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Unit 15

Molecular Theory of Gases

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Temperature:

Temperature a measure of the average translational kinetic energy of the Molecules of body.

Scales of Temperature:

There are three scales of temperature

(i) Centigrade or Celsius scale
(ii) Fahrenheit scale
(iii) Kelvin or absolute scale are commonly used these days

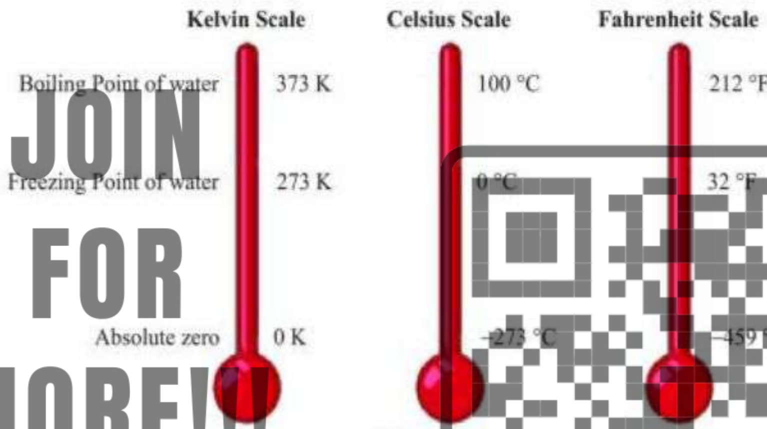


Figure 15.1
Scales of temperature mentioning the different temperatures.

The Triple Point of Water:

The vapor, liquid, and solid states of water can coexist in thermal equilibrium only at a specific pressure and temperature.

The triple point of water occurs at a specific temperature and pressure, where all three phases are in thermodynamic equilibrium. This means that at the triple point, ice, liquid water, and water vapor can exist together without any phase changing to another.

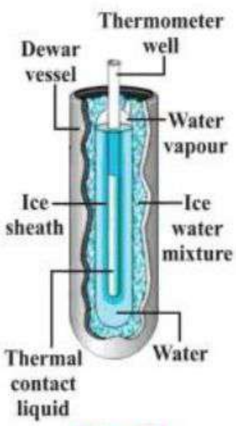


Figure 15.2

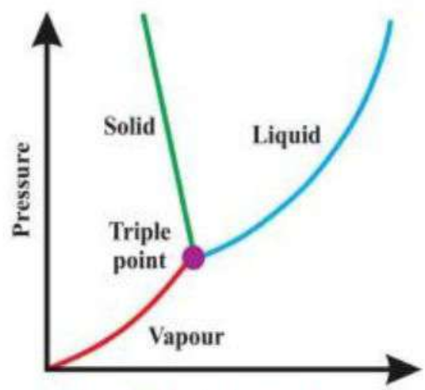


Figure 15.3 A triple point of water

Gas Laws

Boyle's Law

Boyle's law states that "Volume V of given mass of a gas Is inversely proportional to the pressure P, provided the Temperature T of the gas remains constant."

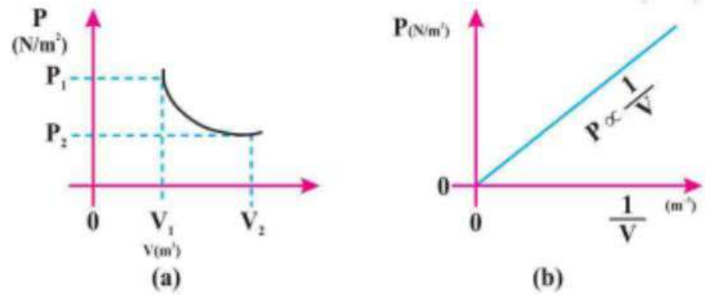
Boyle's law can be written as

V $\alpha \frac{1}{P}$ (at constant temperature) corresponds to the end

PV= constant

Boyle's law can written as

$P_1V_1 = P_2V_2$=Constant



Charles's Law:

This law states that "The volume V of a given mass of a gas is directly proportional to the absolute temperature T at constant pressure P":

Charles law can be written as

V α T (at constant pressure)

Or $\frac{V}{T}$=constant

Charles's Shows relation between law is represented as

$$\frac{V_1}{T_1} = \frac{V_2}{T_2}$$

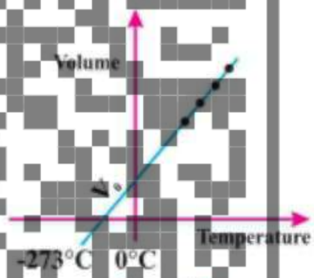


Figure 15.5

Avogadro's Law:

Avogadro's law which states that "equal volume of all gases contains the same number of molecules at the same temperature and pressure".

V α n (at constant temperature and pressure)

General Gas Law:

In order to derive general gas law, we make use of Boyle's law, Charles's law and Avogadro's law. An interrelation among the physical quantities

According to Boyle's law:

V $\alpha \frac{1}{P}$ (when n number of mole and temperature T are kept constant)

According to Charles's law:

$V \alpha T$ (when n and pressure P are kept constant)

According to Avogadro's law:

$V \alpha n$ (when T and P are kept constant)

Consider for a moment that none of the variable are to be kept constant, then all the above three relationships can be joined together.

$V \alpha \frac{nt}{P}$

$V = \text{constant} \frac{nt}{P}$

$V = \frac{Rnt}{P}$

Where **R** is constant of proportionally and is called General gas constant or universal gas constant and does not depend on the quantity of gas in the sample.

If P is measured in Nm^{-2}

V in m^3

T in Kelvin

then the volume of universal gas constant is $R = 8.314\ J\ mol^{-1}k^{-1}$

$PV = nRT$

Kinetic theory of gases:

Basic Postulates of Kinetic Theory of Gases:

The basic postulates of Kinetic Theory of gases are as under

1) A gas contains a very large number of particles called molecules. Depending on the gases each molecule consists of an atom or a group of atoms.
2) A finite volume of a gas consists of very large number of molecules. This assumption is justified by experiments. At standard conditions there are 3×10^{25} molecules per cubic meter.
3) The size of the molecules is much smaller than separation between molecules; it is about 3×10^{-10}m.
4) The molecules move in all directions with various speeds collide elastically with one another and with the walls of the container.
5) The molecules exert no forces on one another except during collisions. In the absence of the external forces, they move freely in straight lines.
6) Laws of mechanics are assumed to be applicable to the motion of molecules.

Pressure of Gas:

The pressure exerted by a gas is merely the momentum transferred to the walls of the container per second per unit area due to the continuous collisions of molecules of the gas.

In order to calculate the pressure of an ideal gas from Kinetic Theory.

Let us consider a cube having side length L whose walls are perfectly elastic contains N number of molecules each of mass m as shown in figure.

Consider a single molecule of mass m moving with velocity V_1 parallel to x-axis. It moves ack and forth, colliding at regular intervals with the ends of the box and thereby contributing to the pressure of the gas.

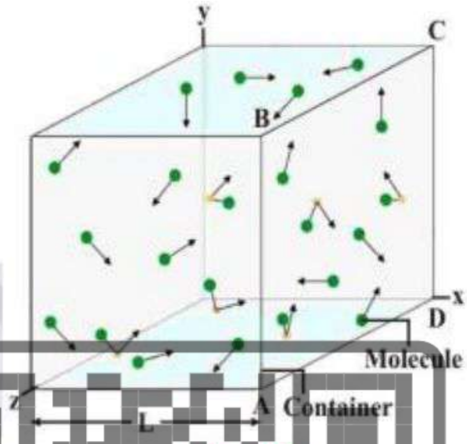


Figure 15.6

A molecule which has a velocity V_1 can be resolved into three rectangular components V_{1x}, V_{1y} and V_{1z} parallel to three co-ordinates axis x, y and z.

A molecule which collides with the face ABCDA of the cube, it will rebound elastically in opposite direction, such that x-component of the velocity V_1x, is reversed, the V_1y and V_1z remain unaffected. Therefore, the momentum before collision is mV_1x and after collision is $-m\ Vx$ causing a change of momentum.

Change in momentum= $P_i - P_f = mV_{1x} - (-mV_{1x}) = mV_{1x} + mV_{1x}$

Change in momentum=$2mV_{1x}$

$$\Delta P = 2mV_{1x}$$

After recoil the molecule travels to opposite face and collides with it, rebounds and travels back to the face ABCDA after covering a distance 2L. The time Δt between two successive collisions with face ABCDA is:

$$\Delta t = \frac{2L}{V_{1x}}$$

But

$$F_1 = \frac{\Delta P}{\Delta t}$$

$$F_1 = \frac{2mv_{1x}}{\frac{2L}{V_{1x}}}$$

$$F_1 = 2mV_{1x} \times \frac{V_{1x}}{2L}$$

$$F_1 = mV_{1x} \times \frac{V_{1x}}{L}$$

$$F_1 = \frac{mV_{1x}^2}{L}$$

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Similarly, the forces due to all other molecules can be determined. Thus, the total X- directed F due to N number of molecules of the gas moving with velocities $V_1, V_2, V_3, \ldots, V_n$, is:

$$F = F_1 + F_2 + F_3 + \ldots\ldots + F_n,$$

$$F = \frac{mV_{1x}^2}{L} + \frac{mV_{2x}^2}{L} + \frac{mV_{3x}^2}{L} + \ldots\ldots + \frac{mV_{nx}^2}{L}$$

$$F = \frac{m}{L}(V_{1x}^2 + V_{2x}^2 + V_{3x}^2 + \ldots\ldots + V_{nx}^2)$$

Multiply and divide by N

$$F = \frac{mN}{L}\left(\frac{V_{1x}^2 + V_{2x}^2 + V_{3x}^2 + \ldots\ldots + V_{nx}^2}{N}\right)$$

$$V_x^2 = \frac{V_{1x}^2 + V_{2x}^2 + V_{3x}^2 + \ldots\ldots + V_{nx}^2}{N}$$

$$F = \frac{mNVx^2}{L}$$

Since,

$$P = \frac{F}{A} \text{ and } A = L^2$$

$$P = \frac{\frac{mNVx^2}{L}}{L^2}$$

$$P = \frac{mNVx^2}{L^3}$$

But. $\rho = \frac{mN}{L^3} = \frac{mN}{V}$ **(V = volume of gas)**

$$P = \rho V_x^2$$

The terms V_x^2. is only one component of the total velocity.

Since $\bar{V}^2 = V_x^2 + V_y^2 + V_z^2$ on the average. $V_x^2 = V_y^2 = V_z^2$ due to randomness of the molecular motion.

Substituting this value into the above equation, we find that:

$$\bar{V}^2 = V_x^2 + V_x^2 + V_x^2$$

$$\bar{V}^2 = 3V_x^2$$

$$V_x^2 = \frac{\bar{V}^2}{3}$$

$$P = \rho\frac{V^2}{3}$$

$$P = \frac{1}{3}\rho\bar{V}^2$$

The relation between Kinetic Energy of Molecules and Temperature:

The relation between molecular Kinetic Energy and temperature can be derived by using

$$P = \frac{1}{3}\rho\bar{V}^2$$

But, $\rho = \frac{mN}{L^3}$

$$P = \frac{1}{3}\frac{mN}{V}\bar{V}^2$$

$$3PV = mN\overline{V^2}$$

Here, PV = nRT

$$3nRT = mN\overline{V^2}$$

But, $n = \frac{N}{N_A}$

$$3\frac{N}{N_A}RT = mN\overline{V^2}$$

$$3\frac{R}{N_A}T = m\overline{V^2}$$

Since, $K = \frac{R}{N_A}$

$$3KT = m\overline{V^2}$$

Multiply ½ on both side

$$\frac{3}{2}KT = \frac{1}{2}m\overline{V^2}$$

As we know that, $K.E_{AV} = \frac{1}{2}m\overline{V^2}$

$$K.E_{AV} = \frac{3}{2}KT$$

The mean translational Kinetic energy of a molecule of an ideal gas is proportional to the Absolute temperature.

Hence, mean translational Kinetic energy of a molecule α T.

EXERCISE

Section (A): Multiple Choice Questions (MCQs)

Choose the correct answer:

1. The relationship between temperature and average kinetic energy of particles in a gas is:

(a) temperature is inversely proportional to average kinetic energy

(b) temperature is directly proportional to average kinetic energy

(c) temperature is independent of average kinetic energy

(d) temperature is proportional to the square of average kinetic energy

2. Standard conditions of temperature and pressure (STP) refer to a gas at:

(a) 0°C and l atm (b) 20°C and 1 atm

(c) 25°C and 1 atm (d) 30°C and 101.3 kPa (1 atm)

3. If the temperature is kept constant and the volume of a gas is doubled, then pressure of A gas is:

(a) Reduced to ½ of the original value. (b) Doubled

(c) Reduced to ¼ of the original value (d) Quadrupled

4. The Avogadro's number is the number of molecules in:

(a) One mole of a substance (b) One kg of a substance

(c) One m' of a gas (d) One kilogram of hydrogen gas

5. Mean translational K.E. per molecule of an ideal at temperature T is:

(a) $\frac{3}{2}$ kT (b) $\frac{1}{2}$ kT (c) $\frac{2}{3}$ kT (d) kT^4

6. The normal human body temperature is:

(a) 98.6°F (37°C) (b) 99.6°F (37.4°C) (c) 100.4°F (38°C) (d) 101°F (38.3°C)

7. The pressure P, the density e and the average speed of molecules of an ideal gas are related by the equation.

(a) $P=\frac{2}{3}mL^2$ (b) $P=\frac{1}{3}mL^2$ (c) $P=\frac{1}{3}\rho V^2$ (d) $P=\frac{2}{3}L^2$

8. In air at S.T.P, the average speed of the:

(a) Oxygen molecules is greater than Nitrogen molecules

(b) Nitrogen molecules is greater than Oxygen molecules

(c) Oxygen molecules is approximately equal to Nitrogen molecules

(d) Helium atoms is greater than both Oxygen and Nitrogen molecules

9. If the absolute temperature of a gas is increased 3 times, the rms velocity of the molecules will be:

(a) 3 times (b) 9 times (c) $\sqrt{3}$ times (d) times

10. A gas is enclosed in an isolated container which is placed on a fast-moving train uniformly. The temperature of the gas:

(a) Increases due to the motion of the train

(b) Decreases due to the motion of the train

(c) Remains constant,

(d) Fluctuates, depending on the train's speed and direction

Section (B) CRQS (Short Answered Questions):

1. Why the earth is not in thermal equilibrium with the sun?

The Earth and the Sun are not in thermal equilibrium because they do not form an isolated system.

The heat radiation from the Sun is emitted in all directions, not just towards the Earth. Therefore, the intensity of sunlight reaching the Earth's surface is much less than the intensity of sunlight radiated by the Sun. Additionally, the Earth radiates heat back into space, which helps to maintain its temperature and prevent it from becoming too hot or too cold.

2. Describe the relationship between temperature and kinetic energy of molecules.

(notes)

3. It is observed that when mercury in glass thermometer is put in a flame, the column of mercury first descends and then rises. Explain.

Explanation: When a mercury-in-glass thermometer is placed in a flame, the mercury column initially descends before rising. This phenomenon is due to the following reasons:

1. **Glass Expansion:** The glass bulb of the thermometer expands more rapidly than the mercury inside it when exposed to heat. This initial expansion causes the mercury level to drop slightly.
2. **Mercury Expansion:** As the heat continues to transfer to the mercury, it expands at a faster rate than the glass. This rapid expansion of the mercury pushes the column upwards, creating the observed rise in the mercury level.

4. What is standard temperature, pressure?

Definition: Standard Temperature and Pressure (STP) is a set of reference conditions used in scientific calculations, particularly in chemistry and physics. It is defined as:

- **Temperature:** 273.15 Kelvin (0 degrees Celsius)
- **Pressure:** 1 atmosphere (atm) or 101.325 kilopascals (kPa)

5. A thermometer is placed in direct sun light. What will it read the temperature?

Thermometer in Direct Sunlight

Reading: A thermometer placed in direct sunlight will likely read a higher temperature than the ambient air temperature. This is because the thermometer is directly absorbing solar radiation, which increases its temperature. The amount of temperature increase will depend on factors such as the intensity of sunlight, the color of the thermometer, and the specific design of the thermometer.

6. The pressure in a gas cylinder containing hydrogen will leak more quickly than if it is containing oxygen. Why?

Explanation: Hydrogen gas will leak more quickly than oxygen gas from a cylinder under the same conditions. This is primarily due to the smaller molecular size of hydrogen compared to oxygen. Smaller molecules can diffuse more easily through the material of the cylinder, leading to a higher rate of leakage. Additionally, hydrogen gas has a higher rate of diffusion than oxygen gas, which further contributes to the faster leakage.

7. When a sealed thermos bottle full of coffee is shaken, what are the changes occur?

When a sealed thermos bottle full of coffee is shaken, several changes occur:

- **Temperature Increase:** The shaking motion can cause friction between the coffee and the inner walls of the thermos, leading to a slight increase in temperature.
- **Mixing:** The agitation from shaking can mix the coffee more thoroughly, potentially affecting its taste or consistency.
- **Pressure Increase:** If the thermos is not completely airtight, shaking can cause air trapped inside to compress, slightly increasing the internal pressure. However, if the thermos is tightly sealed, the pressure will remain relatively constant.

8. How does the Kinetic theory account for the following observed facts:

(a) A gas exerts pressure

(b) The pressure of a gas depends upon its temperature.

a) Gas Exerts Pressure According to the kinetic theory of gases, gas molecules are in constant random motion. When these molecules collide with the walls of a container, they exert a force on the walls. This force, distributed over the area of the container, is perceived as pressure.

b) Pressure of a Gas Depends on Temperature As the temperature of a gas increases, the average kinetic energy of its molecules also increases. This means the molecules are moving faster and colliding with the container walls more frequently and with greater force. This increased rate and force of collisions result in a higher pressure.

9 Calculate the average speed of an air molecule at room temperature (20°C) and compare it to the speed of sound in air (330 m/s).

Section (C): ERQs (Long Answered Questions):

1. What is temperature? Explain the scales of temperature in detail.

Temperature is a physical quantity that measures the average kinetic energy of the particles (atoms or molecules) in a substance. In simpler terms, it is a measure of how hot or cold something is.

Scales of Temperature

There are three primary scales used to measure temperature:

1. **Celsius (°C):**

- This is the most commonly used scale in everyday life and scientific applications.
- The freezing point of water is 0°C, and the boiling point of water is 100°C.
- The Celsius scale is based on the work of Swedish astronomer Anders Celsius.

2. **Fahrenheit (°F):**

- This scale is primarily used in the United States and a few other countries.
- The freezing point of water is 32°F, and the boiling point of water is 212°F.
- The Fahrenheit scale was developed by German physicist Daniel Fahrenheit.

3. **Kelvin (K):**

- This scale is used in scientific measurements, particularly in thermodynamics.
- It is an absolute scale, meaning there is no negative temperature on the Kelvin scale.
- Zero Kelvin (0 K) is known as absolute zero, the lowest possible temperature.
- The freezing point of water is 273.15 K, and the boiling point of water is 373.15 K.

2. Define and explain Boyle's law, Charles's and Avogadro's law.

Notes

3. Derive general gas law by making use of gas laws.

Notes

4. Describe the molecular movement causes the pressure exerted by gas, derive pressure equation.

Notes

5. Interpret mathematically that temperature is a measure of average translational K.E of the molecules of a gas.

Notes

Section (D): Numerical:

15.1. The freezing point of mercury is -39°C.Convert it into °F and the comfort level temperature of 20° into Kelvin. (Ans: -38.2°F, 293K)

15.2. The boiling point of liquid nitrogen is -321°F. Change it into equivalent Kelvin temperature. (Ans: 77K)

15.3. Calculate the volume occupied by a gram-mole of a gas at 0°C and a pressure of 1.0 atmosphere. (Ans: 22.4 liters/mole)

15.4. An air storage tank whose volume is 112 liters contain 3kg of air at a pressure of 18 atmospheres. How much air would have to be forced into the tank to increase the pressure to 21 atmospheres, assuming no change in temperature? (Ans: 0.5kg)

15.5. A balloon contains 0.04m of air at a pressure of 120KPa. Calculate the pressure required to reduce its volume to 0.025 m at constant temperature. (Ans: 1.9×10^5Pa)

15.6. The molar mass of nitrogen gas N2 is 28gmol^{-1}. For 100g of nitrogen, calculate.

(a) the number of moles. (Ans: (a) 3.57 mole)

(b) the volume occupied at room temperature (20°C) and pressure of 1.01×10^5 Pa. (Ans: (b) 0.086m or 86dm')

15.7. A sample of a gas contains 3.0×10^{24} atoms. Calculate the volume of the gas at a temperature of 300K and a pressure of 120K Pa. (Ans: 0.104m^3)

15.8. Calculate the root mean square speed of hydrogen molecules at 0°C and 1.0 atm pressure. Assuming hydrogen to be an ideal gas. The density of hydrogen is 8.99×10^{-2} kg/m. (Ans: 1835.86ms^{-1})

15.9. Calculate the root mean square speed of hydrogen molecule at 500K (mass of proton $=1.67 \times 10^{-27}$ kg and K = 1.38×10^{-34} J/molecule .K) (Ans: 2489.49ms-1)

15.10. (a) Determine the average value of the Kinetic energy of the particles of an ideal gas at 10°C and at 40°C. (Ans: 5.86×10^{-21}J, 6.48×10^{-21}J)

(b) What is the Kinetic energy per mole of an ideal gas at these temperatures?

(Ans: 3526.57J, 3901J)

Unit 16

First Law of Thermodynamics

Thermal Energy and Work:

Internal Energy and Heat (Q): In thermodynamics, thermal energy is associated with the internal energy of a system. Heat (Q) is the transfer of thermal energy between systems due to a temperature difference.

Heat Flow:

It flows spontaneously from a region of higher temperature to one of lower temperature. The rate at which heat is transferred can be quantified using the equation:

$$Q = mc\Delta T$$

Where Q is the heat transferred, m is the mass of the substance, c is the specific heat capacity of the substance, and AT is the temperature change.

Internal Energy:

"The sum of the random distribution of kinetic and potential energies within a system of molecules."

The symbol for internal energy is U and its SI unit is Joule (J).

Internal Energy & Temperature:

The internal energy of an object is intrinsically related to its temperature.

When a gas in a container is heated, the gas molecules move faster, increasing their kinetic energy.

In a solid, where molecules are tightly packed, heating causes the molecules to vibrate more.

In both liquids and solids, molecules have both kinetic and potential energy due to intermolecular forces that keep them close together.

However, ideal gas molecules are assumed to have no intermolecular forces, meaning they only possess kinetic energy and no potential energy. The (change in) internal energy of an ideal gas is equal to:

$$\Delta U = \frac{3}{2} k\Delta T$$

Therefore, the change in internal energy is proportional to the change in temperature

$$\Delta U \propto \Delta T$$

Where: ΔU= change in internal energy (J)

ΔT = change in temperature (K)

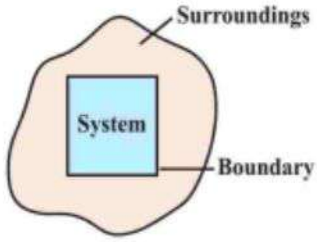
"As the container is heated up, the gas molecules move faster with higher kinetic energy and therefore higher internal energy".

Define thermodynamics and various terms associated with it.

Thermodynamic terms and basic concepts:

The study of the flow of heat or any other form of energy into or out of a system as t undergoes a physical or chemical transformation is called thermodynamics.

Boundary:



The boundary is the physical or imaginary separation between the system and its surroundings.

Surroundings:

The surroundings refer to everything outside the boundaries of the system.

Thermodynamic Systems:

1. Open System:

In an open system, both heat and matter can be exchanged with the surroundings. For instance, steam (matter) can escape from the coffee, and heat can be lost to the surrounding air.

Example: A cup of hot coffee.

2. Closed System:

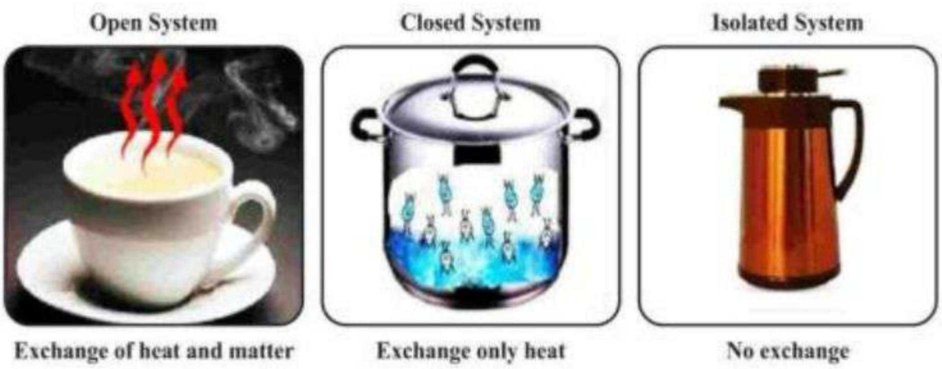
In a closed system, only heat can be exchanged with the surroundings, but matter cannot. In this example, heat can still transfer through the pot, but the water vapor (matter) is trapped inside the pot and cannot escape.

Example: A pot with a lid.

3. Isolated System:

In an isolated system, neither heat nor matter can be exchanged with the surroundings. A thermos flask is designed to prevent heat transfer, keeping the contents inside hot or cold for a long period without any exchange with the Environment.

Example: A thermos flask.



Work Done by a Gas:

When a gas expands, it does work on its surroundings by exerting pressure on the walls of the container it's in. This is important, for example, in a steam engine where expanding steam pushes a piston to turn the engine. The work done when a volume of gas changes at constant pressure is defined as:

$W = P\Delta V$

Where:

W= work done (J)

P= external pressure (Pa)

V=volume of gas (m)

For a gas inside a cylinder enclosed by a moveable piston, the force exerted by the gas Pushes the piston outwards, Therefore, the gas does work on the piston

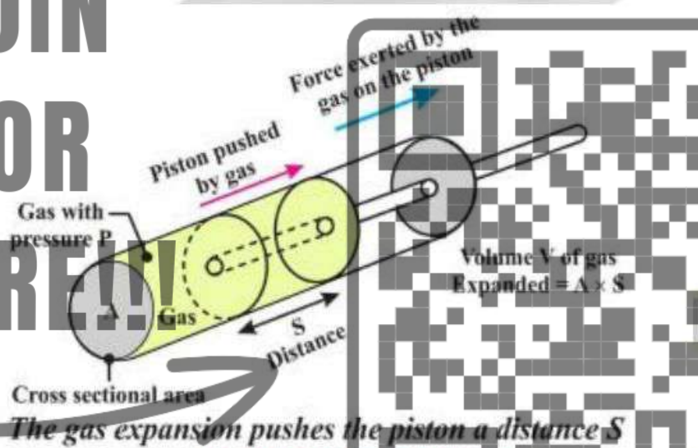


Figure 16.5 Work Done by a Gas

Derivation:

The volume of gas is at constant pressure. This means the force F exerted by the gas on the piston is equal to:

$$F = P \times A$$

The definition of work done is:

$$W = F \times S$$

The displacement of the gas d multiplied by the cross-sectional area A is the increase in volume ΔV of the gas:

$$W = P \times A \times S$$

Since, $AS = \Delta V$

$$W = PAV$$

Where: ΔV= increase in the volume of the gas in the piston when expanding (m^3)

The first law of thermodynamics, internal energy and the heating of the System& conservation of energy:

First law of thermodynamics:

The first law of thermodynamics states that,

"The change in internal energy of a system equals the net heat transfer into the system minus the net work done by system"

In equation form,

$\Delta U = \Delta Q - W$

ΔU →change in internal energy of the system

ΔQ → net heat transferred into the system

W → net work done by the system

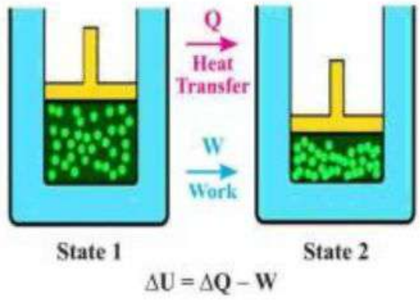


Figure 16.6 states of system

Applications of the first law thermodynamics:

Applications of first law of thermodynamics are all based on the principle that

"The three forms of energy: internal energy; heat; and work can be inter converted."

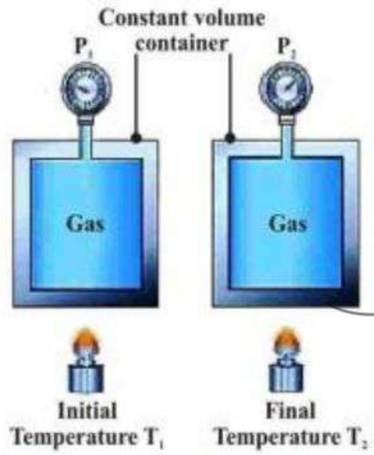
- ✓ The processes in which any one of the three terms of the equation is zero.
- ✓ The processes in which any one of the state variables P,V,T of the system are held constant.

(a) Isochoric Process: Constant volume

"The thermodynamics process during which the volume of the system remains constant is called isochoric process".

We consider the gas contained in a cylinder having a conducting base and non-conducting walls and with a fixed piston at the end as shown in the figure. Let heat ΔQ be imparted to the gas. The gas is then heated at constant volume. The pressure of the gas increases from P_1 to P_2 while its temperature increases from T_1 to T_2.
Since the system neither expands nor contracts, work neither done by system nor on the system i.e

$\Delta W = 0.$



using the first law of thermodynamics equation

We have:

$\Delta Q = \Delta U + \Delta W$

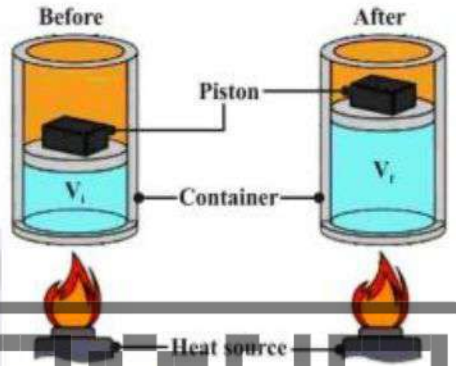
$\Delta Q = \Delta U$

This means that in an isochoric process the entire amount of heat supplied to the gas is converted the internal energy of the gas.

(b) Isobaric Process:

"The thermodynamics process during which the pressure is kept constant is called an isobaric process"

Isobaric expansion of a system is often used to convert heat into work. Practically all heat engines depend on the transformation of heat into work. Consider a gas contained in a cylinder having a conducting base and non-conducting walls and frictionless piston of cross-sectional area (A)



When the gas is heated, a certain amount of Heat energy is transferred into the system.

The gas expands and moves the piston outward.

Temperature changes from T_1 to T_2 and Volume changes from V_1 to V_2.

If the displacement of the piston is kept very small, the pressure of the gas will not change much and can be considered constant.

The work done by the gas which expands at constant pressure is:

$\Delta W = P(V_2 - V_1)$

$\Delta W = P\Delta V$

Using the first law of thermodynamics equation

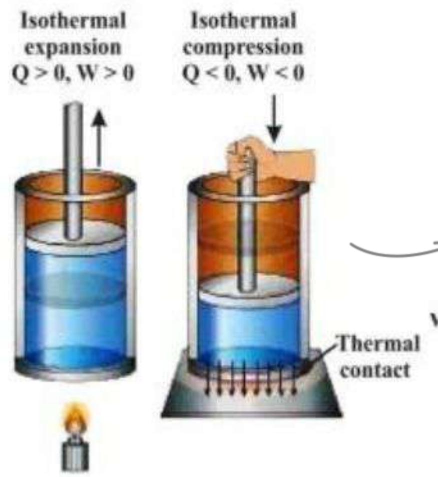
$\Delta Q = \Delta U + \Delta W$

$\Delta Q = \Delta U + P\Delta V$

The work performed by the expanding or contracting gas comes from one or both sources:

- Heat supplied to the gas and
- the internal energy of the gas

The graph of isobaric process is called an "isobar", which is a straight line, parallel to The volume axis.



(c) Isothermal Process:

"The thermodynamics process which is carried out in such a way that a system undergoes changes but its temperature remains constant is called an isothermal process".

During isothermal expansion some work is done by the gas in pushing up the piston in the cylinder. Since the temperature remains constant, there is no change in the internal energy of the gas, that is, $\Delta U = 0$

$\Delta Q = \Delta U + \Delta W$

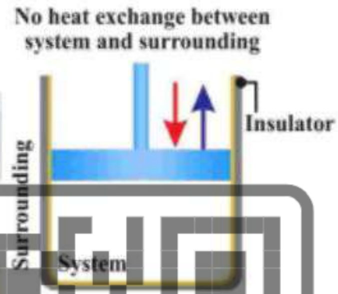
$\Delta Q = 0 + \Delta W$

$\Delta Q = \Delta W$

This shows that:

If the gas expands and does external work, an equal amount of heat has be supplied in order to maintain its temperature constant.

(d) Adiabatic Process:



"The thermodynamics process during which no heat enters or leaves a system is called an adiabatic process".

For every adiabatic process $\Delta Q = 0$, A truly adiabatic process is an ideal one which cannot be realized. However, the

flow of heat may be prevented either by surrounding the system with a thick layer of heating insulating material such as cork, asbestos, or by performing the process very quickly. The flow of heat requires finite time, so any process performed quickly Enough will be practically adiabatic. To perform an adiabatic process on a gas, we consider the gas to be contained in a completely insulated cylinder with a movable piston at the end.

Heat capacity:

Amount of heat required to raise the temperature of a substance through 1°C or 1K is known as heat capacity

$\Delta Q = c\Delta T$

"c" is Heat capacity

Specific Heat:

Amount of heat required to raise the temperature of unit mass a substance through 1°C or 1K is known as heat capacity

$\Delta Q = mC\Delta T$

"c" is Specific heat capacity

Molar Specific Heat:

Amount of heat required to raise the temperature of unit mole a substance through 1°C or 1K is known as heat capacity

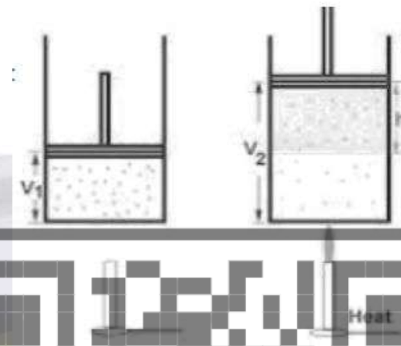
$\Delta Q = nC_m\Delta T$

"C_m" is molar Specific heat

The relationship between C_P and C_V for an Ideal Gas:

Relation between Specific Heat at Constant Pressure and Specific Heat at Constant Volume:

Consider a gas in a container if we heat the gas so that gas is allowed to expand and pressure of the gas remain constant all the heat energy will be used to increase the internal energy of the gas and to do work than according to first law of thermodynamics.



$\Delta \boldsymbol{Q} = \Delta \boldsymbol{U} + \Delta \boldsymbol{W}$

Since

Above equation will become

$\Delta Q_P = \Delta U + P\Delta V$ ------ (1)

Using general gas law

$PV = nRT$

Hence

$P\Delta V = nR\Delta T$

Putting in Equation (1) we get

$\Delta Q_P = \Delta U + nR\Delta T$

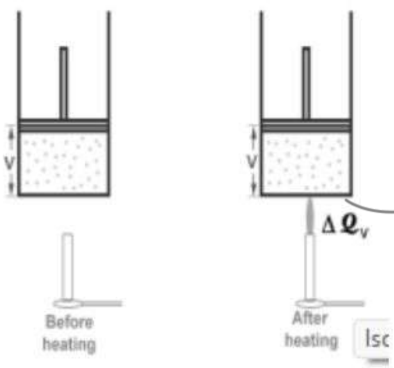
Since

$\Delta Q_P = nC_P\Delta T$

Above equation will become

$nC_p\Delta T = \Delta U + nR\Delta T$-- (a)

Consider a gas in a container if we heat the gas so that gas is not allowed to expand so that volume of the gas remain constant and all the heat energy will be used to increase the internal energy of the gas than according to first law of thermodynamics.



$\Delta \boldsymbol{Q} = \Delta \boldsymbol{U} + \Delta \boldsymbol{W}$

Since work done is Zero

$\Delta \boldsymbol{Q_v} = \Delta \boldsymbol{U}$

Since,

$\Delta Q_v = nC_v\Delta T$

Above equation will become

$\Delta U = nC_v\Delta T$ -- b

Putting equation (a) in equation (b) we get

$nC_P\Delta T = nC_v\Delta T + nR\Delta T$

Or

$nC_P\Delta T = n\Delta T(C_v + R)$

Or

$C_P = C_v + R$

Or

$C_P - C_v = \boldsymbol{R}$

EXERCISE

Section (A): Multiple Choice Questions (MCQs)

Choose the correct answer:

1. What type of process occurs when a system exchanges both heat and work with its surroundings, and there is no change in internal energy?

(a) Isothermal process (b) Adiabatic process

(c) Isobaric process (d) Isochoric process

2. During an isobaric process, what remains constant?

(a) Temperature (b) Pressure (c) Volume (d) Internal energy

3. In which thermodynamic process does a system exchange heat with its surroundings but undergoes no change in temperature?

(a) Isothermal process (b) Adiabatic process

(c) Isobaric process (d) Isochoric process

4. What is the characteristic of an adiabatic process?

(a) Constant pressure (b) Constant temperature

(c) No heat exchange with the surroundings (d) Constant volume

5. In an isochoric process, what is the primary feature?

(a) Constant temperature (b) No work done

(c) Constant volume (d) No heat exchange

6. What is internal energy in a thermodynamic system?

(a) The energy associated with motion

(b) The energy associated with the system's position

(c) The sum of kinetic and potential energy

(d) The total energy contained within the system

7. How is the change in internal energy (AU) defined in terms of heat (A Q and work (A W)

(a) $\Delta U = \Delta Q + \Delta W$ (b) $\Delta U = \Delta Q - \Delta W$ (c) $\Delta U = \Delta Q$ times W (d) $\Delta U = \Delta Q / \Delta W$

8. What is the internal energy of an ideal gas related to?

(a) Temperature only (b) Pressure only

(c) Volume only (d) Temperature, pressure, and volume

9. During an adiabatic process, what happens to the internal energy of the system?

(a) Increases (b) Decreases

(c) Remains constant (d) Depends on the specific heat

10. What is the equation for the internal energy change of a system in an isochoric process?

(a) $\Delta U = \Delta Q + \Delta W$ (b) $\Delta U = \Delta Q - \Delta W$ (c) $\Delta U = \Delta Q$ times W (d) $\Delta U = \Delta Q / \Delta W$

Section (B): CRQS (Short Answered Questions):

1. Explain the concept of the first law of thermodynamics in your own words.

The first law of thermodynamics is essentially a statement of energy conservation. It says that energy cannot be created or destroyed, only transferred or transformed from one form to another. In simpler terms, the total amount of energy in a system and its surroundings remains constant.

2. How does the first law of thermodynamics relate to the conservation of energy?

The first law of thermodynamics is a direct application of the principle of conservation of energy. It states that energy is always conserved, and the total amount of energy in an isolated system remains constant.

3. Distinguish between the work done by a system and the heat exchanged with the surroundings in the context of the first law.

Work: This is energy transferred to or from a system due to a force acting over a distance. For example, when a gas expands against a piston, it does work on the surroundings.

Heat: This is energy transferred between a system and its surroundings due to a temperature difference. For example, heat flows from a hot object to a cold one.

4. Give an example daily life that illustrates the principles of the first law of thermodynamics.

Consider a car engine. The chemical energy stored in gasoline is converted into heat energy through combustion. This heat energy is then transformed into mechanical energy to propel the car. The total energy remains constant, although it changes form.

5. Explain the role of the system and its surroundings in the context of the first law of thermodynamics.

System: This is the part of the universe that we are focusing on. It could be a gas in a container, a living organism, or even the entire Earth.

Surroundings: Everything outside of the system. The system and its surroundings together form an isolated system.

6. How does heat capacity relate to the amount of energy required to change the temperature of a substance?

Heat capacity: This is a property of a substance that measures how much heat is required to raise its temperature by a certain amount.

Energy change: The amount of energy needed to change the temperature of a substance depends on its heat capacity and the desired temperature change. A substance with a higher heat capacity requires more energy to raise its temperature compared to a substance with a lower heat capacity.

Section (C) ERQS (Long Answered Questions):

1. Provide the mathematical expression of the first law of thermodynamics and explain each term.

Notes

2. Describe what happens to the internal energy of a system in an adiabatic process, and why.

Notes

3. What is meant by the internal energy of a system, and how does it change during various thermodynamic processes?

Notes

4. Explore the concept of positive and negative work done by a gas, depending on whether the gas is expanding or compressing.

Notes

5. Explain the concept of heat capacity and its significance in thermodynamics. Discuss how heat capacity relates to the ability of a substance to store thermal energy and its implications for temperature changes.

Notes

Section (D) Numerical:

1. A gas undergoes isothermal expansion at a constant temperature of 300 K. If the gas absorbs 500 J of heat during the process, calculate the work done by the gas. (500 J)

2. A piston compresses a gas adiabatically. If the initial volume is 0.02 m_3 and the final volume is 0.01 m_3, and the initial pressure is 200 kPa, determine the final pressure. Assume the gas behaves ideally. (400 kPa)

3. A system undergoes an isobaric process where the pressure is kept constant at 150 kPa. If the volume increases from 0.05 m to 0.08 calculate the heat added to the system. (600 J)

4. During an isochoric process, the internal energy of a gas increases by 300 J. If no work is done, determine the heat added to the system. (300 J)

5. A gas undergoes a cyclic process, starting at point A with a volume of 0.02 m_3, going to B (isochoric heating), then to C (isothermal expansion), and finally back to A. If the heat added during isothermal expansion is 1000 J and the heat rejected during isochoric heating is 500 J, calculate the net work done by the system. (500 J)

6. A gas expands from 0.03 m^3 to 0.06 m^3 against a constant pressure of 100 kPa. Calculate the work done in both a reversible and an irreversible process, and compare the results. (300 J and 600 J)

7. A 50 g piece of copper at 100°C is placed in 200 g of water at 20°C. If the final temperature of the system is 30°C, calculate the specific heat capacity of copper. (Specific heat capacity of water = 4.18 J/gC) (0.39 J/g°C)

8. How much heat is required to raise the temperature of 1 kg of lead from 25°C to 100°C? (Specific heat capacity of lead = 0.128 J/g°C). (0240J).

Unit 17

Second Law of Thermodynamics

Introduction:

The first law of thermodynamics is a particular form of the law of conservation of energy. However, there are some limitations regarding the transformation of heat energy into mechanical energy, which are covered by the 2nd law of thermodynamics.

Second law of thermodynamics:

Lord Kelvin and Rudolf Clausius formulated the second law of thermodynamics. It consists of two statements.

Kelvin Statement:

According to this statement It is impossible to construct an engine, operating continuously in a cycle that can take heat from a source and coverts completely into work".

OR

In other words, it is impossible device an engine that would have an efficiency of 100%, even though the first law of thermodynamics will be satisfied.

Clausius Statement:

According to Clausius statement

"It is impossible to cause heat to flow from a cold body to a hot body without the expenditure of energy".

Efficiency of heat engine:

"The thermal efficiency "" of a cycle heat engine is defined to the ratio of the network W' done by the engine in each cycle to the heat absorbed Q; in each cycle".

Efficiency (η) = $\frac{output}{input}$

$$\eta = \frac{W}{Q_1}$$

$$\eta = \frac{Q_1 - Q_2}{Q_1}$$

$$\eta = 1 - \frac{Q_2}{Q_1}$$

Reversible Process:

"A reversible process is one which can be retraced in exactly reverse order, without producing any change in the surroundings":

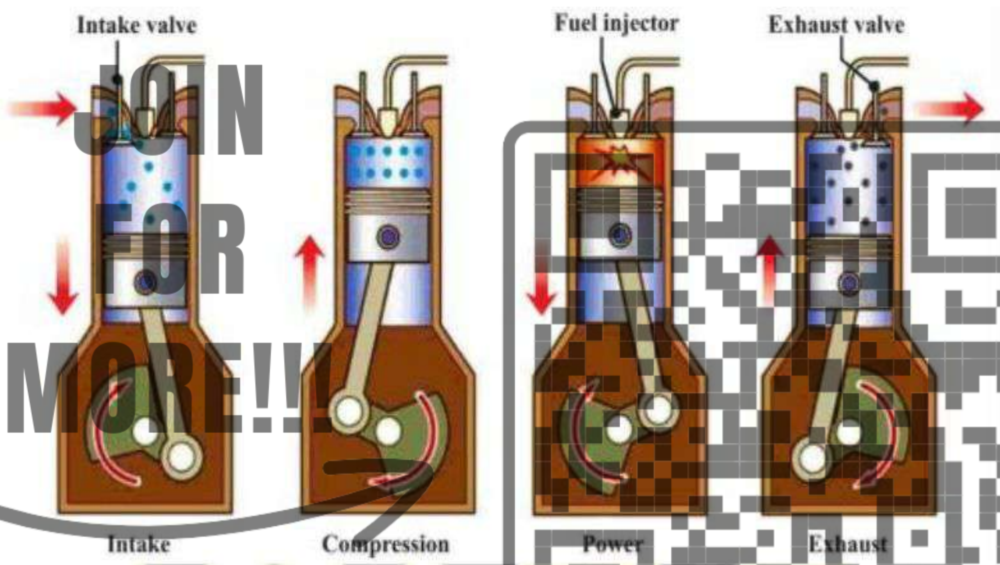
Irreversible Processes

"The process which cannot be retraced in the backward direction by reversing the controlling factors is known as irreversible process"

Petrol Engine:

Petrol engine is an internal combustion engine designed to run on volatile fuel such as petrol (gasoline), which has spark-ignition. In these engines air and fuel are generally mixed post-compression.

