla.}$$

It is also defined as the magnetic force experienced by

unit north pole placed at a given point in a magnetic field.

$$B = \frac{F}{m} \text{ unit: Newton/Ampere metre.}$$

Magnetic field intensity (H):- Magnetic field intensity at any point in a magnetic field is equal to $\frac{1}{\mu}$ times the force acting on the unit north pole placed at that point, where μ is permeability of the medium in which the magnetic field is situated.

$$\therefore H = \frac{B}{\mu} = \frac{F}{\mu m}$$

units: ampere turn/metre

Permeability (μ):- It is defined as ratio between magnetic field induction and magnetic field intensity at a given point in that medium. Permeability of the specimen gives the information about the number of magnetic lines of force present per unit area in the medium per unit applied magnetic field intensity.

$$\mu = \frac{B}{H} = \frac{\phi}{AH}$$

unit: Henry/metre

Relative permeability (μ_r):-

It is defined as the average magnetic moment present per unit volume of free space.

$$\therefore \mu_r = \frac{\mu}{\mu_0} \therefore \text{Henry/m.}$$

$$\Rightarrow \mu_0 = 4\pi \times 10^{-7}$$

unit: No unit.

magnetisation (m):- Process of converting a non-magnetic sample into a magnetic sample is called magnetization

Intensity of magnetisation (I) - It is defined as the average magnetic moment present per unit volume in a system.

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$I = N\bar{\mu}$ where N is the number of atoms or molecules per unit volume $\bar{\mu}$ is the average dipole moment.

The magnetic field intensity and intensity of magnetisation both are having same units and dimensions. Hence, in the presence of magnetic field (H) the magnetic field induction (B) can be expressed

$$B = \mu_0(I + H) = \mu H$$

$$\therefore \mu = \frac{B}{H} \text{ \& } \mu_0 = \frac{B}{I + H}$$

Susceptibility:- It may be defined as the ratio of intensity of magnetisation and applied magnetic field intensity

$$\therefore \chi = \frac{I}{H} = \frac{M}{H}$$

Relation between the susceptibility (χ) and relative permeability (μ_r):

The good materials should have high permeability and high susceptibility.

From the definition of relative permeability

$$\mu_r = \frac{\mu}{\mu_0}$$

we know that $\mu = \frac{B}{H}$ and $\mu_0 = \frac{B}{I + H}$

$$\mu_r = \frac{\frac{B}{H}}{\frac{B}{I + H}} = \frac{I + H}{H} = \frac{I}{H} + 1$$

$$\therefore \boxed{\mu_r = \chi + 1}$$

Show that $B = \mu_0(H + M)$ Proof:-

The magnetic flux density (or) magnetic induction (B) inside the material is directly proportional to the applied magnetic field (H) on the material. i.e. $B \propto H \Rightarrow B = \mu H = \mu_0 \mu_r H$

we know that $\mu_r = \frac{M}{H} + 1$

$$\therefore B = \mu_0 \left(\frac{M}{H} + 1 \right) H = \mu_0 (M + H) H$$

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$$\boxed{B = \mu_0 (M + H)}$$

In atoms the permanent magnetic moments can arise due to

- (1) The orbital magnetic moment of the electrons
- (2) The spin magnetic moment of the electrons
- (3) The spin magnetic moment of the nucleus.

Orbital magnetic moment of the electrons:-

In an atom electrons revolve around the nucleus in different circular orbits. Let m be the mass of the electron and r be radius of the orbit in which it moves with angular velocity ω .

$\therefore$ electric current due to the moving electron

$$I = -(\text{number of electrons flowing per sec} \times \text{charge of an electron})$$

ω is the angular velocity, number of revolutions made by electron per sec = $\frac{\omega}{2\pi}$



$$\therefore \frac{I}{e} = -\frac{e\omega}{2\pi} \rightarrow (1)$$

The current flowing through a circular coil produces a magnetic field in a direction perpendicular to the area of the coil and it is identical to a magnetic dipole. The magnitude of the magnetic moment produced by such dipole is

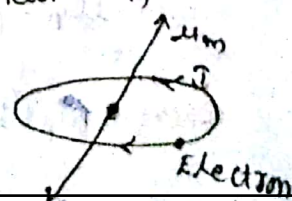
$$\mu_m = \frac{I}{e} \cdot A = -\frac{e\omega}{2\pi} (\pi r^2) = -\frac{e\omega r^2}{2}$$

$$\Rightarrow \mu_m = -\frac{e}{2m} m r^2 \omega = \left(-\frac{e}{2m}\right) L \rightarrow (2)$$

where $L = m r^2 \omega$ is the orbital angular momentum of electron. -ve sign indicates that the magnetic moment μ_m is antiparallel to the angular momentum L .

As per Bohr's theory in an atom only

those orbits are allowed, where the angular momentum of the electron



$$\therefore h = \frac{h}{2\pi} \rightarrow (3)$$

(3)rd equation Substitute in equation (2)

$$\mu_m = -\frac{eh}{4\pi m} = -\left(\frac{eh}{4\pi m}\right) L = -\mu_B M_L$$

where $\mu_B = \frac{eh}{4\pi m}$ is known as Bohr magneton.

The magnitude of spin moment contributed by an electron is known as Bohr magneton.

$$\therefore \mu_B = \frac{eh}{4\pi m} = 9.27 \times 10^{-24} \text{ ampere-m}^2$$

Spin magnetic moment of the electrons:-

Besides the orbital motion of an electron, it rotates about its own axis. Magnetic moment associated with spinning of electron is called spin magnetic moment.

The electronic spin dipole moment is given by

$$\mu = \left(\frac{-e}{2m}\right) S = \text{where } S = \sqrt{S(S+1)}$$

where S is spin angular momentum and is defined as the ratio of the magnetic dipole moment of an electron due to its spin motion and the spin angular momentum.

$$\therefore \mu_s = 9.4 \times 10^{-24} \text{ Ampere-m}^2$$

Spin magnetic moment of the ~~electrons~~ nuclei:-

Nuclear magnetic moment arises due to the spinning of nucleus (proton).

$$\therefore \mu_n = \left(\frac{-eh}{4\pi M_p}\right) = 5.05 \times 10^{-29} \text{ A-m}^2$$

where M_p is the mass of the proton.

Magnetic Substances are those which are affected by a magnet. They can be classified as diamagnetic, paramagnetic and ferromagnetic. The behaviour of magnetic substances can be classified explained on the basis of electron theory.