It works on the Otto cycle and the name comes from the German Engineer Nikolaus Otto (1876), who made the first working prototype. Although different engines may differ in their construction technology but they are based on the principle of Carnot cycle. A typical four stroke petrol engine also undergoes four successive processes in each cycle.



1. The cycle starts on the intake stroke in which piston moves outward and petrol air mixture is drawn through an inlet valve into the cylinder from the carburettor at atmospheric pressure.

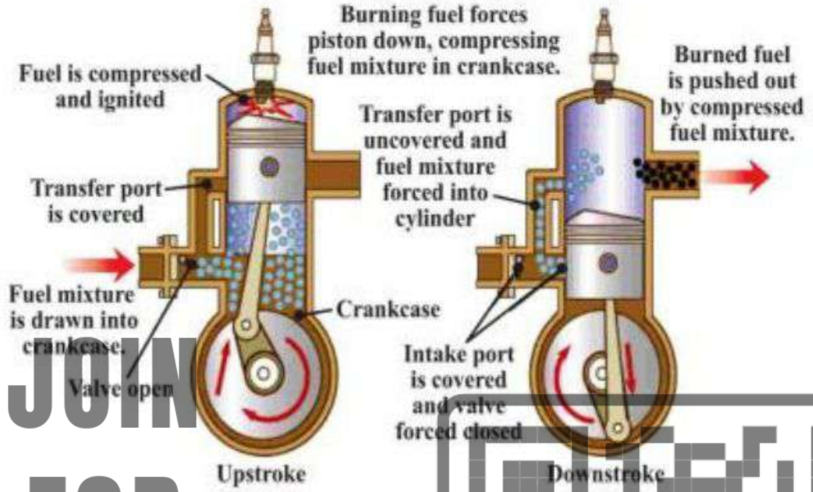
2. On the compression stroke, the inlet valve is closed and the mixture is compressed adiabatically by inward movement of the piston.

3. On the power stroke, a spark fires the mixture causing a rapid increase in pressure and temperature. The burning mixture expands adiabatically and forces the piston to move outward. This is the stroke which delivers power to crankshaft to drive the flywheels.

4. On the exhaust stroke, the outlet valves open. The residual gases are expelled and piston moves inward. The cycle then begins again. Most motorbikes have one cylinder engine but cars usually have four cylinders on the same crankshaft. The cylinders are timed to fire turn by turn in succession for a smooth running of the car. The actual efficiency of properly tuned engine is usually not more than 25% to 30% because of friction and other heat losses.

Diesel Engine:

The diesel engine named after Rudolf Diesel (German inventor and Mechanical Engineer), is an internal combustion engine. He patented his original design in 1892. When the fuel comes into contact with high temperature, it ignites, creating energy that drives the piston down transferring energy to the crankshaft. There are two classes of diesel engine: two strokes and four strokes. Most diesel engines generally use the four-stroke cycle.



No spark plug is needed in the diesel engine. Diesel is sprayed into the cylinder at maximum compression. Because air is at very high temperature immediately after compression, the fuel mixture ignites on contact with air in the cylinder and pushes the piston outward. The efficiency of diesel engine is about 35% to 40%.

The Carnot Engine

Carnot Engine:

Introduction:

Carnot engine is an ideal heat engine which converts heat energy into mechanical energy. It is an imaginary heat engine free from friction & heat losses due to radiations or conduction.

Construction:

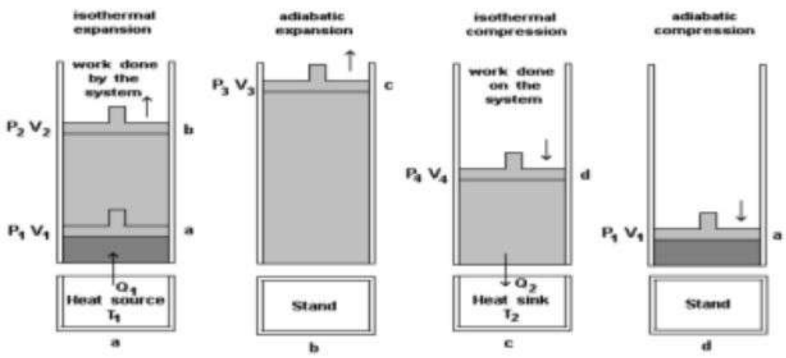
It consists of an ideal gas cylinder having conducting base, non-conducting walls and nonconducting movable frictionless piston.

Carnot Cycle:

A Carnot engine converts heat energy into mechanical energy using a cyclic process consisting of two isothermal and two adiabatic reversible processes called Carnot Cycle.

Working:

Working of Carnot engine consist of steps as follows



Step#1: (Isothermal Expansion).

Gas in cylinder is initially at pressure P1, volume V1 and temperature T1. The cylinder is than placed at a heat reservoir and absorbs heat energy($Q1$)and gas can expand isothermally, and physical variables changes to **P2, V2, T1**.

Step#2: (Adiabatic Expansion).

The cylinder is than placed at an insulator and external work is done and gas can expand adiabatically, and physical variables changes to **P3, V3, T2**.

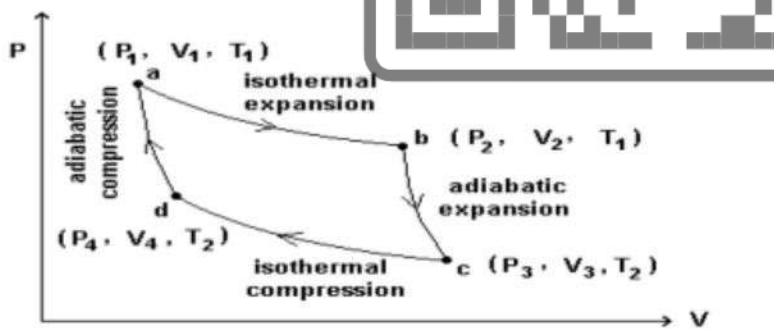
Step#3: (Isothermal Compression).

The cylinder is than placed at a cold reservoir and eject heat energy($Q2$) and gas is allowed to compress isothermally and physical variables changes to **P4, V4, T2**.

Step#4: (Adiabatic Compression).

The cylinder is than placed at an insulator and external work is done and gas can compress adiabatically, and physical variables changes to **P1, V1, T1**.

Graphical Representation of Carnot Cycle:



Carnot cycle

Efficiency of Carnot Engine:

Since throughout the Carnot Cycle net change in internal energy is zero there for firth law of thermodynamics will be written as

$\Delta Q = \Delta W$

$\Delta Q = Q_1 - Q_2$

Efficiency of the Carnot engine can be written as

$$\eta = \frac{Output}{input}$$

$$\eta = \frac{W}{Q_1}$$

$$\eta = \frac{Q_1 - Q_2}{Q_1}$$

$$\eta = 1 - \frac{Q_2}{Q_1}$$

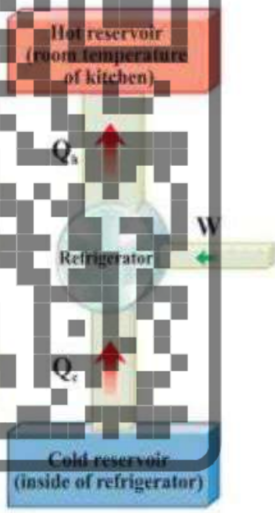
show that the efficiency of the engine increases as the ratio decreases. It can also be proved that the heat transferred to or from a Carnot engine is directly proportional to the temperature of the hot or cold body.

$$\frac{Q_2}{Q_1} = \frac{T_2}{T_1}$$

Thus, the efficiency of Carnot engine can be written as

$$\eta = 1 - \frac{T_2}{T_1}$$

Refrigerator:



According to the 2nd law of the thermodynamics heat will always flow spontaneously from hot to cold body, and never the other way around.

A refrigerator causes heat to flow from cold to hot by doing work, which cools the space inside the refrigerator.

In a heat engine, the direction of energy transfer is from the hot reservoir to the cold reservoir, which is the natural direction. role of heat engine is to process the energy from the hot reservoir so as to do useful work.

For example, houses in summer are cooled using refrigerators called air conditioners. The air conditioner transfers energy from the cool room in the home to the warm air outside.

In Practice,

A refrigerator includes a circulating fluid that gases through two sets of metal coils that can exchange energy with the surroundings.

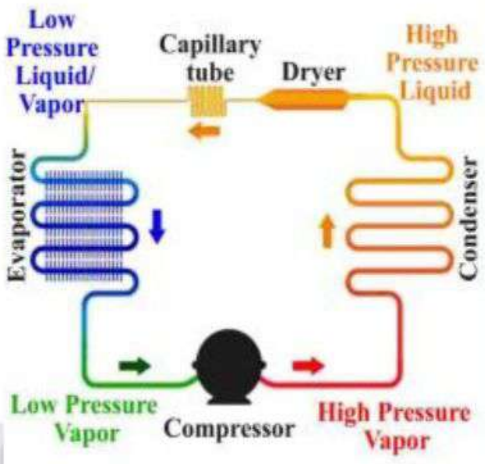
The fluid is cold and at low pressure when it is in the coils located in a cool environment, where it absorbs energy by heat.

The resulting warm fluid is then compressed and enters the other coils as a hot, high-pressure fluid.

There it releases its stored energy to the warm surroundings.

In an air conditioner, energy is absorbed into the fluid in coils located in a building's interior; after the fluid is compressed, energy leaves the fluid through coil. In a refrigerator, the external coils are behind or underneath the unit the internal coils are in the walls of the refrigerator and absorb energy from the food.

Efficiency of a Refrigerator:



The effectiveness of a refrigerator is described in terms of a number called the coefficient of performance (COP).

COP of refrigerator = $heat \frac{extracted}{\text{work}}$

COP = $K = \frac{Q_c}{W}$

$Q_h = Q_c + w$

$W = Q_h - Q_c$

COP = $K = \frac{Qc}{Qh - Qc}$

We know that for Carnot cycle $Q_1 \propto T_1$ and $Q_2 \propto T_2$

COP = $K = \frac{T_c}{T_h - T_c}$

T_c is the cryogenic temperature at which the heat is removed

T_h is the temperature at which the heat is rejected

It can also be seen from above relations that the coefficient of performance of refrigerator can be larger than 100% unlike the efficiency of heat engine which is always less than 100%. A good refrigerator should have a high COP, typically 5 or 6.

Entropy:

"The measure of a system 's thermal energy per unit temperature that is unavailable for doing useful work".

$\Delta S = \frac{\Delta Q}{T}$

The S.I unit of entropy is JK^{-1}. If heat is removed from a system, the change in entropy written as negative.

Increase in Entropy Means Degradation of Energy:

Suppose a quantity of heat Q in a reservoir at temperature T_1. Let the temperature of the coldest available reservoir be To. A Carnot engine working between the temperatures T_1 and T_o can absorb heat Q at temperature T_1 and do useful work Wi given by:

$W_1 = Q - \theta_2$

The efficiency of Carnot engine is

$\eta = \frac{W_1}{Q} = 1 - \frac{T_o}{T_1}$

$W_1 = Q(1 - \frac{T_o}{T_1})$ ----- 1

Equation gives maximum available energy which can be converted into useful work, when heat Q is stored in the reservoir at temperature T_1.

Consider an irreversible process, in which heat Q flows from the reservoir at temperature T_1. to another reservoir at a lower temperature T_2. A Carnot engine working between the temperatures T_2. and To can now take heat Q from the reservoir at temperature T_2. and do useful work W_2 given by:

$\eta = \frac{W_2}{Q} = 1 - \frac{T_o}{T_2}$

$W_2 = Q(1 - \frac{T_o}{T_2})$ ----- 2

Equation 2 gives the maximum available energy which can be converted into useful work. When heat Q is stored in the reservoir at lower temperature T_2. As $T_2 < T_1$, we see from equation 1 and 2 that W_2 is less than W_1, i.e. available energy decreases with the increase of entropy during an irreversible process.

Since all natural processes are irreversible, we conclude that the energy of the universe is continuously becoming unavailable for useful work. This is called the degradation of energy.

From the equation 1 and 2, we get

$W_1 - W_2 = Q(\frac{T_o}{T_2} - \frac{T_o}{T_1})$

$W_1 - W_2 = T_o(\frac{Q}{T_2} - \frac{Q}{T_1})$

Now $\frac{Q}{T_1}$ decrease in entropy of the reservoir at temperature T_1 and $\frac{Q}{T_2}$ = increase in entropy of the reservoir at temperature T_2.

Thus $(\frac{Q}{T_1}, \frac{Q}{T_2})$ is increase in entropy of the universe. Also $(W_1 - W_2)$ is the amount of energy which has been degraded or made available for useful work.

Hence equation shows that the increase of unavailable energy is equal to the increase in entropy of the universe multiplied by the temperature of the coldest available reservoir. Using eq an entropy increases, so unavailable energy also increases, so the useful energy decreases. It is called degradation of energy.

Energy is Degraded During All-Natural Processes:

It is believed that the temperature of the universe is increasing gradually and its entropy is also increasing. The mode of increase of entropy indicates that after a very long time, the entropy of the universe will be maximum and all the objects will be at the same temperature. At that time, no useful energy will be available and life will cease to exist, which is known as the "Heat Death" of the universe, which may not occur in near future.

Systems Tends to Become Less Orderly Over Time:

The disorder of the system increases during any natural process, a stage will reach when universe will approach a stage of maximum disorder. At this stage, matter will become a uniform mixture i.e. whole universe will be at uniform temperature. No work can then be done and heat flow will cease.

In all the processes going on in practical life, the entropy always increases with time and disorder is produced more and more. Hence this increase of entropy is identification for the time passage.

EXERCISE

Section (A): Multiple Choice Questions (MCQS)

Choose the correct answer:

1. A frictionless heat engine can be 100% efficient only if its exhaust temperature is:

(a) 0°C (b) Equal to its input temperature

(c) 0 K (d) half of its input temperature

2. A refrigerator, with its door open. The temperature of the room will

(a) Rise (b) Fall

(c) Remains the same (d) Rise or fall depending on the area of the room

3. Which device is not used in a diesel engine

(a) Outlet Valve (b) Piston (c) Sparking Plug (d) Injector

4 Which one of the following processes is irreversible?

(a) Slow compression of an elastic spring

(b) Slow evaporation of a substance in an isolated vessel

(c) Slow compression of a gas

(d) A chemical explosion

5 According to 2nd law of thermodynamics, 100% conversion of heat into mechanical work is:

(a) Possible (b) Possible, if the conditions are ideal

(c) Not possible (d) Possible, if the process is adiabatic

6 The change in entropy is given by

(a) $\Delta S = \frac{\Delta Q}{T}$ (b) $\Delta S = \Delta Q.\ T$ (c) $\Delta S = \frac{\Delta U}{T}$ (d) $\Delta S = \frac{\Delta W}{T}$

The net change in entropy as a system in a natural process is

(a) Positive (b) Negative (c) Zero (d) Infinite

8 The efficiency of diesel engine is

(a) Greater than petrol engine (b) Less than petrol engine

(c) Equal to petrol engine (d) both have efficiency 1

9. Second law of thermodynamics states that:

(a) Energy can't be converted. (b) Entropy decreases over time.

(c) Heat flows from cold to hot. (d) Entropy increases over time

10. The process violates the 2nd law of thermodynamics is:

(a) Refrigerator cooling.
(b) Heat engine working.
(c) Gases mixing.
(d) Heat flowing from cold to hot.

Section (B): CRQs (Short Answered Questions):

1. What are some factors that affect the efficiency of automobile engines?

Factors Affecting Automobile Engine Efficiency

1. **Compression Ratio:** A higher compression ratio can improve efficiency by extracting more energy from the fuel.
2. **Fuel Quality:** Higher octane fuels can allow for higher compression ratios, improving efficiency.
3. **Engine Design:** Features like direct injection, variable valve timing, and turbocharging can enhance efficiency.
4. **Driving Conditions:** Factors like traffic, driving style, and road conditions can impact fuel consumption.
5. **Maintenance:** Regular maintenance, such as oil changes and tune-ups, can help optimize engine performance.

2. What happens to the temperature of a room in which an air conditioner is left running on table in the middle of the room?

When an air conditioner is left running on a table in the middle of a room, the temperature of the room will decrease over time. The air conditioner removes heat from the air and expels it outside, causing the room to cool down. However, if the air conditioner is not properly vented or if the room is poorly insulated, the cooling effect may be limited.

3. Under what conditions can heat be added to a system without changing its temperature?

Conditions for Adding Heat Without Changing Temperature

Heat can be added to a system without changing its temperature under certain conditions:

- **Phase Transition:** When a substance undergoes a phase change (e.g., from solid to liquid or liquid to gas), heat can be added without changing the temperature. The added heat is used to overcome the intermolecular forces holding the substance together in its current phase.

- **Adiabatic Process:** An adiabatic process is one in which no heat is transferred between the system and its surroundings. In this case, the temperature of the system can change due to work being done on or by the system.

4. Is it possible to cool a room by keeping the refrigerator door open?

Cooling a Room with a Refrigerator Door Open

No, it is not possible to cool a room by keeping the refrigerator door open. The refrigerator actually removes heat from the inside of the appliance and releases it into the room. Leaving the door open will simply cause the refrigerator to work harder to cool its interior, and the net effect will be to heat the room.

5. When does the entropy of a system decrease?

When Entropy Decreases

Entropy is a measure of disorder or randomness in a system. It generally increases over time due to the second law of thermodynamics. However, there are situations where the entropy of a system can decrease:

- **Isolated Systems:** In an isolated system, the total entropy cannot decrease. However, the entropy of a particular part of the system can decrease as long as the entropy of another part increases by a greater amount.
- **Open Systems:** In open systems, entropy can decrease due to the transfer of energy or matter between the system and its surroundings. For example, a living organism can maintain a low level of entropy by consuming energy and expelling waste.

6. it possible, according to the 2nd law of thermodynamics to construct an engine that is free from thermal pollution?

Thermal Pollution and the Second Law

According to the second law of thermodynamics, it is not possible to construct an engine that is completely free from thermal pollution. Any heat engine that converts heat into work must also release some waste heat to the surroundings. This is because the efficiency of any heat engine is always less than 100%, and the remaining energy must be expelled as waste heat.

7. Can heat be completely converted to work?

Converting Heat to Work

Heat can be converted to work, but not completely. The maximum efficiency of a heat engine is given by the Carnot efficiency, which depends on the temperatures of the hot and cold reservoirs. In practice, real-world heat engines always have efficiencies lower than the Carnot efficiency due to various factors such as friction and heat losses.

8. Define that why entropy has often been called as "time arrow".

Entropy has often been called the "arrow of time" because it provides a directionality to time. The second law of thermodynamics states that the entropy of an isolated system always increases over time. This means that

events tend to proceed from a state of lower entropy (greater order) to a state of higher entropy (greater disorder). This directionality is often used to distinguish between past and future, as the past is generally characterized by a lower entropy state than the future.

Section (C): ERQs (Long Answered Questions):

1. Give the two statements of the second law of the thermodynamics. Elaborate the concept of entropy and state the second law of thermodynamics in terms of this concept.

2. Explain the working principle of heat engine and also derive the formula for its efficiency.

3. Describe the concept of reversible and irreversible process.

4. What is Carnot engine? Give the operation of Carnot cycle and shovw that the efficiency of even this engine is less than 100%.

5. Describe that refrigerator is a heat engine operating in reverse as that of an ideal heat engine and find its efficiency.

6. Explain that change in entropy is positive when heat is added and negative when heat is removed from the system.

7. Explain that increase in entropy means degradation of energy.

Section (D): Numerical:

1. A Carnot engine takes 2000J of heat from a reservoir at 500K does some work, and discards some heat to a reservoir at 350K. How much heat is discarded, how much work does the engine do, and what is the efficiency? (Ans: 1400J, 600J, 30%)

2. One kilogram of ice at 0°C is melted and converted to water at 0°C. Compute its change in entropy. (Ans: 1220 J.K-l)

3. In a high-pressure steam turbine engine, the steam is heated to 600°C and exhausted at about 90°C. What is the highest possible efficiency of any engine that operates between these two temperatures? (Ans: 58.4 %)

4. Temperature difference between the surface water and bottom water Manchester Lake might be 5°C.Assuming the surface water to be at 20°C. What highest efficiency a steam engine could have if it operates between these two temperatures? (Ans: 1.71%)

5. A heat engine works at the rate of 500kW. The efficiency of the engine is 30%. Calculate the loss of heat per hour. (Ans: 4.2 x 10°J)

6. A heat engine performs work of 0.4166 watts in one hour and rejects 4500J of heat to the sink. What is the efficiency of engine? (Ans: 24.9%)

7. A Carnot engine operates between the temperatures 850K and 300K. the engine performs 1200J of work in each cycle, which takes 0.25 sec

(a) What is the efficiency of this engine?

(b) What is the average power of this engine?

(c) How much energy is extracted as heat from the high temperature reservoir?

(d) How much energy is delivered as heat to the low temperature reservoir?

(Ans (a) 65% (b) 4.8KW (c) 1855J (d) 655J)

8. A Carnot engine absorbs 52kJ as heat and exhaust 36kJ as heat in each cycle. Calculate:

(a) The engine efficiency

(b) The work done per cycle in kilojoules. [Ans (a) 30.76% (b) 16KJ]

Unit 18

Magnetic Fields

Introduction:

A magnetic field is a fundamental concept in physics that describes the region around a magnet or a current-carrying conductor where magnetic forces are exerted on other magnets, conductors, or charged particles.

Permanent magnets, such as iron magnets, have their own intrinsic magnetic fields due to the alignment of their magnetic domains.

Magnetic fields have numerous practical applications, including:

- Electric motors
- Transformers
- MRI machines (Magnetic Resonance Imaging)
- Magnetic levitation trains
- Magnetic compasses
- Magnetic data storage (hard disk drives)

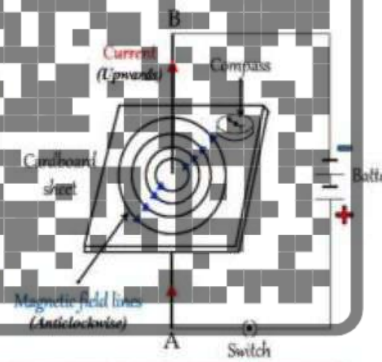
Magnetic Fields:

Magnetic field can be defined as "An area around a permanent magnet or a current carrying conductor, where they generate a magnetic force".

Magnetic fields can be generated through two primary methods:

- From permanent magnets.
- From current carrying conductors, also known as electromagnets

Magnetic Force on a current carrying conductor:



When we place a current-carrying conductor with in a uniform External magnetic field, the interaction between the magnetic field produced by the conductor and the external magnetic field gives rise to external force, denoted as F, acting on the conductor, as illustrated in figure.

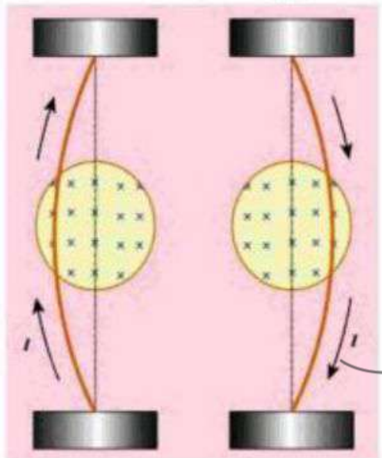


Figure 18.2 Magnetic Force on a current carrying conductor

Factors on which the force acting on current carrying conductor in a magnetic field:

The force acting on a current-carrying conductor depends on several factors, such as, length, current, and the strength of the external magnetic field

The force (F) is directly proportional to the length of the conductor (L) that lies within the magnetic field

$$F \propto L$$

The force is also directly proportional to the current (I) passing through the conductor.

$$F \propto I$$

Similarly, the force is directly proportional to the strength of the external magnetic field (B).

$$F \propto B$$

Combining these factors, we will obtain the following relationship:

$$F \propto BIL$$

Here, "k" is the proportionality constant, and in the SI unit system, its value is equal to 1.

Therefore, we can express the force as:

$$F = BIL$$

If the magnetic field is not perpendicular to the wire, Above equation can be modified to:

$$F=I(L \times B)$$

where 'x' denotes the vector cross product.

The magnitude of the force (F) is determined by:

$$F= BIL\sin\theta$$

Where, θ represents the angle between the direction of the conductor's length (L) and the external magnetic field (B).

Maximum Force:

The deflecting force reaches its maximum when the angle (θ) between the length of the conductor and the external magnetic field is = 90° degrees, assuming other factors remain constant.

Minimum Force:

Conversely, the deflecting force is minimized when -0 degrees, signifying that the magnetic field and conductor are aligned.

Since magnetic force is a vector quantity, its direction can be determined using Fleming's lefthand rule, which provides a straight forward way to establish the direction of the force in relation to the current and magnetic field.

Thrust or Fleming's left-hand rule: Motion

Fleming's left-hand rule is used to determine the direction of force acting on a current carrying wire placed in a magnetic field, also to identify the direction of the forces in an electric motor in order to apply Fleming's left-hand rule, follow these steps: Extends our fore finger, thumb, and Middle finger such that they are mutually perpendicular as shown in figure.

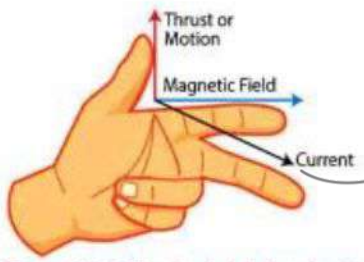


Figure 18. 3 Fleming's left-hand rule

Magnetic Flux:

Magnetic flux is defined as the number of magnetic lines of force passing through an area held perpendicular to it.

It is calculated by taking the dot product between the magnetic field and area vector.

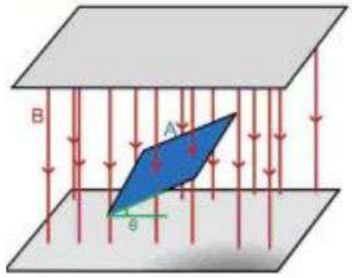


Figure 18.4 Magnetic Flux

$\phi_B = B.A$

or $\phi_B = BA\cos\theta$

Where B is uniform magnetic field

A is an area vector whose magnitude is equal to the surface element and directed perpendicular to the given surface element.

Maximum Magnetic Flux:

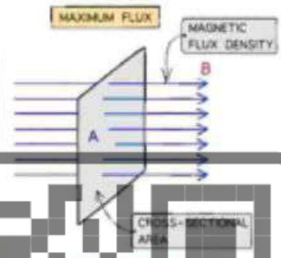


Figure 18.5 (a) Maximum Magnetic Flux

The magnetic flux will be maximum when the angle between magnetic field B and area vector A is zero,

i.e. $\theta = 0^o$ surface will be perpendicular to the magnetic lines. This case is shown in figure

Minimum Magnetic Flux:

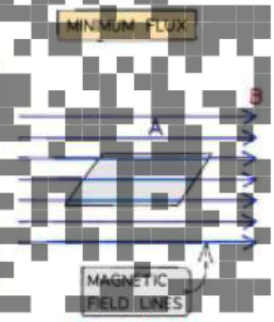


Figure 18.5 (b) Minimum Magnetic Flux

Similarly when the angle between area vector and magnetic field is $\theta = 90^o$ then lines of force do not pass through the surface and magnetic flux will be minimum as shown in figure.

Unit of Magnetic Flux:

The SI unit of magnetic flux is Weber (Wb) = $1Wb = \frac{Nm}{A}$

Magnetic Flux Density:

The magnetic flux density at a specific point in space is the force experienced per unit length by along straight conductor carrying unit current, placed perpendicular to the field at that particular location.

$$B = \frac{F}{IL}$$

Unit of Magnetic Flux Density:

The SI unit of magnetic flux density is Tesla (T), named after the Serbian-American inventor Nikola Tesla.

One Tesla: is defined as follows, If a conductor having length 1 m and carries a current of 1A placed perpendicularly the magnetic field experience a force of one Newton then magnetic flux density will be 1Tesla.

In essence, the Tesla provides a standardized measure of the strength of a magnetic field, with larger values indicating stronger magnetic fields and smaller values representing weaker fields.

Amperes Law:

It is known that an electric current flowing through a wire creates a magnetic field in its vicinity. When we envision a closed circular path with the wire positioned at its center, the Magnetic flux density (B) within this circular region changes, depending on both the current (I) and the distance (r) from the wire as shown in figure

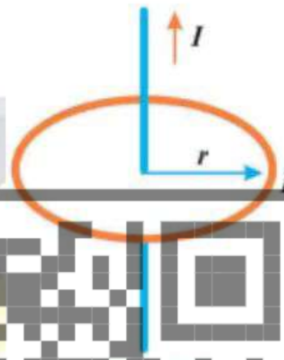


Figure 18.7
Current carrying wire

$B \propto 2I$ -----i

Or $B \propto \frac{1}{r}$ -----ii

Combing (i) and (ii), we get

$B \propto \frac{2I}{r}$

$B = \frac{\mu_o I}{2\pi r}$

Where μ_o is permeability of free space = $4\pi \times 10^{-7}$ Wb A^{-1} m^{-1}

Now consider an Amperian loop in form of a closed path around the current carrying wire as shown in figure 18.7. For any path element ΔL we can write

$B. \Delta L = \mu_o I$

Since angle between B and L is zero so $B. \Delta L = B\Delta L = \mu_o I$

Now adding up over whole closed path

$\sum B.\Delta L = \mu_o I$

Hence Ampere's law can be defined as the integral of the magnetic field (B) around a closed loop is directly proportional to the total electric current (I) passing through the loop.

Application of Ampere's Law:

(i) Solenoid:

A solenoid is along, tightly wound coil of wire, and often used to generate a uniform magnetic field within the coil's interior. It consists of many closely spaced turns of wire, and when an electric current flow through it, it creates a magnetic field that is similar to the field produced by a bar magnet. To determine the magnitude of B of a solenoid let us Consider an Amperian loop abcd with lengths l_{ab}, l_{bc}, l_{cd} and l_{da} shown in figure.

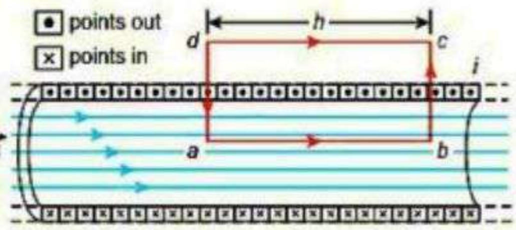


Figure 18.8 Amperian loop Solenoid

Then from Ampere's law

$\sum B.\,Al = \mu_o I$

The left hand side of equation is

$\sum B.\Delta l = -B.L_{ab} + B.L_{bc} + B.l_{dc} + Bl_{da}$

As the element al lengths along bc and da are perpendicular to the magnetic field so

$B.l_{bc}$ and $B.l_{da} = 0$

Moreover, the magnetic field intensity outside of solenoid ≈ 0, so $B.L_{cd} = 0$

Hence the magnetic field due to solenoid is given by

$\sum B.\Delta l = B.l_{ab} = \mu_o I$

For N number of turns on the solenoid

$\sum B.\Delta l = B.l_{ab} = \mu_o NI$

The number of turns per unit length is given by $n = \frac{N}{l_{ab}}$

$B = \mu_o nI$

Hence it is shown that B is independent of the position within the solenoid which shows that the field is uniform with in a solenoid.

(ii) Toroid:

A toroid can be considered as a solenoid that is bent into the shape of a circle. It also generates a magnetic field within its interior. The magnetic field lines inside a toroid are generally circular and concentrated within the coil.

Suppose a toroid consist of N closely packed turns of copper wire and carry a current I as shown.

Imagine a hollow circular ring wound with N number of turns of current-carrying wire. In this case, within the toroid, point P is our point of interest, and we will denote the magnetic field at this location as B. Inside the toroid, we construct an Amperian loop forming a circle that passes through point P., This arrangement gives rise to concentric circles within the toroid.

Because of the symmetrical nature of the magnetic field, the magnitude of the field at all points along the circle is uniform, and the field direction is tangential to the circle.

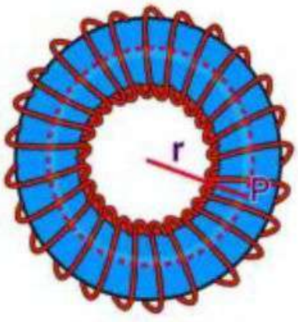


Figure 18.9 A toroid

Therefore,

$\sum B. Al = \sum B\Delta l \, Cos(0) = B\sum \Delta l = (2\pi r)$

Now, we can apply Ampere's law:

$2\pi r = \mu_o NI$

$B = \frac{\mu_o NI}{2\pi r}$

This is the expression for the magnetic field strength inside a toroid. It is inversely proportional to the radius r and directly proportional to the number of turns per unit length N and the current I flowing through the turns.

Force on a charged particle in a uniform magnetic field:

When a charged particle moves through a uniform magnetic field, it experiences a force known as the magnetic force. This phenomenon is described by the Lorentz force equation, which can be written as:

$$F = (v \times B)$$

Charge to mass ratio of Electron:

Measuring the charge-to-mass ratio (e/m) of an electron is a classic experiment in the field of electromagnetism and particle physics. This experiment, known as the "e/m experiment, "involves applying both a magnetic field and an electric field to a beam of electrons. Here's a step-by-step method to measure the e/m of an electron:

Apparatus and Materials:

1) Cathode Ray Tube (CRT): This is a vacuum tube that produces a beam of electrons. It consists of an electron gun, focus in, deflection plates, and a fluorescent screen
2) Magnetic Field Source: We'll need a strong and uniform magnetic field source, such as a Helmholtz coil or a solenoid.
3) Voltage Source: A variable voltage source to create an electric field.
4) Fluorescent Screen: A screen coated with a phosphorescent material to visualize the electron beam. C
5) Rulers and Measurement Devices: To measure the radius of the electron beam's circular path and he electric potential applied.

Experimental Procedure:

1. Setup:

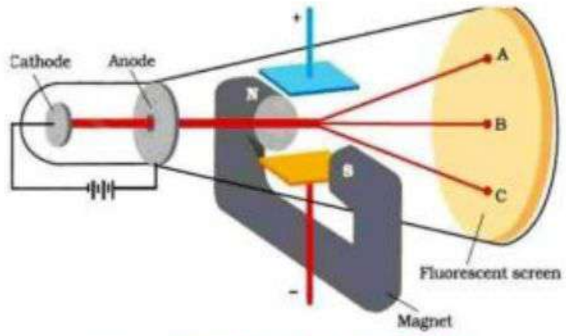


Figure 18.10 Cathode Ray Tube (CRT)

Set up the CRT in a vacuum chamber to ensure the electron beam doesn't interact with air molecules.

Position the Helmholtz coil (or solenoid) around the CRT, providing a uniform magnetic field parallel to the beam path.

Connect the voltage source to the focusing and deflection plates to create an electric field perpendicular to the magnetic field.

2. Calibration:

Calibrate the magnetic field by measuring its strength at the location of the electron beam. We can do this using a magnetic field strength meter.

3. Electron Beam Production:

Apply a high voltage across the cathode and anode of the CRT to generate a beam of electrons from the cathode (electron gun).

Use the focusing and deflection plates to control and direct the electron beam.

4. Observe the Electron Beam:

Turn off the magnetic field and electric field to observe the electron beam's straight- line path on the fluorescent screen.

5. Apply the Magnetic Field:

Turn on the magnetic field, which causes the electron beam to bend in a circular path due to the Lorentz force (the interaction between the magnetic field and the moving electrons).

6. Measure the Radius(r):

Measure the radius of the circular path formed by the electron beam on the screen. Ensure the screen is marked with a scale for accurate measurement.

7. Apply the Electric Field:

Apply a known electric potential (voltage) across the focusing and deflection plates perpendicular to the magnetic field. This will introduce an electric force on the electrons.

8. Adjust the Voltage:

Adjust the voltage until the electron beam returns to its original, undeflected straight-line path.

9. Measure the Electric Potential (V):

Measure the voltage applied across the plates.

Calculations:

An electron is released from cathode and it gains speed while passing through the potential difference V, hence gaining kinetic energy of 1eV. This electron kinetic energy is calculated by:

$$\frac{1}{2} mv^2 = Ve$$

The magnetic field produced by Helmholtz coils is perpendicular to this velocity, and produces a magnetic force which is transverse to both v and B: this provides the centripetal force makes an electron move along the circular trajectory; the radius of this trajectory r can be found from

$$mv^2 = qvB$$

From this equation, we obtain the expression for the charge-to-mass ratio of the electron,

we can calculate the e/m ratio of the electrons which was found to be 1.7588×10^{11} C/kg

Measuring Instruments:

Galvanometer:

A Galvano meter is an instrument used to detect and measure electric currents. It is a highly sensitive electromagnetic apparatus capable of measuring even very small currents, such as those on the order of a few micro amperes.

Figure 18.11 Galvanometer

Principle:

It works based on the principle of electromagnetic induction. When a coil carrying an electric current is positioned within an external magnetic field, it undergoes magnetic torque. The degree of deflection observed in the coil, caused by this magnetic torque, is directly proportional to the current's magnitude flowing through the coil.

Construction:

1. **Coil:** The key component of a Galvano meter is a coil of wire (usually wound around as oft iron core) suspended within a magnetic field. The coil is mounted on a spindle so that it can rotate freely.

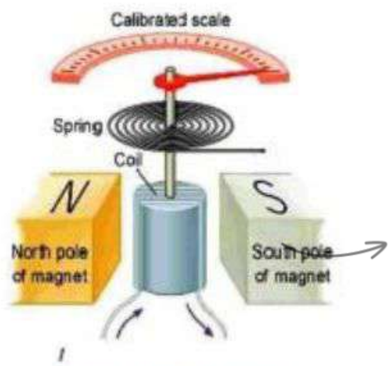


Figure 18.12 schematic diagram of Galvanometer

2. **Magnet**: A permanent magnet or an electromagnet is placed around the coil. The magnetic field lines from magnet pass through the coil.

3. **Spring**: A delicate torsion spring is attached to the coil, providing a restoring torque when the coil is deflected.

4. **Pointer**: A thin pointer or needle is attached to the coil, allowing for the measurement of the deflection.

Working:

Consider a rectangular coil consisting of N turns, each with a current I flowing through them and across-sectional area A. When this coil is situated within a uniform radial magnetic field B, it undergoes a torque as shown in figure

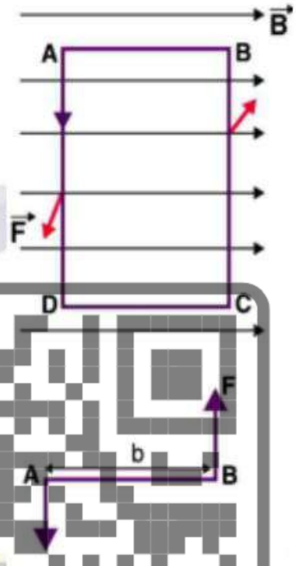


Figure 18.13 torque on rectangular coil

Let's examine a single turn ABCD of the rectangular coil, characterized by a length L and breadth b as shown in figure. This turn is suspended within a magnetic field with strength of B, arranged so that the coil's plane is parallel to the magnetic field lines. As sides AB and DC are aligned parallel to the magnetic field, they do not experience any discernible force due to the magnetic field. However, sides AD and BC, which are perpendicular to the field's direction, encounter an effective force denoted as F, given by

$$F = BIL.$$

By employing Fleming's left-hand rule, we can recognize that the forces acting on sides AD and BC are oriented in opposite directions each other. When a pair of equal and opposite forces, denoted as F and collectively referred to as a couple, act on the coil, they generate a torque. This torque induces a deflection in the coil.

The torque(t) is calculated as the product of the force(F) and the perpendicular distance (b) between these forces:

$$\tau = F \times b$$

Substituting the known value of F, we have:

Torque(τ) acting on a single-loop ABCD of the coil

$$\tau = BIL \times b$$

Where L X b represents the area (A) of the coil. Consequently, the torque acting on a coil with n turns is given by

$$\tau = NIAB$$

This magnetic torque causes the coil to rotate, leading to the twisting of the phosphor bronze strip. Simultaneously, the spring (S) attached to the coil exerts a counter-torque, known as there storing torque ($k\theta$), resulting in a stable angular deflection.

Under equilibrium conditions, we find :

$$k\theta = NIAB$$

Here, k is termed the torsional constant of the spring, representing the restoring couple per unit twist. The deflection or twist (θ) is quantified as the reading displayed on a scale by a pointer connected to the suspension wire.

$$\theta = \left(\frac{NAB}{k}\right) I$$

$$\theta \propto I$$

Therefore

The quantity $\left(\frac{NAB}{k}\right)$) is a constant for a given galvanometer. Therefore, it is evident that the deflection observed in the galvanometer is directly proportional to the current flowing through it.

Conversion of Galvanometer to Ammeter:

To convert a galvanometer into an ammeter, a low-resistor known as a shunt is connected in parallel with the galvanometer.

The selection of an appropriate shunt is based on the desired current range of the ammeter.

From the circuit as shown in figure,

Rg represents the resistance of the galvanometer.

G denotes the Galvanometer coil.

I stand for the total current flowing through the circuit.

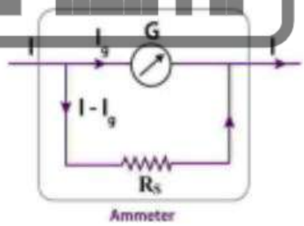


Figure 18. 14 Ammeter and its schematic diagram

Ig represents the total current passing through the galvanometer, which corresponds to the full-scale reading.

Rs represent the value of the shunt resistance.

When the current Ig lows through the Galvanometer, the current passing through the shunt is determined by

$$I_s = I - I_g$$

The voltages across both the galvanometer and shunt are R_s equal due to their parallel connection.

Hence, we can establish the following equation:

$$R_g I_g = (I - I_g) \times R_s$$

$$Rs = \frac{R_g I_g}{I - I_g}$$

Conversion of Galvanometer to Voltmeter

A galvanometer is converted into a voltmeter by connecting it in series with high resistance as shown in figure. A suitable high resistance is chosen depending on the range of the voltmeter.

R_g stands for the resistance of the galvanometer.

R_x represents a high resistance component called series resistance.

G denotes the galvanometer coil.

I is the total current flowing through the circuit.

I_g signifies the total current passing through the galvanometer, corresponding to a full scale deflection.

V represents the voltage drop across the series connection of the galvanometer and the high resistance.

When the current Ig flows through the series combination of the galvanometer and the high resistance R, the voltage drop across the branch ab can be expressed as:

$$V = V_g + V_x$$

Current in series combination remain conserved therefore;

$$I_g = I_x$$

$$V = I_g R_g + I_g R_x$$

$$I_g R_x = V - I_g R_g$$

$$R_x = \frac{V - I_g R_g}{I_g}$$

$$R_x = \frac{V}{I_g} - \frac{I_g R_g}{I_g}$$

$$R_x = \frac{V}{I_g} - R_g$$

This equation can be used to determine the value of R_X.

Section (A): Multiple Choice Questions (MCQs)

Choose the correct answer:

1. If were verse the direction of electric current, then the direction of magnetic field will be:

(a) Same (b) reversed (c) tangent (d) normal

2. The application of magnetic field is:

(a) microwave oven (b) magnetic levitation trains

(c) electrolysis (d) plant photosynthesis

3. The equation F=BIL can only be used, if the magnetic field, length of conductor, and electric current are:

(a) At right angles to each other (b) in same direction

(c) Anti-parallel to each other (d) anti-perpendicular to each other

4. The charge on a particle is doubled, and its velocity remains the same, how then the magnetic force on the particle will be:

(a) doubled (b) halved (c) Is the same. (d) quadrupled

5. Strength of magnetic field of solenoid can be increased by:

(a) Increasing number of turns

(b) decreasing number of turns

(c) increasing the current through the solenoid

(d) inserting a ferromagnetic core (e.g., iron) into the solenoid

6. The magnetic field inside along solenoid is:

(a) equal to zero (b) uniform

(c) decreases as we go away from the center to surface

(d) increases as we go to wards the surface

7. The force between two current carrying conductor arises due to

(a) Magnetic effect of current (b) Polarization

(c) Electromagnetic induction (d) Electrostatic interaction

8. To measure a higher voltage, what should you do with the voltmeter's internal resistance?

(a) Increase it (b) Decrease it

(c) Keep it the same (d) It doesn't affect the measurement

9. A proton moves perpendicular to a uniform magnetic field. What is the direction of the force experienced by the proton?

(a) Parallel to the magnetic field
(b) In the direction of the proton's velocity
(c) Perpendicular to the magnetic field and the proton's velocity
(d) Opposite to the direction of the proton's velocity

10. An electron moves parallel to a uniform magnetic field. What is the magnitude of the force experienced by the electron?

(a) Maximum, since the electron is moving in the same direction as the field

(b) Minimum, since the electron is moving perpendicular to the field

(c) Zero, since the electron is moving parallel to the field

(d) Depends on the speed of the electron

Section (B): CRQs (Short Answered Questions):

1. Charge particles are fired in vacuum tube hit a fluorescence screen. Will it be possible to know whether they positive or negative?

Yes, it is possible to determine whether the charged particles fired in a vacuum tube are positive or negative based on their deflection in a magnetic field. If a magnetic field is applied perpendicular to the path of the particles, positive and negative charges will be deflected in opposite directions. This phenomenon is known as the **Lorentz force**.

2. What is a solenoid, and how does it differ from a simple coil of wire?

A **solenoid** is a coil of wire wound into a tight helix. It differs from a simple coil in that the turns are closely packed together and often have a cylindrical shape. This configuration creates a uniform magnetic field inside the solenoid.

3. Can a solenoid generate a magnetic field without any current flowing through it? Why or why not?

No, a solenoid cannot generate a magnetic field without any current flowing through it. The magnetic field is produced by the movement of electric charges, which in this case is the current flowing through the wire.

4. Explain why a toroid is often preferred over a straight solenoid when designing certain types of electrical components.

A **toroid** is a solenoid that has been bent into a circular shape to form a donut-like structure. It is often preferred over a straight solenoid in certain applications because:

- **Confined Magnetic Field:** The magnetic field produced by a toroid is confined within the toroidal core, minimizing external interference and reducing magnetic field leakage.
- **Uniform Field:** The magnetic field inside a toroid is more uniform than that of a straight solenoid, especially near the ends.

- **Reduced Inductance:** Toroids generally have lower inductance compared to straight solenoids, which can be beneficial in some circuits.

5. What role does the Ampere's circuital law play in understanding them agnetic field inside a toroid?

Ampère's circuital law is a fundamental law of electromagnetism that relates the magnetic field around a closed loop to the electric current passing through the loop.

In the case of a toroid, Ampère's law can be used to calculate the magnetic field inside the toroid. By choosing an appropriate Amperian loop that encloses the toroid's core, we can determine the magnetic field strength at any point within the toroid.

6. What is a galvanometer, and what is its primary function in an electrical circuit?

A **galvanometer** is an electromechanical instrument used to measure electric current. It consists of a coil of wire suspended between the poles of a permanent magnet. When a current flows through the coil, it experiences a torque due to the interaction

with the magnetic field, causing the coil to rotate. The deflection of the coil can be used to indicate the magnitude and direction of the current.

Section (C) ERQS (Long Answered Questions):

1. Can a galvanometer measure both DC and AC currents? Explain any limitations it might have with AC measurements.

Notes

2. Why should an ammeter ideally have a very low resistance compared to the circuit it is measuring?

Notes

3. What is the potential risk of using a voltmeter with a high internal resistance in a circuit? How can this risk be mitigated?

Notes

4. Describe the basic working principle of a voltmeter. How does it measure voltage across a component in a circuit?

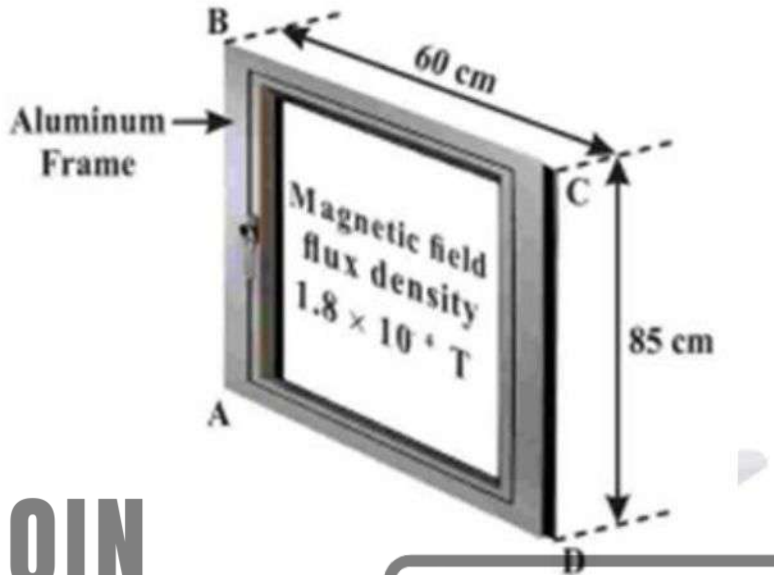
Notes

Section (D): Numerical:

1. An aluminum window has a width of 60 cm and length of 85 cm as shown in the figure

a. When the window is closed the magnetic flux density is 1.8×10^{-4} A Tisnormal to window.

b. Calculate the magnetic flux through the window. (9.18×10^{-5}Wb)



2. The poles of a horse shoe magnet measures 8cm x 3.2cm.the magnetic flux density between the magnet poles is 80mT. Outside of the magnet the magnetic flux density is zero. Calculate the magnetic flux density between the poles of a magnet.(2.048×10^{-4} Wb)

3. A wire 1.80 m long carries a current of 13.0 A and makes an angle of 35.0° with a uniform magnetic field of magnitude B = 1.50T. Calculate the magnetic force on the wire. (19.46 N)

4. A solenoid has length L= 1.23 m and inner diameter d = 3.55 cm, and it carries a current I= 5.57 A. It consists of five close-packed layers, each with 850 turns along length L. What is B at its center? (Ans:24.2 mT)

5. A moving coil galvanometer has resistance of 50 Ω and it gives full scale deflection at 4mA current. A voltmeter is made using this galvanometer and a 5Kohms resistance. Calculate the maximum voltage that can be measured using this voltmeter. (Ans:20.2V)

6. Compute the magnitude of the magnetic field of a long, straight wire carrying a current of 1A at distance of 1m from it. Compare it with Earth's magnetic field. (Ans:2×10^{-7} and 100times than earth field)

7. Find the current in a long straight wire that would produce a magnetic field twice the strength of the Earth's at a distance of 5.0cm from the wire. (Magnetic field of Earth =5.0×10^{-5} T). (Ans:25A).

8. What is flux density at a distance of 0.1m in air from along straight conductor carrying a current of 6.5 A. calculate the force per on a similar parallel conductor at a distance of 0.1m from the first and carrying a current of 3A. (Ans: 13×10^{-6} Weber/m^2, 39×10^{-6}N).

Unit 19

Electromagnetic Induction

Induced Electromotive force EMF

Induced electromotive force (emf) can be generated in two primary ways: by relative movement and by changing a magnetic field.

(i) By Relative Movement (The Generator Effect):

This method is based on Faraday's Law of Electromagnetic Induction, which states that an emf is induced in a conductor when it experiences a change in magnetic flux. The generator effect, also known as motional emf, occurs when there is a relative motion between a conductor and a magnetic field.

Example:

In a simple electrical generator, a coil of wire rotates within a magnetic field. This induced emf drives an electric current through an external circuit.

(ii) By Changing a Magnetic Field (The Transformer Effect):

This method also relies on Faraday's Law but involves changing the strength or orientation of a magnetic field around a stationary conductor.

Example:

In a transformer, an alternating current in the primary coil creates a changing magnetic field. This is the basis for how transformers transfer electrical energy between circuits at different voltages.

Generator Effect:

Induced emf due to relative motion between a conductor and a magnetic field.

Transformer Effect:

Induced emf due to a changing magnetic field around a stationary conductor.

Both effects are fundamental principles in electromagnetism and are widely utilized in various electrical devices and systems.

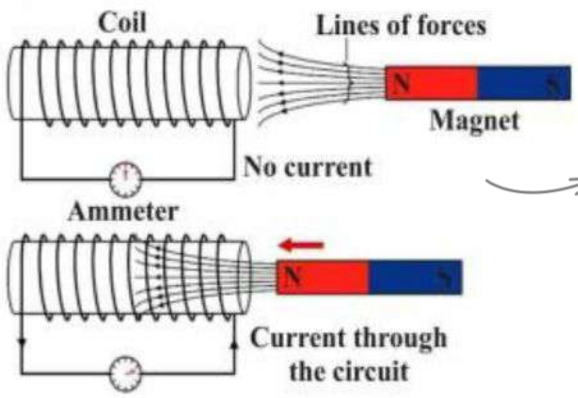
Faraday's law of electromagnetic induction:

It can be stated as follows:

The electromotive force (emf) induced in a closed circuit is directly proportional to the rate of change of magnetic flux passing through the circuit.

Mathematically, Faraday's law is often expressed as:

$$\xi = \frac{N\Delta\phi}{\Delta t}$$



Where ξ represents the induced electromotive force (emf) measured in volts (V).

$\frac{\Delta\phi}{\Delta t}$ At Represents the rate of change of magnetic flux with respect to time, it is measured in weber per second (Wb/s V), and N indicates number of turns of the coil: Negative sign is introduced because the induced emf opposes the change in flux. It will be explained in Lenz's law.

Factors affecting the magnitude of the induced emf:

The factors include

1. Magnetic Flux Change
2. Number of Turns in the Coil
3. Area of the Coil
4. Angle between Magnetic Field and Coil
5. External Factors

Lenz's law and principle of conservation of energy:

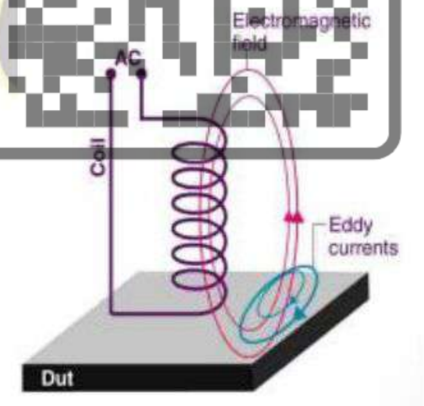
After the introduction of Faraday's law of electromagnetic induction, Heinrich Friedrich Lenz formulated a rule for determining the direction of an induced current within a loop.

According to Lenz's law

"The direction of induced emf in a circuit is always such that it opposes the cause which produces it"

Lenz's law and Conservation of Energy:

When we apply this principle to electromagnetic induction, we see that the work done in changing the magnetic field is converted into electrical energy the form of the induced current. Hence lenz's law is in accordance with the law of conservation of energy.



Eddy currents and their magnetic and heating effects:

Eddy currents are circulating currents induced in a conductor when it is exposed to a changing magnetic field. They are a common phenomenon in electromagnetic systems. These currents can have both magnetic and heating effects. Now let's discuss about the production of eddy currents and their effects:

Production of Eddy Currents:

Eddy currents are produced according to Faraday's law of electromagnetic induction, which state that a changing magnetic field induces an electromotive force (emf) in a conductor. When a conductor, such as a metal plate or a coil of wire, is subjected to a changing magnetic field, the magnetic flux through the conductor changes, leading to the induction of eddy currents. As shown in figure.

Magnetic Effects of Eddy Currents:

Counteracting Magnetic Field:

Eddy currents generate their own magnetic fields, and the direction of these fields opposes the original magnetic field that induced them as a result, eddy currents create a magnetic field that counteracts the original magnetic field's change, thereby reducing the net magnetic field.

Magnetic Damping:

In applications like electromagnetic brakes and magnetic dampers, eddy currents are intentionally induced to create a magnetic resistance that opposes motion. This magnetic damping effect is useful for controlling the movement of objects and slowing them down.

Heating Effects of Eddy Currents:

Joule Heating:

Eddy currents experience resistance as they flow through the conductor, and this resistance results in the conversion of electrical energy into heat, following Joule's law. Eddy currents can heat up the conductor. In some cases, such as induction heating for metal processing or cookware, this heating effect is used for practical applications.

Reduction of Eddy Currents:

In many electrical systems, eddy currents represent an undesirable source of energy loss, especially in transformers and electric motors. To minimize these losses, laminated cores are used in transformers to break up the conducting paths and reduce the formation of eddy currents.

Enhanced Efficiency:

By reducing the losses associated with eddy currents, laminated cores improve the overall efficiency of electric motors, generators, and transformers. Less energy is wasted as heat, allowing these devices to operate more efficiently and with less energy consumption.

Mitigation of Vibration and Noise:

Eddy currents generated in a solid iron core can lead to vibrations and noise, which can be undesirable in many applications. Laminated cores help reduce these vibrations and noise levels, making the devices quieter and more mechanically stable.

Better Cooling and Thermal Management:

Since laminated cores result in reduced heat generation due to decreased eddy current losses, they often allow for more efficient cooling and thermal management in these devices.

This can lead to longer operational lifetimes and improved reliability.

Self Induction:

When an electric current pass through a coil, it creates a magnetic field around it. If the current in the coil changes, either increasing or decreasing, the magnetic flux within the coil also changes accordingly. As a result of the change in magnetic flux, an induced emf is generated in the same coil. This process, where a changing current in the coil induces an emf in the coil itself, is known as self-induction.

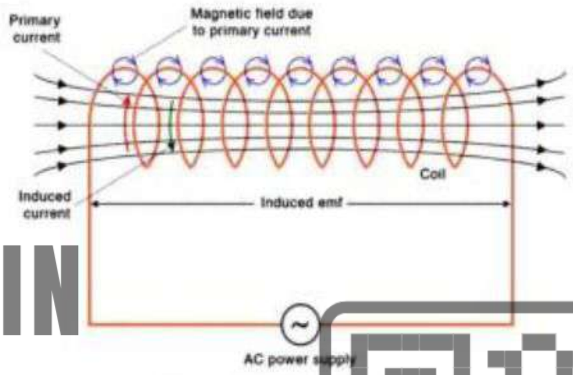


Figure 19.6 Self Inductions

Consider the circuit shown in Figure. which comprises a coil connected in series with a battery and a rheostat. When the rheostat is adjusted, it changes the current flowing through the circuit, leading to changes in the magnetic flux within the coil.

These variations in magnetic flux result in the induction of an electromotive force (emf) within the coil.

If we denote the magnetic flux through a single loop of the coil as ϕ, then the total magnetic flux passing through the N turns of the coil would be $N\phi$. This relationship holds true because the magnetic flux, directly proportional to the magnetic field, which, in turn, is proportionate to the current (I) flowing through the circuit

$$N\phi \propto I$$

$$N\phi = LI \qquad \text{---- 1}$$

Where $L = \frac{N\phi}{I}$ is constant of proportionality called the self inductance of coil. It depends on factors such as the coil's number of turns, its cross-sectional area, and the material used for the core. Hence inductance of coil made up of soft iron is greater than the air core coil.

By the Faradays law of electromagnetic induction

$$\xi = -N\frac{\Delta\phi}{\Delta t} \qquad \text{---- 2}$$

Substitute equation (1) in Equation (2), we get

$$\xi = -L\frac{\Delta I}{\Delta t}$$

Above equation (19.4) shows that the self-induced electromotive force (emf) within a coil is directly proportional to the rate of change of current within the coil.

Unit of Inductance:

The unit of self-inductance is the Henry (H), named after the American physicist Joseph Henry.

One Henry (1 H) is defined as the amount of self-inductance in a circuit when a change in current of 1 ampere per second (1 A/s) induces an electromotive force (emf) of 1 volt (1 V) within the same circuit. Mathematically, this relationship can be expressed as:

$$1\text{ Henry} = \frac{1\,Volt}{1\text{ Ampere per Second}}$$

Energy Stored in an Inductor:

An inductor is a passive electrical component that stores energy in the form of a magnetic field when an electric current flow through it.

The ability of an inductor to store electric potential energy is based on the fundamental principle of electromagnetic induction.

Here's a simple explanation of how an inductor stores electric potential energy:

Current Flow:

When an electric current flow through a coil of wire (the inductor), it creates a magnetic field around the coil.

Magnetic Field Buildup:

As the current increases, the strength of the magnetic field around the coil also increases. This process takes a short amount of time, as the magnetic field does not build up instantly; it grows with the rate of change of the current.

Energy Storage:

The energy is stored in the magnetic field. The inductor stores electric potential energy in this magnetic field. The more current that flows through the inductor or the faster the current changes, the stronger the magnetic field, and thus, the more energy is stored.

Magnetic Field Collapse:

When the current decreases or stops (like when you turn off the power), the magnetic field starts to collapse. As it collapses, it induces an electromotive force (EMF) or voltage in the coil.

Released Energy:

This induced voltage represents the stored energy being released. The inductor converts the stored magnetic energy back into electric energy. This energy can be used to sustain the current for a short period or can be transferred to other parts of the circuit.

Energy produced in Self Induction:

An inductor stores energy in its magnetic field when it carries a direct current (DC).

This energy remains stored as long as the inductor continues to carry the current. When the current in the inductor increases, the stored energy also increases, and conversely, it decreases when the current is reduced.

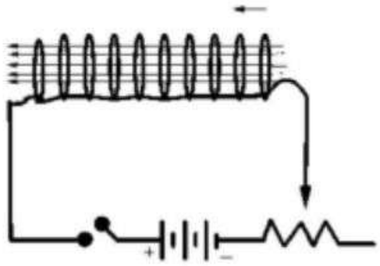


Figure 19.7 Energy produced in Self Induction

Consider an inductor connected to a DC power source through a switch, as depicted in Figure. When the switch is closed, the current in the inductor gradually rises until it reaches its maximum value, denoted as I. This changing current leads to a corresponding change in the magnetic flux within the coil, causing an induced electromotive force (emf) to establish itself in the coil. Consequently, an induced current is generated in the circuit, which works to minimize the current produced by the battery in accordance with Lenz's law.

As a result, the battery must perform work on the charges to build up the current I. This work is mathematically expressed as follows:

$$W = \Delta V \Delta q$$

As the induced emf is produced in the inductor so $\Delta V = \xi_L = L\frac{\Delta I}{\Delta t}$ and using work energy relation above equation can be written as

$$E = \frac{\Delta q}{\Delta t} L \Delta I$$

On solving we get

Since,

$$E = \frac{1}{2} L I^2$$

Where:

E is the energy stored in joules (J).

Lis the self-inductance of the inductor in Henries (H).

I is the current flowing through the inductor in amperes (A).

Mutual Inductance:

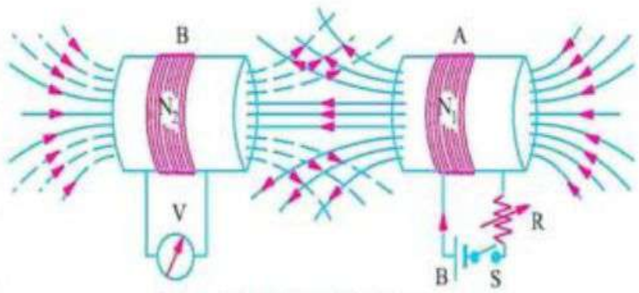


Figure 19.8 Mutual Inductance

"A phenomenon where a changing current in one coil induces an electromotive force (EMF) in another coil is known as mutual induction".

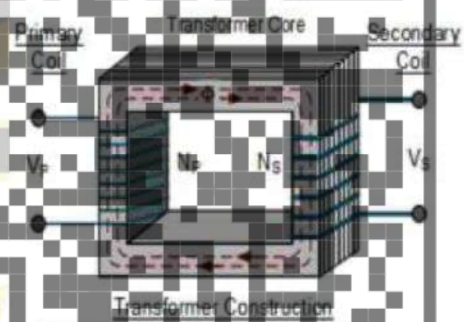
$$M = -\frac{\xi_s}{\left(\frac{I_p}{\Delta t}\right)}$$

Transformer:

A transformer is an electrical device used to transfer electrical energy between two or more coils of wire through electromagnetic induction.

Construction of a Transformer:

The transformer consists of following main components as shown in figure



Core:

Transformers consist of two coils of wire, known as the primary coil and the secondary coil, wound around a common magnetic core.

The core is typically made of materials with high magnetic permeability, such as laminated iron or ferrite, to enhance the efficiency of the transformer.

Primary Coil:

Transformer Construction The primary coil is connected to the input voltage V_p source. It consists of a specific number of turns of wire wound around one section of the core denoted as N_p.

Secondary Coil:

The secondary coil is connected to the load or the device that needs the transformed voltage. It has a different number of turns of wire wound around another section of the core denoted by N_s.

Insulation:

Both the primary and secondary coils are insulated from each other to prevent electrical contact and ensure electrical isolation.

Working of a Transformer:

Imagine we have an alternating electromotive force (emf) applied to the primary coil. If, at a certain moment (t), the magnetic flux within the primary coil is changing at a rate of $\frac{\Delta\varnothing}{\Delta t}$ this change in flux will induce a counteracting electromotive force (emf) in the primary coil, opposing the applied voltage. We can express the instantaneous value of this self-induced emf as follows:

$$\text{Self-induced emf} = -N_p \frac{\Delta\varnothing}{\Delta t}$$

If the coil's resistance can be considered negligible, then the opposing emf in the primary coil is equal in magnitude but opposite in direction to the applied voltage. This relationship can be represented as:

$$V_p = -N_p \frac{\Delta\varnothing}{\Delta t} \quad \text{---- 1}$$

Here, N_p represents the number of turns in the primary coil.

Now, let's assume that the flux passing through the primary coil also flows through the secondary coil. In other words, these two coils are magnetically linked. Hence, the rate of change of magnetic flux in the secondary coil will also be $\frac{\Delta\varnothing}{\Delta t}$ and the magnitude of the induced emf across the secondary coil can be expressed as:

$$V_s = -N_s \frac{\Delta\varnothing}{\Delta t} \quad \text{-----2}$$

Where N_s is number of turns in secondary

When we divide equation (1) by equation (2), we obtain

$$\frac{V_s}{V_p} = \frac{N_s}{N_p}$$

Step-Up or Step-Down Transformers:

The ratio of the number of turns in the primary coil (N_p) to the number of turns in the secondary coil (N_s) determines whether the transformer is a step-up or step-down transformer.

If $N_s > N_p$ than it's a step-up transformer and it increases the voltage.

Conversely, if $N_p > N_s$ it is a step-down transformer and it decreases the voltage.

Step up transformer:

Step-up transformers are designed to increase the voltage of electricity.

They have more turns in the secondary coil than in the primary coil, resulting in a higher secondary voltage compared to the primary voltage.

- Reduced Current
- Efficient Long-Distance Transmission

Step-Down Transformers:

- Voltage Reduction
- Balanced Current

Transmission of Electricity:

Step-down and step-up transformers are used for the electric supply from power station to houses and electric appliances. Here's how they are used in the electric supply process a shown in figure

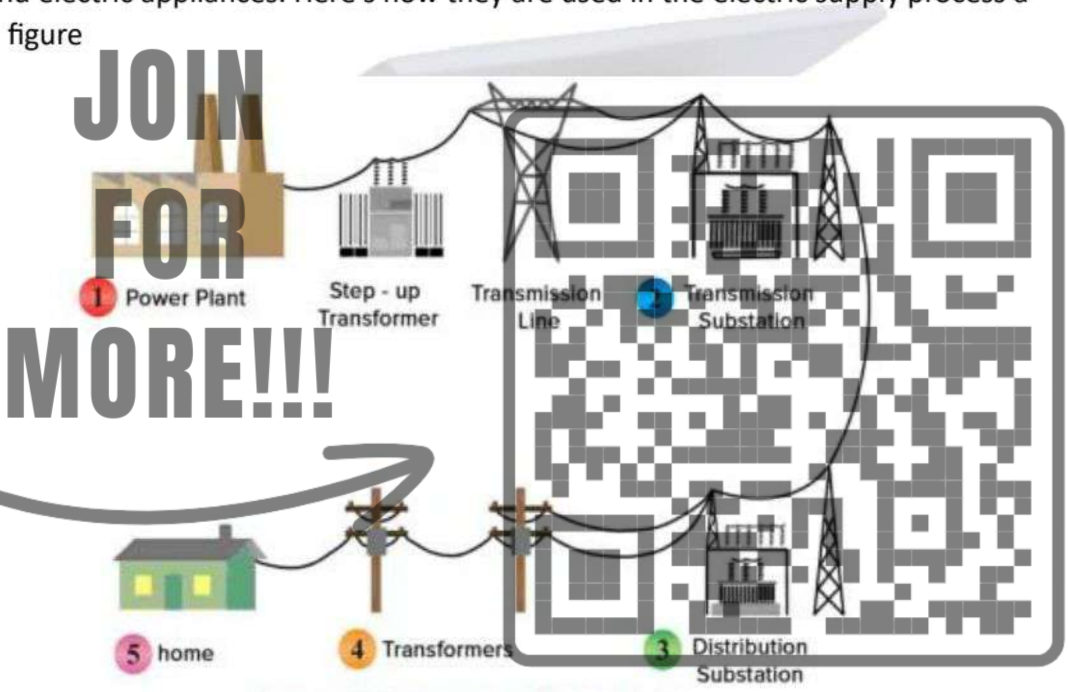


Figure 19.10 Transmission of Electricity

1. Power Generation at the Station:

Electricity is generated at power stations, often using generators powered by various sources

2. Step-Up Transformers at the Power Station:

To raise the voltage to levels suitable for long-distance transmission, step-up transformers are employed at the power station.

3. Transmission and Substations:

The high-voltage electricity is transmitted over transmission lines to substations located at various points in the electricity distribution network.

4. Step-Down Transformers in Substations:

Step-down transformers reduce the high-voltage electricity to lower, safer voltage levels, suitable for local distribution. This lower voltage is then distributed to houses through distribution lines.

Motional emf:

Motional electromotive force (emf) is a phenomenon that arises when a conductor moves through a magnetic field, inducing an electromotive force within the conductor.

This concept is based on Faraday's law of electromagnetic induction and is a fundamental aspect of electromagnetism.

AC Generator

An AC generator, also known as an alternator, is a device that converts mechanical energy into electrical energy in the form of alternating current (AC). It's based on the principle of electromagnetic induction, which was first described by Michael Faraday.

Construction of an AC Generator:

An AC generator typically consists of the following four components as shown in figure

(i) Armature

(ii) Slip-rings

(ii) Field magnet

(iv) Brushes

Figure 19.12 AC generator

Armature:

The armature or rotor is a rectangular coil mounted on a rotating shaft. It is the component that spins within a magnetic field to induce electrical current.

Permanent magnet:

The permanent magnet or stator is a stationary part of the generator that produces a magnetic field. It is typically made up of a set of magnets or electromagnets arranged in a circular or cylindrical configuration around the rotor.

Slip Rings and Brushes:

The ends of the rotor coil are connected to slip rings, which are conductive rings that rotate with the rotor. Brushes, typically made of graphite, press against the slip rings to collect the generated electrical current.

Shaft and Bearings:

The rotor is mounted on a shaft that allows it to rotate freely. Bearings are used to reduce friction and enable smooth rotation.

Working of an AC Generator:

The working of an AC generator involves several steps:

Rotation of the Armature coil:

The coil or rotor is mechanically rotated using an external source of power, such as an engine, a turbine, or any other energy source.

Generation of a Changing Magnetic Field:

As the rotor spins within the stator's magnetic field, the magnetic field within the rotor coil changes. This changing magnetic field induces an electromotive force (emf) or voltage in the coil,

Generation of Alternating Current:

The induced voltage causes an electric current to flow through the coil, and since the magnetic field's direction is changing, the current produced is alternating in nature. This means the direction of the current constantly switches back and forth, resulting in an AC output.

Collection of Output:

The alternating current generated in the rotor coil is collected using slip rings and brushes. The brushes maintain contact with the slip rings as they rotate, allowing the generated AC to be drawn from the generator.

Induced EMF of an AC generator:

Suppose the armature coil AHCD rotates counterclockwise. As it rotates, the magnetic flux linked with it changes, inducing a current in the coil as shown in figure (a,b). The direction of the induced current follows Fleming's right-hand rule.

When the armature in the vertical position and rotates counterclockwise, wire AH moves downward, while DC moves upward. This causes the induced electromotive force (emf) to flow from H to A and from D to C, within the coil, forming a current path of DCHA.

In the external circuit, the current flows along BRB2. This current direction remains consistent during the first half-turn of the armature.

However, during the second half-revolution, wire AH moves upward, and wires CD move downward, leading to a reversal in the direction of induced current within the coil to AHCD. In the external circuit, the direction changes to B_2RB_1. Therefore, the direction of the induced emf and the current alternates after every half revolution in the external circuit as well. Consequently, the current produced switches direction in each cycle.

When the coil is rotated, a motional electromotive force (emf) is generated in each of its sides, but these emfs have opposite directions because the two sides are moving in opposite directions relative to the magnetic field. However, the other two sides of the coil are moving in the same direction with respect to the field.

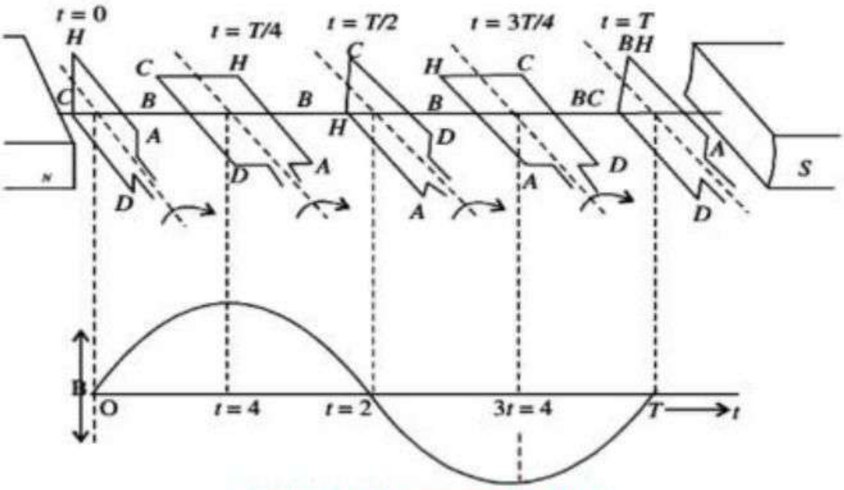


Figure 19.13(a) armature coil AHCD

Consequently, emfs are induced in these sides in the same direction, leading to a mutual cancellation effect. As a result, the total emf induced in the coil is given by

ε= 2vBNISinωt

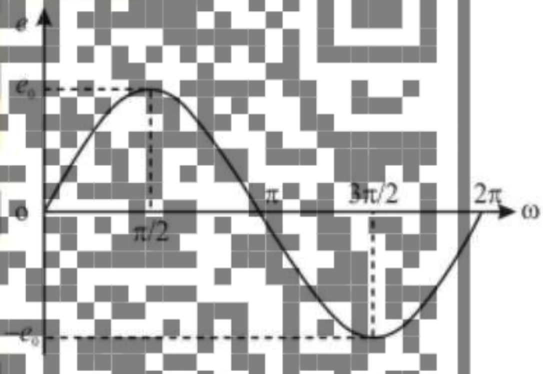


Figure 19.13(b) armature coil AHCD

Where

v = linear velocity,

B = magnetic field,

N = Number of turns,

L = length of coil

and ω = angular velocity.

Since each particle of the sides AH and CD rotates in a circle of radius equal to the width of the coil b.

$$v = b/2\ \omega$$

$$\varepsilon = 2\ b/2\ \omega\ B\ \sin\omega t$$

$$\varepsilon = ANB\ \omega\ \sin\omega t$$

Where ε_o =ANBω is the maximum or peak value of the emf which depends on the area and number of the coil, intensity of the field and speed of rotation.

In terms of the frequency "f" i.e number of turns per second.

$$\varepsilon = \varepsilon_o\ \text{Sin}2\pi ft$$

A.C Motor:

An AC (Alternating Current) motor is a device designed to convert electrical energy into mechanical energy by using alternating current. There are various types of AC motors, but the main features and components are generally consistent across different designs. The primary components as shown in figure and their roles in an AC motor are as follows:

Stator:

The stator is the stationary part of the motor and contains the primary windings. Its main role is to produce a rotating magnetic field when AC voltage is applied. The rotating magnetic field interacts with the rotor to induce motion.

Rotor:

The rotor is the rotating part of the motor. It can be of different types, such as squirrel- cage or wound rotor, depending on the motor design. When the stator produces a rotating magnetic field, the rotor experiences a torque due to the interaction with the field. This torque causes the rotor to rotate and generate mechanical output.

Bearings:

Bearings are essential components that support and allow the rotor to rotate within the stator. They reduce friction, enabling smooth and efficient operation of the motor.

Shaft:

The shaft is connected to the rotor and extends beyond the motor housing. It transfers mechanical energy to the outside world, allowing the motor to perform useful work when connected to a load.

Cooling System:

Many AC motors incorporate cooling systems, such as fans or fins, to dissipate heat generated during operation. Efficient cooling is important to prevent overheating and prolong the motor's lifespan.

The main features and components work together to enable the AC motor to function. When AC voltage is applied to the stator windings, a rotating magnetic field is created, which exerts a torque on the rotor. The rotor's rotation results in mechanical work being performed by the motor, and the motor can be used to drive various mechanical devices, such as fans, pumps, conveyor belts, and more.

The efficiency and performance of an AC motor depend on the design and quality of its components, the load it drives, and its operating conditions. Proper maintenance and control mechanisms, such as speed control, are often used to optimize the motor's performance in different applications.

EXERCISE

Section (A): Multiple Choice Questions (MCQs)

Choose the correct answer:

1. Electricity production by magnetism involves

(a) the conversion of chemical energy to electrical energy.

(b) the use of static electricity for power generation.

(c) the movement of conductors within magnetic fields.

(d) the absorption of solar energy by photovoltaic cells.

2. Induced e.m.f can be generated by relative movement, known as the generator effect, and by changing magnetic fields, known as the transformer effect.

(a) True in transformers only.

(b) False in all cases.

(c) Applicable to both cases.

(d) True only for static magnetic fields.

3. The magnitude of induced e.m.f. increases with

(a) the decrease in the speed of the conductor's motion.

(b) the decrease in the strength of the magnetic field.

(c) the increase in the number of turns in the coil.

(d) the reduction in the area of the coil.

4. Faraday's law of electromagnetic induction states

(a) that current in a circuit always opposes the change in magnetic flux.

(b) that the induced e.m.f. is directly proportional to the rate of change of magnetic flux.

(c) that a changing electric field produces a magnetic field.

(d) that magnetic fields can only be produced by electric currents.

5. Lenz's law predicts the direction of an induced current

(a) to conserve electric charge.

(b) by stating that the induced current will oppose the change causing it.

(c) by following the direction of the applied magnetic field.

(d) based on the magnitude of the electric field.

6. Eddy currents produce:

(a) static electricity in conductive materials.

(b) alternating magnetic fields with no heating effects.

(c) magnetic fields that oppose the inducing field and cause heating in conductors.

(d) uniform electric fields that have no impact on power generation.

7. Laminated iron cores are used in electric motors and transformers to

(a) reduce the weight of the device.

(b) enhance the mechanical strength.

(c) minimize eddy current losses and reduce heating.

(d) increase the magnetic permeability of the core.

8. Self-induction is the phenomenon where

(a) a changing electric field induces a magnetic field.

(b) a changing magnetic field within a coil induces an emf in the same coil.

(c) a constant magnetic field induces a constant emf.

(d) two coils induce emf in each other through mutual induction.

9. An inductor stores electric potential energy in:

(a) the electric field around it.

(b) the magnetic field within its coil.

(c) the capacitance of its windings.

(d) the heat generated by its resistance.

10. Transformers work on the principle of

(a) converting direct current (DC) to alternating current (AC).

(b) electromagnetic induction between primary and secondary coils.

(c) generating electricity through chemical reactions.

(d) using permanent magnets to maintain a constant voltage.

Section (B): CRQS (Short Answered Questions):

1. Explain Faraday's law of electromagnetic induction.

Faraday's law states that when a magnetic field changes through a surface, it induces an electromotive force (EMF) in the loop bounding that surface. In simpler terms, a changing magnetic field can create an electric current in a conductor.

2. State Lenz's law and discuss its significance in the context of electromagnetic induction.

Lenz's Law

Lenz's law states that the direction of the induced current in a conductor is such as to oppose the change in magnetic flux that produced it. This means that the induced current will create a magnetic field that opposes the change in the original magnetic field.

Significance: Lenz's law is crucial in understanding the direction of the induced current and the resulting magnetic field. It ensures that the induced current always acts to counteract the change that caused it, maintaining a balance in the system.

3. How does a step-up transformer differ from a step-down transformer?

Step-Up vs. Step-Down Transformers

- **Step-up transformer:** A step-up transformer increases the voltage of an alternating current (AC) while reducing the current. This is achieved by having a larger number of turns in the secondary coil than in the primary coil.
- **Step-down transformer:** A step-down transformer decreases the voltage of an AC while increasing the current. This is achieved by having a smaller number of turns in the secondary coil than in the primary coil.

4. Describe the principle of operation of an AC generator.

Principle of Operation of an AC Generator

An AC generator, also known as an alternator, operates based on the principle of electromagnetic induction. It consists of a rotating coil placed within a stationary magnetic field. As the coil rotates, the magnetic flux through it changes, inducing an EMF in the coil. This EMF generates an alternating current.

5. Define self-induction and explain how it occurs in a coil.

Self-Induction

Self-induction occurs when a changing current in a coil induces an EMF in the same coil. This happens because the changing current creates a changing magnetic field, which in turn induces an EMF in the coil itself. The magnitude of the induced EMF depends on the rate of change of the current and the inductance of the coil.

6. Define mutual induction and provide an example of a system exhibiting mutual induction.

Mutual induction occurs when a change in current in one coil induces an EMF in a nearby coil. This phenomenon is due to the magnetic field produced by the changing current in one coil interacting with the other coil.

Example: A transformer is a common example of mutual induction. It consists of two coils wound around a common iron core. When an alternating current flows through the primary coil, it produces a changing magnetic field. This changing magnetic field induces an EMF in the secondary coil, which can be used to step up or step down the voltage.

7. How does the arrangement of coils influence the degree of mutual induction between them?

Arrangement of Coils and Mutual Induction

The arrangement of coils can significantly influence the degree of mutual induction between them. Some factors that affect mutual induction include:

- **Proximity:** Coils that are closer together have a higher degree of mutual induction due to the stronger magnetic field coupling.
- **Orientation:** The relative orientation of the coils can also affect mutual induction. If the coils are aligned parallel to each other, the mutual induction is generally higher than if they are perpendicular.
- **Core Material:** The material used for the core of the coils can influence mutual induction. Iron cores can enhance mutual induction compared to air cores.

8. Define motional electromotive force (emf)

Motional EMF is the EMF induced in a conductor moving through a magnetic field. It occurs due to the interaction between the magnetic field and the charges within the conductor. The magnitude of the motional EMF depends on the velocity of the conductor, the strength of the magnetic field, and the length of the conductor within the field.

9. Differentiate between motional emf and electromagnetic induction in terms of their fundamental principles.

Motional EMF: This is induced due to the motion of a conductor in a magnetic field. The key factor is the relative motion between the conductor and the magnetic field.

Electromagnetic Induction: This is induced due to a changing magnetic field through a stationary conductor. The key factor is the change in magnetic flux through the conductor.

10. Differentiate between AC (alternating current) and DC (direct current) in the context of long-distance power transmission.

- **AC (Alternating Current):** AC is preferred for long-distance power transmission due to its ability to be easily stepped up or stepped down using transformers. This allows for efficient transmission of power over long distances at high voltages, reducing power losses.

- **DC (Direct Current):** DC was once used for long-distance transmission, but it has several drawbacks. DC transmission requires more complex and expensive equipment, and it is difficult to step up or step down the voltage efficiently. Additionally, DC transmission can cause problems with ground currents and electromagnetic interference.

Section (C): ERQs (Long Answered Questions):

1. How does the strength of the magnetic field affect the induced electromotive force (emf) in a coil according to Faraday's law? b. Explain the relationship between the magnetic field strength and the magnitude of the induced emf.

Notes

2. In Faraday's law, why is the area of the coil an important factor in determining the induced emf?

Notes

3. How does changing the orientation of a coil with respect the magnetic field influence the induced emf? Also describe the role of the number of turns in a coil in the context of induced emf. How does increasing the number of turns in a coil affect the induced emf, and why?

Notes

4. According to Faraday's law, why is the rate of change of magnetic flux crucial for inducing emf? Discuss how the speed of motion or change in magnetic field influences the induced emf.

Notes

5. How does the resistance of the conductor impact the flow of induced current in a circuit? In what situations might the resistance of the conductor become a significant factor in induced emf?

Notes

6. Explain the relationship between the frequency of the changing magnetic field and the induced emf. How does the frequency of the AC source affect the generation of induced emf in a coil?

Notes

7. Discuss how the material properties of a coil, such as its conductivity, can influence induced emf. In what ways might the type of material used in a coil affect its response to changing magnetic fields?

Notes

8. Why is the presence of a core material significant in transformers concerning induced emf? Explain how the type and properties of the core material can impact the efficiency of a transformer.

Notes

9. Why are slip rings used in AC generators, and how do they differ from commutator used in DC generators.

Notes

10. Why a commutator is necessary in DC motors, and how does it facilitate the continuous rotation of the motor?

Notes

11. What are the common applications of DC motors in everyday devices?

Notes

Section (D) Numerical:

1. Two coils are placed adjacent to each other, and a change in current the first coil induces an emf of 0.5 V in the second coil. If the mutual inductance is 0.2 H, calculate the rate of change of current in the first coil. (2.5A/s)

2. A coil with an inductance of 0.5 H experiences a rate of change of current of 2 A/s. Calculate the induced EMF in the coil. (-1V)

3. Two coils are placed close to each other. If a change in current of 3 A/s in the first coil induces an EMF of 4V in the second coil, calculate the mutual inductance. (1.33H)

4. A transformer has 200 turns in the primary coil and 400 turns in the secondary coil. If the primary voltage is 120 V, calculate the secondary voltage fora step-up transformer. (240V)

5. An inductor with an inductance of 0.02H has a current flowing through it of 2 A. Calculate the energy stored in the inductor. (0.04J)

6. A coil stores energy in form of electric potential energy of0.2J when it carries a current of 2A. Calculate the inductance of coil. (0.1H)

7. An AC generator produces an alternating current with a maximum voltage of 240 V. If the frequency of the generated AC is 50 Hz, calculate the peak value of the voltage. (339V)

8. A transformer has 1000 turns in its primary coil and 200 turns in its secondary coil. If the primary voltage is 120 V, calculate the secondary voltage for a step-down transformer. (24V)

9. A conductor of length 0.4 m moves at a velocity of 5 m's perpendicular to a magnetic field of 0.3 T. Calculate the motional EMF induced in the conductor. (0.6V)

Unit 20

AC Circuits

Introduction:

Alternating current is the back bone of electrical engineering and physics. In addition, we will explore the dynamic nature of AC current, which is quite different when comparing with its counterpart, Direct Current (DC).

Cycle:

One complete set of both positive and negative values of an alternating quantity is known as a cycle.

Time Period (T):

The time period of an alternating current (AC) or voltage wave is the duration it takes to complete one full cycle.

Frequency (f):

It refers to the number of complete cycles of the current waveform that occur in one second.

Instantaneous Peak Value:

The instantaneous peak value refers the maximum amplitude of the alternating current or voltage at any specific point in time.

For a sine wave, this is the highest positive or negative value reached during a cycle. It is usually denoted as I_{peak} for current or V_{peak} for voltage.

Root Mean Square (rms) Value:

The average value of voltage or current is not used in electric power calculations. The reason being that the AC cycle consists of positive and negative half cycles so the average value is zero.

However, there exists a mathematical relation between the peak value Vo of alternating voltage and a direct current (d.c) voltage that yields an equivalent average electrical power. This constant d.c. voltage is referred to as the root-mean-square (r.m.s)

value of the alternating voltage V_{rms}- The d.c voltage is approximately 70% of V_{peak} as shown in figure.