The matter is made up of atoms. each atom has a positively charged nucleus at its centre and around the nucleus negatively charged electrons revolve in various orbits. The revolving electron behaves like a magnetic dipole, which has some magnetic moment. This magnetic moment arises due to orbital motion and spin motion. The contribution to the magnetic moment due to orbital revolution is negligibly small. Hence most of the magnetic moment is produced due to electron spin. The magnetic moment vectors are oriented in different directions in an atom.

Diamagnetic materials:-

When the no. of orbits and their orientations is such that the vector sum of magnetic moment is zero, then the material is said to be diamagnetic. The property of diamagnetism is generally found in those substances whose atoms or molecules have even number of electrons which form pairs. In the electron pair, the direction of spin of one electron is opposite to that of the other. In this way the magnetic moment of one electron is neutralised by that of the other and the net magnetic moment is zero.

- (1) Diamagnetic material possesses no permanent dipole moment (or) magnetic moment in each atom is zero. The induced magnetic moment produced by the external magnetic field decreases the magnetic induction present in the material.
- (2) Susceptibility χ is negative for these materials and is independent of temperature and strength of applied magnetic field.
- 3- No spin alignment is present.

4. In the presence of magnetic field, the magnetic lines of force are

pulled out from the material. Hence magnetic field induction is greater outside the material than inside. i.e. $B_{out} > B_{in}$



5. In the case of perfect diamagnetic material like low temperature superconductor, the diamagnetic property disappears if the temperature is increased above the superconducting transition temperature then it behaves like a normal material.

6. Ex: Bi, Zn, H₂O, Gold etc.

Paramagnetic materials:- When the arrangement of ^{orbits} such that the vector sum of magnetic moment is not zero, then the atom has a resultant magnetic moment. The substance is known as paramagnetic substances. So the atoms or molecules of a paramagnetic substance possess a permanent magnetic moment. The property of paramagnetism is found in the substances whose atoms or molecules have single electrons and their orbitals oriented in a random way such that the permanent magnetic moment is greater than zero.

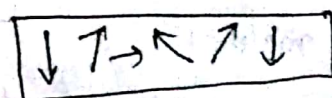
1. Paramagnetic material possess permanent dipole moment or magnetic moment in each atom. The induced magnetic moment produced by the external field increases the magnetic induction present in the material.

2. Susceptibility χ is positive and small for these materials. And the susceptibility is inversely proportional to the temperature T .

$$\text{i.e. } \chi \propto \frac{1}{T}$$

$$\chi = \frac{C}{T} \text{ where } C \text{ is Curie's temperature constant.}$$

3. All spins or magnetic moments are randomly oriented in



4. In the presence of magnetic field, the magnetic lines of force are attracted towards the centre of the material and hence the magnetic induction inside the material is greater than

2. Below Superconducting transition temperature,

the paramagnetic materials exhibit the diamagnetism.

6. Ex: Al, Pt, Mn.

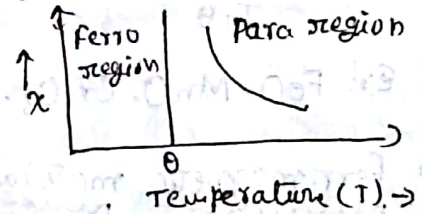
Ferromagnetic materials:-

when all the orbits of single's are oriented in a systematic manner such that the atom as a whole possesses a large magnetic moment, then the substance is known as ferromagnetic material.

1. Ferromagnetic material possess enormous permanent dipole moment or magnetic moment in each atom. The induced magnetic moment produced by the external magnetic field is very large and it increases the magnetic induction present in the material.

2. Susceptibility is always positive and large it depends upon temp in a complex manner.

$$\chi = \frac{C}{T - \theta} \quad (\text{only in paramagnetic region i.e. } T > \theta)$$



where θ is Curie temperature.

3. All spins or magnetic moments are orderly oriented.

4. In the presence of magnetic field, the magnetic lines of force are highly attracted towards the centre of the material and hence, the magnetic field induction inside the material is very greater than the outside i.e. $B_{in} \gg B_{out}$.

5. When the temperature of material is greater than its Curie temperature then it converts into paramagnetic material.

6. Ex: Fe, Ni, Co.

Classification of ferromagnetic materials:-

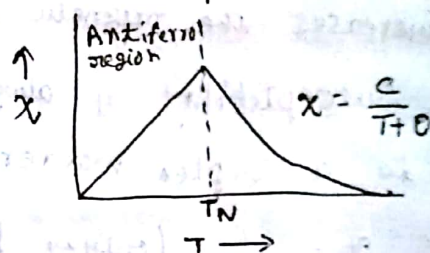
Depending upon the spin orientation of the electrons, ferromagnetic materials are classified into two types, they are

(i) Anti ferro magnetic material

(ii) Ferrimagnetic material.

1. These are the ferromagnetic materials in which equal number of opposite spins with same magnitude such that the orientation of neighbouring spin is in antiparallel manner are present.
2. Susceptibility is small and positive for these
3. spin alignment is in antiparallel manner
4. The temperature at which antiferromagnetic material converts into paramagnetic (substance) material is known as Neel's temperature.
5. Susceptibility is inversely proportional to the temperature.

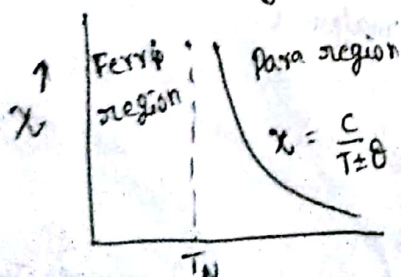
$$\chi = \frac{C}{T + \theta} \text{ when } T > T_N$$



6. Ex: FeO, MnO, Cr₂O₃... etc.

Ferrimagnetic materials:-

1. These are the ferromagnetic materials in which equal number of opposite spins with different magnitude such that the orientation of neighbouring spin is in antiparallel manner are present.
2. Susceptibility is positive and very large for these materials.
3. spin alignment is in antiparallel manner.
4. Susceptibility is inversely proportional to temperature.

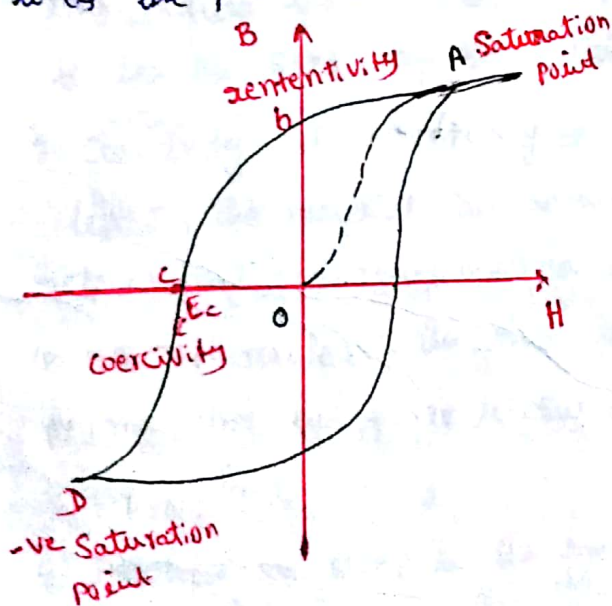


$$\chi = \frac{C}{T + \theta} \text{ when } T > T_N \text{ (Neel's temp)}$$

5. Ferrites are the best examples of ferrimagnetic materials.
6. Ex: ZnFeO₄, CuFe₂O₄

A hysteresis loop shows the relationship between the induced magnetic flux density (B) and the magnetizing force (H). It is often referred to as the B - H loop.

The loop is generated by measuring the magnetic flux of a ferromagnetic material while the magnetizing force is changed. A ferromagnetic material that has never been previously magnetized or has been thoroughly demagnetized will follow the dashed line as H is increased. As the line ~~increased~~ demonstrates, the greater the amount of current applied (H), the stronger the magnetic field in the component (B). At point A almost all of the magnetic domains are aligned and an additional increase in the magnetizing force will produce very little in magnetic flux. The material has reached the point of magnetic saturation. When H is reduced to zero, the curve will move from point A to B. At this point, it can be seen that some magnetic flux remains in the material even though the magnetizing force is zero. This is referred to as the point of retentivity on the graph and indicates that the



remanence or level of residual magnetism in the material. As the magnetizing force is reversed, the curve moves to point 'C', where the flux has been reduced to zero. This is called the point of coercivity on the curve. The force required to remove the residual magnetism from the material is called the coercive force or coercivity of the material.

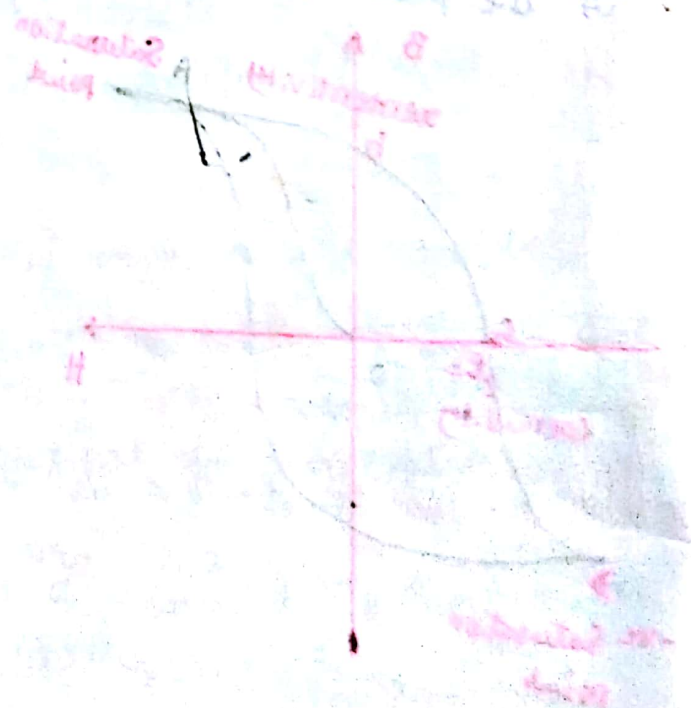
As the magnetizing force is increased in the negative direction, the material will again become magnetically saturated but in the opposite direction to the previous saturation point (A). Reducing H to zero brings the curve to point 'C'. It will have a level of residual magnetism equal to that achieved in the other direction. Increasing H back in the +ve direction will return B to zero. Notice that the curve did not return to the

magnetism.

1) Retentivity:- A measure of the residual flux density corresponding to the saturation induction of a magnetic material. In other words, 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. Note that residual magnetism and retentivity are the same when the material has been magnetized to the saturation point. However, the level of residual magnetism may be lower than the retentivity value when the magnetizing force did not reach the saturation level.

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.



Introduction:- A dielectric is a nonconducting substance, i.e. an insulator. Although dielectric and insulator are generally considered synonymous, the term dielectric is more often used to describe the insulating material between the metallic plates of capacitor, while insulator is more often used when the material is being used to prevent a current flow across it.

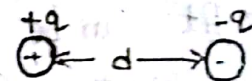
Dielectric is the study of dielectric materials and involve physical models to describe how an electric field behaves inside the material. It is characterized by how an electric field interacts with an atom and therefore possible to approach from either a classical interpretation or a quantum one.

Definitions:-

Electric dipole:- A system consisting two equal and opposite charges separated by a distance is called electric dipole.

Dipole moment (μ):- The product of charge and distance between two charges is called dipole moment.

$$\mu = qd \quad \text{Units: coulombs metre}$$



Permittivity (ϵ):- Permittivity is a quantity which represents the dielectric property of a medium.

Permittivity of a free space $\epsilon_0 = 8.85 \times 10^{-12} \text{ F/m}$

Dielectric Constant (ϵ_r):- It is defined as the ratio between the permittivity of that medium and the permittivity of free space

$$\epsilon_r = \frac{\epsilon}{\epsilon_0} = \frac{C}{C_0}$$

where C is capacitance of capacitor that medium with dielectric

C_0 is capacitance of capacitor without dielectric

Capacitance: The property of a conductor that describes its ability to store electric charge.

$C = \frac{Q}{V}$ where V is potential difference between plates
 Q is charge on the capacitor plates
 $C = \frac{A\epsilon}{d}$ A is area of capacitor plates
 d is distance between capacitor plates

Electric polarisation:— when an electric field is applied to a crystal or glass containing positive and negative charges. The positive charges are displaced in the direction of the field, while negative charges are displaced in the opposite direction. This displacement of charges produce local dipoles throughout the solid. This process of producing dipoles by the influence of an electric field is electric polarisation.

polarizability (α):— The average dipole moment of a system is proportional to the electric field applied

$$\mu \propto E \quad \therefore \alpha = \frac{\mu}{E}$$

It can be defined as the ratio of average dipole moment to the electric field applied.