For a sinusoidal wave, the rms value is approximately 0.707 times the peak value. Mathematically,

$V_{rms} = 0.707 \times V_{peak}$ for voltage

and $I_{rms} = 0.707 \times I_{peak}$ for current.

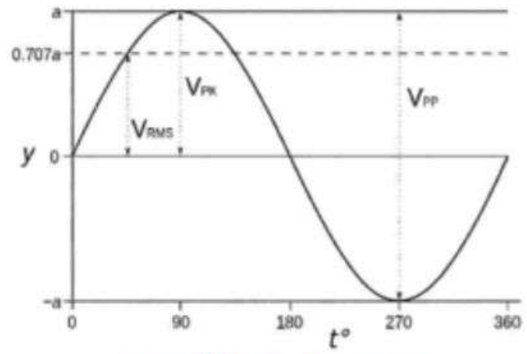


Figure 20.3 Cycle of ac current

Alternating Current OR voltage equation:

Alternating Current (AC) or Voltage refers the type of electrical flow or potential difference that periodically changes direction and magnitude over time.

The fundamental equation describing AC voltage or current in a sinusoidal waveform is:

$$V = V_o \sin\omega t$$

$$I = I_o \sin\omega t$$

Where,

V, I represent the instantaneous value of the voltage and alternating current respectively

V_o. $I_o$is the amplitude of the waveform, which represents the maximum value of alternating voltage and alternating current respectively

ω is the angular frequency, given by $w = 2\pi f$

Phase of AC:

The phase difference between two waves carries more important than their magnitudes. The phase describes the relative positions of these waveforms.

Hence in alternating current (A.C.) circuits, the concept of phase refers to the relationship between different waveforms as time passes.

Now we discuss different states of phase within AC circuit.

In-phase:

When two waveforms have the same frequency and reach their peak values or zero values \ the same time, they are said to be in phase

Phase Lag:

If one waveform reaches its peak or zero value after the other, there is a phase difference, and the second waveform is said to lag the first.

Phase Lead:

Conversely, if one waveform reaches its peak or zero value before the other, the second waveform is said to lead the first.

The representation of phase lead and lag between two alternating quantities is effectively demonstrated by showing the two AC quantities as vectors also known as "Phasor".

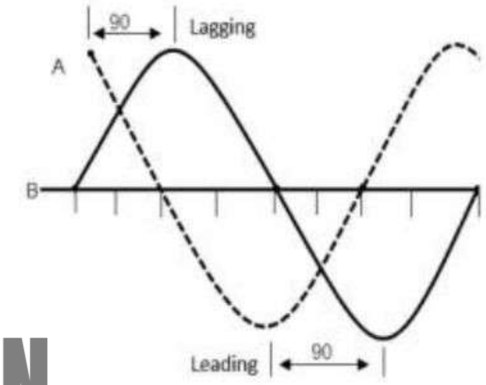


Figure 20.5
The two waves are 90° out of phase.

AC through a resistor

Consider a circuit comprising a pure resistor (R) connected to an alternating voltage source, as depicted.

The alternating voltage induces oscillatory motion of free electrons within the resistor, constituting the alternating current. At any given time 't,' the potential difference across the resistor's terminals is expressed

$$V = V_o \sin\omega t$$

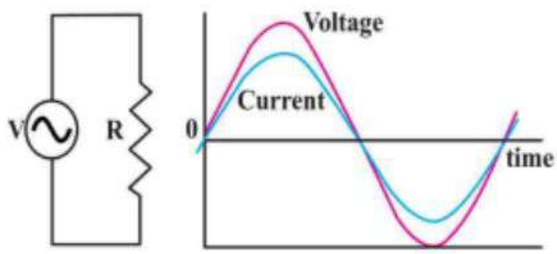
where Vo signifies the peak value of the alternating voltage. The circuit's current (I) is governed by Ohm's law:

$$I = \frac{V}{R} = \frac{Vo}{R} \sin\omega t$$

Or

$$I = I_o \sin\omega t$$

The current achieves its maximum value when $\sin\omega t = 1$.



Phasor diagram of Resistive circuit

The current I_R flowing through a resistor R is in phase with the voltage V_R across the resistor. This alignment can be visually represented on a phasor diagram by depicting a vector (I_R) that coincides with the voltage (V_R)

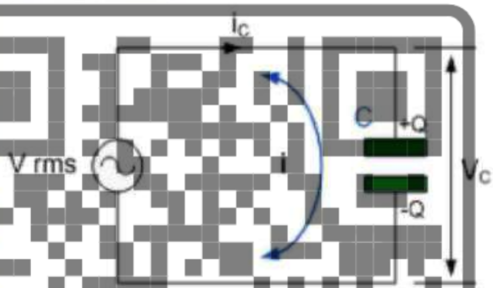
The power loss in a resistor in an AC circuit is a result of the conversion of electrical energy into heat due to the resistance of the resistor. The instantaneous power in the resistance is can be expressed using the formula

$$P=I^2R$$

$$P= V_{rms}I_{rms}$$

A.C through capacitors:

Now consider a capacitor connected to the AC source as shown in figure. During the positive half cycle of alternating voltage, the electrons flow from upper capacitor plate to the source leaving it as positively charged +Q and source supplies equal number of electrons to the lower plate making it as negatively charged -Q as shown in figure 20.9.



During the negative half cycle of alternating voltage, the direction of motion of electrons is also reverted resulting in the capacitor plates becoming charged in the opposite manner and current flows in opposite direction, hence capacitor charges and discharges. In this way the alternating current flows through the capacitor.

If alternating source voltage $V = V_o \sin\omega t$ is applied to the capacitor the charge on any plate of capacitor is given by

$$q= CV = CV_o \sin\omega t \qquad \text{---- 1}$$

From above equation it is clear that q and V are in phase. Due to the applied current flows through the capacitor as given by

$$I = \frac{\Delta q}{\Delta t} \qquad \text{---- 2}$$

Substitute equation (1) in (2), we get

$$I = \frac{CV_o \Delta \sin\omega t}{\Delta t}$$

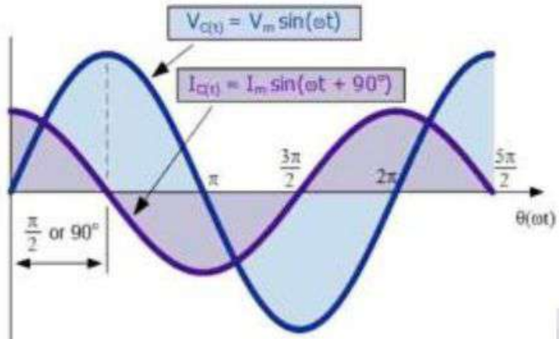
$$\text{OR} \qquad I = CV_o\,\omega \cos\omega t \qquad \text{---- 3}$$

Multiply and divide right side of equation (3) by ωc

$$I = \frac{V_o Sin\omega t}{\frac{1}{\omega c}}$$

$$I = I_o Sin(\omega t + \frac{\pi}{2}) \qquad \text{---- 4}$$

Equation (4) shows that in pure capacitive circuit the current exhibits sinusoidal variation and it leads the voltage by 90 degrees



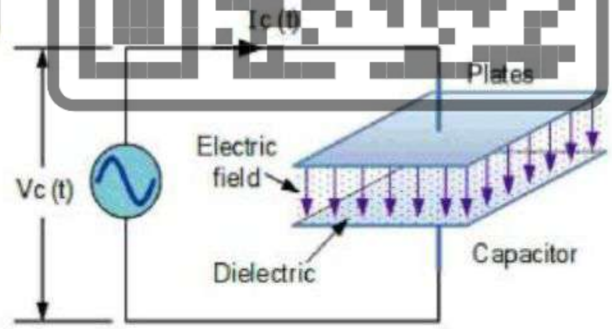
Reactance of Capacitor:

In a purely capacitive circuit, capacitive reactance represents the opposition to alternating current flow. Similar to resistance, reactance is measured in Ohms, but it is denoted by the symbol Xc to differentiate it from purely resistive values.

Since,

$$I = \frac{V_o}{\frac{1}{\omega c}}$$

Similar to ohms law the term in denominator of equation represents the opposition to flow of current; in this case it is called reactance of capacitor.



Hence,

$$Xc = \frac{1}{\omega c}$$

Since

$$Xc = \frac{1}{2\pi f c}$$

The capacitive reactance shows an inverse relationship with the frequency of the applied alternating voltage.

Consequently, for lower frequencies, the reactance of capacitor increases, while at high frequencies, the reactance decreases.

A.C through inductor:

An inductor is a passive electrical component which can be formed by wounding a conducting wire over an insulating object, such as pencil. The primary purpose of an inductor is to oppose changes in current. It resists the flow of alternating current (AC) and stores energy in its magnetic field during the on time of the AC cycle and releases it during the off-time. Solenoid is an example of inductor.

Consider an inductor in form of solenoid connected with A.C source

When the switch is closed current start to flow through the inductor, notice that the magnitude and direction of current is changing hence associated magnetic field also varies due to which an induced emf is set up in the inductor so as to oppose the change in accordance with the Lenz law. The magnitude of induced emf is given by

$$\varepsilon = L\frac{\Delta I}{\Delta t}$$

Therefore, to sustain the current, the applied voltage must match the back electromotive force (EMF). Thus, the magnitude of voltage supplied to the coil is expressed as

$$V = L\frac{\Delta I}{\Delta t}$$

The alternating voltage produces a sinusoidal current given by

$$I = I_o \sin\omega t$$

Hence above equation becomes

$$V = L\frac{I_o \sin\omega t}{\Delta t} \text{ Or } V = \omega L I_o \cos\omega t$$

Where $wLI_o = V_o$

$$V = V_o \cos\omega t$$

Using that $\cos\omega t = \sin(wt + \frac{\pi}{2})$

$$V = V_o \sin(\omega t + \frac{\pi}{2})$$

Choke coil:

A choke coil, commonly known as choke, is an inductor used in electronic circuits. It is used to block high frequencies above a certain frequency, while allowing the direct current to pass through.

Inductive Reactance:

The term inductive reactance refers to the opposition that an inductor offers to the flow of alternating current. It is denoted by X_L. It is measured in ohms. The inductive reactance can be calculated by following the method.

The formula for inductive reactance is given by:

$X_L = wL$

Or $X_L = 2\pi fL$

where:

X_L is the inductive reactance,

F is the frequency of the AC signal,

L is the inductance of the inductor.

RLC Circuits:

An RLC circuit is an electrical circuit consisting of a resistor (R), inductor (L), and capacitor (C), connected in series or parallel.

RLC circuits are fundamental in electronics for filtering signals, tuning circuits, and resonant applications due to their ability to manipulate frequencies and impedance.

Impedance triangle:

A circuit containing resistor, inductor and capacitor offer opposition to flow of current due to all these circuit elements known as impedance. It is denoted by Z. The impedance triangle.

$$Z = \sqrt{R^2 + X_T^2}$$

Where

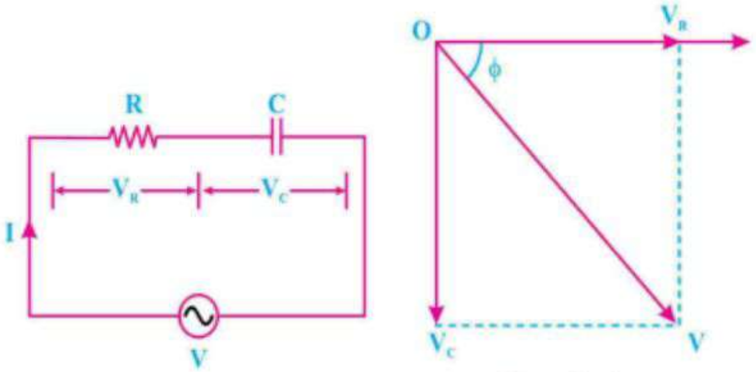
Z = impedance

R = Resistance in circuit

X^2_T = sum of capacitive

AC through RC Series circuits:

Consider a circuit containing resistor and capacitor connected in series with an alternating voltage source as shown in figure 20. 16. Due to series circuit same current will flow through each circuit element. While voltage across resistor will be VR and V_t across capacitor.



The phasor diagram is drawn taking current as reference direction.

From the phasor diagram, using Pythagoras theorem

$$V = \sqrt{V_R^2 + V_C^2}$$

Substituting voltage across resistor = IR and across capacitor = IX_c in above equation

$$V = \sqrt{(IR)^2 + (IX_c)^2}$$

$$V = \sqrt{I^2R^2 + I^2{X_c}^2}$$

$$V = I\sqrt{R^2 + {X_c}^2}$$

Comparing equation ($V = I\sqrt{R^2 + {X_c}^2}$) and ($Z = \sqrt{R^2 + X_T^2}$), we find that qauntity V represents the impedance of Z series circuit.

Phase angle between current and voltage as shown in figure 20.19 is calculated by

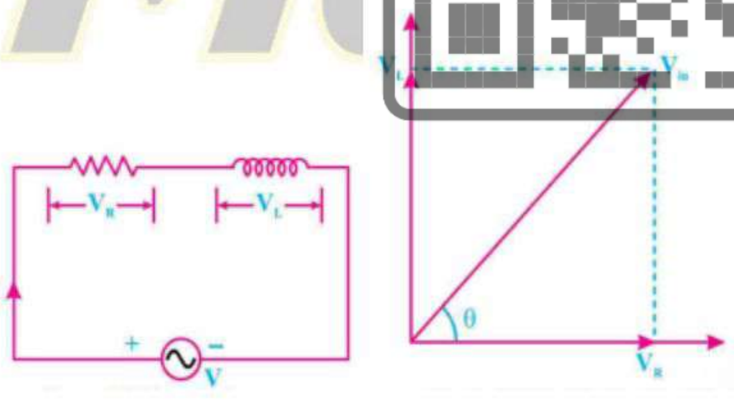
$$\tan\phi = \frac{V_c}{V_R} = \frac{V_C}{R}$$

OR

$$\phi = \tan^{-1}\left(\frac{X_c}{R}\right)$$

AC through RL Series circuits:

Next in order to calculate the impedance of RL series circuit, consider a circuit containing inductor and resistor connected in series with an alternating voltage as shown in figure. The voltage across resistor and inductor in V_R and V_L respectively.



When an inductor is connected with alternating voltage then due to generation of back EMF current lag the voltage by 90_o it is represented by line perpendicular to the reference phasor i-e current / as shown in figure. Also as discussed in section 20.31 in resistor the current and voltage are in phase. In phasor diagram it is V_R line.

To calculate the impedance of RL circuit, apply Pythagoras theorem on phasor

$$V = I\sqrt{R^2 + {L_c}^2}$$

and $Z = \sqrt{R^2 + L_C^2}$ represents the impedance of the RL circuit.

Phase angle between current and voltage as shown in figure is calculated by Figure 20.20

$\tan\phi = \frac{X_L}{R}$ OR $\phi = \tan^{-1}(\frac{X_L}{R})$

RLC Series AC Circuit:

An RLC series circuit consists of a resistor (R), inductor (L), and capacitor (C) connected in series to an AC voltage source as shown. In such circuit, the electrical components influence the behaviour of the current flowing through the circuit.

Power in A.C Circuits:

Power dissipation in AC circuit is expressed as follows

$P = VI\cos\theta$

Where $\cos\theta$ represents power factor.

Resonant Frequency:

For a certain frequency the capacitive and inductive reactance becomes equal, $X_c = X_L$. This frequency is called resonant frequency f_r and circuit is said to be in resonance state. To calculate the resonant frequency, use the fact that

$$X_c = X_L$$

$$\frac{1}{2\pi f c} = 2\pi f L$$

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

Parallel RL Circuit:

In some respects, the circuit of figure is similar to the purely inductive parallel circuit.

For instance, applied voltage V is still the quantity which is common to both components and is therefore plotted in standard position in the phasor diagram. Also the magnitude of the individual branch currents is determined by the opposition (reactance) of the individual branches. The figure shows a composite diagram of waveforms and phasors.

Since the phasor diagram shows that the two branch currents are not in phase, it will be necessary to use phasor addition in order to determine the total current.

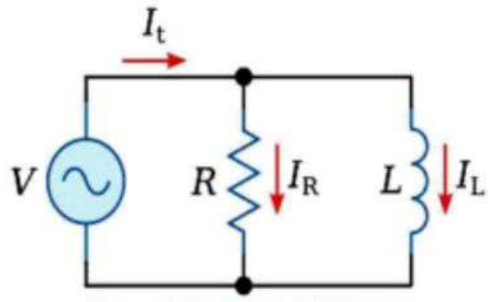


Figure 20.24 Parallel RL Circuit

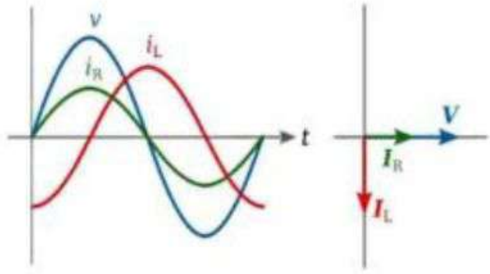


Figure 20.25 Waveforms and phasors

Parallel RC circuits

Parallel RC circuits may be resolved in much the same way as are parallel RL circuits.

The figure illustrates a parallel RC circuit.

The figure shows a composite diagram of waveforms and phasors as per circuit conditions. The current phasors IR and IC are out of phase; therefore, phasor addition must be used to determine total current. The solving of an RC circuit follows the method previously applied to LR circuits.

Figure 20.26 Parallel RC Circuit

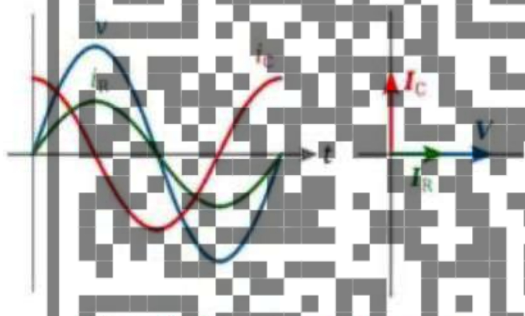
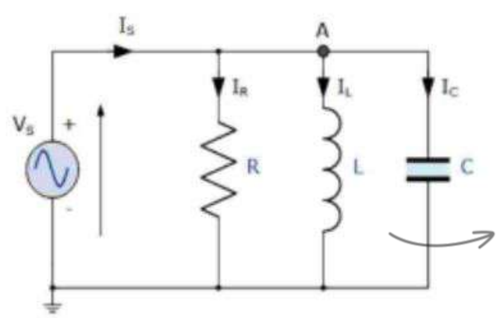


Figure 20.27 Waveforms and phasors

Parallel RLC AC Circuit:

A Parallel RLC AC Circuit one where the resistor, inductor, and capacitor are connected in parallel to each other and the AC source. In this configuration, the voltage across each component is the same, but the currents through them differ. The parallel arrangement affects the overall impedance and current distribution in the circuit, making it distinct from its series counterpart. In a parallel circuit, the voltage V (RMS) across each of the three elements remains the same. Hence, for convenience, the voltage may be taken as a reference phasor.



In the parallel RLC circuit, the supply voltage Vs is common to all three components, while the supply current Is consisting of three parts: the current through the resistor (R), the current through the inductor (I_L), and the current through the capacitor (Ic). The current flowing through each branch, and therefore through each component, will differ from one another and from the supply current I_s.

The total current drawn from the supply is not simply the arithmetic sum of the three individual branch currents but their vector sum.

Similar to the series RLC circuit, we can solve this circuit using the phasor or vector method. However, in this case, the vector diagram will use the voltage as its reference, with the three current vectors plotted relative to this reference voltage.

The phasor diagram for an AC RLC parallel circuit is created by combining the individual phasors for each component and adding the currents vectorially.

Since the voltage across the circuit is common to all three circuit elements, we can use it as the reference vector, with the three current vectors drawn relative to this reference at their corresponding angles. The resulting vector current I_s is obtained by first adding the vectors I_L And I_G and then adding this sum to the vector I_R. The angle between V and I_s

Resonance of Parallel RLC AC Circuit:

A parallel circuit containing a resistance, R, an inductance, L and a capacitance, C will produce a parallel resonance (also called anti-resonance) circuit when the resultant current through the parallel combination is in phase with the supply voltage. At resonance there will be a large circulating current between the inductor and the capacitor due to the energy of the oscillations, then parallel circuits produce current resonance.

A parallel resonant circuit stores the circuit energy in the magnetic field of the inductor and the electric field of the capacitor. This energy is constantly being transferred back and forth between the inductor and the capacitor which results zero current and energy being drawn from the supply.

In the solution of AC parallel resonance circuits, we know that the supply voltage is common for all branches, so this can be taken as our reference vector. Each parallel branch must be treated separately as with series circuits so that the total supply current taken by the parallel circuit is the vector addition of the individual branch currents.

$$I_R = \frac{V}{R}$$

$$I_L = \frac{V}{X_L} = \frac{V}{2\pi f L}$$

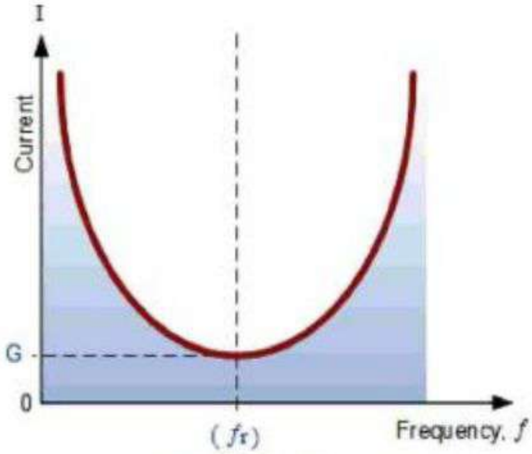
Therefore, I_T = vector sum of (I_R + I_L+I_C)

$$I_T = \sqrt{I_R^2 + (I_L + I_C)^2}$$

At resonance, currents IL and IC are equal and cancelling giving a net reactive current equal to zero. Then at resonance the above equation becomes.

$$I_T = \sqrt{I_R^2 + (0)^2}$$

$$I_T = I_R$$



Parallel Resonance

Therefore, the circuit current at this frequency will be at its minimum value of V/R and the graph of current against frequency for a parallel resonance circuit is shown in figure.

The frequency response curve of a parallel resonance circuit shows that the magnitude of the current is function of frequency and plotting this onto a graph shows us that the response starts at its maximum value, reaches its minimum value at the resonance frequency

when IMIN = IR and then increases again to maximum as f becomes infinite.

The result of this is that the magnitude of the current flowing through the inductor, L and the capacitor, C tank circuit can become many times larger than the supply current, even at resonance but as they are equal and at opposition (180° out-of-phase) they effectively cancel each other out.

As a parallel resonance circuit only functions on resonant frequency, this type of circuit is also known as an Rejecter Circuit because at resonance, the impedance of the circuit is at its maximum thereby suppressing or rejecting the current whose frequency is equal to its resonant frequency. The effect of resonance in a parallel circuit is also called "current resonance'".

Maximum Power Transfer Theorem:

According to this theorem, maximum power is transferred from a source to a load when the impedance of the source matches with the impedance of the load.

Mathematically, suppose R, denotes the resistance of load and R, is source resistance.

Metal Detectors:

The oscillator circuit is used in metal detectors. Metal detectors used for security checks operate on the principle of electromagnetic induction. A simplified explanation of working of metal detector is described below:

1. Generating an Electromagnetic Field:

The metal detector contains a coil of wire through which an electric current flow, creating a magnetic field around the coil. This coil is often housed in a special arrangement, such as a loop or wand.

2. Interaction with Metals:

When a conductive metal object is brought into the vicinity of the electromagnetic field, it disturbs the field. This disturbance induces a secondary magnetic field in the metal object.

3. Eddy Currents:

The changing magnetic field induces circulating electric currents within the metal object, known as eddy currents. These eddy currents, in turn, generate their own magnetic fields.

4. Detection of Changes:

The metal detector has a receiver coil or coils that are in close proximity to the transmitter coil. The receiver coil(s) detect changes in the magnetic field caused by the presence of the metal.

5. Alert Mechanism:

When the metal detector senses a significant change in the magnetic field, indicating the presence of a metal object, it triggers an alert. This alert can be in the form of an audible sound, a visual signal, or both, depending on the design of the metal detector.

The Electrocardiograph:

The electrocardiograph (ECG) is a medical diagnostic tool used to record the electrical activity of the heart over a period of time.

Oscillator Circuit

An oscillator circuit is an electronic circuit that generates a continuous periodic signal at a specific frequency.

Resonance in Tuning circuit of Radio:

In radio tuning circuits resonance is a important phenomenon that enables the selective reception of a desired radio frequency while rejecting others.

Importance of Broadcasting:

Broadcasting remains a powerful medium with far-reaching impacts on society. It informs, educates, entertains, and connects people, playing a crucial role in cultural preservation, economic development, and social cohesion. Its ability to reach a wide audience makes it an indispensable tool for communication in the modern world.

EXERCISE

Section (A): Multiple Choice Questions (MCQs)

Choose the correct answer:

1. In alternating current, the flow of electric charge periodically reverses direction. The term for this specific phenomenon is:

(a) Alternation (b) Oscillation (c) Cycle (d) Resistance

2. The frequency of standard household alternating current in Pakistan is:

(a) 50 Hz (b) 60 Hz (c) 100 Hz (d) 120 Hz

3. The parameter for measuring the rate of change of alternating current or voltage with respect to time is:

(a) Amplitude (b) Frequency (c) Phase angle (d) Peak Voltage

4. In AC circuits, what is the phase difference between current and voltage in a purely resistive circuit?

(a) 0° (b) 450 (c) 90º (d) 180°

5. A device used to measure the root mean square (RMS) value of an AC voltage or current is:

(a) Voltmeter (b) Oscilloscope (b) Ammeter (d) AVO meter

6 In an AC circuit. The term "reactance" represents the:

(a) Ohmic resistance only (b) Resistance to DC currents only

(c) Capacitive and inductive opposition to current flow

(d) Total impedance, including resistance and phase angle

7 A type of a circuit characterized by equal values of resistance and reactance is:

(a) Resistive (b) Inductive (c) Capacitive (d) Resonant

8 In an AC sine wave, the peak-to-peak voltage is:

(a) Double the peak voltage

(b) The difference between the peak voltage and zero

(c) The sum of the peak voltage and zero

(d) The difference between the positive and negative peak voltages

9 What is the power factor of a purely resistive circuit?

(a) 0 (b) 0.5 (c) 1 (d) -1

10. The purpose of a transformer in an AC power distribution system.

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(a) To convert AC to DC

(b) To step up or step down voltage

(c) To store electrical energy

(d) To regulate current flow

Section (B):

CRQs (Short Answered Questions):

1. Define RMS voltage and explain its significance in AC circuits.

RMS (Root Mean Square) voltage is a type of effective voltage that measures the equivalent DC voltage that would produce the same amount of heat in a resistor. It is calculated by taking the square root of the average of the squared instantaneous voltages over one cycle.

Significance:

- **Power calculation:** RMS voltage is used to calculate the power dissipated in an AC circuit, as it gives a true measure of the effective voltage.
- **AC measurements:** Most AC voltmeters measure RMS voltage, as it provides a more representative value of the AC signal's power-carrying capacity.

2. Explain the difference between peak voltage, RMS voltage, and average voltage in AC circuits.

Peak voltage: The maximum instantaneous voltage value reached during a cycle.

RMS voltage: As defined above, the effective voltage that produces the same heat as a DC voltage.

Average voltage: The average of all instantaneous voltages over one cycle. In a pure sine wave, the average voltage is zero.

3. Define alternating current (AC) and explain how it differs from direct current (DC).

- **Alternating current (AC):** A current that periodically reverses its direction. It is typically represented by a sinusoidal waveform.
- **Direct current (DC):** A current that flows in one direction only. It is typically represented by a constant value.

Key differences:

- **Direction:** AC changes direction, while DC flows in one direction.
- **Transmission:** AC is more efficient for long-distance transmission due to its ability to be easily stepped up or down in voltage using transformers.
- **Applications:** AC is used for most household and industrial applications, while DC is used in batteries, electronic devices, and specific industrial processes.

4. Define reactance in AC circuits and differentiate between capacitive and inductive reactance.

Reactance: The opposition to the flow of alternating current in a circuit. It is measured in ohms.

Capacitive reactance (Xc): The opposition to the flow of AC current offered by a capacitor. It decreases as frequency increases.

Inductive reactance (Xl): The opposition to the flow of AC current offered by an inductor. It increases as frequency increases.

5. Describe the behaviour of capacitors and inductors in AC circuits.

Capacitor: Stores energy in an electric field. In an AC circuit, a capacitor acts as an open circuit at low frequencies and a short circuit at high frequencies.

Inductor: Stores energy in a magnetic field. In an AC circuit, an inductor acts as a short circuit at low frequencies and an open circuit at high frequencies.

6. Explain the phase relationship between voltage and current in capacitive and inductive AC loads.

Capacitive load: Current leads voltage by 90 degrees.

Inductive load: Voltage leads current by 90 degrees.

7. What is resonance in AC circuits? Discuss its conditions and applications.

Resonance: A condition in an AC circuit where the inductive reactance and capacitive reactance are equal, resulting in a maximum current flow at a particular frequency.

Conditions: The circuit must contain both a capacitor and an inductor.

Applications: Resonance is used in tuning circuits in radios, televisions, and other communication devices.

8. Discuss the role of transformers in AC circuits and explain how they work.

Transformers: Devices that change the voltage of an AC signal without affecting its power.

How they work: Transformers operate on the principle of electromagnetic induction. A changing magnetic field in the primary winding induces a voltage in the secondary winding. The ratio of the number of turns in the primary and secondary windings determines the voltage ratio.

9. Explain the behavior of an RLC series circuit in terms of impedance, resonance, and phase angle.

Impedance: The total opposition to the flow of current in an RLC series circuit, which is the combination of resistance, capacitive reactance, and inductive reactance.

Resonance: The frequency at which the impedance of the RLC series circuit is minimum, resulting in maximum current flow.

Phase angle: The phase difference between the voltage and current in an RLC series circuit. It depends on the relative magnitudes of the resistance, capacitive reactance, and inductive reactance.

10. Describe the operation and applications of a transformer in AC circuits.

Operation: As explained above, transformers operate on the principle of electromagnetic induction.

Applications: Transformers are used in a wide range of applications, including:

- Power transmission and distribution
- Electrical appliances
- Electronics
- Medical equipment
- Industrial processes

Section (C) ERQS (Long Answered Questions):

1. Explain the concept of phasor in the context of AC voltage. How are phasors used to represent sinusoidal voltages?

Notes

2. Describe the concept of impedance in AC circuits. How does impedance differ from resistance, and what are the units of impedance?

Notes

3. How does the reactance of an inductor and a capacitor change with frequency in an AC circuit? Provide an explanation based on the fundamental formulas?

Notes

4. Discuss the concept of resonance in RLC circuits. What conditions lead to resonance, and how does it affect the behaviour of the circuit?

Notes

5. Compare and contrast series and parallel resonance in RLC circuits. What are the key differences between the two resonance configurations?

Notes

6. Explain the transient response of an RLC circuit when initially connected to an AC source. What happens to the currents and voltages in the circuit?

Notes

7. Why alternating current (AC) is commonly used for long-distance power transmission?

Notes

8. Describe the purpose and function of a choke coil in AC circuits.

Notes

Section (D): Numerical:

1. A resistor (R) of 20 ohms is connected in series with a capacitor (C) of 10 μF in an AC circuit with a frequency of 50 Hz. Calculate the total impedance? (Ans. 3182 ohms)

2. For an inductor with an inductance (L) of 0.5 H and a frequency of 100 Hz, calculate the inductive reactance? (Ans. 314.16 ohms)

3. In an RL circuit, the resistance (R) is 30 ohms, and the inductance (L) is 0.2 H. Calculate the total impedance at a frequency of 60 Hz? (Ans. 81.1ohms)

4. In an RC circuit, the resistance (R) is 50 ohms, and the capacitance (C) is 20 μF. Calculate the capacitive reactance? (Ans. 31.83 ohms)

5. An AC circuit has a resistance of 40 ohms, an inductive reactance of 30 ohms, and a capacitive reactance of 20 ohms. Draw the impedance triangle and calculate the total impedance? (Ans. 41.2ohms)

6. In a series RL circuit, the resistance (R) is 25 ohms, and the inductance (L) is 0.1 H. Calculate the phase angle and impedance at a frequency of 80 Hz? (63.8°, 502 ohms)

7. In a parallel RC circuit, the resistance (R) is 60 ohms, and the capacitance (C) is 30 μF. Calculate the total current flowing through the circuit at a frequency of 120 Hz? (Ans. 60 V)

8. In an RLC circuit, the resistance (R) is 50 ohms, the inductance (L) is 0.1 H, and the capacitance (C) is 50 μF. Calculate the resonance frequency? (Ans. 70.7Hz)

Unit 21

Physics of Solids

Classification of Solids:

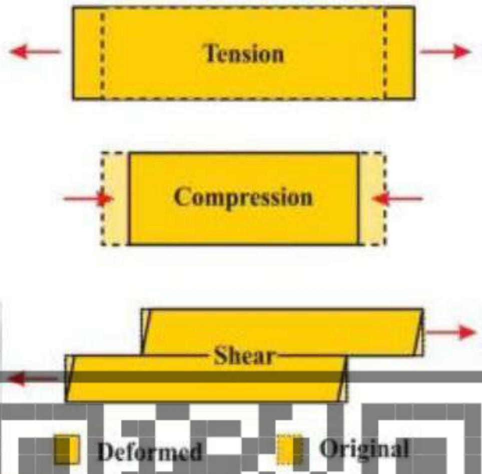
Solids are usually crystalline substances their molecules are arranged in a definite pattern and in fixed positions. The way in which a solid behaves depends on its internal structure and there are three types of solid.

(i) Crystalline solids (i) Amorphous solids (iii) Polymeric solids

Deformation:

In material science, deformations refer to modifications of the shape or size of an object due to applied forces or a change in temperature.

Deformation is usually caused by forces such as tensile (pulling) or Compressive (pushing)



Deformation in one dimension (1D):

Stress:

It is usually defined as force applied to a material per unit arca. Stress is a quantity which defines the magnitude of force that cause deformation.

Strain:

Strain is a measure of how much a material deforms (stretches or compresses) when a force is applied to it.

It is calculated by dividing the change in length by the original length of the material

Mechanical Properties of Solids

Mechanical properties of solids refer to the characteristics that describe how a solid material responds to applied forces or deformation.

Some important mechanical properties of solid are Elasticity, Ductility, Brittleness, and Hardness etc.

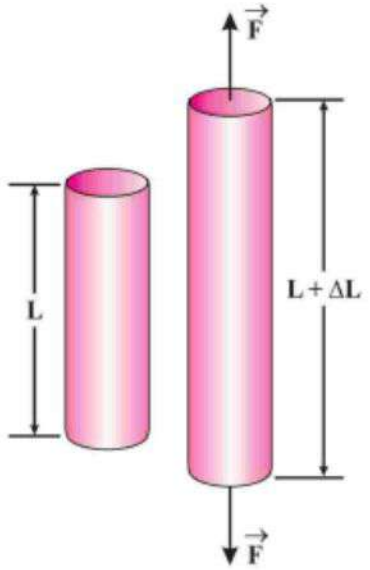
Young's Modulus (modulus of elasticity)

It is a mechanical property of solids that measures the stiffness or elasticity of a solid material and it computes how much a material will deform (stretch or compress) under a given force.

$Y = \frac{Force}{Area}$

It is denoted by the symbol Y and has (Pascal, pas, N/m^2)

Modulus is defined as the ratio of stress to strain.



$$Y = \frac{Stress}{Strain}$$

$$Y = \frac{\frac{F}{A}}{\frac{\Delta L}{L}}$$

$$Y = \frac{FL}{\Delta L A}$$

Shear Modulus:

Shear modulus, also known as the modulus of rigidity is a mechanical property that describes a material's resistance to shear deformation when a force is applied perpendicular to the material's surface.

It is denoted by the symbol G or S and has units of force per unit area, typically expressed in Pascal (Pa) or Giga Pascal (GPa).

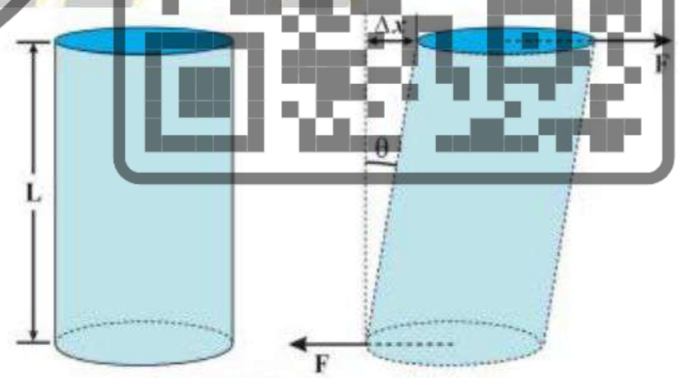


Figure 21.4: shear modulus

$$G = \frac{\frac{F}{A} \times L}{\Delta X}$$

Bulk Modulus: Compressibility

Bulk modulus, also known as the modulus of compressibility, is a mechanical property that describes the resistance of a material to compression under uniform external pressure. It is denoted by the symbol K and has units of pressure (usually expressed in Pascal, Pa or Giga Pascal (GPa).

Bulk modulus is defined as the ratio of the change in pressure applied to a material to the resulting fractional change in volume that occurs in the material. Mathematically, it is expressed as:

$$\frac{\Delta V}{V} = -\frac{P}{B}$$

$$B = -\frac{\Delta P}{\frac{\Delta V}{L}}$$

where B is the bulk modulus

ΔP is the change in pressure applied to the material

ΔV is the resulting change in volume,

V is the original volume of the material.

Electrical Properties of Solids:

The electrical property of a good conductor depends on its ability to transmit energy without boiling, melting, or changing its composition in any way.

Resistivity:

The resistance per unit length and cross-sectional area is called resistivity. It varies from material to material. Its SI unit is Ohm-meter (2- m).

Conductivity:

It is a measure of a material's ability to conduct electric current, which is influenced by the availability and mobility of charge carriers within the solid.

Temperature Coefficient of resistivity:

The temperature coefficient of resistance is defined as the change in electrical resistance of a substance with respect to per degree rise in temperature. When the temperature increases, the process of electron collision becomes rapid and faster. As a result, the resistance will increase with the rise in temperature of the conductor.

The quantity of charge carriers' n, the number of chare carriers per unit volume, can be found from measurement of the Hall Effect. Its SI unit is m^{-3}.

Energy Bands in Solids:

When isolated atoms comes together to form a solid, interactions between neighbouring atoms cause the electron energy levels to split and overlap, creating continuous energy bands.

Valence Band:

The valence band is the range of energy levels occupied by electrons that are bound to atoms and participate in chemical bonding. It is the highest energy band that contains electrons under normal conditions.

Forbidden Band (Energy Gap):

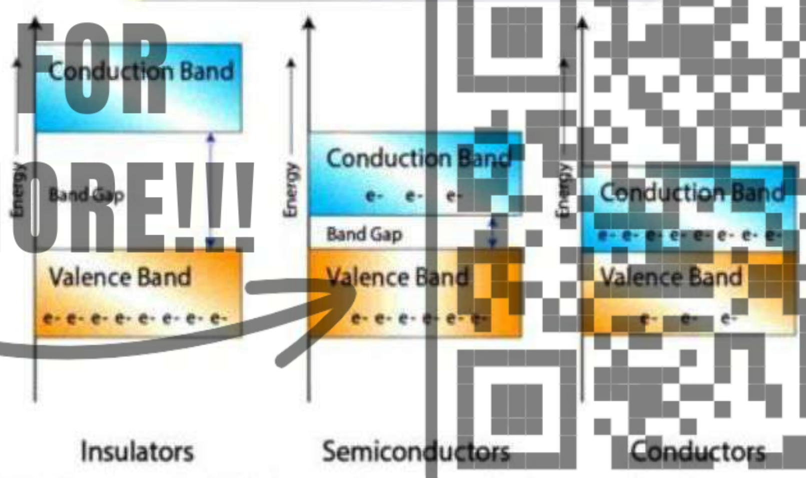
The forbidden band, or energy gap, is the range of energy levels between the valence band and the conduction band where no electron states exist. This gap influences material's electrical properties; a larger gap typically means the material is less conductive.

Conduction Band:

The conduction band is the range of energy levels where electrons are free to move throughout the material, allowing electrical conduction. Electrons in the conduction band are not bound to any particular atom and can carry electric current through the solid.

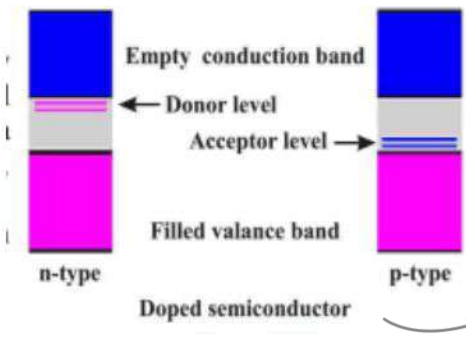
Classification of Solids:

Depending on the electrical conductivity solids are classified into three main categories: conductors, semiconductors and insulators.



There are two types of semiconductors:

a) Intrinsic semiconductor:



When energy is provided to intrinsic semiconductors like silicon and germanium, electrons leave their positions, creating positive holes. Under an electric field, electrons and holes move in opposite directions, enabling electrical conductivity. Group IV elements are considered as an intrinsic semiconductors

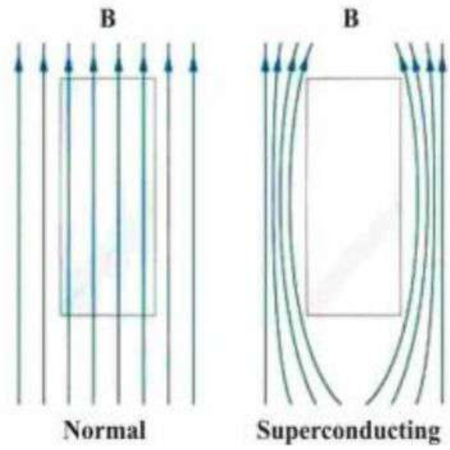
b) Extrinsic semiconductor:

Silicon and germanium have low

conductivity at room temperature. Adding small amounts of group III or group V impurities, a process called doping, increases their conductivity, resulting in extrinsic semiconductors.

Superconductor:

A superconductor is a material that can conduct electricity without resistance when it is cooled below a certain critical temperature, typically near absolute zero.



Curie Point:

Curie point is also known as Curie temperature. Some magnetic materials lose their magnetic properties as the temperature rises above the Curie temperature. The Curie temperature weakens the magnetic properties of the material.

Curie's Law:

The Curie law states that in a paramagnetic material,

"Magnetization is directly proportional to an applied a permanent magnet is magnetic field".

$$M \propto H$$

$$M = \chi H$$

But when it is heated, the relation is reversed, i.e., the magnetization becomes inversely proportional to temperature.

Mathematically, it is written as:

$$M = \frac{C \times H}{T}$$

Hard and Soft Ferromagnetic Substances:

Ferromagnetic materials fall into two main categories: Hard and Soft.

Hard ferromagnetic:

Materials like neodymium, samarium cobalt, and alnico are permanent magnets with high coercivity, suitable for stable magnetic fields in applications like speakers and generators.

Soft ferromagnetic:

Including iron, nickel, and cobalt, these materials have low coercivity, making them easy to magnetize and demagnetize.

They are used in devices like transformers inductors that require rapidly changing magnetic fields.

EXERCISE

Section (A): Multiple Choice Questions (MCQs)

Choose the correct answer:

1. The property of a body by virtue of which it tends to regain its original size and shape when the applied force is removed is called

(a) Elasticity (b) Plasticity (c) Rigidity (d) Compressibility

Substances which can be stretched to cause large strains are called

(a) Brittle (b) Ductile (c) Plastic (d) Elastomer

3 If the load is increased beyond the point, the strain increases rapidly for even a small change in the stress.

(a) Elastic point (b) Yield point (c) Plastic point (d) Fracture point

4 The reciprocal of the bulk modulus is called

(a) Compressibility (b) Volume stress (c) Modulus of rigidity (d) Volume strain

5 Which of the following statements is/are wrong?

i. Hollow shaft is much stronger than a solid of the same length and same mass.

ii. Reciprocal of bulk modulus of elasticity is called compressibility.

ii. It is difficult to twist along rod as compared to small rod.

(a) III only (b) I only (c) II and III (d) I and II

6 Metals are good conductors of heat and electricity. This property is conferred by

(a) Covalent (b) Ionic (c) Metallic (d) Hydrogen

7 For a metallic crystal, delocalized electrons occupied band is:

(a) Conduction band (b) Valence band

(c) Conduction and valence bands (d) there are no delocalized electrons

8 The semiconductors have resistivity

(a) Between conductor and insulator (b) More than insulators

(c) Less than conductors (d) Depending upon the semiconductor material property.