Polarisation vector ($\vec{P}$):— The dipole moment per unit volume of the dielectric material is called polarisation vector ($\vec{P}$).

$\therefore \vec{P} = N\vec{\mu}$ where N is the number of atoms present per unit volume.

Units: Coulomb/meter²

Electric susceptibility (χ):— when a dielectric is placed in an electric field (E) then polarization takes place. The polarization vector ($\vec{P}$) is proportional to the applied electric field.

$$\therefore \vec{P} \propto E \quad \therefore \vec{P} = \chi E$$

$$\chi = \frac{P}{E}$$

The electric susceptibility may be defined as the polarisation vector to the electric field.

Displacement vector (D):- The number of lines of forces received by unit area is called flux density or displacement vector.

$$D = \frac{1}{4\pi} \frac{q}{r^2} \rightarrow (1)$$

The electric field at a point in a medium is

$$E = \frac{q}{4\pi \epsilon \pi r^2} \rightarrow (2)$$

From eqn's (1) & (2) $E = \frac{D}{\epsilon} \Rightarrow D = \epsilon E$

$$\therefore D = \epsilon_0 \epsilon_r E \rightarrow (3) \quad (\because \epsilon_r = \frac{\epsilon}{\epsilon_0})$$

If p is the polarisation of the dielectric material due to the applied electric field (E), then the flux density ' D ' is equal to flux density in vacuum plus polarisation of the material.

$$\therefore D = \epsilon_0 E + P \rightarrow (4)$$

From Equation (3) & (4) $\epsilon_0 \epsilon_r E = \epsilon_0 E + P$

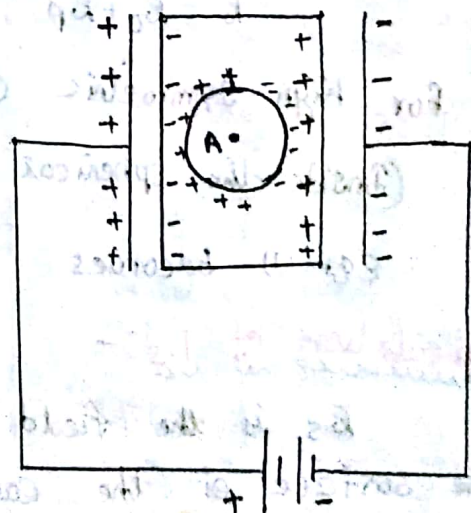
$$\therefore P = \epsilon_0 (\epsilon_r - 1) E$$

The electric susceptibility is

$$\chi = \frac{P}{\epsilon_0 E}$$

Internal or Local or Lorentz field:-

In dielectric solids, the atoms or molecules experience not only the external applied electric field but also the electric field produced by the dipoles. The resultant electric field acting on the atoms or molecules of dielectric substance is called the local field or an internal field.



The calculation of different fields by different fields by different sets of dipoles acting on a molecule or atom of a dielectric was done by Lorentz as follows.

The dipole at the point A is imagined to be surrounded by a spherical cavity of radius r such that the radius r is large compared with the intermolecular distance so that the sphere contains many molecules but small compared to the dimensions of the whole dielectric. If this dielectric is placed between two capacitor plates, the electric field experienced by a molecule of the dielectric, is assumed to be placed at the centre of the cavity is given by

$$E_{\text{local}} = E_0 + E_p + E_s + E_m \longrightarrow (1)$$

where E_0 is the field intensity at the point A due to charge density on the plates of the capacitor.

E_p is the field at the point A due to the polarized charges on the plane surface of the dielectric.

E_s is the field intensity at the point A due to polarized charges on the surface of the imagined spherical cavity

E_m is the field at the point A due to all the dipoles inside the spherical cavity.

The macroscopic electric field (E) inside the dielectric is

$$E = E_0 + E_p \longrightarrow (2)$$

For high symmetric crystals $E_m = 0$

(Inside the spherical cavity there is no dipoles)

$\therefore$ Eqn (1) becomes

$$E_{\text{local}} = E + E_s \longrightarrow (3)$$

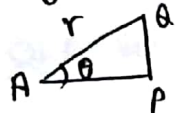
Calculation of E_s :-

E_s is the field intensity due to polarisation charges on the surface of the cavity and was calculated by Lorentz

If dA is the area of an areal element on surface of sphere of radius ' r ' making angles θ and $\theta + d\theta$ with reference to the direction of the applied field.

From the figure the area of an element $dA = 2\pi (PA) (QR) \rightarrow (4)$

From the fig $\triangle APA$



$$\sin \theta = \frac{PQ}{AP}$$

$$\Rightarrow PA = AP \sin \theta = r \sin \theta$$

From the fig $\triangle AQR$

$$d\theta = \frac{QR}{AR}$$

$$d\theta = \frac{QR}{r} \Rightarrow QR = r d\theta$$

Substitute the PA , QR values in equation no (4) then we can get $dA = 2\pi r^2 \sin \theta d\theta \rightarrow (5)$

The charge dq on the surface is equals to the normal component of the polarisation vector ($P \cos \theta$) multiplied by the area

$$dq = P \cos \theta dA$$

$$\Rightarrow dq = P \cos \theta 2\pi r^2 \sin \theta d\theta \rightarrow (6)$$

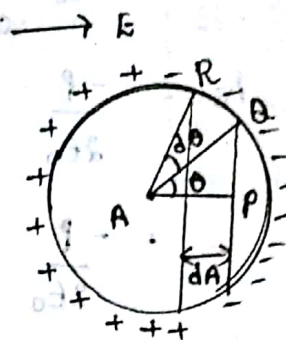
The intensity of the electric field dE_s at the centre due to this charge element in the direction ' r ' is

$$dE_s = \frac{dq \cos \theta}{4\pi \epsilon_0 r^2} \rightarrow (7)$$

(6) in (7)

$$dE_s = \frac{P \cos \theta 2\pi r^2 \sin \theta d\theta}{4\pi r^2 \epsilon_0}$$

$$dE_s = \frac{P \sin \theta \cos \theta d\theta}{2\epsilon_0}$$



Polarization vector

$$\vec{P} = \frac{\vec{u}}{V}$$

$$\Rightarrow \vec{P} = \frac{\vec{u}}{A} \quad (\text{Here we consider area})$$

$$\vec{P} = \frac{Q \cdot d}{A \cdot d} \quad (\because u = Qd)$$

$$\Rightarrow Q = \vec{P} \cdot A$$

for small element

$$dq = \vec{P} \cos \theta dA$$

$$\int_0^\pi dE_s = \frac{P}{2\epsilon_0} \int_0^\pi \sin\theta \cos\theta d\theta$$

$$E_s = -\frac{P}{2\epsilon_0} \int_1^{-1} x^2 dx$$

$$= -\frac{P}{2\epsilon_0} \left[\frac{x^3}{3} \right]_1^{-1} = -\frac{P}{2\epsilon_0} \left[\frac{-1}{3} - \frac{1}{3} \right]$$

$$\therefore E_s = -\frac{P}{2\epsilon_0} \left[-\frac{2}{3} \right]$$

$$\therefore E_s = \frac{P}{3\epsilon_0} \rightarrow (8)$$

Substitute Eqn no. (8) in Eqn (3)

$$E_{\text{Local}} = E + \frac{P}{3\epsilon_0}$$

i.e. It should be observed that the local field is greater than the applied electric field.