9 A ferromagnetic substance becomes a permanent magnet when it is placed in a magnetic field because

(a) All the domains get oriented in the direction of the magnetic field.

(b) All the domains get oriented in the direction opposite to the direction of the magnetic field.

(c) Domains get oriented randomly.

(d) Domains are not affected by the magnetic field.

10. Identify methods to demagnetize a ferromagnet.

(a) By cooling, heating, or submerging water

(b) By heating, hammering, and spinning it in an external magnetic field

(c) By hammering, heating, and rubbing with cloth

(d) By cooling, submerging in water, or rubbing with cloth

Section (B): CRQs (Short Answered Questions):

1. Why are the springs made of steel and not of copper?

Steel is preferred over copper for making springs due to its **higher elasticity and strength**. This means it can be deformed under stress and return to its original shape without breaking. Copper, while ductile, is not as strong or elastic as steel, making it less suitable for applications requiring resilience and durability.

2. The breaking force for a wire is F. What will be the breaking force for two parallel wires of the same size?

If two parallel wires of the same size are connected together, the **breaking force** will be **double** that of a single wire. This is because the combined cross-sectional area of the two wires is twice that of a single wire, which means they can support a greater load before breaking.

3. Distinguish between intrinsic and extrinsic semiconductor.

Intrinsic semiconductor: A pure semiconductor material with equal numbers of free electrons and holes.

Extrinsic semiconductor: A semiconductor material that has been doped with impurities (either donor or acceptor atoms) to increase its conductivity.

4. A wire is replaced by another wire of same length and material but of twice the diameter. What will be the effect on the:

(a) Increase in its length under a given load? (b) Maximum load which it can bear?

(a) **Increase in length under a given load:** Doubling the diameter of a wire will **decrease** its length under a given load. This is because the cross-sectional area of the wire increases, making it more resistant to deformation.

(b) **Maximum load which it can bear:** Doubling the diameter of a wire will **increase** the maximum load it can bear. This is because the larger cross-sectional area provides more material to resist stress before breaking.

5. Sand does not possess any definite shape and volume, still it is solid. Give reason.

Sand is considered a solid because it has a **definite shape** and **volume** when it is contained in a container. Although the individual grains of sand can move and flow, the overall shape and volume of the sand within the container remain constant.

6. Specify the importance of stress-strain curve.

Elastic limit: The point beyond which a material will not return to its original shape.

Yield strength: The point at which a material begins to deform plastically.

Ultimate tensile strength: The maximum stress a material can withstand before breaking.

Ductility: The ability of a material to be drawn into a wire.

Toughness: The ability of a material to absorb energy before breaking.

7. Why liquids don't possess rigidity?

Liquids do not possess rigidity because their molecules are not fixed in position and can slide past each other. This allows liquids to flow and take on the shape of their container.

8. Give applications of Curie point.

The Curie point is the temperature at which a ferromagnetic material loses its magnetism. It has applications in:

- **Magnetic data storage:** The Curie point is used to write and erase data on magnetic storage devices such as hard drives.
- **Magnetic sensors:** Curie point sensors can be used to measure temperature.
- **Magnetic separation:** Curie point separators can be used to separate magnetic materials from non-magnetic materials.

9. What are amorphous materials and what are their uses?

Amorphous materials are materials that lack a crystalline structure. They have a random arrangement of atoms or molecules. Some examples of amorphous materials include glass, plastics, and rubber.

Uses of amorphous materials:

- **Glass:** Windows, lenses, containers
- **Plastics:** Packaging, toys, furniture
- **Rubber:** Tires, gaskets, seals
- **Amorphous silicon:** Solar cells, thin-film transistors

Section (C): ERQS (Long Answered Questions):

1. Explain Force-Extension graph.

Notes

2. Derive relation for Young's Modulus and Shear Modulus.

Notes

3. Distinguish between structure of crystalline, glassy, amorphous, and polymeric solids.

Notes

4. Describe the energy bands in solids.

Notes

5. Describe superconductivity and its applications.

Notes

6. Discuss the applications of superconductors for MRI, Maglev's, and supercomputers.

Notes

7. Describe hysteresis loss.

Notes

8. Synthesize hysteresis loop for relationship between magnetic field strength and magnetizing current.

9. Discuss energy bands and their classification. Explain magnetic properties of soft and hard magnetic materials.

Notes

Section (D): Numerical:

1. The lead' in pencils is a graphite composition with a Young's modulus of 1.0×10^9 N/m^2. Calculate the change in length of the lead in an automatic pencil if you tap it straight into the pencil with a force of 4.0 N. The lead is 0.50 mm in diameter and 60 mm long. (Ans. 1.0mm)

2. A wire of 2.2 m long and 2.25 mm in diameter, when stretched by a weight of 8.8 kg, its length has been increased by 0.25 mm. Find the stress, strain, and Young's modulus of the material of the wire. Given g = 9.8 ms^{-2}. (Ans. 2.2×10^7 N/m, 1.14×10^{-4}, 2×10^{11} N/m^2)

3. A farmer making juice fills a glass bottle to the brim and caps it tightly. The juice expands more than the glass when it warms up, in such a way that the volume increases by 0.2% (i.e., $\frac{\Delta V}{V_O} = 2 \times 10^{-3}$) relative to the space available. Calculate the normal force exerted by the juice per square centimetre, if its bulk modulus is 1.8×10^9 N/m^2. Assuming that the bottle does not break. (Ans. 432 N/cm^2)

4. The elastic limit of copper is 1.5×10^8 N/m^2. It is to be stretched by a load of 10 kg. Find the diameter of the wire if the elastic limit is not to be exceeded. (Ans. 0.912 mm)

5. What would be the greatest length of a steel wire which is fixed at one end, and can it be changed freely without breaking? The breaking stress of steel is 7.8×10^8 N/m^2, and the density of steel is 7800 kg/m^3. (Ans. 1.02×10 m)

6. A mild steel wire of radius 0.55 mm and length 3.5 m is stretched by a force of 52 N. Calculate: (a) Longitudinal stress, (b) Longitudinal strain, and (c) Elongation produced in the wire if Young's modulus is 2.1×10^{11} N/m^2. (Ans. 5.47×10^7 N/m^2, 2.6×10^{-4}, 0.91 mm)

7. Calculate the change in volume of a lead block of volume 1.3 m^3 subjected to a pressure of 12 atm. Also, calculate the compressibility of lead. Given the bulk modulus as $B = 80 \times 10^9$ N/m^2. (1.97×10^{-5} m^3, 1.25×10^{-11} N/m)

8. The thickness of a metal plate is 0.35 inches. It's drilled to have a hole of radius 0.08 inches on the plate. If the shear strength is 4×10^4 Ibs/in^2, determine the force needed to make that hole. (Ans. 0.176 in^2, 7×10^3lbs)

Unit 22

Solid State Electronics

Solid-state electronics is a branch of electronics that deals with the flow of electric current through solid materials, such as semiconductors, insulators, and conductors.

It involves the design, development, and application of electronic devices and circuits that use these materials to control and manipulate electrical energy.

Solid-state electronics has revolutionized the field of electronics, enabling the creation of smaller, faster, and more efficient devices, such as transistors, diodes, integrated circuits, and microprocessors, which are essential components in modern computers, smart phones, and other electronic devices.

The field is constantly evolving, with advancements in materials science, nanotechnology, and quantum mechanics.

Intrinsic (Pure) and Extrinsic (Doped) Semiconductors:

Intrinsic (Pure) Semiconductors:

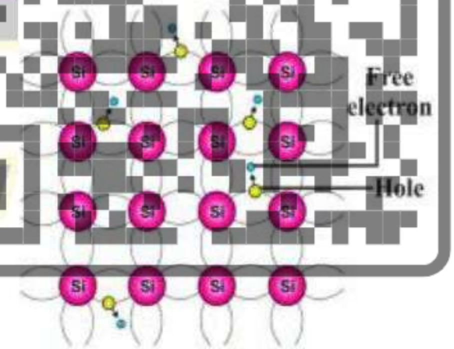
Intrinsic semiconductors are materials that are chemically pure, meaning they do not contain any significant amount of impurity atoms.

The two most commonly used intrinsic semiconductors are silicon (Si) and germanium (Ge).

These materials have a crystalline structure, and their electrical properties are determined by the arrangement and behaviour of their atoms.

Extrinsic (doped) Semiconductors:

Doped semiconductors are created by introducing impurity atoms into the intrinsic semiconductor material. This process is known as doping, and it significantly alters the electrical properties of the semiconductor.

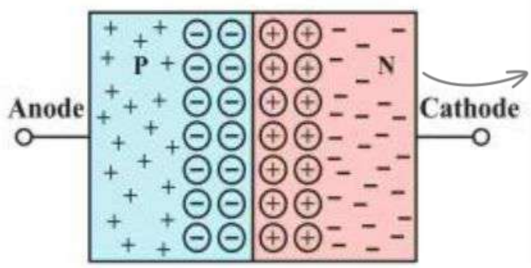


Production of P-Type and N -Type Semiconductors:

The intentional addition of impurities alters the conductivity and electrical properties of the semiconductor, allowing for the controlled operation of charge carriers.

N-type Semiconductors: electron

It is characterized by an excess of positively charged carriers, known as "holes," or majority Positive charge carriers.



P-type Semiconductors:

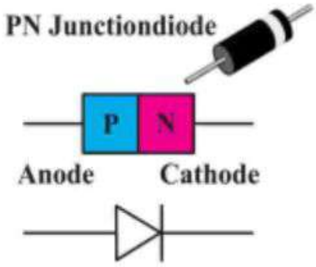
It is characterized by an excess of negatively charged carriers, namely electrons, or majority negative charge carriers.

P-N Junction:

The P-N junction is formed when the p-type and n-type semiconductors are joined, is called as P-N junction

P-N Junction as Diode:

A diode is a semiconductor device that is formed through P-N junction and used in allowing the flow of electric current in one direction and blocking in the opposite.



Properties of Diode:

Below are some of the common properties of a diode:

1. Diode has the ability to rectify electric current.

2. It can create a potential barrier and make use of its capacitance properties.

3. Diode creates various nonlinear current-voltage characteristics.

Diode Biasing:

Forward Bias:

When the P-type is connected to the positive terminal of the battery and the N-type is connected to the negative terminal is called Forward bias.

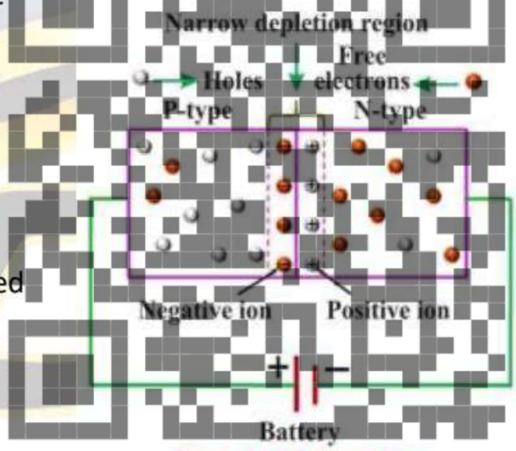
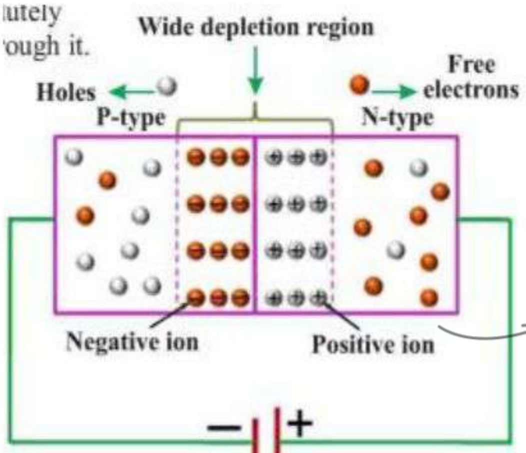


Figure 22.8 Forward Bias

Reverse Bias:

When the P-type is connected to the P-type N-type negative terminal of the battery and the N- type is connected to the positive side is called Reverse

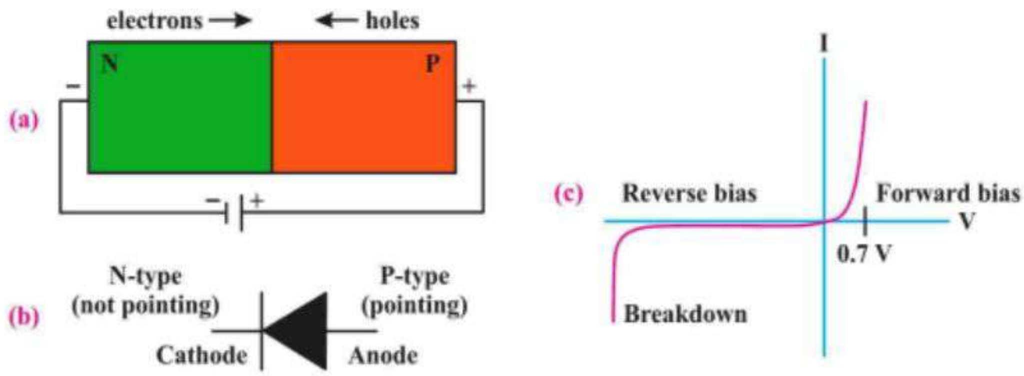


I-V Characteristics of p-n Junction:

The relationship between the voltage across the junction and current through the circuit is known as the (V-I) characteristics of a P-N junction or semiconductor diode.

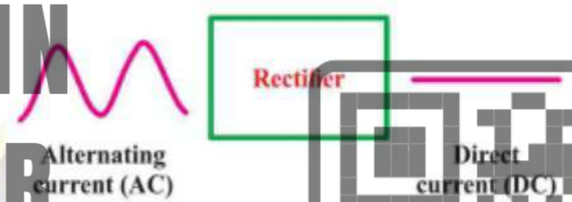
The V-I characteristics of the P-N junction can be explained in three cases:

- Zero bias or unbiased
- Forward bias
- Reverse bias



Rectification:

Rectification is the process of converting an alternating current (AC) waveform into a direct current (DC) waveform, ie, creating a new waveform that has only a single polarity.



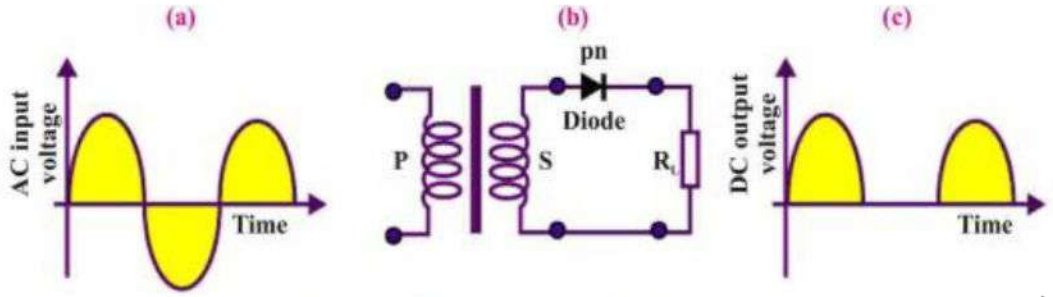
Rectification is classified into two types according to the output characteristics which are:

(i) half-wave rectification and

(ii) full-wave rectification.

Half Wave Rectification:

Since a diode allows AC current to flow only in one direction, it can serve as a rectifier. The AC source applies a voltage across the diode alternately positive and negative. When the positive cycle of AC voltage passes through the diode, the diode is forward biased and act as a closed circuit there is current through the resistor R.



Applications of a Half-wave Rectifier:

Low power simple battery charger circuit.

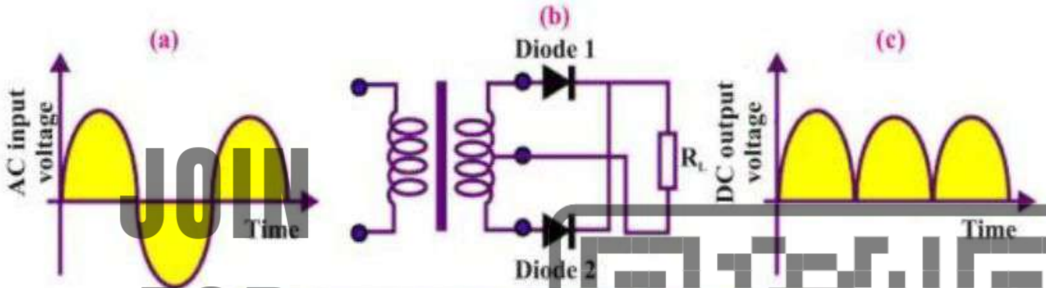
- Fire Alarm circuits.
- Soldering Iron circuit.

- Amplitude Modulation (AM) Radio circuits as a Detector.

Full-Wave Rectification:

Full-wave rectification uses two diodes. During the positive half cycle of input AC signal, this makes the diode D_1 forward biased (acts as closed switch) and diode D_2 reverse biased (acts as open switch). Therefore, current flows through the load resistor R.

During the negative half cycle of input AC signal, this makes the diode D_2 forward biased and the diode D_1 reverse biased. Therefore, the current will flow through diode D_2 through, load resistor R and lower half of the secondary winding.



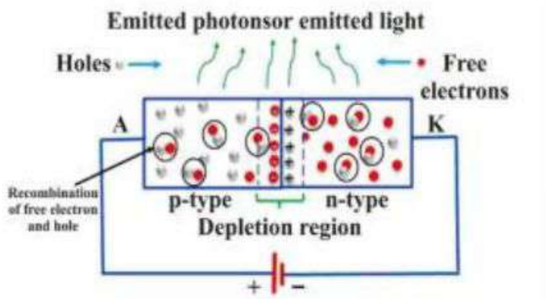
Applications of a Full-wave Rectification:

- Mobile phones, laptops, charger circuits.
- Uninterruptible Power Supply (UPS) circuits to convert AC to DC.
- Our home inverters convert AC to DC.
- LCD, LED TVS.

Function and uses of light emitting diode (LED), Photodiode, Photo voltaic cell:

1. Light Emitting Diode (LED):

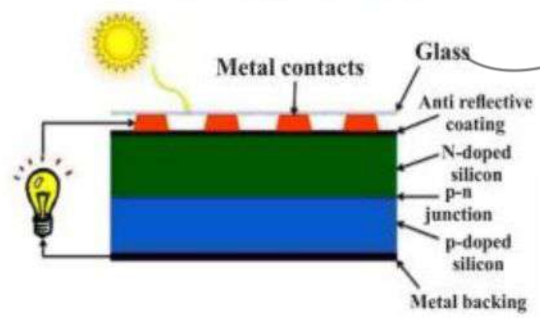
A light-emitting diode (LED) is a special type of junction in which current flows, when it is activated in a forward direction



2. Photodiode:

photodiode is a type of light detector that converts light into current or voltage. It includes optical filters, built-in lenses, and surface areas.

3. Photo Voltaic Cells:



Solar cell or photovoltaic cell is heavily doped P-N junction diodes used to convert sunlight into electric energy.

Uses of Photodiodes:

Camera: Light meters, Automatic Shutter Control, Photographic Flash Control

Medical: CAT Scanners, X-Ray Detection, Pulse Oximeters, Blood Particle Analysis

Automotive: Headlight Dimmer, Twilight Detectors

Communication: Fiber Optic Link, Optical Remote Control

Industry: Bar Code Scanners, Light Pen, Encoders, Surveying Instruments, Copiers- Density of Toner.

Transistors and their characteristics:

A transistor is a semiconductor device that amplifies or switches electronic signals by controlling the flow of current between its three layers: base, collector, and emitter. It acts as a gatekeeper, allowing or blocking the flow of current between the collector and emitter, based on the voltage applied to the base.

Both N-P-N and P-N-P transistors can be made.

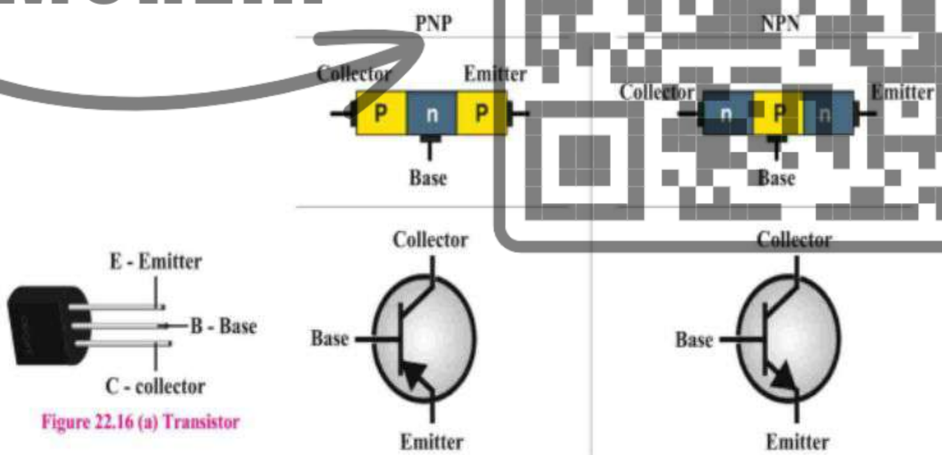


Figure 22.16 (a) Transistor

There are three main characteristics listed below:

1. Input Characteristics

2. Output Characteristics

3. Constant-Current Characteristics.

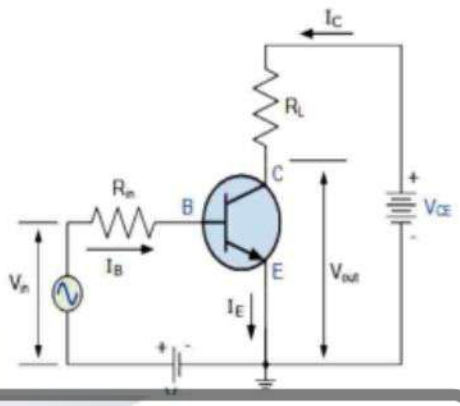
Transistors current equation:

It is a three-terminal device, with three possible ways to connect it within an electronic circuit with one terminal being common to both the input and output signals.

Bipolar Junction Transistor Configurations:

Each method of connection responding differently to its input signal within a circuit as the static characteristics of the transistor varies with each circuit arrangement.

The Common Emitter Amplifier Circuit



In this circuit shown in Figure 22.19, the current leaving the transistor must be equal the currents entering it because the emitter current (Ig) is the, sum of the collector current (Ic) and the base current (I_B).

The common emitter transistor configuration has a substantial current gain because the load resistance (RL) is connected in series with the collector. The current gain is represented by Beta (B),which is the ratio of Ic to IB. For the common emitter setup,

$$I_E = I_C + I_B$$

where the ratio of I_c to I_E is known as Alpha (α).It's important to note that Alpha is always less than one.

The mathematical relationship between Alpha (a) and Beta (B) expresses the current gain of the transistor.

$$\alpha = \frac{I_C}{I_E}$$

$$\beta = \frac{I_C}{I_B}$$

$$I_C = \alpha I_E + \beta I_B$$

As $\alpha = \frac{\beta}{\beta+1}$ and $\beta = \frac{\alpha}{1-\alpha}$

$$I_E = I_C + I_B$$

Where:

I_C is the current flowing into the collector terminal

I_B is the current flowing into the base terminal

I_E is the current flowing out of the emitter terminal.

Operation Principles and -V Characteristics and Methods of Transistor Biasing:

Bipolar Junction Transistor (BJT):

Operation Principles:

1. Emitter, Base, and Collector:

- The three layers of a BJT are called the emitter (E), base (B), and collector (C).
- The flow of current in an N-P-N transistor is from the emitter to the collector, and in a P-N-P transistor, it's from the collector to the emitter.

2. Transistor Action:

The operation of a BJT involves the injection of minority carriers (electrons in N-P-N or holes in P-N-P) from the emitter into the base region. This controls the majority carrier flow from the collector to the emitter.

Biasing Methods:

Biasing is the process of applying external voltages to a transistor to establish a desired operating point for proper amplification or switching.

There are several biasing methods for transistors. Here are some common biasing methods:

Bipolar Junction Transistor (BJT) Biasing Methods:

1. Fixed Bias (Base Bias):

- Connects a resistor between the base and the power supply to establish a fixed voltage at the base.
- Simple but not very stable.

2. Emitter Bias (Emitter Stabilized Bias):

- Connects a resistor from the emitter to the power supply, stabilizing the operating point.
- More stable than fixed bias.

3. Collector Feedback Bias:

- Combines features of fixed bias and emitter bias for improved stability.
- Uses a resistor network to provide feedback.

4. Voltage Divider Bias:

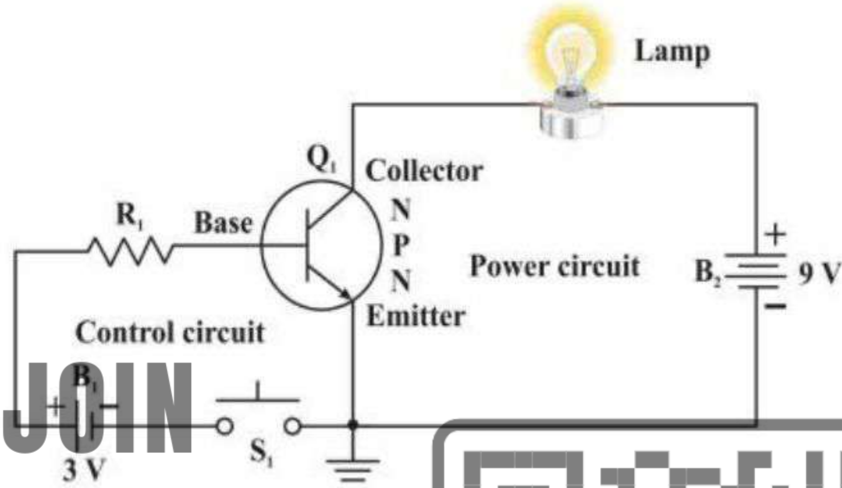
- Utilizes a resistor divider network to bias the base and provide stability.
- More stable than fixed bias but less stable than emitter bias.

The transistors as a switch:

A transistor can be used as a switch in electronic circuits, where it functions to either allow or block the flow of current.

There are two main configurations for using a transistor as a switch: the NPN (negative-positive-negative) and PNP (positive-negative-positive) configurations.

NPN Transistor as a Switch:



Here are key points to note:

1. Off State:

Normally, Q_1 allows no output current unless we apply forward voltage to its base- emitter circuit.

2. Forward Voltage:

The amount of output current is controlled by the forward voltage that controls base current.

- ➢ The input control circuit determines base current.
- ➢ The output current is collector current for the power circuit.
- ➢ Q_1 is an NPN transistor, needing a positive VBE for forward voltage.
- ➢ The emitter is common to both input control and power circuits.
- ➢ Common-emitter (CE) circuit is the most common transistor arrangement.

When switch S_1 is open:

- ➢ No current flows the base-emitter or control circuit because no forward voltage is applied.
- ➢ Resistance from emitter to collector of the transistor is very high.
- ➢ No current flows in the power circuit, and the lamp doesn't light up.

When switch S_1 is closed:

- A small current flows in the control circuit.
- R_1 limits current in the base circuit.
- Resistance from emitter to collector of Q1 decreases.
- A large current flows in the power circuit, lighting up the lamp.

Opening switch in the control circuit turns off the lamp in the power circuit because resistance from emitter to collector of Q_1 increases again, almost to infinity.

Common Collector (CC) Circuit:

Advantages:

CC amplifiers offer high current gain and low input impedance, making them suitable for applications where a high-resistance input needs to drive a low-resistance output load.

Applications:

Commonly used in impedance matching and signal buffering circuits due to their favorable characteristics.

Operational Amplifier:

An operational-amplifier is a direct coupled high gain amplifier. It can be operated on both with AC and DC signals. Operational Amplifier, also called as an Op-Amp, is an integrated circuit, which can be used to perform various linear, non-linear, and mathematical operations

Effects of negative feedback on the gain of an operational amplifier:

Negative Feedback:

Negative feedback occurs when a portion of the output signal, like voltage or current, is feedback into the input in a way that opposes or subtracts from the input signal.

Advantages:

1. Reduced Gain: Negative feedback decreases the overall gain of the system.

2. Decreased Distortion and Noise: It minimizes distortion and noise, leading to a cleaner output signal.

3. Improved Stability: The gain becomes more stable and less sensitive to external changes, such as temperature.

4. Increased Bandwidth: Enhances the system's bandwidth.

5. Better Impedance: Lowers the output impedance and raises the input impedance.

EXERCISE

Section (A): Multiple Choice Questions (MCQs)

Choose the correct answer:

1. A semiconductor is an element with a valence electron

(a) Four (b) Eight (c) Two (d) One

2. A pure semiconductor is known as

(a) Extrinsic (b) Intrinsic (c) Transistor (d) Diode

3. An acceptor atom is also called

(a) Penta-valent atom (b) Trivalent atom

(c) Minority carrier (d) Majority carrier

4. With which one of the following elements silicon should be doped so as to give p-type of semiconductor?

(a) Germanium (b) Arsenic (c) Selenium (d) Boron

5. For a full-wave rectifier, the output frequency

(a) Equals one-half the input frequency (b) Equals the line frequency

(c) Equals two times the input (d) Is three times the line frequency

6. LED construction needs a semiconductor material is:

(a) Silicon (b) Germanium (c) Gallium (d) Gallium arsenide

7. The frequency of a half-wave signal is

(a) Twice the line frequency (b) Equal to the line frequency

(c) One-half of the line frequency (d) One-fourth the line frequency

8. The voltage gain of an emitter follower circuit is

(a) High (b) Low (c) Very high (d) Moderate

9. What is also called as the conventional amplifier?

(a) Common-collector circuit (b) Emitter follower circuit

(c) Common base circuit (d) Common emitter circuit

10. An op-amp with negative feedback provides output parameter.

(a) Gain (b) Bandwidth

(c) Input-output impedance (d) Amplified

Section (B): CRQS (Short Answered Questions):

1. Describe a p-n junction (diode) and how holes and electrons are produced in semiconductor?

A **p-n junction** is formed when a p-type semiconductor (doped with acceptor atoms) is joined with an n-type semiconductor (doped with donor atoms).

- **Holes:** In a p-type semiconductor, the majority charge carriers are holes, which are essentially the absence of an electron.
- **Electrons:** In an n-type semiconductor, the majority charge carriers are electrons.

When a p-n junction is formed, electrons from the n-side diffuse into the p-side, and holes from the p-side diffuse into the n-side. This results in a region near the junction called the **depletion region** where there are no free charge carriers.

2. Define and distinguish between p-n-p & n-p-n transistors?

- **p-n-p transistor:** A transistor with three layers: p-type, n-type, and p-type.
- **n-p-n transistor:** A transistor with three layers: n-type, p-type, and n-type.

The main difference between the two is the type of majority charge carrier that flows through the transistor. In a p-n-p transistor, holes flow, while in an n-p-n transistor, electrons flow.

3. Explain common-base and common collector configurations?

Common-base configuration: In this configuration, the base terminal is common to both the input and output. It is characterized by high input impedance and low output impedance.

Common-collector configuration: In this configuration, the collector terminal is common to both the input and output. It is characterized by low input impedance and high output impedance.

4. Describe the operations of transistors.

Transistors can be used as switches or amplifiers.

- **Switch:** When a transistor is in saturation mode (with a high base current), it acts as a closed switch, allowing current to flow between the collector and emitter. When the base current is low, the transistor is in cutoff mode, acting as an open switch.
- **Amplifier:** In the common-emitter configuration, a transistor can be used as a small-signal amplifier. A small change in base current can produce a large change in collector current, resulting in amplification.

5. Explain the use of transistors as a switch and an amplifier (common-emitter).

Switch: As mentioned above, a transistor can be used as a switch to control the flow of current. This is a fundamental application in digital circuits.

Amplifier: In the common-emitter configuration, a transistor can amplify small AC signals. This is used in audio amplifiers, radio receivers, and other electronic devices.

6. How would you understand the effects of negative feedback on the gain of an operational amplifier?

Negative feedback is a technique where a portion of the output signal is fed back to the input in a way that opposes the original input signal. This has several effects on the amplifier:

- **Reduces gain:** Negative feedback reduces the overall gain of the amplifier.
- **Increases stability:** It makes the amplifier less sensitive to variations in component values and temperature.
- **Reduces distortion:** It helps to reduce nonlinear distortion in the amplifier's output.
- **Improves bandwidth:** It can increase the amplifier's bandwidth, allowing it to amplify a wider range of frequencies.

The amount of gain reduction due to negative feedback depends on the feedback factor, which is the ratio of the feedback voltage to the output voltage.

7. Draw and briefly describe the circuit diagrams for both the inverting and the non-inverting amplifier for single signal input?

8. Derive an expression for the gain of inverting amplifiers by using virtual earth approximation.

9. Describe the properties of an ideal operational amplifier.

Infinite Open-Loop Gain: This means that the op-amp can produce an arbitrarily large output voltage in response to an infinitesimally small input voltage.

Infinite Input Impedance: The op-amp has an extremely high input impedance, which means that it draws negligible current from the input signal source.

Zero Output Impedance: The op-amp has a very low output impedance, which means that it can deliver a large current to a load without experiencing a significant voltage drop.

Infinite Bandwidth: The op-amp can amplify signals of any frequency without attenuation.

Zero Input Offset Voltage: The op-amp produces zero output voltage when there are no input signals applied.

Zero Input Offset Current: The op-amp does not produce an output voltage when there are no input currents flowing.

Section (C) ERQS (Long Answered Questions):

1. Define Intrinsic (pure) and doped semiconductors. And How the N-type and P-type semiconductors are produced

2. Describe a P-N junction (diode) discus its forward and reverse biasing.

3. Describe the I-V characteristic curves of P-N junction.

4. Define rectification and describe the use of diodes for half and full wave rectifications.

5. Describe the function and use of LED, Photodiode and Photo voltaic cell Describe the function and use of LED, Photodiode and Photo voltaic cell.

6. Explain the use of transistors as a switch and an amplifier (common-emitter).

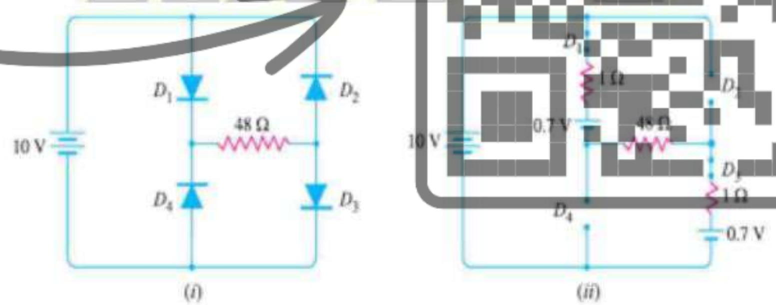
7. Describe the properties of an ideal operational amplified.

Section (D)) Numerical:

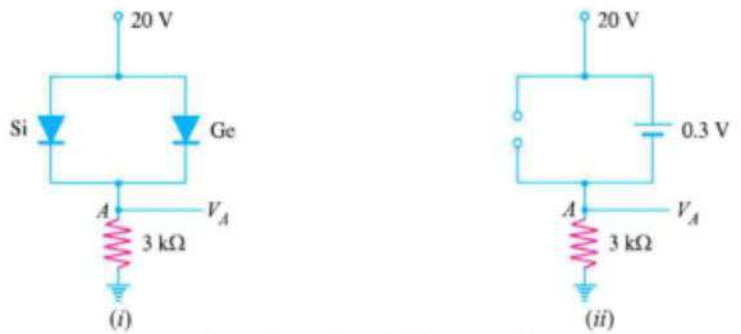
1. A Ge diode has a voltage drop of 04 V when 12 mA flow through it. If the same 470 Ohm is used, what battery voltage is needed? (6.04 V)

2. A semiconductor diode laser has a peak emission wavelength of 1.55 μm. Find its band gap in eV. (0.8 eV)

3. Calculate the current through 48 2 resistor in the circuit shown in Fig. (i). Assume the diodes to be of silicon and forward resistance of each diode is 1 Ω. (8.6 V, 50 Ohm, 172 mA)



4. Find the voltage Va in the circuit shown in Fig.(i). Use simplified model. (19.7 V)

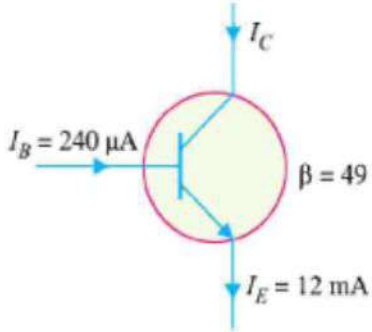


5. In a common base connection, I; = ImA, Ic=0.95mA. Calculate the value of IB. (0.05 mA)

6. Find the value of β if (i) α= 0.9 (ii) α=0.98 (iii) α =0.99. (9,49, 99)

7. Calculate Ie in a transistor for which B= 50 and Ip 20 μA. (1.02 mA)

8. Find the α rating of the transistor shown in Fig. Hence determine the value of Ic using both α and β rating of the transistor. (0.98, 11.76)



Unit 23

Digital Electronics

Introduction:

Digital electronics is a branch of electronics that deals with the manipulation of digital signals, represented as binary digits (Os and 1s).

Digital signal levels:

In digital electronics, signal levels are represented in various ways. Here are common digital signal levels:

1. Low Level (0): KNOW

- This represents the binary digit 0. Noise immunity is a
- In terms of voltage, it is associated with a lower voltage measure of how well a level.
- Often referred to as "low" or "logic 0."

2. High Level (1): electrical signals or noise

- This represents the binary digit 1. without reacting to them.
- In terms of voltage, it is associated with a higher voltage level.
- Often referred to as "high" or "logic 1."

3. Threshold Level: DO YOU

- The threshold level is the voltage level that separates low and high states.
- Signals below this threshold are interpreted as 0, signals above it are interpreted as 1.
- The threshold level helps define the noise margin and ensure reliable signal interpretation.

4. Logic Levels: HIGH or LOW can be

- Depending on the technology and the system, different utilized.
- logic levels might be used.

5. Swing or Voltage Range:

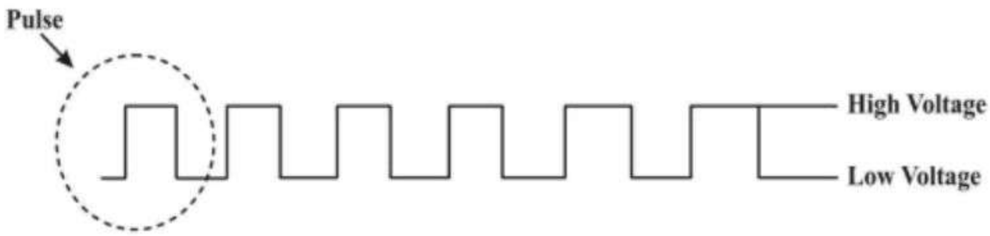
- The difference in voltage levels between low and high states is often referred to as the swing or voltage range. For example, voltage varies from -5V to +5V will have a swing or voltage range of 10V.
- A larger voltage swing can enhance noise immunity and signal reliability.

Understanding Digital Signal Levels:

In digital electronics, the 'high' and 'low' states are often symbolically represented as 'I' and '0,' respectively. This binary notation helps describe the states of open and closed circuits.

High State (1): When a digital signal is in a high' state, it is typically associated with a closed circuit or a voltage level close to the maximum specified value. The symbolic representation for this state is "I. It signifies the 'on' or 'active' state in many digital systems.

Low State ('0): Conversely, the 'low' state is linked to an open circuit or a voltage level close to the minimum specified value. It is symbolically represented as 0". This state signifies the 'off or 'inactive' state in digital systems.



Logic gates:

Logic gates are tiny electronic switches that enable decision-making in computers and other devices. They combine to perform logical operations, playing a crucial role in information processing.

Types of Logic Gates:

Logic gates are the basic components of the digital circuit with one output and more than one input.

AND, OR, and NOT gates are the basic gates,

while NAND and NOR are the universal gates.

EX-OR and EX-NOR are the special gates.

1. AND Gate:

The AND gate produces a 'high' output only when all its inputs are 'high.'

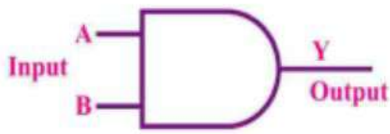


Figure 23. 2 AND gate

2. OR Gate:

An OR gate generates a 'high' output if any of its inputs are 'high.

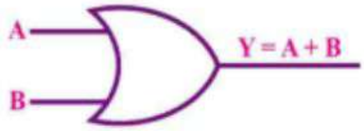


Figure 23. 3 OR gate

3. NOT Gate:

It is used to perform the inversion operation in digital circuits,

For example, the output of a NOT gate attains state 1 if and only if the input does not attain state 1.

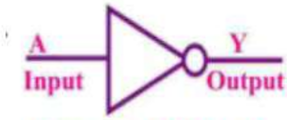


Figure 23. 4 : NOT gate

4. NAND Gate:

Similarly, a NAND gate is an AND gate followed by a NOT gate, yielding the opposite output of an AND gate.

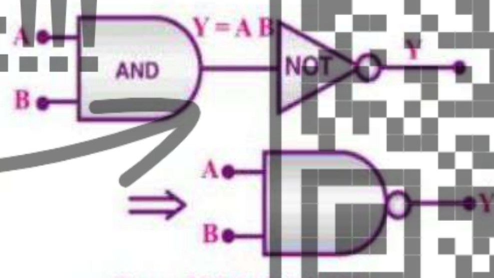


Figure 23.5 NAND GATE

5. NOR Gate:

A NOR gate is an OR gate followed by a NOT gate, providing the opposite result of an OR gate.

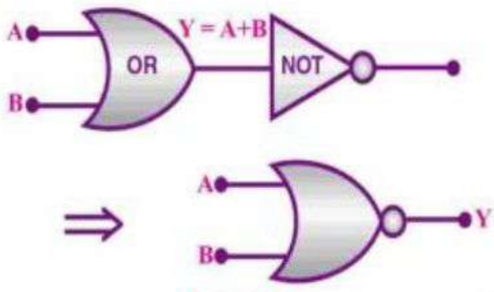
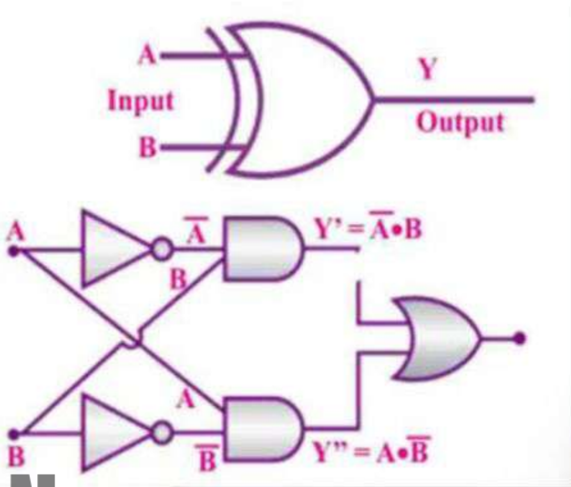


Figure 23. 6
NOR gate and its equivalent diagram

6. XOR Gate (Exclusive-OR Gate):

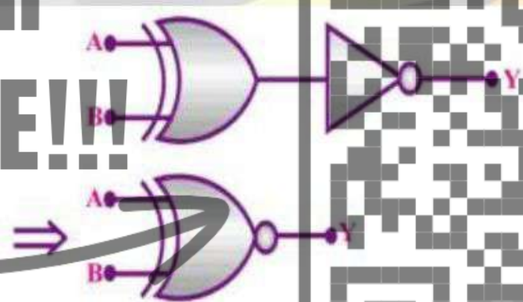
The XOR gate outputs a 'high' signal if the number of "high' inputs is odd.

In other words, the Input Output output of a two-input XOR gate attains state 1 if one B adds only input and attains state 1.



7. XNOR Gate (Exclusive-NOR Gate):

In the XNOR gate, the output is in state I when both inputs are the same, that is, both 0 or both 1.



EXERCISE

Section (A): Multiple Choice Questions (MCQS)

Choose the correct answer:

1. The voltage level, typically associated with a 'low' state in digital electronic is:

(a) -5 volts (b) 0 volts (c) +5 volts (d) +10 volts

2. In binary representation, the correspond of 0' in digital electronics is:

(a) Low state (b) High state (c) Open circuit (d) Closed circuit

3. The primary purpose of a truth table in digital electronics is to:

(a) Determine input voltage

(b) Measure circuit resistance

(c) Analyze output states based on input combinations

(d) Calculate circuit power

4. Which logic gate combination produces an output of"1' when at least one input is '1?

(a) AND (b) OR (c) XOR (d) NOT

5. In a circuit with a 2-input OR gate, the status of the lamp if either switch is closed

(a) OFF (b) ON (c) Blinking (d) Flickering

6. The behavior of 2 input AND gate, when both switches are closed, Lamp is

(a) OFF (b) ON (c) blinking (d) flickering

7. In a 3-input OR gate, if all inputs are '0'sothe output will be:

(a) 1 (b) 0 (c) Undefined (d) Both A and B

8. If the input is '1', The output of a NOT gate will be:

(a) 1 (b) 0 (c) Undefined (d) Both A and B

9 In a 2-input XOR gate, when both inputs are '1' than the output will be

(a) 1 (b) 0 (c) Undefined (d) Both A and B

10. Which combination of logic gates is equivalent to an XOR gate?

(a) AND + OR (b) NOT+ NOR (c) OR + NAND (d) AND+ NAND

Section (B): CRQs (Short Answered Questions):

1. Explain the significance of signal levels in digital electronics and how they are represented in terms of voltage.

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Signal levels are essential in digital electronics as they represent the fundamental units of information, '0' and '1'. These levels are typically defined in terms of voltage ranges.

- **High Level:** This corresponds to a voltage above a certain threshold, often denoted as 'V_H'. It represents the logical '1' state.
- **Low Level:** This corresponds to a voltage below a certain threshold, often denoted as 'V_L'. It represents the logical '0' state.

The specific voltage thresholds for high and low levels depend on the technology used (e.g., TTL, CMOS). However, the key point is that there must be a clear distinction between the two levels to ensure reliable data transmission and processing.

2. Describe the binary representation used in digital electronics. How is this representation related to the 'high' and 'low' states?

Binary representation is the system used to represent data in digital electronics. It uses only two digits, '0' and '1', to represent different values. Each digit is called a **bit**.

The relationship between binary representation and high/low states is straightforward:

- **'1'** in binary corresponds to the **high** signal level.
- **'0'** in binary corresponds to the **low** signal level.

For example, the binary number '101' represents the decimal number 5, where the first '1' is a high level, the '0' is a low level, and the second '1' is a high level.

3. Choose any three logic gate symbols and explain their operations.

Here are three common logic gate symbols and their operations:

- **AND Gate:**
  - Symbol: ∧
  - Output is high only when both inputs are high.
- **OR Gate:**
  - Symbol: ∨
  - Output is high when at least one input is high.
- **NOT Gate:**
  - Symbol: ¬
  - Output is the inverse of the input (high if input is low, and vice versa).

4. Create a combination of logic gates that mimics the behavior of an XOR gate.

An XOR (exclusive OR) gate produces a high output only when the inputs are different. We can create an XOR gate using AND, OR, and NOT gates as follows:

1. **Create two AND gates:** Connect one input of each AND gate to each input of the XOR gate.
2. **Invert the outputs of the AND gates:** Use two NOT gates to invert the outputs of the AND gates.
3. **Create an OR gate:** Connect the outputs of the inverted AND gates to the inputs of an OR gate.

The output of the OR gate will now mimic the behavior of an XOR gate.

Section (C): ERQs (Long Answered Questions):

1. Design a simple circuit using a 2-input AND gate, a switch, a lamp, and a battery. Explain how the circuit operates and the conditions under which the lamp will be illuminated.

2. Construct a truth table for a 3-input OR gate. Explain how the truth table represents the relationship between input combinations and the resulting output.

Unit 24

Relativity

Frame of References

A rigid framework (usually x, y and z- axes) relative to which the position and motion of an object can be measured is called frame of references.

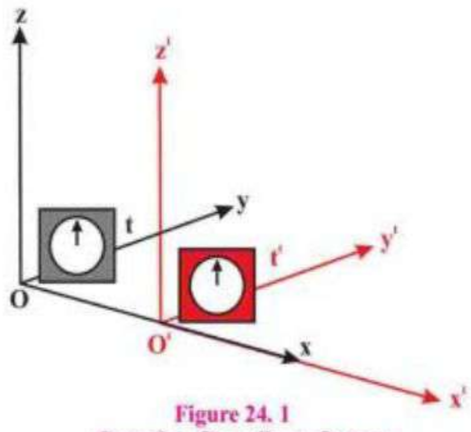


Figure 24. 1
Cartesian Co-ordinate System

Relative Motion:

Relative motion is a concept that describes the motion of an object in relation to another observer or frame of reference. This viewpoint recognizes that motion is not absolute but depends on the observer's point of view.

Types of Frames of References:

There are two types of frames of reference, Inertial frames of reference an non-cinertial frames of reference.

Criteria Inertial frame of Reference Non-Inertial frame of Reference

Acceleration: Inertial frames are not accelerating, while non-inertial frames are.

Newton's Laws: Newton's laws of motion apply directly in inertial frames. In non-inertial frames, additional forces (called fictitious or pseudo-forces) must be introduced to explain the observed motion.

Examples:

- **Inertial frame:** A car moving at a constant speed on a straight highway.
- **Non-inertial frame:** A car accelerating or turning a corner, a rotating merry-go-round.

Special Theory of Relativity:

Special theory of relativity explains how to interpret motion between different inertial frames of reference.

In other words, it deals with the problems in which one frame of reference moves with a constant linear velocity relative to another frame of reference.

The Postulates of Special Relativity:

The special theory of relativity is based on two essential assumptions, commonly known as postulates.

Postulate 1 (Principle of Relativity):

The laws of Physics have the same form in all inertial frames of reference.

Postulate 2 (Constancy of the speed of light):

The speed of light in vacuum has the same value, $c=3 \times 10^8$ m/s in all inertial reference frames, regardless of the velocity of the observer or the velocity of the source emitting the light.

Space and Time are Relative:

When the speed of light is constant, the time and space become relative concepts and are no longer absolute according to Newton.

Consequences of Special Theory of Relativity:

In Relativity, there is no such thing as an absolute length or absolute time interval.

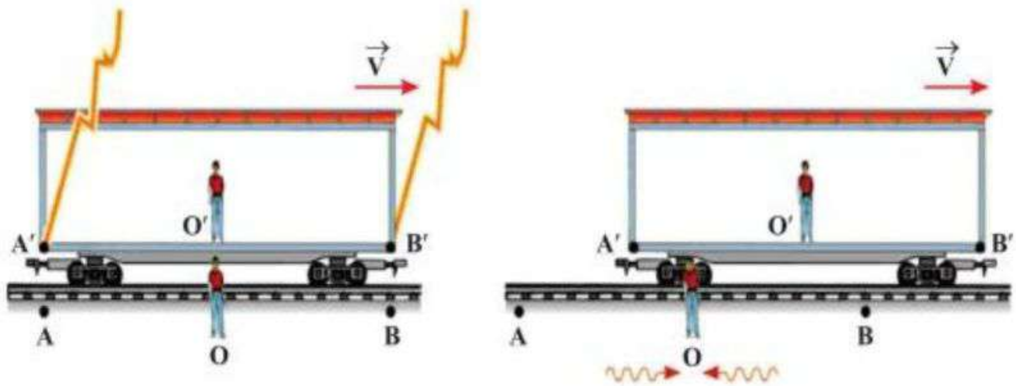
Here are some of the most important consequences of special relativity:

Relativity of Simultaneity:

Two events that are simultaneous in one reference frame are in general not simultaneous in a second frame moving relative to the first.

Here's an example to illustrate this concept:

Imagine two observers, Boy A and B, standing on a train platform. They are equidistant from the center of the platform. At the exact moment when the train passes the center of the platform, lightning strikes both ends of the train.



From boy A's perspective:

Boy A sees the lightning strikes happen the same time because he is stationary relative to the platform. Since light travels at a finite speed, the light from both lightning strikes reaches boy A simultaneously.

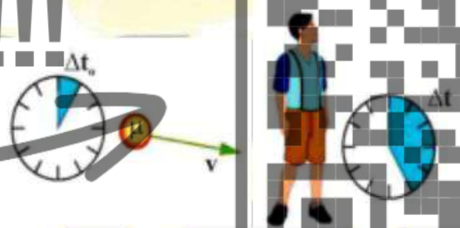
From boy B's perspective:

Boy B, however, is sitting on the moving train. Because the train is moving toward the lightning strike at the front of the train and away from the lightning strike at the back of the train, light takes longer to reach him from the back of the train than from the front. As a result, Boy b perceives the lightning strike at the front of the train before the lightning strike at the back of the train. Thus, for boy B, the lightning strikes are not simultaneous.

This example demonstrates how the perception of simultaneity can differ between observers depending on their relative motion. In this case, what appears simultaneous to boy A (the lightning strikes) does not appear simultaneous to boy B due to his motion relative to the events.

Time Dilation:

The time interval, between two events occurring at a given point in the moving frame S' appears to be longer to the observer in the stationary frame S. This effect is called time dilation.



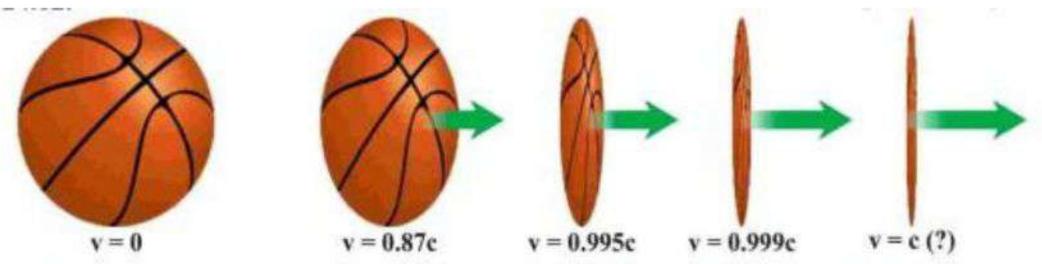
Let At, be the proper time measured by a clock that is at rest. The relative time t measured in another frame of reference is given by

$$\Delta t = \frac{\Delta t_o}{\sqrt{1-\frac{v^2}{c^2}}}$$

Length Contraction:

Let L, be the length of a rod when the rod is stationary. If there is relative motion at speed v between an observer at rest and the rod along the length of the rod, then observer will calculate a relativistic length L given by

$$L = L_O\sqrt{1-\frac{v^2}{c^2}}$$



Mass Variation:

Let m, be the rest mass of an object. If the object is moving at speed v then its relativistic mass m will be given by

$$m = \frac{m_o}{\sqrt{1 - \frac{v^2}{c^2}}}$$

Mass Energy Relationship:

For an object to travel at light

According to Einstein's special theory of relativity, mass and energy are interchangeable. An object's mass m and the equivalent energy E, are related by:

$$E_o = mc^2$$

If the object is moving, it has additional energy in the form of kinetic energy K. The total energy E is the sum of its mass energy and its kinetic energy:

$$E = E_o + K + mc^2 + K$$

$$E = \gamma mc^2$$

where γ is the Lorentz factor for the object's motion.

E is the total relativistic energy of the object.

From above equations, relative kinetic energy can be calculated as:

$$K = E - E_o = E - mc^2 = \gamma mc^2 - mc^2$$

$$K = mc^2 (\gamma - 1)$$

Maximum Velocity of A Particle:

A basic result of the special theory of relativity is that the speed of an object cannot equal or exceed the speed of light. That the speed of light is a natural speed limit in the universe can be seen from above equations of mass variation, length contraction, time dilation and mass-energy relationship. If an object is accelerated to greater speeds, its mass becomes larger and larger. Indeed, if v were equals to c, the denominator in the equation would be zero and the mass would become infinite. To accelerate an object up to y=c would thus require infinite energy, and so it is not possible.

Time Dilation:

Special relativity also predicts time dilation, meaning that as an object approaches the speed of light, time appears to slow down for the object relative to an observer at rest. This effect becomes more pronounced as the object's velocity approaches c. Consequently, from the perspective an observer, it would take an infinite amount of time for a massive object to reach the speed of light.

Length Contraction:

Another consequence of special relativity is length contraction, where objects moving at relativistic speeds appear shorter in the direction of motion when observed from a stationary frame. This effect prevents objects from achieving relativistic velocities within a finite distance because, as the object's velocity increases, its length contracts in the direction of motion, making it increasingly difficult to accelerate further.

Relativistic Effects in Space Travel:

The implications of mass increase, time dilation, and length contraction for space travel are profound and have significant consequences for our ability to explore the universe at relativistic speeds. Here's how each of these effects impacts space travel:

Mass Increase:

- The implication for space travel is that as spacecraft approach relativistic speeds, their mass increases exponentially. This makes it increasingly difficult to accelerate them further, requiring enormous amounts of energy.
- Overcoming the mass increase becomes a significant engineering challenge for spacecraft propulsion systems. Current propulsion technologies, such as chemical rockets, would become impractical at relativistic speeds due to the massive energy requirements.

Time Dilation:

- For space travelers moving at relativistic speeds, time dilation means that their perception of time differs from that of stationary observers. A journey that may take several years according to Earth-based observers could be experienced as much shorter by the travelers due to time dilation.
- Time dilation has implications for interstellar travel, where long-duration missions could be undertaken without experiencing the full effects of time passing, as perceived by Earth-based observers. However, it also presents challenges for communication and synchronization with mission control on Earth.

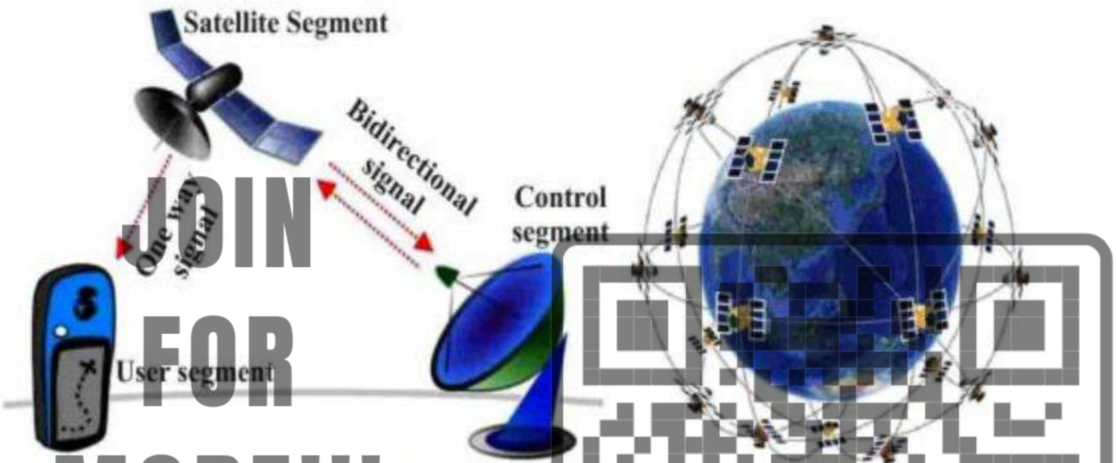
Length Contraction:

- For space travelers, length contraction means that distances along their direction of motion appear shorter. This has implications for navigation and spacecraft design, as distances may be perceived differently by travelers moving at relativistic speeds compared to stationary observers.

- Additionally, length contraction affects the perception of space travel distances. What may appear as a vast distance to stationary observers could be contracted from the perspective of travelers moving at relativistic speeds.

Navigation Satellite Timing and Ranging (NAVSTAR) SYSTEM):

It is the official name for the Global Positioning System (GPS). It's a network of 24 satellites orbiting Earth that allows us to determine our location on the planet with incredible accuracy.



General Theory of Relativity:

Albert Einstein's general theory of relativity is a new way to explain gravity.

According to Newton, tossed balls curve because of a force of gravity.

According to Einstein, tossed balls and light don't curve because of any force, but because the space time in which they travel is curved.

General relativity describes how gravity is caused by the curvature of space-time.

The general theory of relativity is based the following two postulates.

Figure 24. 14
Spacetime wrapping near heavy objects

Postulate I:

The laws of physics may be expressed in equations having the same form in all frames of reference, regardless of their states of motion.

Thus, the general theory covers uniform as well as accelerated motion. Hence it is able to describe gravitational phenomena.

Postulate II (Principle of equivalence):

There is no way to spot the difference between gravity and acceleration for an observer in a closed laboratory

General relativity has a number of consequences:

- Einstein's general theory of relativity states that time is a fourth dimension adding to the three dimensions of space. Einstein called this four-dimensional geometry as space-time.
- The general theory of relativity also predicted light coming from a strong gravitational field would have its wavelength shifted toward longer wavelengths, called a red-shift.
- The theory also predicted that when gravity becomes great enough, it would produce objects called black holes. Black holes are objects whose gravity is so massive that light cannot escape from the surface at all. Since no light can escape, such objects would appear black
- Light is bent as it passes through curved space-time. This can cause distant objects to appear distorted or magnified. Gravitational lensing has been used to study distant galaxies and other objects.
- The expansion of the universe: General relativity predicts that the universe is expanding. This has been confirmed by astronomical observations.

Gravity as Space Time Continuum:

According to General Theory of Relativity, when you put mass in space-time, it bends the geometry of space- time.

According to this theory, gravity is not just a force between masses, as described by Newtonian physics, but rather a manifestation of c the curvature of space-time caused by mass and energy.

Here's a breakdown of what this concept entails:

Space and time Continuum

Space and time are unified into a single, four- dimensional entity known as space-time. In the absence of gravity or significant mass, space time is flat.

However, the presence of mass and energy warps or curves the fabric of space-time. This curvature is what we perceive as the force of gravity.

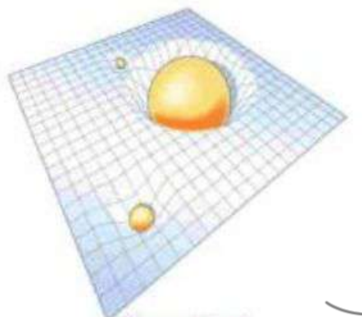


Figure 24. 15
Heavier object bends the geometry of spacetime more than lighter object

Curvature of Space-time:

- Massive objects, such as stars, planets, and galaxies, curve the space-time around them. The greater the mass or energy density, the greater the curvature of space-time.
- Objects move along paths dictated by the curvature of space-time, which we perceive as being influenced by gravity. For example, Earth orbits the Sun because the Sun's mass curves the space-time around it, causing Earth to follow a curved path.

Effects of Gravity

- In the presence of gravity, objects follow the shortest possible paths, known as geodesics, through the curved space-time. These paths are not necessarily straight. direction
- Lines in the traditional sense but are instead curved trajectories determined by the gravitational field.
- The strength of gravity is determined by the curvature of space-time. The steeper the curvature, the stronger the gravitational force experienced by nearby objects.

Physical Interpretation:

Gravity is thus interpreted as the result of objects moving through the curved space-time created by mass and energy. Massive objects "warp" the space-time around them, causing other objects to move in response to this curvature.

This concept provides a unified explanation for both the gravitational force and the motion of objects in space, incorporating both space and time into a single framework.

EXERCISE

Section (A): Multiple Choice Questions (MCQS)

Choose the correct answer:

1. The General Theory of Relativity was a new way of understanding of

(a) The speed of light (b) gravity (c) mass (d) force

2. An object at rest has a mass of 1 kg. What is its mass when it is moving at a speed of 0.9c?

(a) Infinite (b) 1.2 kg (c) 2.3 kg (d) 1 kg

3. The equivalence of principle in general relativity is:

(a) The equivalence of inertial and gravitational mass

(b) The equivalence of electric and magnetic fields

(c) The equivalence of space and time

(d) The equivalence of matter and energy

4. Which of the following phenomena is NOT predicted by special relativity?

(a) Time dilation (b) Length contraction

(c) Gravitational waves (d) Relativistic mass increase

5. What does the equivalence principle state about acceleration and gravity?

(a) They are completely different forces (b) They are indistinguishable for an observer

(c) Gravity is stronger than acceleration (d) Acceleration cancels out gravity

6. Light passing near a massive object like a star will bend due to:

(a) Gravitational lensing (b) refraction

(c) reflection (d) diffraction

7. What is the main reason astronomers cannot directly observe black holes?

(a) They are too small (b) They deflect light

(c) They are too far away (d) their immense gravity traps light

8. Objects cannot exceed the speed of light because:

(a) Their mass becomes infinite (b) Their length becomes zero

(c) Time slows down to zero (d) they lose all energy

9. Why is the Galilean transformation not valid at high speeds?

(a) It cannot handle accelerating frames

(b) It violates the constancy of the speed of light

(c) It only works in flat spacetime

(d) It neglects time dilation effects

10. The example of inertial frame in our everyday life is:

(a) A car accelerating on a highway

(b) A train moving smoothly at constant speed

(c) A person standing on a spinning platform

(d) an airplane encountering turbulence

Section (B): CRQs (Short Answered Questions):

1. Show that for values of $v << c$, Lorentz transformation reduces to the Galilean transformation.

The Lorentz transformation equations are:

A basic result of the special theory of relativity is that the speed of an object cannot equal or exceed the speed of light. That the speed of light is a natural speed limit in the universe can be seen from above equations of mass variation, length contraction, time dilation and mass-energy relationship. If an object is accelerated to greater speeds, its mass becomes larger and larger. Indeed, if v were equals to c, the denominator in the equation would be zero and the mass would become infinite. To accelerate an object up to y=c would thus require infinite energy, and so it is not possible.

So, $v << c$

2. If a particle could move with the velocity of light, how much K.E. would it possess?

The relativistic kinetic energy of a particle is given by:

$K.E = (\gamma - 1)mc^2$

As v approaches c, γ approaches infinity. Thus, the kinetic energy of a particle moving at the speed of light would be infinite. This is why it's impossible for a particle with mass to reach the speed of light

3. Explain the difference between Special and General Relativity in simple terms.

Special Relativity deals with the physics of objects moving at constant velocities. It introduces concepts like time dilation, length contraction, and mass-energy equivalence.

General Relativity extends the principles of special relativity to include gravity. It describes gravity as a curvature of spacetime caused by mass and energy. General relativity is essential for understanding phenomena like black holes and the expansion of the universe.

4. Differentiate between Inertial Frames of Reference and Non- Inertial Frames of Reference.

Inertial frames of reference are those in which an object at rest remains at rest, and an object in motion continues to move in a straight line at a constant speed unless acted upon by an external force.

Non-inertial frames of reference are those that are accelerating or rotating. In these frames, the laws of motion do not hold true in their original form.

5. Why can't any object move at the speed of light?

As shown in the answer to question 2, the kinetic energy of a particle moving at the speed of light would be infinite. This is impossible as it would require an infinite amount of energy.

6. What is the limitation in the Galilean Transformation Equation, and how did Lorentz solve it?

The Galilean transformation breaks down at high speeds, especially near the speed of light. It predicts different results for the speed of light measured in different reference frames, which contradicts experimental observations.

7. Calculate the value of y (Lorentz factor) if the object is moving at the speed of light.

As v approaches c, γ approaches infinity. Therefore, the Lorentz factor for an object moving at the speed of light is infinite.

Section (C) ERQS (Long Answered Questions):

1. State and explain the basic postulates of Einstein's special theory of relativity. Discuss length-contraction, mass variation and time-dilation.

Notes

2. Explain the concept of mass-energy equivalence. Derive Einstein's mass-energy relation and demonstrate that 1 atomic mass unit (u) is equivalent to 931 MeV.

Notes

3. Discuss the important conclusions derived from General Theory of relativity. What are the experimental observations in favour of these conclusions?

Notes

4. How does it principle of relativity differ from the classical Galilean view?

Notes

5. Explain the concept of spacetime curvature in general relativity and how it is used to visualize the effects of gravity.

Notes

6. Derive the basic equations of the Galilean transformation and explain how they relate the positions and velocities of objects in different inertial frames.

Notes

7. Discuss the Lorentz transformation equations in special relativity and how they describe the relationship between space and time coordinates in different inertial frames. Give examples to illustrate their application.

Notes

Section (D): Numerical:

1. A rod 1 meter long is moving along its length with a velocity 0.6c. Calculate its length

as it appears to an observer (a) on the earth (b) moving with the rod itself. |Ans: (a) 0.8m, (b) 1 m]

2. How fast would a rocket have to go relative to an observer for its length to be contracted to 99% of its length at rest? (Ans: 42.45 x 10^6m/s)

3. A particle with a proper lifetime of l us moves through the laboratory at 2.7 x 10^8 m/s. (a) What is its lifetime, as measured by observers in the laboratory? (b) What will be the distance traversed by it before disintegrating? (Ans: (a) 2.3 x 10^{-6}s, (b) 620m)

4. At what speed is a particle moving if the mass is equal to three times its rest mass? (Ans:$\frac{2\sqrt{2}}{3}c$)

5. If 4 kg of a substance is fully converted into energy, how much energy is produced?

(Ans: 3.6 x 10^{17}J)

6. Calculate the rest energy of an electron in joules and in electron volts. (Ans: 8.2x 10^{-14}J, 0.511MeV]

7. Calculate the K.E. of an electron moving with a velocity of 0.98 times the velocity of light in the laboratory system. |Ans: 3.3 x 10^{-13}J]

At what velocity does the K.E. of a particle equal its rest energy? (Ans:$\frac{\sqrt{3}}{2}$c)

9. A particle of rest mass m_o moves with speed $\frac{c}{\sqrt{2}}$. Calculate its mass, momentum, total energy and kinetic energy. (Ans: $\sqrt{2}m_o$, m_oc, $\sqrt{2}$ m_oc^2, 0.41 m_oc^2)

10. The nearest star to Earth is Proximal Centauri, 4.3 light- years away. A spaceship with a constant speed of 0.800c relative to the Earth travels toward the star.

(a) How much time would elapse on a clock as measured by travelers on the spacecraft? (Ans: (a) 3.22 years)

(b) How long does the trip take according to Earth observers? (Ans: (b) 5.38 years)

Unit 25

Quantum Physics

Introduction:

Quantum physics is the study of matter and energy at atomic and sub-atomic level.

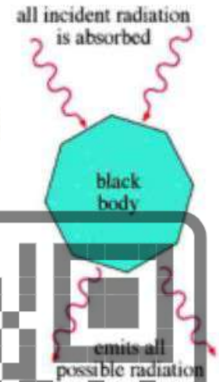
It aims to discover the properties and behaviours of the very building blocks of nature.

Quantum Theory of Radiation:

It was introduced by Max Planck and Albert Einstein It explains how energy is emitted and absorbed in discrete packets (quanta), the key points of Quantum theory of radiation are:

- Energy is quantized (small packets, not continuous)
- Frequency (not amplitude) determines energy of radiation
- Radiation has both wave and particle properties (duality)

This theory revolutionized our understanding of light and radiation



Black Body Radiation:

A black body is an idealized object which absorbs all incident radiation and also emits it in a continuous spectrum of colors, depending upon its temperature

Classical explanation of black body significant challenge to radiation:

Rayleigh-Jeans Law:

This Law states that the energy per unit volume per unit wavelength of blackbody radiation is inversely proportional to the fourth power of the wavelength (λ), not directly proportional to the square of the wavelength.

The law is given by the formula:

$$E(\lambda, T) = \frac{2cKT}{\lambda^4}$$

Mathematically expressed as:

$$E(\lambda, T) = \frac{Constant}{\lambda^4}$$ where:

E(λ, T) is the spectral radiance Intensity

λ is the wavelength

Wien's Displacement Law:

This law breaks down completely at low frequencies.

Wien's displacement law states that the wavelength at which the intensity of blackbody radiation is maximum is inversely proportional the temperature of the blackbody.

As the temperature increases, the peak of the blackbody radiation curve shifts to shorter wavelengths. This relationship is mathematically expressed as:

$$\lambda_{max} T = \text{Constant}$$

$$\lambda_{max} = \frac{Constant}{T}$$

Where λ_{max} is the wavelength at which a blackbody radiates at a given temperature I.

Stefan's Law:

The experimental relation is known as Stefan Boltzmann's law;

It states that the total energy radiated per unit surface area of a black body is proportional to the fourth power of its temperature.

Mathematically, it is expressed as:

$$P = \sigma A T^4$$

Where A is the surface area of a blackbody, T is its temperature. temperature and σ is the Stefan's-Boltzmann constant,

$\sigma = 5.67 \times 10^{-8}$ W/ (m^2. K^4).

Planck's Hypothesis:

Planck proposed that electromagnetic energy could only be emitted or absorbed in discrete packets, which he called "quanta." This assumption led to the concept of energy levels being quantized, meaning that the energy could only take on certain discrete values. The energy (E_n) of an oscillator in the cavity walls is given by the equation:

$$E_n = nhf$$

where: E_n is the energy of the oscillator is an integer (1, 2, 3, ...), h is Planck's constant, f is the frequency of the oscillator.

Photoelectric Effect:

When electromagnetic radiation like light is shined on certain metallic materials; electrons are emitted due to absorption of light by the electrons on the surface of material.

Photoelectric Effect Phenomenon:

The photoelectric phenomenon is shown in figure in which an evacuated tube containing two electrodes cathode and anode; connected with a variable source voltage V. A monochromatic light source is shined onto cathode through a quartz window and anode (collecting electrode) is connected either positive or negative potential with respect to the cathode. An ammeter is connected with circuit to record the current due to photo-electrons.

Following observations were made during this experiment:

1. For a constant potential difference between the cathode and anode, the number of electrons emitted from cathode increases with increasing intensity of radiation.

2 For a constant intensity and frequency of incident radiation the photoelectric current varies with the potential difference V between the cathode and anode and reaches a constant value beyond which further increase of potential difference does not affect the photoelectric current, instead, if the anode is made more and more negative with respect of the photo-cathode surface the current decreases. This negative potential (with respect to cathode) of the plate is called retarding potential.

For a particular value of retarding potential, photoelectric current becomes zero.

This potential is called cut-off or stopping potential lVo and is measure of maximum kinetic energy of photo-electrons and we can write

$$K.\ E_{max} = eV_o$$

3. The stopping potential and hence the maximum kinetic energy K. Emax of photo-electrons is independent of the intensity of incident radiation and depends only on the frequency v of radiation.

4. For each substance there exists a characteristic frequency vo such that for radiation with frequency below the photo-electrons are not ejected from the surface. This frequency is called the threshold frequency and the corresponding wavelength is called Threshold wavelength, $\lambda_o = \frac{hc}{\varphi}$

5. The time lag between the incidence of radiation and the emission of a photoelectron is very small, less than 10^{-9} seconds.

Explanation of photo-electric effect on Quantum Theory:

Einstein proposed that radiation energy is not continuously distributed over the wave-front, but the light energy consists of discrete quanta of energy hv, which penetrates the surface of the cathode, all of its energy is transformed to an electron; it's depicted in figure 25.6. The photon's energy would be associated with its frequency *v*, through a proportionality constant known as Planck's constant h, or alternately, using the wavelength . and the speed of light c:

$$K.E = hv = \frac{hc}{\lambda}$$

or the momentum equation:

$$p = \frac{h}{\lambda}$$

When a photon is incident on the surface of a material, some of its energy is spent in making the electron free and the rest appears as kinetic energy of the electron. The electrons at the surface of the material are most loosely bound and require minimum energy for their liberation. This energy is called the work function φ of the material. The maximum kinetic energy of photo electrons ejected from the surface is given by

$$K.E_{max} = \frac{1}{2} mv^2 = h\nu - \phi$$

So, work function the minimum energy that must be supplied to the electron for it to leave the Metal surface.

Consequently there exists a minimum frequency that is independent of the intensity of light, below which electrons cannot be ejected from the metal. This proposal was proved by Millikan when in 1914 he published his results of the voltage required to stop photoelectrons ejecting from a metal surface.

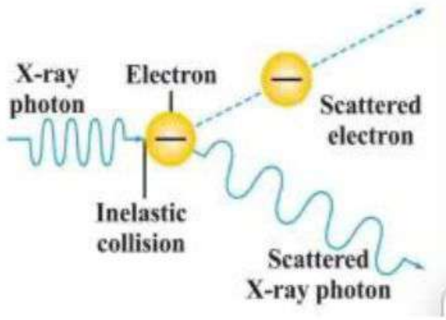
Photoelectric effect in solar cells and photocells:

Photovoltaic cells are made up of p-type and n-type silicon semiconductors. When light falls on the junction between p-type and n-type semiconductors, electrons are emitted according to the photoelectric effect. These electrons are collected in an external circuit to produce an electric current.

- Photocell, a device that uses the photoelectric effect to generate or control a current.
- Photovoltaic cells and photoconductive cells are examples of photoelectric cells.
- Solar cell, a device that converts electromagnetic energy into electrical energy.
- Photovoltaic cells are used to power a wide variety of devices, and are often used in conjunction with a battery that stores the power they produce.

Compton Effect:

He observed that the scattered light had a slightly longer wavelength than did the incident light, and therefore a slightly lower frequency indicating a loss of energy.



He explained this result based on the photon theory as incident photons colliding with electrons.

Compton Effect Qualitatively:

Compton's Effect, as illustrated in Figure 25.8, can be qualitatively explained as follows:

Initial Interaction:

A photon, which is a packet of electromagnetic energy, interacts with an electron in a material, typically a target like a metal or graphite.

Scattering Process:

During the interaction, the photon transfers some of its energy and momentum to the electron. This transfer causes the photon to change its direction and wavelength (or equivalently, its frequency).

Change in Photon Energy:

The scattered photon emerges with less energy (longer wavelength) than the initial incident photon. The amount of energy lost by the photon is directly related to the energy and momentum gained by the electron.

Quantum Nature:

Compton's Effect cannot be explained using classical wave theory alone. Classical wave theory predicts that light should scatter uniformly without a change in wavelength.

However, Compton's observations demonstrated that the scattered light has a shifted wavelength, indicating a particle-like interaction.

Experimental Confirmation:

Compton conducted experiments where X-rays were targeted at graphite and the scattered X-rays were observed. By measuring the scattering angle and change in wavelength, he confirmed that the results were consistent with the predictions of quantum theory.

Wavelength Shift:

The wavelength shift observed in Compton scattering is directly proportional to the Compton wavelength, which depends on the mass of the electron and the Planck constant. This relationship provides crucial evidence for the particle nature of photons.

The Compton shift can be evolved as under:

$$\lambda 2 - \lambda 1 = \frac{hc}{E_o}(1 - Cos\theta) = \frac{h}{m_o c}(1 - Cos\theta)$$

$$\Delta\lambda = \frac{h}{m_o c}(1 - Cos\theta)$$

This equation describes the phenomenon known as Compton Effect.

Pair Production:

Pair production is a phenomenon in quantum mechanics that occurs when a photon with sufficient energy interacts with matter and spontaneously transforms into a particle-antiparticle pair i.e., an electron and a positron, as shown in figure 25.9.

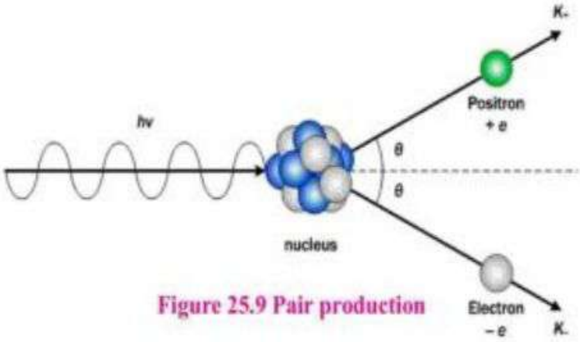


Figure 25.9 Pair production

Conservation laws of Pair-Production:

Facts of pair production process are:

1. The pair production process obeys law of conservation of energy, momentum and electric charge respectively.

2. During collision, the antiparticle of an electron i.e., positron has the same physical properties as electron, except its charge, as both have opposite charge to each other. The sum of charges happens to be zero which is equal to photon before interaction. Therefore, electric charge is conserved.

3. The law of conservation of energy is antiparticle counterpart.

(a) $hf = (K.E)_{e-} + (K.E)_{e+}$

(b) $hf = 2m_oc^2 + (K.E)_{e-} + (K.E)_{e+}$

Annihilation of Matter:

Electron-positron annihilation occurs when an electron and a positron collide. The result of the collision is the conversion of the electron and positron to the creation of gamma-ray photons.

Conservation laws of annihilation of matter:

$$e^- + e^+ \rightarrow \gamma + \gamma$$

Each photon has an energy equal to the rest mass of electrons 0.51 MeV.

Pair production and Annihilation of matter supports that energy and mass are inter convertible i.e. $E=mc^2$.

Wave Nature of Particles:

The wave nature of particles implies that particles can behave like waves, displaying properties such as reflection, refraction, interference, diffraction, and other wave-like characteristics. In essence, this duality suggests that matter and radiation can co-exist both particle and wave attributes.

Examples of particles that exhibit this dual nature include:

1. Matter particles, such as electrons, protons, and neutrons.
2. X-rays.
3. Photons.
4. Electromagnetic radiation.

De Broglie wave:

De Broglie's idea suggested that both matter and energy could exhibit both particle and wave properties. This unified description was a departure from the classical distinction between particles and waves, providing a more comprehensive understanding of the behavior of particles at the quantum level.

De Broglie Wavelength:

According to de Broglie hypothesis, all matter particles like electrons, protons and neutrons in motion are associated with waves. These waves are called de Broglie waves or matter waves. The momentum of photon of frequency f is given by

$$p = \frac{hf}{c} = \frac{h}{\lambda}$$

The wavelength of a photon in terms of its momentum is

$$\lambda = \frac{h}{p}$$

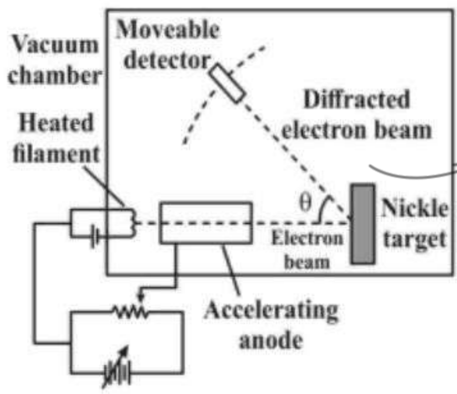
According to de Broglie, the above equation is completely applicable to matter particles as well. Therefore, for a particle of mass m travelling with speed v, the wavelength is given by

$$\lambda = \frac{h}{mv}$$

This wavelength of the matter waves is known as de Broglie wavelength.

Davisson - Germer Experiment:

They demonstrated that electron beams are diffracted when they fall on crystalline solids. Since crystal can act as a three- dimensional diffraction grating for matter waves, the electron waves incident on crystals are diffracted off in certain specific directions. shows a schematic representation of the apparatus for the experiment.



The experimental parts are given as under:

1. An electron gun emits electrons via thermionic emission produced by the tungsten filament used in it, ie., when heated to a specific temperature.

2. Two opposite charged plates known as Electrostatic Particle Accelerator, which accelerates the electrons at a certain potential.

3. The accelerator is enclosed within a cylinder called Collimator which a narrow passage for the electrons along its axis.

4. The target is a Nickel crystal on which the electron beam is fired normally.

5. When the electrons are scattered from Ni crystal, these are captured by the semicircular movable detector.

Davisson Germer Experiment and de Broglie Relation:

Let us consider an electron of mass (mo), charge (e) accelerated from rest through a potential V. Then, the kinetic energy K. E of the electron equals to the work done (eV) on it by the electric field:

$$K.E = eV$$

$$\text{Now, } K.E = \frac{1}{2}mv^2 = \frac{P^2}{2m_o}$$

$$P = \sqrt{2m_o K.E} = \sqrt{2m_o eV}$$

Then, the de Broglie wavelength of electron is given by

$$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2m_o eV}}$$

By using

$h = 6.626 \times 10^{-34}$ J-s,

$m_o = 9.11 \times 10^{-31}$ kg,

$e = 1.6 \times 10^{-19}$ C

we get

$\lambda = \frac{1.227}{\sqrt{V}}$ nm

Where V is the magnitude of accelerating potential (wavelength of electron in volts.

Electron Microscope:

De Broglie hypothesis are used in the field of electron optics. In the electron microscope design, the wave properties of electrons have been utilized with higher resolution, which is giving a great improvement in visualization.

A special type of microscope that uses an electron beam with its wavelike properties to illuminate a specimen able to magnify objects in high resolution (nanometers), which are formed by controlled use of electrons in a vacuum captured on a phosphorescent screen. Ernst Ruska (1906-1988), a German engineer and academic professor, built the first Electron Microscope (EM) in 1931, and the same principles behind his prototype still govern modern EMs.

De Broglie hypothesis of electron have wave paved the way for the development of the electron microscope (EM), which can produce images of much greater magnification than an optical microscope. There are two types of electron microscopes which are transmission electron microscope (TEM), which produces a two-dimensional image, and the scanning electron microscope (SEM), which produces images with a three-dimensional.

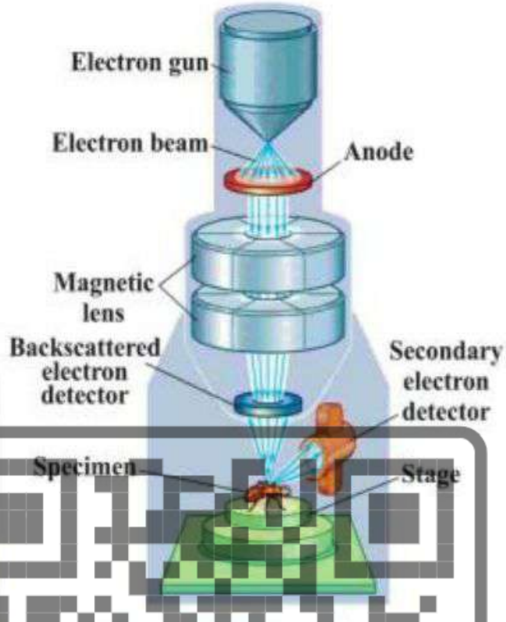


Figure 25.13 Electron Microscope

Working:

In both types i.e., TEM & SEM, the objective and eyepiece lenses are actually magnetic fields that exert force on the electrons to bring them to a focus. The fields are produced by carefully designed current-carrying coils of wire.

EM's measure the intensity of electrons, producing mono chromatic image. Color is often added artificially to highlight. The probe tip of scanning electron microscope, as it is moved horizontally, automatically moves up and down to maintain a constant tunneling current, and this motion is translated into an image of the surface.

Applications:

That of visible light photons, Electron microscopes are used to investigate the ultra-structure of a wide range of biological and inorganic specimens including microorganisms, cells, large molecules, biopsy samples, metals, and crystals. Industrially, electron microscopes are often used for quality control and failure analysis.

Modern electron microscopes produce electron micrographs using specialized digital cameras and frame grabbers to capture the images.

The advancement of microbiology is significantly indebted to the electron microscope, which has revolutionized our understanding of microorganisms such as bacteria, viruses, and other pathogens, thereby greatly enhancing the effectiveness of disease treatments.

Role of Electron Microscope:

1. Higher Resolution: Electron microscope offers significantly higher resolution compared to optical microscopes, allowing observation at the nanometer scale due to the shorter wavelength of electrons.

2. Trans mission Electron Microscope (TEM):

TEMs study internal structures of thin specimens, producing detailed images of cells, organelles, and crystalline structures.

Valuable in biology, materials science, and nanotechnology.

3. Scanning Electron Microscope (SEM):

SEMs provide 3D surface images by scanning specimens and detecting emitted secondary electrons. Widely used in biology, geology, and materials science for surface analysis.

4. Energy- Dispersive X-ray Spectroscopy (EDS): With EDS detectors, electron Viruses attacking a cell of bacterium microscopes analyze elemental composition (< 50000) by TEM by detecting X-rays emitted when high-energy electrons interact with the sample.

5. Materials Science: Crucial for studying the microstructure of materials, aiding understanding of relationships between microstructure and properties in metals, ceramics, and polymers.

6. Nanotechnology: Essential for imaging and characterizing nano-materials, contributing to the development of new materials and devices Figure 25.14 (b) through observation and manipulation of Viruses attacking a cell of bacterium nano-particles and nanostructures. (<35000) by SEM

7. Advancements in Medicine: Contributes to medical research by providing insights into the structure of viruses, bacteria, and cellular organelles, aiding understanding of diseases and therapeutic development.

8. Quality Control in Industry: Used across industries for quality control and failure analysis, helping identify defects, analyse material composition, and ensure product integrity at the microscopic level.

Uncertainty Principle:

The uncertainty principle mainly applied to experiments in physics labs, however some real-world effects are given.