Clausius - Mosotti Equation:-

It is a relation between the dielectric constant (ϵ_r) of a dielectric and the polarisability (α) of the atoms. If there are 'N' number of atoms per unit volume of the electric dipole moment per unit volume is polarisation, vector.

$$\vec{P} = N\vec{u} = N\alpha E$$

$$\therefore \vec{P} = N\alpha E_{\text{Local}} \rightarrow (1)$$

$$E_{\text{Local}} = E + \frac{P}{3\epsilon_0}$$

$$P = N\alpha \left(E + \frac{P}{3\epsilon_0} \right) = N\alpha E + \frac{N\alpha P}{3\epsilon_0}$$

$$\Rightarrow P - \frac{N\alpha P}{3\epsilon_0} = N\alpha E$$

$$\Rightarrow P \left(1 - \frac{N\alpha}{3\epsilon_0} \right) = N\alpha E$$

The relation between the flux density and intensity of the applied electric field is $D = \epsilon E = \epsilon_0 \epsilon_r E \rightarrow (3)$

the relation between D and P is

$$D = \epsilon_0 E + P \rightarrow (4)$$

from (3) & (4) $\epsilon_0 \epsilon_r E = \epsilon_0 E + P$

$$\Rightarrow P = \epsilon_0 \epsilon_r E - \epsilon_0 E = \epsilon_0 E (\epsilon_r - 1)$$

$$\therefore P = \epsilon_0 E (\epsilon_r - 1) \rightarrow (5)$$

Equate the Equations (2) and (5)

$$\epsilon_0 E (\epsilon_r - 1) = \frac{Nd}{1 - \frac{Nd}{3\epsilon_0}}$$

$$\Rightarrow 1 - \frac{Nd}{3\epsilon_0} = \frac{Nd}{\epsilon_0 (\epsilon_r - 1)}$$

$$\Rightarrow 1 = \frac{Nd}{3\epsilon_0} + \frac{Nd}{\epsilon_0 (\epsilon_r - 1)}$$

$$\Rightarrow 1 = \frac{Nd}{3\epsilon_0} \left(1 + \frac{3}{\epsilon_r - 1} \right) = \frac{Nd}{3\epsilon_0} \left(\frac{\epsilon_r - 1 + 3}{\epsilon_r - 1} \right)$$

$$\Rightarrow \frac{Nd}{3\epsilon_0} \left(\frac{\epsilon_r + 2}{\epsilon_r - 1} \right)$$

$$\boxed{\frac{Nd}{3\epsilon_0} = \frac{\epsilon_r - 1}{\epsilon_r + 2}}$$

Types of Polarisation mechanism:-

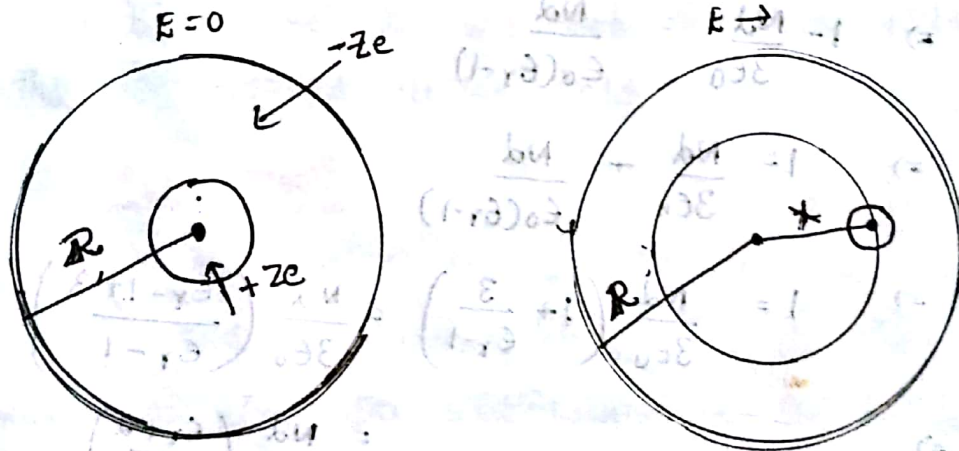
Polarization occurs due to Several atomic mechanisms when the specimen is applied inside a d.c electric field.

(1) Electronic polarization (2) Ionic polarization

(3) Orientation polarization

When electric field is applied on a dielectric material then all the positive nuclei of atoms move in the field direction and all the negative electron clouds of atoms move in opposite direction, hence dipoles will be formed. This phenomenon is known as electronic polarization. Electronic polarisation takes place in all dielectrics.

Let us consider an atom of dielectric material such that its atomic number is Z and atomic radius is R , the charge centres of electron cloud and positive nucleus are at the same point and hence there is no dipole moment. [Suppose this atom is placed in a d.c electric field of strength E , due to Lorentz force the positive nucleus will move towards the field direction and the electron cloud will move in the opposite direction of the field]



Due to application of an electric field electron cloud and nucleus are displaced from their equilibrium positions. Here two forces are come into play. One force is Coulomb force. It will tend to maintain the original position. Another force is Lorentz force. It will tend to separate the nucleus and electron cloud of the atom from their equilibrium position.