Heisenberg Uncertainty Principle:

It states that it is impossible to measure simultaneously, certain pairs of properties of a subatomic particle, such as its position and momentum, with absolute certainty.

$$\Delta x . \Delta p \geq \frac{h}{4\pi}$$

EXERCISE

Section (A): Multiple Choice Questions (MCQs)

Choose the correct answer:

1. If h is the Planck constant, then ħ is:

(a) $2\pi h$ (b) 2h (c) h/2 (d) $h/2\pi$

2. In a photoelectric effect experiment the stopping potential is:

(a) the energy required to remove an electron from the sample

(b) the kinetic energy of the most energetic electron ejected

(c) the potential energy of the most energetic electron ejected

(d) the electric potential that causes the electron current to vanish

3. The work function for a certain sample is 2.3 eV. The stopping potential for electrons ejected from the sample by 7.0×10^{-14}Hz electromagnetic radiation is:

(a) 0 (b) 0.60 V (c) 2.3V (d) 2.9V

4. In Compton scattering from stationary particles the maximum change in wavelength can be made smaller by using:

(a) higher frequency radiation (b) lower frequency radiation

(c) more massive particles (d) less massive particles

5. Of the following, Compton scattering from electrons is most easily observed for:

(a) infrared light (b) visible light (c) ultraviolet light (d) X-rays

6. the Compton scattering from stationary electrons the largest change in wavelength occurs when the photon is scattered through

(a).0° (b) 45° (c) 90° (d) 180°

7. A free electron has a momentum of 5.0×10^{-24} kg ms^{-1}. The wavelength of its wave function is:

(a) 1.3×10^{-8}m (b) 1.3×10^{-10}m (c) 2.1×10^{-11}m (d) 2.1×10^{-13} m

8. In Photoelectric Effect, when light fall on the surface of metal, the material should emit

(a) Electrons (b) Protons (c) Positrons (d) Neutrons

9. Threshold frequency is defined as the frequency of incident light which can cause photo electric emission

(a) Maximum (b) Minimum (c) Average (d) highest

10. The amount of energy which is necessary to start photo electric emission is called:

(a) Maximum (b) Average (c) Minimum (d) Littlest

Section (B):

CRQS (Short Answered Questions):

1. Differentiate between wave and particle.

Wave: A wave is a disturbance that propagates through a medium, transferring energy without transferring matter. Waves exhibit properties like wavelength, frequency, and amplitude.

Particle: A particle is a discrete unit of matter that has a specific mass and location. Particles can interact with other particles.

2. Is it possible for the de Broglie wavelength of a particle?

Yes, it is possible for a particle to have a de Broglie wavelength. According to de Broglie's hypothesis, every particle has a wave-like nature, and its wavelength is inversely proportional to its momentum.

3. Estimated Broglie wavelength of a cricket ball on the pitch?

The de Broglie wavelength of a cricket ball on the pitch is **extremely small** and essentially negligible. This is because the mass of a cricket ball is relatively large, and its velocity is relatively low.

4. Differentiate between the continuous and discrete emission of radiation?

Continuous emission: Radiation is emitted over a continuous range of wavelengths. This is typical of incandescent objects.

Discrete emission: Radiation is emitted at specific, discrete wavelengths. This is characteristic of excited atoms or molecules.

5. What is threshold frequency?

The **threshold frequency** is the minimum frequency of light required to eject electrons from a metal surface in the photoelectric effect. It depends on the metal used.

6. How has the photoelectric effect been applied in real-world technologies or devices, and what are its practical implications?

The photoelectric effect is used in various technologies, including:

- **Solar cells:** Convert sunlight into electricity.
- **Photodiodes:** Detect light and convert it into an electrical signal.

- **Image sensors:** In cameras and scanners.
- **Smoke detectors:** Detect smoke particles.

7. What are the advantages of an electron microscope over an optical microscope?

Higher resolution: Electron microscopes can achieve much higher resolutions than optical microscopes, allowing for the observation of smaller structures.

Greater magnification: Electron microscopes can magnify objects to much larger extents.

Ability to image non-visible materials: Electron microscopes can image materials that are not visible to the human eye.

8. Is it possible to create only an electron through matter and photon interaction?

Yes, it is possible to create an electron through matter-photon interaction. This process is known as **pair production**, where a high-energy photon is converted into an electron-positron pair.

9. Give construction of electron microscope?

An electron microscope consists of the following components:

- **Electron gun:** Emits a beam of electrons.
- **Electromagnetic lenses:** Focus and control the electron beam.
- **Specimen stage:** Holds the sample to be imaged.
- **Detector:** Detects the electrons that interact with the sample.

10. Elaborate the particle nature of electromagnetic radiation.

The **particle nature** of electromagnetic radiation is evident in phenomena like the photoelectric effect, where light behaves as a collection of discrete particles called photons. Each photon has a specific energy and momentum. This particle-like behavior is particularly apparent at high frequencies and energies.

Section (C) ERQS (Long Answered Questions):

1. Describe how energy is distributed over the wavelength range for different temperatures.

2. Explain the particle model of light in terms of photons with particular energy and frequency.

3. Describe conservation laws in pair production and annihilation of matter.

4. Describe Compton's effect qualitatively.

5. Explain how the very short wavelength of electrons, and the ability to use electrons and magnetic fields to focus them, allows electron microscope to achieve very high resolution.

6. Describe the impact of de Broglie proposal that any kind of particle has both wave and particle properties.

7. Describe the confirmation of de Broglie proposal by Davisson and Germer experiment in which the diffraction of electrons by the surface layers of a crystal lattice was observed.

Section (D): Numerical:

1. The Sun's surface temperature is 5700 K.

(i) How much power is radiated by the Sun?

(ii) Given that the distance to Earth is about 200 Sun radii, what is the maximum power possible from one square kilometer solar energy installation?

(iii) What is the wavelength of maximum intensity of solar radiation?

(5.98×10^{7} W/m^2, 3.6×10^{26} Watts, 5.1×10^{-7} m)

2. The temperature of your skin is approximately 32 °C. What is the wavelength at which the peak occurs in the radiation emitted from your skin? (9.05×10^{-5} m)

3. An FM radio transmitter has a power output of 100 kW and operates at a frequency of 94 MHz, How many photons per second does the transmitter emit? (6.23×10^{-26}J, 1.61×10^{30} s^{-1})

4. A light source of wavelength illuminates a metal and ejects photoelectrons with a maximum kinetic energy of 1.0 eV. A second light source with half the wavelength of the first ejects photoelectrons with a maximum kinetic energy of 4.0 eV. Determine the work function of the metal. (2 eV)

5. A 430 nm violet light is an incident on a calcium photo electrode with a work function of 2.71 eV. Find the energy of the incident photons and the maximum kinetic energy of ejected electrons. (2,88 eV, 0.17 eV)

6. Cut-off frequency for the photoelectric effect in some materials is 8×10^{13} Hz. When the incident light has a frequency of 1.2×10^{14} Hz, the stopping potential is measured as –0.16 V. Estimate a value of Planck's constant from these data and determine the percentage error of your estimation. (5.17 eV, 1.30 V)

7. The work function of some metals is 1listed below. The number of metals which will show photoelectric effect when light of 300 nm wavelength falls on the metal is:

Metal	Li	Na	K	Mg	Cu	Ag	Fe	Pt	W
φ in eV	2.4	2.3	2.2	3.7	4.8	4.3	4.7	6.3	4.75

(4 Metals)

8. X-rays with an energy of 300 keV undergo Compton scattering with a target. If the scattered X-rays are detected at 30° relative to the incident X-rays, determine the Compton shift at this angle, the energy of the scattered X-rays, and the energy of the recoiling electron. (0.35 pm, 278keV, 22keV)

9. A photon with a wavelength of 6.0x 10l? m collides with an electron. After the collision the photon wavelength is found to have been changed by exactly one (Compton Wavelength is 2.43×10^{-12} m).

(i) What is the photon's wavelength after collision?

(ii) Through what angle has been deflected in this collision?

(ii) What is the angle for the electron after the collision?

(iv) What is the electron's kinetic energy, in eV, after collision?

(8.4×10^{-12} m, 90^0, $< 90^0$, 5.9×10^4 eV)

10. Find the de Broglie wavelength of an electron in the ground state of hydrogen. (3.324°A)

11. Determine the minimum uncertainties in the positions of the following objects if their speeds are known with a precision of 1.0×10°m/s: (a) an electron and (b) a bowling ball of mass 6.0 kg. (5.8cm, 33 m)

Unit 26

Atomic Physics

Atomic Spectra:

Atomic spectra deal with the spectrum of frequencies of electromagnetic radiation emitted or absorbed by an electron during transitions between different levels of energy within an atom.

Optical Spectra:

An optical spectrum is obtained, when light passes through a prism or a diffraction- grating. This spectrum can be obtained from the intensity and wavelength of the radiation.

(i) Continuous spectra: These are emitted by solids, liquids and dense opaque gases at high temperatures. The spectrum of the sun, or of a black body, is a continuous spectrum. Gases at low pressures emit line spectra.

(ii) Band spectra: These are associated with similar changes in the molecules under high pressure. Emission lines

(iii) Line spectra: These have their origin in the energy changes which take place in the atoms of a gas.

Spectral lines:

A line of particular frequency or wavelength emitted or absorbed by atoms is called spectral line.

The four visible lines occur at the wavelengths 656 nm, 486 nm, 434 nm, and 410 nm. The complete set of lines is called the Balmer series. The wavelengths of these lines can be Between 1860 and 1885, described by the following equation

1. Lyman series $\frac{1}{\lambda} = R_H\left(\frac{1}{1^2} - \frac{1}{n^2}\right)$

2. Balmer Series $\frac{1}{\lambda} = R_H\left(\frac{1}{2^2} - \frac{1}{n^2}\right)$

3. Paschen Series $\frac{1}{\lambda} = R_H\left(\frac{1}{3^2} - \frac{1}{n^2}\right)$

4. Lyman Series $\frac{1}{\lambda} = R_H\left(\frac{1}{4^2} - \frac{1}{n^2}\right)$

5. Brackett Series $\frac{1}{\lambda} = R_H\left(\frac{1}{5^2} - \frac{1}{n^2}\right)$

6. P Fund Series $\frac{1}{\lambda} = R_H\left(\frac{1}{6^2} - \frac{1}{n^2}\right)$

Identification of Elements by Uniqueness of Spectra:

Each element has its own unique line spectrum which is referred as the "fingerprint" of a particular element.

Bohr's Model and its Postulates:

In 1913, Niels Bohr introduced atomic model in order to give quantitative determination of frequency emitted during de-excitation of an electron in Hydrogen atom.

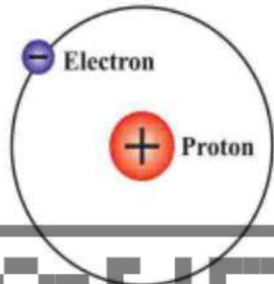
The discovery of the electron in the late 19th century marked the beginning of a new era in scientific research, helping physicists understand the structure and nature of atoms

Niels Bohr had a remarkable idea that explained the atom of hydrogen-consist of a proton and an electron revolving around the nucleus.

The following are the postulates of Bohr

Postulates I:

The electron in a hydrogen atom orbits the nucleus,



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

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

Postulates II:

The magnitude of the angular momentum L of the electron in its orbit is equal to the integral multiple of $\frac{h}{2\pi}$ i.e.

$$L = \frac{nh}{2\pi}, =n\ 1,2,3,4.$$

where h is called Plank's constant and n is positive integer

Postulates III:

Only certain orbits are stable in which electrons are revolving and these orbits are called stationary states. The atom emits radiation (photon) when the electron makes a transition from a higher energy state (E) to the lower energy state (E_p).

$h\nu = E_n - E_p$

where ν is the frequency of emitted photon.

Bohr's radius:

The electron revolving around the nucleus is in uniform circular motion and thus experiences a centripetal force. Here centripetal force is provided by electrostatic force between electron and proton.

$$F_c = \frac{mv^2}{r} \qquad \text{----- 1}$$

where V is the speed of electron. The magnitude of electrostatic force ($F_e = k\frac{q_1 q_2}{r^2}$) between the electron ($q_1 = -e$) and the proton ($q_2 = +e$) separated by the orbital radius r is given as.

$$F_e = \frac{Ke^2}{r^2} \qquad \text{----- 2}$$

where $k = 9.0 \times 10^9\ Nm^2/C^2$ is called Coulomb's constant.

The electron can only move in a particular orbit if the above two forces are balanced each other.

Comparing equation (1) and (2)

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

$$\frac{Ke^2}{r} = mv^2 \qquad \text{---- 3}$$

From Bohr's postulate (2),

$$mvr = \frac{nh}{2\pi}$$

$$v = \frac{nh}{2\pi mr}$$

$$v^2 = \frac{n^2h^2}{4\pi^2m^2r^2}$$

Substitute v^2 in eq 3

$$\frac{Ke^2}{r} = m\frac{n^2h^2}{4\pi^2m^2r^2}$$

$$Ke^2 = \frac{n^2h^2}{4\pi^2mr}$$

Since, $K = \frac{1}{4\pi\varepsilon_o}$

$$\frac{1}{4\pi\varepsilon_o}e^2 = \frac{n^2h^2}{4\pi^2mr}$$

$$r = \frac{\varepsilon_o n^2h^2}{\pi me^2}$$

Where,

$h = 6.63 \times 10^{-34}$ js

$m = 9.1 \times 10^{-31}$ ka

$\varepsilon_o = 8.85 \times 10^{-12} c^2/Nm^2$

$r = r_o n^2$

where $r_o = 5.29 \times 10^{-10}$-m = 0.53A° is called Bohr's first orbit.

Orbital Energy of hydrogen atom:

The allowed energy levels and quantitative values of the emission wavelengths of the hydrogen atom can be calculated from the postulate (3) suggests the qualitative existence of a characteristic discrete emission spectrum and corresponding absorption spectrum for hydrogen. The electron has kinetic energy ($K = \frac{1}{2}mV^2$) and electric potential energy ($U = -\frac{kq_1q_2}{r}$), The total energy will be

$$E = K + U$$

$$E = \frac{1}{2}mV^2 - \frac{Ke^2}{r}$$

Putting the value of $mv^2 = \frac{Ke^2}{r}$ in above

$$E = \frac{Ke^2}{2r} - \frac{Ke^2}{r}$$

$$E = -\frac{Ke^2}{2r}$$

Substitute, $r = \frac{\varepsilon_o n^2 h^2}{\pi m e^2}$ and $K = \frac{1}{4\pi\varepsilon_o}$

$$E = -\frac{1}{4\pi\varepsilon_o} \times \frac{e^2}{2r} \times \frac{\pi m e^2}{\varepsilon_o n^2 h^2}$$

$$E = -\frac{me^4}{8n^2\varepsilon_o^2 h^2}$$

The numerical value of this energy will be

$$E_n = -\frac{13.6}{n^2}$$

Excitation & Ionization Energy:

Excitation:

The process of transferring energy to an atom or molecule, raising it to a higher energy state, often resulting in the emission of photons as it returns to its ground state.

Ionization Energy:

The minimum energy required to remove an electron from an atom or molecule, resulting in the formation of an ion.

The spectrum of Hydrogen atom:

The electron in a hydrogen atom can jump between quantized energy levels by emitting or absorbing Photon for some different values of wavelengths. Any such wavelength is often called a line spectrum which can be absorption or emission lines. The lines for hydrogen are said to be grouped into series, according to the level at which upward jumps start and downward jumps end. The formula for these series corresponding to the different wavelengths can be obtained from equation

$$E = -\frac{me^4}{8n^2\varepsilon_o^2h^2}$$

The frequency of the photon emitted when the electron makes a transition from an orbit to an inner orbit as stated in postulate -III.

$v = \frac{E_n - E_p}{h}$

$$E_n = -\frac{me^4}{8n^2\varepsilon_o^2h^2}$$

$$E_p = -\frac{me^4}{8p^2\varepsilon_o^2h^2}$$

$$v = \frac{1}{h}\left(-\frac{me^4}{8n^2\varepsilon_o^2h^2} - -\frac{me^4}{8p^2\varepsilon_o^2h^2}\right)$$

$$v = \frac{me^4}{8\varepsilon_o^2h^3}\left(\frac{1}{p^2} - \frac{1}{n^2}\right)$$

$$\frac{1}{\lambda} = \frac{me^4}{8c\varepsilon_o^2h^3}\left(\frac{1}{p^2} - \frac{1}{n^2}\right)$$

where $R_H = \frac{me^4}{8c\varepsilon_o^2h^3} = 1.097 \times 10^7 m^{-1}$, is called Rydberg constant.

$$\frac{1}{\lambda} = R_H\left(\frac{1}{p^2} - \frac{1}{n^2}\right)$$

X-Rays:

These are powerful electromagnetic rays of higher energy and can pass through most objects, including the body.

Most of them have a wavelength ranging from 0.01 to 10 nanometers, corresponding to frequencies 3×10^{19} Hz to 3×10^{16} Hz.

X-rays are used to generate images of tissues and structures inside the body.

LASER :Light Amplification by Stimulated Emission of Radiation:

Lasers are designed to produce and amplify this stimulated form of light into intense and focused beams. Compared to conventional sources of ordinary light, the light from a laser is quite intense, monochromatic, and emitted in a unidirectional beam limited by diffraction.

Stimulated or Induced Absorption:

When an atom induced by the photon (energy packet and do transition to one of its allowed states (excited state) called Stimulated Or induced absorption.

Spontaneous Emission:

The process of photon emission by an excited atom with no external influences is called spontaneous emission.

Stimulated Emission:

Radiation, which occurs as a result of external exposure, is called induced or stimulated. In the stimulated emission two photons are involved: the primary photon, causing the emission of radiation by an excited atom and the secondary photon emitted by the atom.

Population Inversion:

Population inversion is a key to produce laser light.

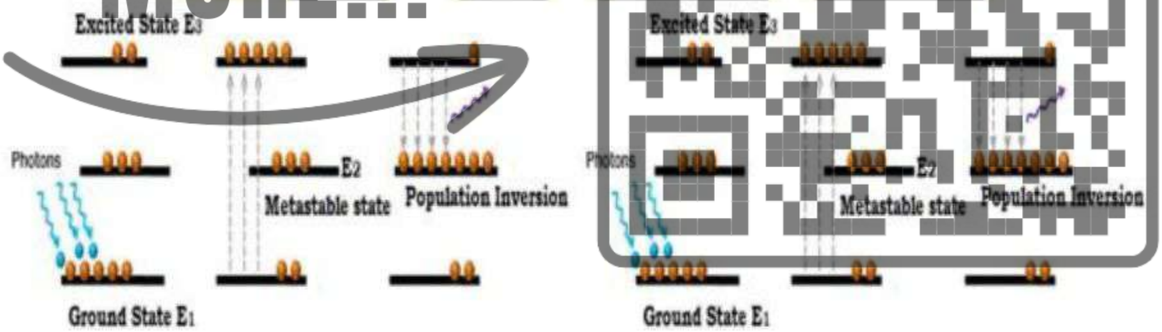
The process of achieving a greater population in a In addition to induced higher energy state compared to a lower energy state.

Population inversion cannot be achieved in a two energy level system, at normal conditions; the number of electrons in the lower energy state (E_1) is always greater as compared to the number of electrons in the higher energy state (E_2).

Metastable States:

Consider a system consisting of three energy levels E_1, E_2, E_3. We assume that the

energy level of E_1 is less than E_2 and E_3, the energy level of E_2 is greater than E_1 and less than E_3, and the energy level of Es is greater than E_1 and E_2. The energy level E_2 is sometimes referred to as Metastable state having a life time of 10 seconds.



He- Ne Gas Laser:

The helium-neon laser was the first continuous wave (CW) laser ever constructed.

It was built in 1961 by Ali Javan, Bennett, and Herriott at Bell Telephone Laboratories.

He-Ne lasers are commonly used in school laboratories and in older barcode readers. The schematic diagram of He-Ne laser is shown below

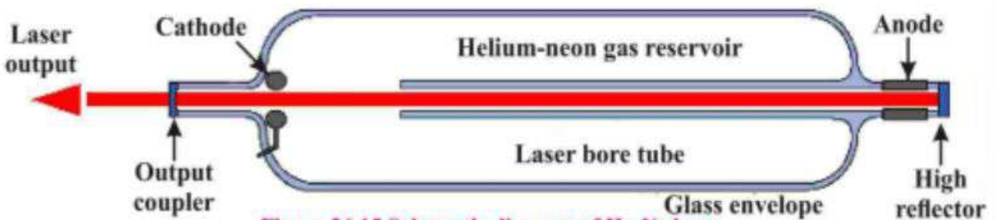


Figure 26.15 Schematic diagram of He-Ne laser

Helium-neon laser construction:

The helium-neon laser consists of three essential components:

Pump Source (high voltage power supply):

The pump energy of the laser is provided by an electrical discharge of several hundred Volts between an anode and cathode at each end of the glass tube. A current of 5 to 100mA is typical for laser operation.

Gain Medium (laser glass tube or discharge glass tube):

Figure shows a gas discharge tube contains a low- pressure mixture of helium-neon in a ratio between 5:1 and 20:1 bound in a glass tube. The partial pressure of helium is 1 mbar whereas that of neon is 0.1 mbar.

Resonating Cavity:

The glass tube (containing a mixture of helium and neon gas) is placed between two parallel mirrors. These two mirrors are silvered or optically coated. Each mirror is silvered differently. The left side mirror is partially silvered and is known as output coupler whereas the right side mirror is fully silvered and is known as the high reflector or fully reflecting mirror. The fully silvered mirror will completely reflect whereas the partially silvered mirror will reflect most part of the light but allows some part of the light to produce the laser beam.

Laser Operation:

This electrical excitation raises the helium atom into a meta-stable state with energy 20.61 eV above the ground state. Neon has a meta-stable state with energy 20.66 eV above its ground state. Collision of the excited helium atoms with the ground-state neon atoms results in transfer of energy to the neon atoms, exciting neon electrons. The difference between the energy states of the two atoms is in the order of 0.05eV, which is supplied by kinetic energy.

The number of neon atoms in the excited states builds up as further collisions between helium and neon atoms occur, causing a population inversion. Spontaneous and stimulated emission results in emission of 632.82 nm wavelength light.

Properties and Uses of Lasers:

Properties of Laser:

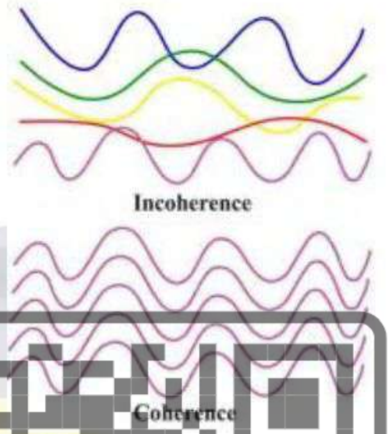
The properties of laser light are very strange as compared to conventional light. The factors that make laser light prominent are: Monochromatic, Highly Intense or Brightness Coherence and Directionality

1. Monochromatic:

A single color or wavelength light is called monochromatic. The light emitted from ordinary light sources has different wavelengths, or colors. However, laser light has a single wavelength or color.

2. Highly Intense or Brightness:

The characteristics of coherence and directionality of the laser makes laser light highly intense as compared to conventional light. It is the power emitted per unit surface area per unit solid angle. A one milli watt He-Ne laser is more intense than the sun intensity.



3. Coherence:

Two or more waves of same frequency are said to be coherent in nature if they have constant phase difference. A predictable correlation of the amplitude and phase at any one point with another point is called coherence. In laser light the property of coherence occurs between any two or more light Coherence waves. Where as in conventional light, the property, coherence exhibits between a source and its virtual source.

4. Directionality or Divergence:

The light ray coming from laser light travels in a single direction. However, an ordinary light source travels in all directions. For example, on travelling a distance of 1 Km the torch light spreads l km distance. But the laser light spreads only few centimetres distance even it travels lacks kilometre distance.

Uses of Lasers:

Lasers are widely used in many fields some of them are:

1. Tools:

- Cutting tools are typically precise, and also simple to automate. They do not require sharpening, unlike that of knives.
- Robot-guided lasers are widely used for the cutting of pieces of cloth.
- Laser tools are used in corneal surgery, restoring a detached retina of eye, and removing kidney stones.

2. Communication:

- Lasers are used in Barcode scanners to convert a printed barcode into a number.
- A semiconductor laser beam helps to convert the printed pattern of data into numbers in a CD/DVD.
- In Photonics, lasers are used in fiber optic cables.

3. Defence:

- In defence field, the military employs laser-guided guns and missiles.
- Laser range-finders use high-resolution scanning to find the distance and speed from an object that is located beyond the point-blank range.

4. Medicine:

- In medicine, the laser beam is used as part of phototherapy for many procedures.
- The development of laser technology in recent decades has enabled the creation of a new field of medicine laser surgery.
- Lasers have uses in dermatology, ophthalmology, urology, rheumatology and dentistry.

5. Holography:

- Holography is a true three-dimensional image recording on film by asers. Holograms are used for amusement, decoration on novelty items and magazine covers.

Safe Handling of Lasers:

- Only trained, authorized personnel may operate lasers, Authorization is received from the authorized laser user and the Laser Safety Officer.
- NEVER put yourself into any position where your eyes approach the axis of a laser beam (even with eye protection on).
- Keep beam paths below or above standing or sitting eye level. Do not direct them towards other people.
- Do not damage laser protective housings, or malfunctioned the interlocks on these housings.
- Eliminate all reflective material from the vicinity of the beam paths.
- Never use viewing instruments to look directly into a laser beam. If this is necessary, install an appropriate filter into the optical element assembly.
- Keep ambient light levels as high as operations will permit.
- Do not work alone when performing high power laser operations.

EXERCISE

Section (A): Multiple Choice Questions (MCQs)

Choose the correct answer:

1. Atomic spectra are also known as:

(a) Discrete spectra (b) Line spectra

(c) Emission spectrum (d) Continuous spectra

2. The ratio of kinetic energy to total energy for an electron in a Bohr orbit is:

(a) 1:1 (b) 2:3 (c) 1:2 (d) 2:1

3. The Bohr radius increases as the principal quantum number:

(a) increases (b) decreases (c) remains constant (d) oscillates

4. Laser beams consist of:

(a) Highly coherent electrons (b) Highly coherent photons

(c) Highly coherent phonons (d) Highly coherent neutrons

5. The ruby laser is an example of:

(a) Optical pumping (b) Electrical pumping

(c) Chemical pumping (d) Thermal pumping

6. Laser action requires a medium with at least:

(a) Three energy levels (b) Four energy levels

(c) Two energy levels (d) Five energy levels

7. Population inversion occurs in:

(a) Active medium (b) Passive medium

(c) Gaseous medium (d) Vapour medium

8. X-rays transfer to metals.

(a) Energy (b) Force (c) Pressure (d) Momentum

9. X-rays are deflected by:

(a) Magnetic fields (b) Electric fields (c) Gravitational fields (d) No fields

10. Doubling the voltage of an X-ray tube:

(a) Halves the intensity (b) Keeps the intensity unchanged

(c) Doubles the intensity (d) Quadruples the intensity

Section (B): CRQs (Short Answered Questions):

1. Why do different elements have different spectra?

Different elements have unique spectra because they have different arrangements of electrons.

Each element has a specific number of protons and electrons, which determines the energy levels available to the electrons. When electrons transition between these energy levels, they emit or absorb light of specific wavelengths, creating a characteristic spectrum for that element.

2. In the Bohr model, how many times larger is the radius of the fifth Bohr orbit compared to that of the first Bohr orbit?

In the Bohr model, the radius of the fifth Bohr orbit is 25 times larger than the radius of the first Bohr orbit. This is because the radius of a Bohr orbit is proportional to the square of the principal quantum number (n). For the first orbit, n = 1, and for the fifth orbit, n = 5. So, $\frac{5^2}{1^2} = 25$.

3. What is the difference between X-Rays and Gamma Rays?

Both X-rays and gamma rays are types of electromagnetic radiation, but they differ primarily in their origin.

- **X-rays** are produced when high-energy electrons collide with a target material, typically a metal. This collision causes the electrons to decelerate, emitting X-rays.
- **Gamma rays** are emitted from the nucleus of an atom during radioactive decay or nuclear reactions. They are often associated with high-energy processes, such as nuclear explosions or supernovae.

4. Sate the properties of X-Rays, which makes it possible to detect cracks in bones.

X-rays are useful for detecting cracks in bones due to their following properties:

- **Penetrating power:** X-rays can penetrate through soft tissues like skin and muscle, but they are absorbed by denser materials like bones.
- **Differential absorption:** Bones absorb more X-rays than soft tissues, creating a contrast that allows doctors to visualize bone structures.
- **Short wavelength:** The short wavelength of X-rays makes them suitable for high-resolution imaging.

5. What is the energy of a photon that, when absorbed by a hydrogen atom, could cause an electronic transition from (a) them n=3 state to the n=5 state and (b) the n=5 state to the n=8 state?

6. What are the (a) wavelength range and (b) frequency range of the Lyman series and the Balmer series?

Lyman Series:

- **Wavelength range:** 91.2 nm to 121.6 nm
- **Frequency range:** 3.28 × 10^15 Hz to 2.47 × 10^15 Hz

Balmer Series:

- **Wavelength range:** 364.6 nm to 656.3 nm
- **Frequency range:** 8.20×10^{14} Hz to 4.57×10^{14} Hz

7. Distinguish between spontaneous and stimulated emission.

Spontaneous emission: An excited atom emits a photon randomly, without external influence.

Stimulated emission: An excited atom emits a photon when it interacts with a photon of the same energy, resulting in two identical photons.

8. Explain why population inversion is necessary in a laser?

Population inversion is necessary in a laser to achieve **lasing**. It occurs when there are more atoms in a higher energy state than in a lower energy state. This condition allows for stimulated emission to dominate over absorption, leading to the amplification of light and the production of a coherent laser beam.

9. In an optically pumped laser, the light that causes optical pumping is always shorter in wavelength than the laser beam. Explain

The **pump light** in an optically pumped laser must have a **shorter wavelength** than the laser beam. This is because the pump light must provide enough energy to excite the atoms to a higher energy level. If the pump light had a longer wavelength, it would not have enough energy to cause the necessary excitation.

10. A hydrogen atom is in its first excited state (n = 2). Calculate (a) the kinetic energy of the electron, (b) the potential energy of the system, and (c) the total energy of the System.

Section (C): ERQs (Long Answered Questions):

1. What are the postulates of Bohr's Model of hydrogen atom? Discuss the importance of this model to explain various series of line spectra in hydrogen atom. Do any of the assumptions of the Bohr's theory of hydrogen atom contradict with the classical Physics? Derive the expression for total energy of electron in nth Bohr orbit and show that- $E_n \alpha \frac{1}{n^2}$.

2. How X-rays are produced? State the purpose of cooling fins in the X-ray tube.

3. Explain why X-rays are appropriate in study of crystalline structure material? Write some main properties of X-rays.

4. What is Laser? Write the characteristics of Laser light. Can a two-level system be used for the production of Laser? Why?

5. What is pumping? What are the different methods of pumping? Explain optical pumping.

6. What is the principle of Laser? Write the construction and working of Helium-neon laser.

7. Give some important properties of lasers. Also write the uses of lasers in the field of medicine, defence and communication.

8. What is wave number? Derive the expression = $1/\lambda = RH \left(\frac{1}{p^2} - \frac{1}{n^2}\right)$

9. Derive the expression for Bohr's radius and develop a general relation for radii of quantized orbits of hydrogen atom.

Section (D): Numerical:

1. Calculate the energy of an electron in the n = 2 orbit of a hydrogen atom according to the Bohr model. (Ans. -5.447 x 10^{-19} j)

2. Calculate the speed of the electron if it orbits in(a) the smallest allowed orbit and (b) the second smallest orbit? (c)If the electron moves larger orbits, does its speed increase, decrease, or stay the same? (Ans. (a) 2.19x 10^6m/s (b) 1.09 x 10^6m/s (c) the speed of the electron will decrease)

3. What are the (a) energy, (b) magnitude of the momentum, and (c) wavelength of the photon emitted when a hydrogen atom undergoes a transition from a state with n -3 to a state with n= 1? (Ans. (a) 12.1 eV (b) 6.45 X 10^{-27} N.s (c) 102 nm)

4. What is the energy of the photon emitted by hydrogen atom when the hydrogen atom changes directly from the n=5 state to the n=2 state? (Ans. 2.85 eV)

5. How much work must be done to pull apart the electron and the proton that make up the hydrogen atom if the atom is initially in (a) its ground state and (b) the state with n =3? (Ans. (a) 13.6 eV (b) 1.51 eV)

6. (a) What is the wavelength of light for the least energetic photon emitted in the Balmer series of the hydrogen atom spectrum lines? (b) What is the wavelength of the series limit? (a) 659 nm (b) 366 nm)

7. A laser emits light with a wavelength of 632.8 nm and has a power output of 55 mW. Calculate the energy of one photon emitted by this laser. (Ans. 3.14×10^{-19} J)

8. Calculate the wavelength of X-rays if the energy of one photon emitted by the X-ray machine is 1.9878×10^{-15} joules. (Ans. 0.1 nm)

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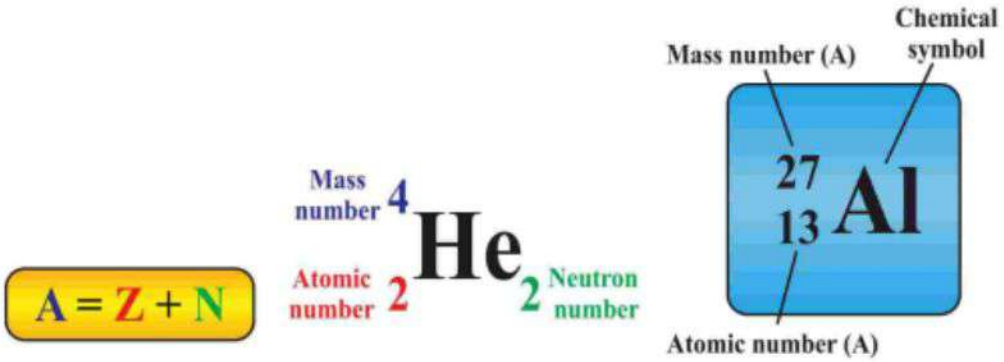
Unit 27

Nuclear Physics



Isotopes:

Two or more forms of the same element that contain equal numbers of protons but different numbers of neutrons in their nuclei, and hence they differ in relative atomic mass but not in chemical properties.

Isotopes are of two types:

Stable isotopes: They do not show any radioactivity and are stable. For example, ${}_7N^{14}$ and ${}_7N^{15}$.

Radioactive isotopes:

They are unstable and show radioactivity. Some of the radioactive isotopes are ${}_6C^{14}$ for carbon, and ${}_{19}K^{40}$ for potassium.

Every element on the periodic table naturally occurs in various having different masses like isotopic forms, although some may be more prevalent than the isotopes of hydrogen others. For instance: have the same physical

Oxygen: About 99.76% of oxygen in nature is Oxygen- 16 (with 8 neutrons). However, Oxygen-17 and Oxygen 18 are also found in much smaller quantities.

Uranium: The naturally occurring isotopes of uranium are Uranium-238 (99.3%) and Uranium-235 (0.7%). Uranium has 35 known isotopes. The most stable isotope of uranium is uranium-238, which has 146 neutrons.

Hydrogen: Hydrogen has only three isotopes: protium, deuterium, and tritium. Protium has no neutrons, deuterium has one neutron, and tritium has two neutrons.

Mass Spectrograph:

A mass spectrograph is a device that can be used to separate isotopes of an element based on their mass and it works by accelerating charged particles through a magnetic field. The particles are then deflected by the magnetic field, and the amount of deflection is determined by the mass of the particle.

Bainbridge mass spectrograph is a type of mass spectrometer that uses a combination of electric and magnetic fields to separate Ions according to their charge-to-mass ratio. It is named after its inventor, Kenneth T. Bainbridge, who developed it in 1933.

Principle:

The fundamental principle behind the Bainbridge Mass Spectrograph is the application of magnetic and electric fields to separate and measure the masses of charged particles, typically Ions. This separation is based on the principles of magnetic deflection and kinetic energy.

The Bainbridge mass spectrograph consists of three main components: an ion source, a velocity selector, and a magnetic analyzer.

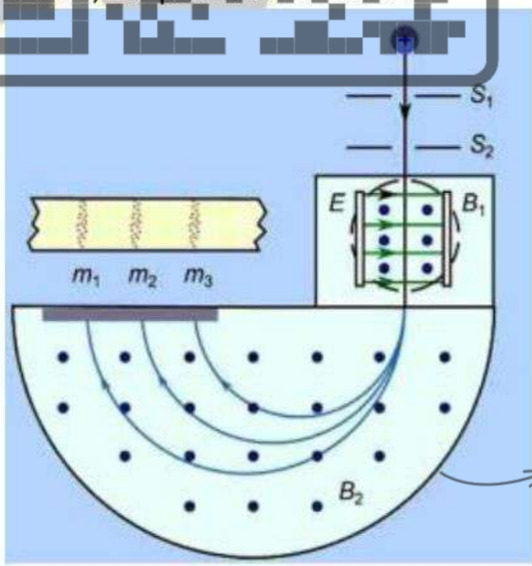
The ion source is where the Ions are produced. The Ions are typically produced by bombarding a sample with electrons, which knocks electrons out of the atoms, creating positively charged Ions.

The velocity selector is used to select Ions of a particular velocity. The Ions are passed through a region of electric and magnetic fields, which are adjusted so that only Ions of a certain velocity can pass through.

The magnetic analyzer is used to separate the Ions according to their charge-to-mass ratio. The Ions are passed through a region of magnetic field, and the radius of their path is determined by their charge-to-mass ratio.

The Ions that are separated by the magnetic analyzer are then detected by a detector, such as a photographic plate or a computer.

A schematic diagram showing the construction of Bainbridge's mass spectrograph is shown in Figure, beam of positive Ions produced in a discharge tube is collimated into a narrow beam by the two slits S_1 and S_2. After emerging from the slit, the positive Ions enter a velocity selector.



The velocity selector consists of two plates E and B_1, between which a steady electric field is maintained in a direction at right angles the ion beam.

The electric field and the magnetic field of the velocity selector are so adjusted that the deflection produced by one is exactly equal and opposite to the deflection produced by the other so that there is no net deflection for Ions having a particular

$$X_e = B_1 ev$$

$$v = \frac{x}{B_1}$$

The Ions were accelerated to a known kinetic energy, ensuring that all Ions of different masses had the same kinetic energy. Positive ions entering the evacuated chamber are subjected to a perpendicular electromagnetic field of intensity B_2, causing them to follow curved paths. The curvature depends on their charge-to-mass ratio (e/m), with heavier ions curving less than lighter ones. This method is very accurate due to the linear mass scale. When a charged particle with mass m and charge e is accelerated through a potential difference v, it gains a velocity v, given by

$$\frac{1}{2}mv^2 = eV \text{ or } v = \sqrt{\frac{2eV}{m}}$$

When this charged particle moving with a velocity v enters a magnetic field B in a direction perpendicular to the field, the force acting on it due to the field is Bev acting in a direction at right angles to the direction of motion of the charged particle and that of the magnetic field. The particle, therefore, moves along a circular path of radius r given by

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

$$Ber = mv$$

Putting v in above

$$Ber = m\sqrt{\frac{2eV}{m}}$$

$$m = \frac{Ber}{\sqrt{\frac{2eV}{m}}}$$

$$m = Ber\sqrt{\frac{m}{2eV}}$$

By squaring we get

$$m^2 = \frac{B^2e^2r^2m}{2eV}$$

$$m = \frac{B^2er^2}{2V}$$

The mass of each ion reaching the detector depends on the value of B^2.

By changing B and keeping other variables constant, ions of different masses can be directed into the detector.

This allows us to create a graph of detector readings versus B, identifying the masses and quantities of the ions present. Multiple peaks in the mass spectrum indicate different isotopes of the same element.

Radioactive Decay:

Radioactivity is the process by which an unstable atomic nucleus loses energy by radiation. A material containing unstable nuclei is considered radioactive.

There are two types of radioactivity:

1. Natural Radioactivity:

Natural radioactivity is the radioactivity that occurs naturally in the environment. is caused by the decay of unstable isotopes of elements that are found in the Earth's crust, such as uranium, thorium, and potassium-40.

2. Induced Radioactivity:

Induced radioactivity is the radioactivity that is created by bombarding a stable material with radiation, such as neutrons or protons. This can be done in a nuclear reactor or particle accelerator.

The main difference between natural and induced radioactivity is the source of the radiation.

In natural radioactivity, the radiation comes from the unstable nuclei of the atoms themselves.

In induced radioactivity, the radiation comes from outside the atoms, and is used to destabilize their nuclei.

Radioactive Decay Process:

The natural radioactivity observed was specific to heavy elements with atomic weights greater than about 206. of the 2,500 identified types of atoms, around 90% are radioactive, meaning they change into other types of atoms over time. These unstable nuclides release energy and particles in much different way of decay types to become stable nuclides.

Alpha Decay:

All atomic nuclei with a proton number (Z) greater than 83 and a mass number (A) greater than 209 undergo spontaneous transformation into lighter nuclei by emitting one or more alpha particles, which are equivalent to helium-4 nuclei.

$$^{A}_{Z}X \longrightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He^{+}$$

where X is parent nuclei, Y is daughter nuclei and He is alpha particle.

Examples of alpha decays are:

$$^{238}_{92}U \longrightarrow {}^{234}_{92}Th + {}^{4}_{2}He^{+}$$

Beta Decay:

The beta-decay is a spontaneous process in which mass number of the nucleus remains unchanged, but the atomic number changes by unity (ΔZ = +1).

The change in atomic number due to emission of an electron, emission of positron or by capture of an orbital electron (K-capture).

If the daughter nucleus doesn't have the right ratio of neutrons and protons to stay stable, it can change through beta decay to become more stable.

There are three types of β-decay processes depending upon their mode of decay:

- β- decay (electron emission),
- β+ decay (positron emission) and
- electron capture.

β-Decay (Electron Emission):

General equation of electron emission is:

$$^{A}_{Z}X \longrightarrow {}^{A}_{Z+1}Y + {}^{0}_{-1}e$$

Whenever, the number of neutron is more than the number of proton then negative beta decay happens. In this process, a neutron is transformed into a proton:

$$^{1}_{0}n \longrightarrow {}^{1}_{1}p + {}^{0}_{-1}e$$

Here is an example:

$$^{14}_{6}C \longrightarrow {}^{14}_{7}N + {}^{0}_{-1}e$$

This equation represents the decay of carbon-14 ($_6c^{14}$) into nitrogen-14 ($_7N^{14}$) with the emission of an electron.

β+-Decay (Positron Emission):

Also known as positive beta decay.

General equation of positron emission is:

$$^{A}_{Z}X \longrightarrow {}^{A}_{Z-1}Y + {}^{0}_{+1}e$$

Whenever, the number of proton is more than the number of neutron then positive beta decay happens. In this process, a proton is transformed into a neutron:

$$^{1}_{1}p \longrightarrow {}^{1}_{0}n + {}^{0}_{+1}e$$

Here is an example:

$$^{11}_{6}C \longrightarrow {}^{11}_{5}C + {}^{0}_{+1}e$$

This equation represents the decay of carbon-11 ($_6C^{11}$) into boron-11 ($_5B^{11}$) with the emission of a positron (e^+).

Electron Capture:

In this process an electron from K-shell of the atom is captured by the nucleus to form a new nucleus and a photon is emitted:

$$^{A}_{Z}X + {}^{0}_{-1}e \longrightarrow {}^{A}_{Z-1}Y + hv$$

In this process, atomic number Z is decreased by one but mass number A remains the same. In this case a proton in the nucleus is converted into a neutron by capture of an orbital electron:

$$ {}_{1}^{1}p + {}_{-1}^{0}e \longrightarrow {}_{0}^{1}n + hv $$

An example of electron capture is the decay of Krypton-81 into Bromine-81:

$$ {}_{36}^{81}K + {}_{-1}^{0}e \longrightarrow {}_{35}^{81}Br $$

In this reaction, the atomic number drops from 36 to 35, while the mass number stays at 81.

Gamma Decay:

During gamma decay, there is no change in mass number A or atomic number Z. An excited nucleus is denoted by an asterisk (*) after or over its usual symbol. Thus $_{38}S^{87}$ refers to $_{38}S^{87}$ in an excited state. The general equation for gamma decay is:

$$ {}_{Z}^{A}X^{*} \longrightarrow {}_{Z}^{A}X + \gamma $$

Here is an example of gamma-decay:

$$ {}_{27}^{60}Co^{*} \longrightarrow {}_{27}^{60}Co + \gamma $$

This equation represents the decay of an excited state of cobalt-60 (${}_{27}^{60}Co^{*}$) into the ground state of cobalt-60 (${}_{27}^{60}Co$) with the emission of a gamma (γ) photon.