Let the distance of separation between the centres of the displaced nucleus and electron cloud be X . According to

will be

$$\rho = \frac{-ze}{\frac{4}{3}\pi R^3}$$

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$\therefore$ Total negative charge in the sphere of radius x will be

$$Q_e = \frac{4}{3}\pi x^3 \rho = \frac{4}{3}\pi x^3 \left(\frac{-ze}{\frac{4}{3}\pi R^3} \right) \quad (\because \text{from above eqn})$$

$$Q_e = -ze \left(\frac{x^3}{R^3} \right) \rightarrow (1) \quad \left[-ze \text{ represents the total negative charge of the atom} \right]$$

Total positive charge of the atom that present in the sphere of radius x will be $Q_p = +ze \rightarrow (2)$

The Coulomb attractive force between the nucleus and the electron cloud being separated at a distance x will be

$$F_c = \frac{1}{4\pi\epsilon_0} \frac{Q_e Q_p}{x^2}$$

$$\text{From (1) \& (2)} \quad F_c = \frac{1}{4\pi\epsilon_0} \frac{-ze \left(\frac{x^3}{R^3} \right) (+ze)}{x^2}$$

$$\therefore F_c = \frac{-1}{4\pi\epsilon_0} \frac{z^2 e^2 x}{R^3} \rightarrow (3)$$

The Lorentz force between the nucleus and the electron will be $F_L = qE = zeE \rightarrow (4)$

At the equilibrium two forces are equal and opposite.
 $\therefore -F_L = F_c$ ($\because$ ve sign indicates opposite direction)

$$zeE = \frac{z^2 e^2 x}{4\pi\epsilon_0 R^3} \quad (\text{from (3) \& (4) eqns})$$

$$\Rightarrow E = \frac{1}{4\pi\epsilon_0} \frac{ze x}{R^3} \rightarrow (5)$$

From the definition of the dipole moment

$$\mu = ze x \rightarrow (6)$$

dipole moment in terms of polarizability

$$\mu = \alpha_e E \rightarrow (7)$$

$$\therefore \epsilon = \frac{\epsilon_e x}{\epsilon_e} \rightarrow (8)$$

comparing equations (7) & (8)

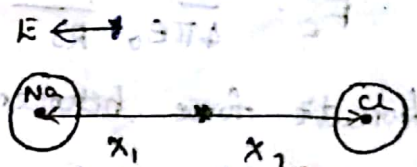
$$\boxed{\epsilon_e = 4\pi \epsilon_0 R^3}$$

The electronic polarizability ϵ_e is depending on the volume of the atom and independent of temperature.

Ionic polarisability (ϵ_i):-

Ionic polarisation takes place only in ionic dielectrics due to displacement of positive and negative ions by the influence of external electric field.

Let us consider M and m are masses of the positive and negative ions respectively. When electric field E is applied on an ionic dielectric then positive ions get displaced in the direction of applied electric field through x_1 units of distance, where as negative ions displace in the opposite direction to the field through x_2 units of distance.



The net distance between two ions is $x = x_1 + x_2 \rightarrow (1)$

The Lorentz force acting on the positive ion = $eE \rightarrow (2)$

Lorentz force acting on the negative ion = $-eE \rightarrow (3)$

When ions are displaced in their respective directions from the mean positions, then a restoring force appears on the ions which tend to move the ions back to mean positions.

The restoring force acting on the positive ion = $-k_1 x_1 \rightarrow (4)$

The restoring force acting on the negative ion = $k_2 x_2 \rightarrow (5)$

$$eE = k_1 x_1 \text{ and } eE = k_2 x_2$$

$$\therefore x_1 = \frac{eE}{k_1} \text{ and } x_2 = \frac{eE}{k_2}$$

where $k_1 = M\omega_0^2$ and $k_2 = m\omega_0^2$ as ω_0 is angular velocity of the ions.

$$\therefore x_1 = \frac{eE}{M\omega_0^2} \text{ and } x_2 = \frac{eE}{m\omega_0^2}$$

Substitute the x_1 and x_2 values in equation (1)

$$\therefore x = \frac{eE}{M\omega_0^2} + \frac{eE}{m\omega_0^2} = \frac{eE}{\omega_0^2} \left(\frac{1}{M} + \frac{1}{m} \right) \rightarrow (6)$$

From the definition of dipole moment, it is equal to the product of Charge and separation between them.

$$\therefore \mu = ex = e \frac{eE}{\omega_0^2} \left(\frac{1}{M} + \frac{1}{m} \right)$$

$$\therefore \mu = \frac{e^2 E}{\omega_0^2} \left(\frac{1}{M} + \frac{1}{m} \right) \rightarrow (7)$$

dipole moment is proportional to the electric field

$$\mu \propto E \Rightarrow \mu = \alpha_i E \rightarrow (8)$$

On comparing equations (7) & (8)

$$\therefore \alpha_i = \frac{e^2}{\omega_0^2} \left(\frac{1}{M} + \frac{1}{m} \right)$$

$\therefore$ Ionic polarizability α_i is inversely proportional to the square of the natural frequency of the ionic molecule and to its reduced mass which is equal to $\left(\frac{1}{M} + \frac{1}{m} \right)^{-1}$. It is also independent of temperature.

In methane molecule (CH_4) the Centre of negative and positive charges coincide, so that there is no permanent dipole moment. In certain molecules such as CH_3Cl , the positive and negative charges do not coincide. Since the electronegativity of chlorine is more than that of hydrogen. Hence even in the absence of an electric field, this molecule carries a dipole moment. When an electric field is applied on such molecules which possess permanent dipole moment, they tend to align themselves in the direction of applied field. The polarization due to such alignment is called orientation polarization and is dependent on temperature. With increase of temperature, the thermal energy tends to randomize the alignment. Orientation polarization can be

$$P_o = N\bar{u} = \frac{N\bar{u}E}{3kT} \\ = Nd_oE$$

$\therefore$ the orientational polarizability, $\frac{\partial P}{\partial E} = Nd_o$

$$d_o = \frac{P}{NE} = \frac{\bar{u}}{3kT}$$

$\therefore$ Orientational polarizability d_o is inversely proportional to absolute temperature of the material.

$\therefore$ The total polarizability $\left(\frac{1}{m} + \frac{1}{m} \right) \frac{e^2}{\omega_o^2} + \frac{\bar{u}}{3kT}$

$$\alpha = \alpha_e + \alpha_i + \alpha_o = 4\pi\epsilon_o R^3 + \frac{e^2}{\omega_o^2} \left(\frac{1}{m} + \frac{1}{m} \right) + \frac{\bar{u}}{3kT}$$

$\therefore$ Total polarization is given by

$$P = NdE = NE \left[4\pi\epsilon_o R^3 + \frac{e^2}{\omega_o^2} \left(\frac{1}{m} + \frac{1}{m} \right) + \frac{\bar{u}}{3kT} \right]$$

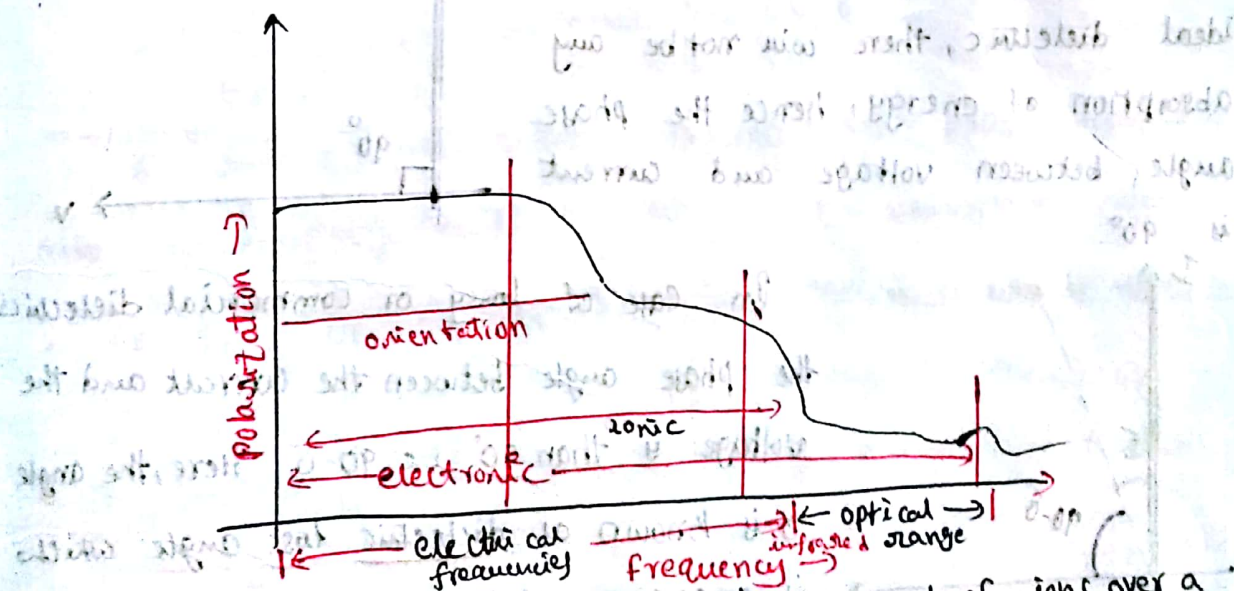
$\therefore$ This equation is known as Langevin-Debye equation.

when a dielectric is subjected to an electric field, the polarization process occurs as a function of time. The total polarization, p , as a function of time, can be expressed as

$$p = p_0 \left[1 - \exp\left(\frac{-t}{T_r}\right) \right]$$

where, p_0 is the maximum polarization gained on continuous application of electric field and T_r is the relaxation time for the particular polarization. The relaxation time T_r is defined as the time taken for a polarization process to reach 0.63 of its maximum value. This T_r will be different for different polarization processes.

Electronic polarization is due to displacement of positive nuclei and negative electron cloud. When the frequency of the applied voltage is very high in the optical range (10^{15} Hz), electronic polarization takes place during every cycle of applied voltage. The electronic polarization is a rapid process.



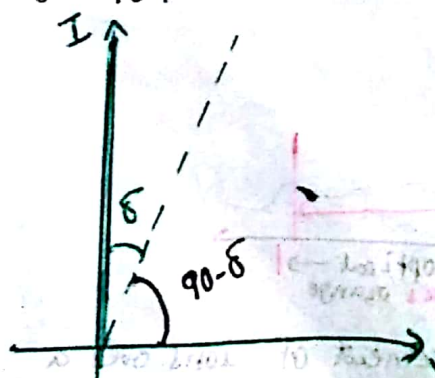
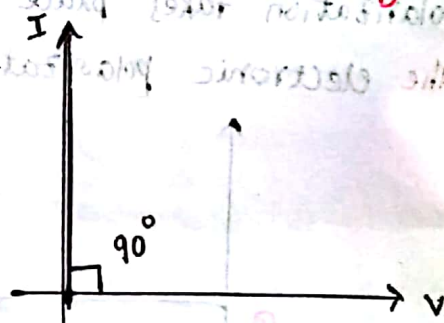
Ionic polarization is due to displacement of ions over a small distance. Since ions are heavier than electron cloud, the time taken for displacement is larger. When the frequency of applied voltage is in the same order of the frequency of lattice vibration (10^{13} Hz), the ionic polarization takes place during every cycle of applied

Voltage. It clearly says that for optical frequency the ions will not respond, because the time required for their oscillations is nearly 100 times larger than the period of applied voltage at optical frequency. The frequency of voltage around 10^{13} Hz, there will be both electronic polarization as well as ionic polarization.

orientation polarization is even slower than ionic polarization. When the frequency of applied voltage is in the audio range (10^8 Hz), orientation polarization takes place. This means in the frequency range 10^6 Hz to 10^{10} Hz, all the three polarizations will take place.

Dielectric loss:- When a dielectric is subjected to the a.c voltage. Some of the electrical energy is absorbed by the dielectric material and later it is dissipated in the form of heat. This dissipated energy is called **dielectric loss** and the dielectric is called **lossy dielectric**.

In case of perfect insulator or ideal dielectric, there will not be any absorption of energy, hence the phase angle between voltage and current is 90° .



In case of lossy or commercial dielectrics, the phase angle between the current and the voltage is less than 90° , i.e. $90 - \delta$. Here, the angle δ is known as dielectric loss angle which is a measure of the power dissipated in each cycle or dielectric loss.

Suppose the dielectric is subjected to an alternating field $E = E_0 \cos \omega t$, the polarization, P , also varies periodically with time and

So does the displacement vector D . However, P and D may lag behind

in phase relative to E .

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$$D = D_0 \cos(\omega t - \delta)$$

$$\Rightarrow D = D_0 \cos \omega t \cos \delta + D_0 \sin \omega t \sin \delta$$

$$\Rightarrow D = D_1 \cos \omega t + D_2 \sin \omega t$$

$$\text{where } D_1 = D_0 \cos \delta \text{ and } D_2 = D_0 \sin \delta$$

For most dielectrics, D_0 is proportional to E_0 , but the ratio D_0/E_0 is generally frequency dependent.

The frequency dependent dielectric constant is

$$\epsilon_r^* = \epsilon_r' - i \epsilon_r''$$

where ϵ_r' and ϵ_r'' are real and imaginary part of dielectric constants.

They can be expressed as

$$\epsilon_r' = \frac{D_1}{E_0} = \frac{D_0 \cos \delta}{E_0}$$

$$\epsilon_r'' = \frac{D_2}{E_0} = \frac{D_0 \sin \delta}{E_0}$$

$$\text{and } \frac{\epsilon_r''}{\epsilon_r'} = \tan \delta, \text{ dielectric loss tangent.}$$

ϵ_r' and ϵ_r'' are frequency dependent so the phase angle δ is also frequency dependent.

* If the dielectric constant is real one, there will be no dielectric loss.

* The dielectric loss is increased by high voltage, high frequency and high temperature.

* The imaginary part of dielectric constant represents dielectric loss.

dielectric materials which are having spontaneous polarisation is called ~~ferromagnetic~~ ^{electric} materials. The phenomenon of possessing spontaneous polarisation in the absence of electric field is called ferroelectricity.

Eg: Rochelle salt, BaTiO_3 .

Properties:-

- (1) All ferro electric materials possess spontaneous polarisation below a certain temperature.
- (2) As temperature increases, the spontaneous polarisation decreases and at a particular temperature, the spontaneous polarisation vanishes. This temperature is known as Curie temperature.
- (3) Curie temperature can also be defined as the temperature at which a ferro ^{electric} material gets converted into para ^{electric} material.
- (4) Below Curie temperature the dielectric constant ~~varies with~~ ^{is a function of} electric field. Above Curie temperature, dielectric constant varies with temperature.

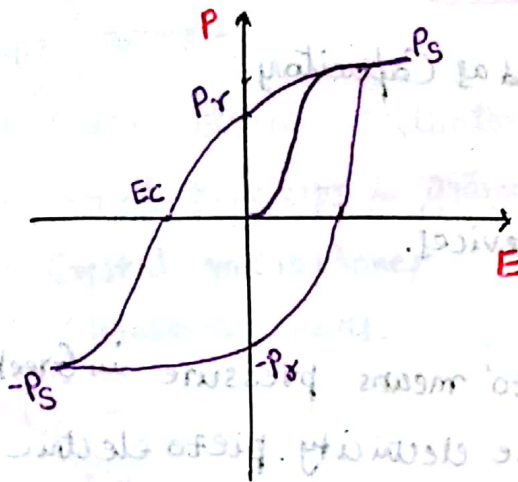
According to Curie weiss

$$\epsilon_r = \frac{C}{T - T_c}$$

T_c is Curie temperature
 C is Curie constant.

Hysteresis:- when an electric field is applied on a ferroelectric material, the polarisation takes place. This polarisation always lags behind the applied electric field. This phenomenon is known as hysteresis of ferroelectric material. The polarisation increases rapidly with the applied field to a value and remains constant. This polarisation is known as saturation

polarisation (P_s). If electric field on the material is reduced back to zero, polarisation will not travel in the initial path, take a new path and, reduces to remanent polarisation (P_r). To remove this polarisation electric field in the opposite direction must be applied. The amount of field required to remove remanent polarisation is called Coersive field. The height and width of the hysteresis decrease with increase of temperature. The hysteresis loop of area represents the dielectric loss that occurs in dielectric materials.



The spontaneous polarisation of the ferroelectric materials depends upon

- (1) Shape of the hysteresis loop.
- (2) Dimensions of the Specimen
- (3) Temperature
- (4) The thermal and electrical properties of the Crystal.

BaTiO₄: Barium ions are at the corners and the oxygen ions are at the centre of the faces. The titanium ion is in the octahedral void at the body centre. Above 120°C, Barium titanate is a cubic crystal. In this state the centre of the negative and the positive charges are coincide. There is no spontaneous dipole moment. If the crystal is cooled to below 120°C, then the titanium ions shift to one side of the body centre. Neighbouring oxygen ions also get shifted. The crystal

Changes from a cubic to form a tetragonal structure. The centre of the positive and negative charges no longer coincides. That's way dipoles are created in the crystal.

Applications of ferroelectric materials:

- (1) Ferroelectric materials are used as Capacitors.
- (2) Magnetostrictive transducers.
- (3) Magnetic information storage devices.

Piezo electricity:- The word 'piezo' means pressure in Greek.

So piezo electricity means pressure electricity. piezo electric phenomenon was discovered by Curie brothers in 1880. piezo electric effect is shown by certain non-centrosymmetric crystals such as quartz, Rochelle salt etc... Electric polarization develops opposite charges on their surface by stress. On these substances, a mechanical stress produces an electric polarization and reciprocally an applied electric field produces a mechanical strain. These effects are called the direct and inverse piezoelectric effects. Crystals with centres of inversion do not exhibit piezoelectricity. Piezo electric effect can observe in Quartz crystal.

Quartz crystal consist of three axes, x-axis is known as electric axis, y-axis is known as mechanical axis and z-axis is known as optical axis. This optical axis is perpendicular to the electrical and mechanical axes.

In the absence of the external stress, all the charges are balanced, net polarisation is zero. But when external stress is applied to the crystal the balance is disturbed and the crystal is polarized. As a result, electrical charge is developed on the faces.

a.c electric field is applied along the electric axis then mechanical vibrations will be produced. i.e for positive half cycle of a.c field, contraction takes place, for negative half cycle of a.c field expansion takes place.

Applications:-

- (1) Piezo electric oscillators
- (2) Sound pick ups in gramophones
- (3) Crystal microphones
- (4) Ultrasonic waves.

Important formulae:-

$$(1) \frac{Nd}{3\epsilon_0} = \frac{\epsilon_r - 1}{\epsilon_r + 2}$$

$$(2) Nd_e = \epsilon_0 (\epsilon_r - 1)$$

$$(3) d_e = 4\pi \epsilon_0 R^3$$

$$(4) E_{local} = E + \frac{P}{3\epsilon_0}$$

$$(5) d_i = \frac{e^2}{\omega_0^2} \left(\frac{1}{m} + \frac{1}{m} \right)$$

$$(6) P = \epsilon_0 (\epsilon_r - 1) E$$

$$(7) d_0 = \frac{u^2}{3kT}$$

$$(8) C = \frac{A\epsilon_0}{d} = \frac{Q}{V}$$

ϵ_0 = Permittivity of free space

$$\epsilon_0 = 8.85 \times 10^{-12} \text{ F/m}$$

k = Boltzmann Constant