The summary of the radiations from nucleus is given below

Particle	Symbols	Composition	Charge	Effect on parent nucleus
alpha	$\alpha\ ({}_{2}^{4}He)$	2 protons, 2 neutrons	+2	mass loss; new element produced
beta	$\beta^{-}\ ({}_{-1}^{0}e)$	electron	−1	no change in mass number; new element produced
	$\beta^{+}\ ({}_{1}^{0}e)$	positron	+1	
gamma	γ	Photon	0	energy loss

Law of Radioactive Decay:

The law of radioactive decay states that the rate of decay of a radioactive sample at any instant is directly proportional to the number of atoms present at that instant.

The Spontaneous and Random Nature of Radioactive Decay:

Radioactive decay is both spontaneous and random.

Spontaneous process:

It is a process which cannot be influenced byy environmental factors, Such as:

(i) Temperature

(ii) Pressure

(iii) Chemical conditions

Random process:

It is a process in which the exact time of decay of a nucleus cannot be predicted The random nature of radioactive decay can be demonstrated by observing the count rate of a Geiger-Muller (GM) tube.

(i) When a GM tube is placed near a radioactive source, the counts are found to be irregular and cannot be predicted.

(ii) Each count represents a decay of an unstable nucleus.

(ii) These fluctuations in count rate on the GM tube provide evidence for the randomness of radioactive decay.

The nucleus has a constant probability, ie. the same chance, of decaying in a given time. Therefore, with large numbers of nuclei, it is possible to statistically predict the behavior of the entire group.

Activity (A):

Sometimes we are more interested in the decay rate A ($A = \frac{\Delta N}{\Delta t}$)than in N itself.

The activity A of a radioactive sample is the number of disintegrations (decays) occurring per unit of time.

Ifa radioactive sample contains N atoms at any time t, then its activity at time t is given as

$$A = -\frac{\Delta N}{\Delta t}$$

where negative sign shows that activity decreases with time. According to law of radioactive decay

$$\frac{\Delta N}{\Delta t} = -\lambda N$$

Therefore,

$$A = \lambda N$$

Since, $N = N_o e^{-\lambda t}$, so

$$A = \lambda N_o e^{-\lambda t}$$

Putting A, = AN, in above equation, we get

$A = A_o e^{-\lambda t}$

The equation $A = \lambda N$ and $A = A_o e^{-\lambda t}$ are alternative forms of the law of radioactive decay.

Exponential Nature of Radioactivity:

Radioactive decay follows an exponential decay pattern. This means that the rate of decay proportionally decreases with the remaining amount of radioactive material and it can be visualized graphically by decay curve.

- The key features of the exponential nature of radioactive decay include:
- The rate at which radioactive atoms decay is proportional to the quantity of the substance present.
- When plotted on a graph, the decay curve is a smooth, continuous curve that approaches but never reaches zero.
- The curve demonstrates a steeper decline at the beginning (short times) and a gradual decrease as time progresses.
- While we can't predict when a specific atom will decay, we can predict the probability of decay within a certain time frame.

Half-Life ($T_{\frac{1}{2}}$):

The half-life of a radioactive substance is the time it takes for half of the initial amount of the substance to decay or transform into another element. It's a measure of the stability of an atom and the rate at which it loses its radioactivity.

Decay Constant (λ):

The decay constant, is a measure of the rate at which a radioactive substance decays.

It's denoted by the symbol à and represents the probability of decay per unit time.

Formula:

The half-life formula is:

$$T_{\frac{1}{2}} = \frac{In(2)}{\lambda}$$

Where:

$T_{\frac{1}{2}}$ is the half-life

In(2) is the natural logarithm of 2 (approximately 0.693)

λ is the half-life constant (decay constant)

This shows that the half-life is inversely proportional to the decay constant. A higher decay constant means a shorter half-life, and vice versa.

Mass Defect and Binding Energy:

When examining the nucleus of an atom, we find that its mass is actually less than the combined mass of its protons and neutrons. This discrepancy is due to the strong nuclear forces holding the nucleus together. To better understand this phenomenon, we need to learn some important terms.

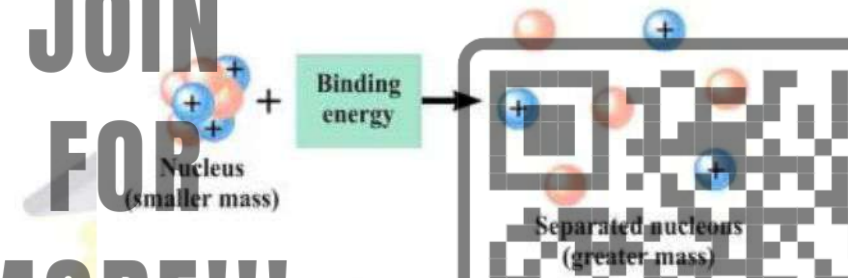
Mass Defect and Binding Energy or the Hidden Energy within Atoms:

Mass Defect:

Mass Defect refers to the difference between the total mass of individual protons, neutrons, and electrons in an atom and the actual mass of the atom.

Binding Energy:

Binding Energy is the energy required to break apart the nucleus of an atom into its constituent protons and neutrons. Exploring the Connection.



Nuclear Reactions:

Any process that involves a change in the nucleus of an atom is called a nuclear reaction.

Mathematically,

$$X + x \rightarrow Y + y + Q$$

Where,

X is the target

x are the projectiles

y are the ejectiles

Y is called the residual(product) nucleus.

Rutherford produced the

Energy Released from Nuclear Reactions:

The energy is either absorbed or emitted which is called Q value and it is equal to the mass defect. The Q value can also be defined as the difference between the rest energies of X and x and the rest energies of Y and y:

$Q = (m_X + m_x - m_Y - m_y)c^2$

Conservation of Atomic and Mass Numbers:

Whenever there is a nuclear decay, there is always some physical quantities need to be conserved or remain constant.

The following are rules for any nuclear reaction:

1. The total of the atomic numbers (Z) on the left is the same as the total on the right of the given equation because charge must be conserved.

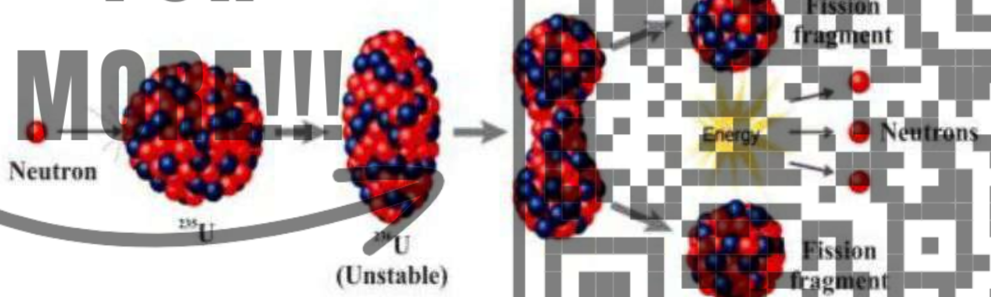
2. The total of the mass numbers (A) on the left is the same as the total on the right of equation because nucleon number must be conserved.

Nuclear Fission and Fusion:

Nuclear Fission:

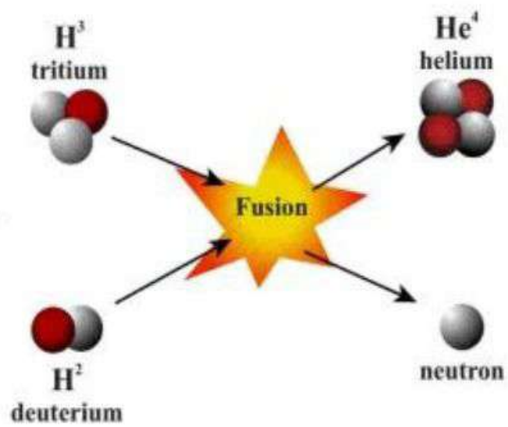
The splitting of a heavy nucleus (A > 230) into two medium-mass nuclei in a nuclear reaction with the release a huge amount of energy due to mass defect is called nuclear fission.

For example, when a uranium nucleus (U-235) is bombarded by a slow moving neutron (called thermal neutron), the U-235 nucleus splits into two medium-mass nuclei with the release of huge amount of energy.



Nuclear Fusion:

The process of combining two light nuclei to form a heavy nucleus with the release of huge amount of energy due to mass defect is known as nuclear fusion.



Fission Chain Reaction:

The nuclear fission which once started continues till all the atoms of the fissionable material are disintegrated is called chain reaction. How chain reaction is initiated in uranium by a single neutron. When a single neutron initially causes the fission of $_{92}U^{235}$ nucleus, 3 neutrons are released along with huge amount of energy. These 3 neutrons in turn cause three more nuclei to split, thereby liberating a total of 9 neutrons and so on. The process proceeds very quickly and in a very short time the whole of the uranium undergoes fission.

For the fission to be self-sustaining, the number of emitted fission neutrons should be more than the incident ones. Under such conditions, the fission neutrons keep on increasing, thus maintaining the chain reaction. A very common term, called neutron multiplication factor (or reproduction factor), is often used in chain reaction. It is represented by k:

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

Obviously, for chain reaction to be self-sustaining, the value of k must be greater than 1. The value of k > 1 means that neutrons increase or multiply with time.

There are two types of fission chain reactions (according to neutron multiplication factor k):

1. Controlled chain reaction:

A controlled chain reaction is a chain reaction in which the number of neutrons produced can be controlled.

This allows for a sustained release of energy, which can be The atomic bombs dropped

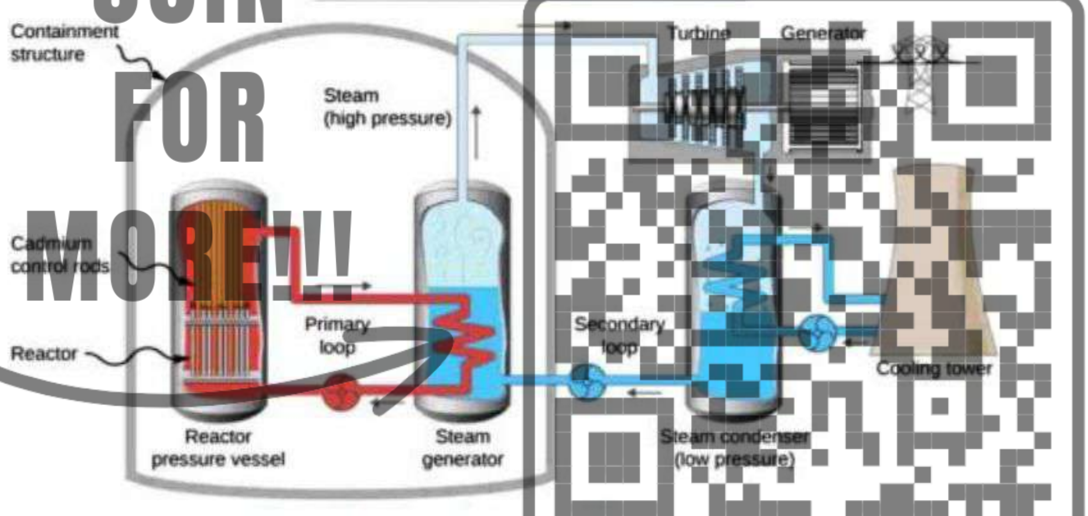
2. Uncontrolled chain reaction:

An uncontrolled chain reaction is a chain reaction in which the number of neutrons produced cannot be controlled. This results in a sudden and rapid release of energy, which can be destructive. For example, atomic bomb.

Nuclear Reactor:

A nuclear reactor is a device in which controlled fission chain reaction takes place. A nuclear reactor is also known as nuclear pile or atomic pile.

Such a system was first achieved with uranium as the fuel in 1942 by Enrico Fermi. He used uranium-235 isotope that releases energy through nuclear fission. The schematic diagram of nuclear reactor.



The following are the main components of the nuclear reactor:

Fissionable Substance:

Nuclear reactors use fuel, typically enriched uranium or plutonium, to sustain the fission chain reaction. The U-235 is fissionable, but uranium from ore typically contains only about 0.7 percent of U-235, with the remaining 99.3 percent being the U-238 isotope. Because uranium-238 tends to absorb neutrons, reactor fuels must be processed to increase the proportion of U-235 so that the reaction can sustain itself. This process is called enrichment.

Moderator:

The function of the moderator is to slow down the highly energetic neutrons produced in the process of fission of U-235 to thermal energies. Heavy water (D20), graphite, beryllium, etc., are used as moderators. Ideally, moderators have low atomic weight and low absorption cross-section for neutrons.

Control Rods:

Control rods are made of materials like boron or cadmium that absorb neutrons, regulating the rate of the fission chain reaction. By adjusting the position of control rods within the reactor core, operators can control the power output and maintain stability.

Coolant:

Coolant circulates through the reactor core to transfer heat away from the fuel and other reactor components. Common coolants include water, heavy water, or gases like helium or carbon dioxide. The heated coolant then transfers its thermal energy to a secondary loop containing water, which turns into steam. This steam drives turbines connected to generators, producing electricity.

Protective Shield:

In a nuclear reactor, there are many types of harmful radiations emitted which are dangerous for all living things. In order to protect from these radiations, the reactor is surrounded by a massive biological shield.

Nuclear Radiation Exposure and its Biological Effects:

Exposure is defined as the amount of ionization produced in a unit mass of dry air at standard pressure (STP), Its unit is I roentgen = IR= 2.58×10^{-4} C/kg.

There are two main types of radiation exposure: external and internal.

1. External radiation exposure occurs when a person exposed to radiation from a source outside the body, such as an X-ray machine or a nuclear power plant.

2. Internal radiation exposure occurs when a person ingests or inhales radioactive material, which can then accumulate in the body and emit radiation.

Radiation exposure can also be measured in other units, including sieverts (Sv), millisieverts (mSv), and microsieverts (uSv).

Biological Effects of Radiation:

When radiation is absorbed by matter, especially living tissue, it can induce significant changes. The biological effects of radiation are diverse and depend on several factors, including:

Type of radiation: Each type interacts differently. Alpha particles, while unable to penetrate deeply, cause disorder within cells they reach. Beta particles travel farther but deposit less energy, while gamma rays can pierce through tissues, potentially affecting multiple organs.

Dose absorbed: This quantifies the energy deposited per unit mass of tissue. Higher doses generally translate to more pronounced effects.

Duration of exposure: Acute (short-term) exposure like an X-ray differs from chronic (long-term) exposure from environmental sources or occupational hazards. Individual sensitivity: Age, health status, and genetic predispositions can influence susceptibility.

The biological effects of radiation include:

Acute radiation syndrome (ARS): High-dose exposure can trigger ARS, a complex condition affecting multiple organ systems with symptoms like nausea, vomiting, hair loss, and bone marrow suppression.

Cancer risk: Chronic low-dose or high-dose exposures can increase the risk of various cancers, depending on the affected tissue.

Genetic effects: Germ cell mutations can lead to congenital disabilities in offspring.

Reproductive issues: Fertility can be impaired, and miscarriage risk may increase.

Developmental effects: Early exposure in uterus can affect fetal development, causing physical and cognitive impairments.

Dosimetry:

Dosimetry is the science of measuring and quantifying radiation dose. It is a field of physics that deals with the interaction of radiation with matter and the biological effects of radiation exposure.

Key Components of Dosimetry:

1. Absorbed Dose: The amount of radiation energy absorbed per unit mass of the material. Measured in Gray (Gy), it is a pivotal metric in understanding radiation's effect on tissues.

2. Equivalent Dose: Not all radiation types have the same biological impact, even if their absorbed doses are identical. To account for this, radiation weighting factors are introduced to derive the equivalent dose. Measured in Sievert (Sv), it provides a more biologically relevant dose metric.

3. Effective Dose: Considering that different tissues have varying sensitivities to radiation, tissue weighting factors are used. The effective dose, also in Sieverts (Sv), offers a measure that summarizes the potential overall harm to the whole organism.

4. Operational Dose Quantities: These are practical quantities used for routine monitoring in radiological protection. They are designed to estimate effective dose or equivalent dose to a particular tissue. Examples include ambient dose equivalent and personal dose equivalent.

Dosimetry is performed using devices known as dosimeters, which can be worn by people working with or around radioactive materials to monitor their exposure levels. These devices can measure and record the dose of radiation over time.

Medical Uses of Nuclear Radiation:

Medical use of nuclear radiation is quite common today's hospitals and clinics.

It contains various diagnostic and therapeutic applications that control the properties of ionizing radiation to diagnose and treat diseases.

Some examples include:

Imaging:

X-rays: The workhorse of medical imaging, X-rays utilize electromagnetic radiation to reveal fractures, bone structures, and internal injuries.

CT scans: Combining multiple X-ray images, CT scans provide detailed cross-sectional views of organs and tissues, aiding in diagnosing tumors, infect Ions, and internal bleeding.

PET scans: Positron emission tomography (PET) utilizes radioactive tracers to map metabolic activity within the body, uncovering cancerous tumors and other metabolic disorders.

Nuclear medicine procedures:

Bone scans:

Radioactive tracers identify bone diseases like osteoporosis and cancer metastases.

Thyroid scans:

Radioactive iodine helps diagnose and treat thyroid disorders.

Lung scans:

Technetium-99m helps assess lung function and detect blood clots.

Treatment:

Radiotherapy:

Harnessing the destructive power of radiation, targeted beams are used to shrink and destroy cancerous tumors with remarkable precision. This non-invasive therapy plays a crucial role treating various cancers, often in conjunction with surgery and chemotherapy.

Brachy therapy:

Radioactive implants placed directly within tumors deliver high doses of radiation locally, minimizing damage to surrounding tissue. This approach is particularly effective for treating prostate, cervical, and head and neck cancers.

Radioisotope therapy:

Radioactive isotopes are used to treat specific conditions like hyperthyroidism (radioactive iodine) and blood disorders (radioactive phosphorus).

Other Applications:

Pain management:

Radiofrequency ablation utilizes radio waves to heat and destroy nerve tissue, offering pain relief for chronic conditions like back pain and arthritis.

Sterilization:

Medical instruments and equipment are sterilized using gamma radiation, ensuring sterility and preventing infections.

Exposure of radiation:

This process creates charged particles (Ions) and free radicals, which can disrupt molecular structures and biological processes. Examples of ionizing radiation include:

X-rays: Electromagnetic radiation produced by high-energy electron beams or X-ray tubes. X-rays are commonly used in medical imaging, security screening, and industrial applications.

Gamma rays: High-energy electromagnetic radiation emitted by radioactive decay processes, such as those occurring in radioactive isotopes like cobalt-60 and cesium-137.

Gamma rays are used in medical imaging (gamma cameras), radiation therapy, and sterilization processes.

Alpha particles: Alpha particles are emitted during the decay of heavy elements like uranium and radium and have low penetrating power but can cause significant damage if inhaled or ingested.

Beta particles: Beta particles can penetrate deeper into tissues than alpha particles but are less damaging. They are used in medical imaging (positron emission tomography) and radiation therapy.

Neutrons: Neutrons can induce nuclear reactions and are used in neutron activation analysis, neutron radiography, and certain types of cancer therapy.

Cosmic rays: High-energy particles from outer space continuously bombard Earth's atmosphere, generating secondary radiation that reaches the surface.

Industrial applications: Gauges, sterilization processes, and smoke detectors often employ ionizing radiation for various industrial purposes.

These forms of ionizing radiation have various applications in medicine, industry, research, and other fields but require careful handling and monitoring to minimize risks to human health and the environment.

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Uses of Radioactive Tracers:

One of the most important uses of nuclear radiation is the location and study o diseased tissue. This can be done by radioactive tracers.

Radioactive tracers are radioactive substances that are used to track the movement and behavior of specific molecules or compounds in various systems. These tracers emit radiation that can be detected through biochemical reactions, metabolic pathways, fluid flow, and environmental transport.

Some examples of the uses of radioactive tracers include:

Medical Imaging:

Positron Emission Tomography (PET):

Radiotracers labeled with positron- emitting isotopes (e.g., fluorine-18, carbon-11) are injected into the body and used to visualize metabolic activity, blood flow, and receptor binding in tissues. PET imaging is valuable for diagnosing and monitoring diseases such as cancer, heart disease, and neurological disorders.

Industrial Processes:

Flow Visualization: Radiotracers are injected into fluids or gases to track flow patterns and detect leaks or blockages in industrial pipelines, heat exchangers, and reactors. This technique is used in industries such as petrochemicals, food processing, and nuclear power.

Process Optimization:

Radiotracers are used to monitor and optimize chemical reactions, mixing processes, and material transport in industrial processes. By tracking the movement of tracers, engineers can identify bottlenecks, improve efficiency, and ensure product quality.

Soil Fertility and Nutrient Uptake:

Radioactive isotopes like phosphorus-32 (P) are used to study nutrient uptake in plants. By tagging fertilizers with these tracers, scientists can track how nutrients move through the soil and are absorbed by plants. This information helps in optimizing fertilizer application, ensuring that crops receive the right amount of nutrients.

Environmental Impact Assessments:

Radioactive tracers help in studying the environmental impact of agricultural practices. For instance, they can be used to trace the movement of pollutants or contaminants from agricultural fields to water bodies, enabling better management practices to protect the environment.

EXERCISE

Section (A): Multiple Choice Questions (MCQs)

Choose the correct answer:

1. Identify particle x in the following nuclear reaction $^{9}_{4}Be + ^{4}_{2}He \rightarrow ^{12}_{6}C + x$

(a) Electron (b) proton (c) neutron (d) photon

2. In the equation $^{27}_{13}Al + ^{4}_{2}He \rightarrow ^{30}_{15}P + X$, The correct symbol for X is:

(a) $^{-1}_{0}e$ (b) $^{1}_{1}H$ (c) $^{4}_{2}He$ (d) $^{1}_{0}n$

3. Beta rays emitted by a radioactive material are:

(a) Electromagnetic radiations (b) The electrons orbiting around the nucleus

(c) Charged particles emitted by the nucleus (d) Neutral particles

4. The number of a and ß particles emitted in the following radioactive decay is:

$$^{200}_{90}X \rightarrow ^{168}_{80}Y + ^{7}_{7}X$$

(a) 8 and 6 (b) 6 and 8 (c) 8 and 8 (d) 6 and 6

5. If radium has half-life of 5 years. Thus for a nucleus in a sample of radium, the probability of decay in ten years is:

(a) 50% (b) 75% (c) 100% (d) 60%

6. Emission of β particles by an element affects its mass number A in the following way:

(a) Increases by 1 (b) decreases by 1 (c) Increases by 2 (d) remains the same

7. As the number of nucleons in a nucleus increases, the binding energy per nucleon:

(a) Increases continuously with mass number

(b) Decreases continuously with mass number

(c) remains constant with mass number

(d) First increases and then decreases with increase of mass number

8. Moderator in a nuclear reactor slows down the neutrons to:

(a) Decrease the probability of escape (b) Increase the probability of nuclear fission

(c) Decrease the probability of absorption (d) all of the above

9. Emission of β particles by an element affects its atomic number Z in the following way:

(a) Increases by 1 (b) decreases by 1 (c) Increases by 2 (d) remains the samn

10. The half life period of a radioactive element is 100 days. After 400 days, 16 g of the element will be reduced to

(a) 8g (b) 4g (c) 2g (d) lg

Section (B): CRQs (Short Answered Questions):

1. Why are protons and neutrons necessary for the stability of an atomic nucleus?

2. How do isotopes of an element differ and why are these differences significant?

3. Name the two methods of controlling a chain reaction.

4. Why is nuclear decay described as spontaneous and random?

5. Explain what happens during the nuclear fusion process.

6. How are activity and decay constant related in radioactive materials?

7. What is meant by binding energy and binding energy per nucleon?

8. Why is the concept of half-life important in studying radioactive substances?

9. Explain the process of positron emission.

Section (C) ERQS (Long Answered Questions):

1. What is radioactivity? State the law of radioactive disintegration. Show that radioactive decay is exponential in nature.

2. Explain the main differences between alpha, beta, and gamma emissions.

3. A fission reactor produces energy to drive a generator. Describe briefly how this ener gy is produced.

4. Define Q-value of a nuclear reaction and its significance.

5. Describe the construction and working of GM counter.

6. Discus nuclear reactions induced by neutrons. Why are neutrons preferred to other particles?

7. What is a nuclear reaction? Explain nuclear fission and fusion.

8. How do the Sun and stars produce energy? What is the proton-proton cycle? Explain with details.

Section (D): Numerical:

1. In 9.0 days the number of radioactive nuclei decreases to one-eighth the number present initially. What is the half-life (in days) of the material? (Ans: 3 days]

2. The $^{32}_{15}P$ isotope of phosphorus has a half-life of 14.28 days. What is its decay constant in units of s^{-1}? (Ans: $5.62 \times 10^{-7} s^{-1}$)

3. Find the binding energy (in MeV) for lithium ZLi (atomic mass =7.016 003 u). (Ans: 39.2 MeV]

4. The binding energy of a nucleus is 225.0 MeV. What is the mass defect of the nucleus in atomic mass units? |Ans: 0.2415 ul

5. A copper penny has a mass of 3.0 g. Determine the energy (in MeV) that would be required to break all the copper nuclei into their constituent protons and neutrons. Ignore the energy that binds the electrons to the nucleus and the energy that binds one atom to another in the structure of the metal. For simplicity, assume that all the copper nuclei are $^{63}_{29}Cu$ (atomic mass = 62.939 598 u). |Ans: 1.51249x10*MeV

6. Write the ß decay process for each of the following nuclei with their proper chemical symbols including Z and A for each daughter nucleus: (a) $^{18}_{9}F$ (b) $^{15}_{8}0$. (Ans: (a), (b))

7. A device used in radiation therapy for cancer contains 0.50 g of cobalt $^{60}_{27}Co$ (59.933 819 u). The half-life of $^{60}_{27}Co$ is 5.27 years. Determine the activity of the radioactive material. (Ans: 2.10×10^{13} decays/second (Bq))

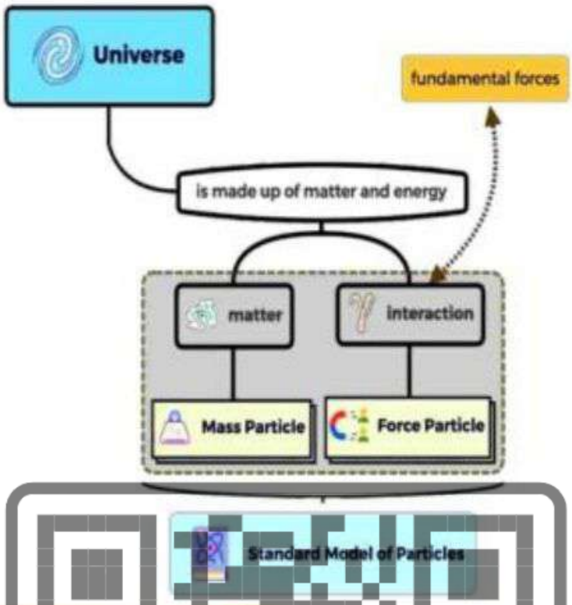
Unit 28

Particle Physics

Standard Model

Particle physics is the branch of modern Physics which deal with the study and search of the ultimate constitute of matter and their interactions

The standard model classified all known elementary particles into two main classes.



Fermions:

These are the matter particles, which make up everything in the universe.

Bosons:

These are the force-carrying particles, which mediate the interactions between fermions.

The Standard Model is a very successful theory. It has been able to predict the existence of many new particles, and it has been confirmed by a wide range of experiments.

However, the Standard Model is not perfect. It does not explain gravity, which is the fourth fundamental force.

It also does not explain dark matter and dark energy, which make up most of the universe.

Fundamental forces and their field particles:

The term "field particles" refers to particles associated with force fields.

According to the Standard Model, bosons are often considered field particles because they are linked to force fields.

For example, the photon is a field particle associated with the electromagnetic field.

Scientists have grouped all fundamental forces into four basic types. In order of increasing strength, these forces and their associated field particles are described as:

1. Gravitational Force:

It is the force that attracts two masses towards each other. It is the weakest of the four fundamental forces but acts over long distances.

Field Particle: The hypothetical particle associated with gravity is the graviton, although it has not been observed yet. The Standard Model doesn't explain gravity.

2. Weak Nuclear Force:

The weak force is responsible for radioactive decay, where unstable atomic nuclei break down into smaller, more stable nuclei. It's responsible for processes like beta decay and neutrino emission. This force is weaker than electromagnetic and strong nuclear forces but stronger than gravitational force.

Field Particle: There are three field particles associates with weak nuclear force. These are W+, W- and Z bosons. These short-lived bosons carry the force over very small distances, explaining the limited range of the weak force.

3. Electromagnetic Force:

This force is responsible for the interactions between charged particles, such as electrons and protons. It includes both electric and magnetic forces. The electromagnetic force is stronger than both gravitational and weak nuclear forces. It is also a long-range force, similar to the gravitational force.

Field Particle: The field particle of electromagnetic force is photon. It is mass less and chargeless particle. When ever charged particles interact, they exchange photons, causing the attractive or repulsive forces we observe.

4. Strong Nuclear Force:

The strong force binds quarks together to form protons and neutrons, and it holds atomic nuclei together. It is the strongest force among all forces and acts at subatomic levels.

Field Particle: Gluons are the field particles that mediate the strong force between quarks.

Particle zoo:

One way of studying elementary particles is to classify them into different categories based on certain behaviours and then to look for similarities or common characteristics among the classifications.

We know that the Standard Model has classified all elementary particles and their interactions into two main groups according to their spins:

Particles that carry force, called boson shaving spin in integer values such as 0,land 2.

Particles that make up all matter, called fermions having spin in odd half integer values such as ½. 3/2 etc.

Bosons:

The arrangement of all elementary particles in the Standard Model constitutes a particle zoo.

All bosons can be classified into two types:

Elementary Boson and Composite Boson.

Composite bosons consist of quark and anti-quark combinations while elementary bosons are not made up of other elementary particles.

Elementary Bosons:

Elementary bosons are the carriers of the fundamental forces in nature. For examples:

- Gluon
- W^+, W^- and Z^0 Bosons
- Photon
- Higgs Boson- gives mass to all particles.
- Graviton

The properties of elementary bosons are given in the table.

The properties of elementary bosons

Force	Boson	Spin	Strength	Mass
Strong	Gluon	1	1	Massless
Electromagnetic	Photon	1	10^{-2}	Massless
Weak	W, Z	1	10^{-7}	80.91GeV
Gravity	Gravitation	2	10^{-39}	Massless

Composite Bosons:

Composite bosons are made up of an even number of fermions.

For examples, mesons are composite bosons that composed of one quark and one antiquark.

Mesons are intermediate mass particles that mediate the strong force between nucleons such as protons and neutrons.

Fermions:

All material particles are made up of fermions. We can further divide fermions in to two sub-classes:

- Elementary fermions
- Composite fermions.

Elementary Fermions:

Elementary fermions are building blocks of all material particles. There are not made of any other particles. The fermions come in two types: leptons and quarks.

(a) Leptons:

Leptons are a group of elementary particles that do not experience the strong nuclear force.

Properties of leptons:

- Electron: Negatively charged; commonly found in atoms.
- Muon and Tau: Heavier counter parts of the electron.
- Neutrinos: Electrically neutral; they interact very weakly with matter.
- Leptons interact via weak and electromagnetic forces but not through the strong force.
- Leptons are stable particles and do not undergo decay under normal circumstances.
- Leptons exist alone and do not form groups.

Quarks:

Quarks are elementary particles that experience all three fundamental forces: strong nuclear force, weak nuclear force, and electromagnetic force.

Properties of Quarks:

They carry fractional electric charges, either +2/3 or -1/3.

Quarks interact strongly with the strong nuclear force, which is mediated by gluons. Quarks are never found as free particles in nature; they are always confined within larger particles called hadrons.

Hadrons are particles made up of quarks held together by the strong nuclear force. Examples of hadrons include protons and neutrons.

Quarks can undergo weak interactions, leading to processes such as beta decay. Weak interactions can change one type of quark into another. For example, a down quark can change into an up quark through weak decay processes.

Composite Fermions:

Composite subatomic particles such as protons, neutrons, alpha particles etc., are composed of two or more elementary particles.

All composite particles are massive.

The composite particles that are made of quarks are called hadrons. The two main categories of hadrons are baryons and mesons.

(a) Baryons:

Baryons are a class of hadrons that consist of three quarks. For example, protons and neutrons are the most well-known baryons, each composed of three quarks:

Proton:

It consists of two up and one down quarks (ūūd). Up (u) quark has +2/3 charge and down quark has -1/3charge.

Therefore, net charge on proton has +1 charge:

Neutron:

It consists of three quarks: one up and two down quarks (ūdd). The net charge on neutron is zero:

(b) Mesons:

Mesons are another class of hadrons, but they consist of one quark and one anti quark. For example, pions (n) are common mesons. They carry the strong nuclear force, binding protons and neutrons together.

Quarks and Beta Decay:

β -decay is a type of radioactive decay process in which a neutron in an atomic nucleus is transformed into a proton. When a B-decay occurs, a down quark emits a field particle called a W-boson (a weak force carrying particle) and transforms into an up quark.

The W-boson quickly breaks up into an electron and an antineutrino. The process is shown

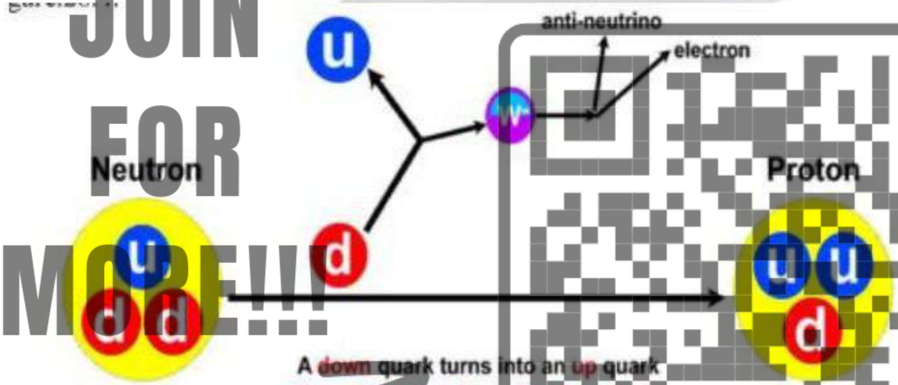


Figure 28.4 Quarks and β - beta decay

Electric charge is conserved during beta decay with the emission of an electron and an antineutrino.

β+ decay is a type of radioactive decay process in which a proton is transformed into a neutron. In B^+ decay, an up quark emits a field particle called a W^+ boson and transforms into a down quark. The W^+ boson quickly breaks up into an anti-electron (positron) and a neutrino. The process is shown

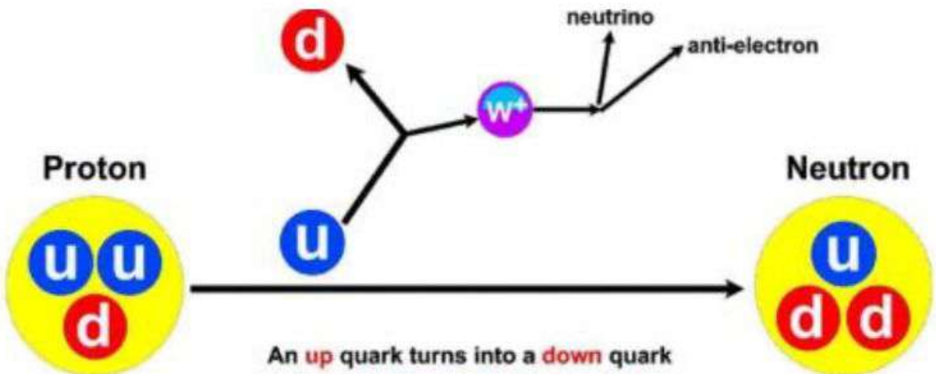


Figure28.5 Quarks and β⁺- beta decay

Radiations Detectors:

Radiations Detectors or Particle Detectors are devices that detect, track, and identify ionizing particles produced by nuclear decay, cosmic radiation, or particle accelerator reactions.

Wilson cloud chambers:

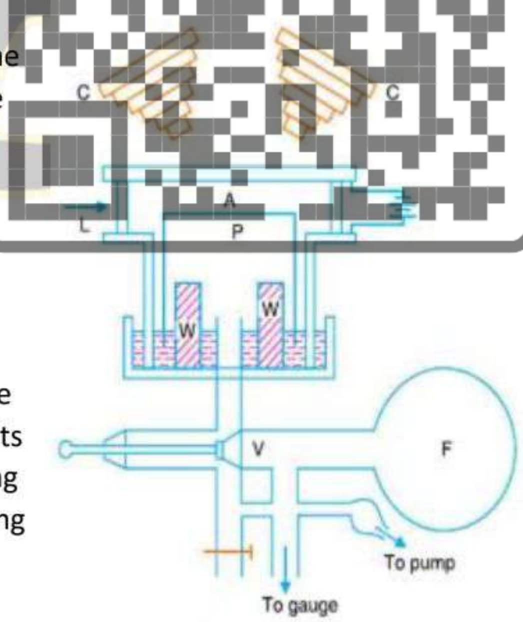
A Wilson cloud chamber is a type of tracking detector which works on the principle of ionization.

Working Principle:

The Wilson Cloud Chamber consists of a sealed container filled with a supersaturated vapor, typically water or ethanol. When a particle passes through the chamber, it ionizes the vapor, creating a trail of droplets that condense around the ionized path. This creates a visible cloud-like track that can be photographed and analyzed.

Construction:

The schematic diagram of Wilson cloud chamber is shown in figure, which consists of a large cylindrical chamber A, with walls and a ceiling made of glass. It contains dust-free air saturated with water vapor. P is a piston working inside the chamber. When the piston moves down rapidly, adiabatic expansion of the air inside the chamber takes place. The piston is connected to a large evacuated vessel F through a valve V. When the valve is opened, the air under the piston rushes into the evacuated vessel F, thereby causing the piston to drop suddenly. The wooden blocks WW reduce the air space inside the piston. Water at the bottom of the apparatus ensures saturation in the chamber. The expansion ratio can be adjusted by altering the height of the piston.



As soon as the gas in the expansion chamber is subjected to sudden expansion, the ionizing particles are shot into the chamber through a side window. A large number of extremely fine droplets are formed on all the ions produced by the ionizing particles. These droplets form a track of the moving ionizing particles. At this stage, the expansion chamber is profusely illuminated by a powerful beam of light L and two cameras CC are used to photograph the tracks as shown in figure 28.10. The process of expansion, shooting of the ionizing particles into the expansion chamber, illuminating the chamber and clicking the camera must all be carried out in rapid succession in order to get satisfactory results.

The type of ionizing particle can be identified by its track in the cloud chamber. Alpha particles, being relatively massive, travel in straight, thick, and clearly defined paths. Beta particles, being lighter, are easily deflected and create thin, curved paths. The cloud chamber has been instrumental in discovering many elementary particles, such as the positron and meson.

Use of Wilson Cloud Chambers:

Particle Identification:

Wilson cloud chambers were historically instrumental in the identification and study of subatomic particles. By observing the curvature of particle tracks a magnetic field and the nature of the tracks themselves, scientists could identify and classify various particles.

Nuclear Physics Research:

Cloud chambers have been used to study the behavior of particles in nuclear reactions and to investigate the structure of atomic nuclei.

Cosmic Ray Studies:

Wilson cloud chambers are also used in cosmic ray research. These instruments can detect and track the passage of cosmic rays, which are high- energy particles originating from space.

Education and Outreach:

Cloud chambers are often used as educational tools in physics classrooms and science museums to help students and the general public visualize the behavior of subatomic particles.

Geiger-Muller counter:

A Geiger-Muller counter (GM counter) is a type of gas radiation detector used to measure ionizing radiation.

It is a portable and versatile device commonly employed for detecting the presence and intensity of various types of ionizing radiation, including alpha particles, beta particles, and gamma rays.

The Geiger-Muller (GM) counter was invented by two German scientists, Hans Geiger and Walther Muller, in 1928.

Construction:

The GM counter consists of a hollow metallic chamber as shown in the figure acts as a cathode.

A thin wire anode is also placed along its axis.

The chamber has a sealed window, through which the radiation enters the chamber.

The chamber is filled with an inert gas at low pressure.

There is a counter connected to this system to measure the radiation.

Working:

The chamber is filled with an inert gas (helium, neon, or argon) at low pressure. A high voltage is applied to this chamber. The metallic chamber will conduct electricity. When radiation enters the chamber through the window, the photons in the radiation will ionize the inert gas inside the chamber. This will make the gas conductive. The electrons produced due to ionization are accelerated due to the potential that we applied and these electrons cause even more ionization. The ionized electrons travel towards the anode. The anode is connected to a counter. The counter counts the electrons reaching the anode. This is how we measure radiation.

Use of GM Counter:

Geiger-Muller counters have a wide range of applications, including:

Radiation Monitoring:

They are commonly used for radiation monitoring in nuclear power plants, laboratories, and industrial settings to measure radiation levels and ensure the safety of workers and the environment."

Environmental Monitoring:

GM counters are employed for environmental radiation monitoring to assess background radiation levels and detect any abnormal increases in radiation.

Health Physics:

Health physicists use GM counters to monitor radiation exposure of individuals working with radioactive materials or in radiation-prone environments.

Education:

Health physicists use GM counters to monitor radiation exposure of individuals working with radioactive materials or in radiation-prone environments.

Radiological Emergencies:

In the event of radiological emergencies or accidents involving radioactive materials, GM counters can be used to assess radiation contamination levels.

EXERCISE

Section (A): Multiple Choice Questions (MCQS)

Choose the correct answer:

1. The Standard Model classifies elementary particles into two main groups:

(a) Baryons and Leptons (b) Fermions and Bosons

(c) Quarks and Gluons (d) Hadrons and Mesons

2. The following is NOT a flavor of quark:

(a) Up (b) Down (c) Electron (d) Top

3. The charge of an up quark is:

(a) +1/2e (b) -1/2 e (c) +2/3e (d) -2/3e

4. The concept of "quark confinement" implies that:

(a) Quarks cannot exist as free particles outside of hadrons.

(b) Quarks are always found in pairs with opposite charges.

(c) Quarks have a strong affinity for gluons.

(d) Quarks are the fundamental building blocks of all matter.

5. The primary role of the Higgs boson in the Standard Model is:

(a) Mediating electromagnetic interactions (b) Providing mass to other particles

(c) Transmitting the strong nuclear force (d) Creating dark matter

6. According to the Standard Model, the term "color" refers to:

(a) Visible light spectrum (b) Charge property of quarks

(c) Mass of particles (d) Spin of particles

7. A particle made up of a quark and an antiquark is called:

(a) Lepton (b) Baryon (c) Meson (d) Neutrino

8. An elementary particle that feels all three fundamental forces (electromagnetic, weak, and strong nuclear forces) is:

(a) Lepton (b) Quark (c) Electron (d) Neutrino

9. The primary function of a Geiger-Müller counter in particle physics is to:

(a) Measure the velocity of particles (b) Detect and count ionizing radiation

(c) Create antimatter particles (d) Generate magnetic fields

10. In a Geiger-Müller counter, the gas commonly used to detect ionizing radiation is:

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(a) Oxygen (b) Neon (c) Argon (d) Helium

Section (B) CRQs (Short Answered Questions):

1. Explain the difference between bosons and fermions and their roles in mediating fundamental forces.

Bosons and **fermions** are two fundamental types of particles that differ in their statistical behavior.

- **Bosons** can occupy the same quantum state simultaneously. This property allows them to mediate forces. Examples of bosons include photons (mediating the electromagnetic force), gluons (mediating the strong nuclear force), W and Z bosons (mediating the weak nuclear force), and the Higgs boson.
- **Fermions** obey the Pauli exclusion principle, which states that no two identical fermions can occupy the same quantum state. This property is crucial for the stability of matter. Examples of fermions include quarks and leptons.

2. Compare and contrast the properties of quarks and leptons, the two main categories of fermions in the Standard Model.

Quarks and Leptons

Both quarks and leptons are fermions, but they have distinct properties.

- **Quarks** are the building blocks of protons and neutrons, which in turn make up atomic nuclei. They interact through all four fundamental forces: the strong, electromagnetic, weak, and gravitational forces. Quarks come in six flavors: up, down, charm, strange, top, and bottom.
- **Leptons** are elementary particles that do not interact through the strong nuclear force. They are divided into three generations: electron, muon, tau; and their corresponding neutrinos. Leptons interact through the electromagnetic, weak, and gravitational forces.

3. Define the term "lepton" and provide examples of leptons. Explain their fundamental properties and role in the Standard Model of particle physics.

Leptons

Leptons are a class of elementary particles that do not experience the strong nuclear force. They are divided into three generations:

- **First generation:** Electrons and electron neutrinos

- **Second generation:** Muons and muon neutrinos
- **Third generation:** Tau particles and tau neutrinos

Leptons have the following fundamental properties:

- **Spin:** They have a spin of 1/2, which means they are fermions.
- **Charge:** Electrons, muons, and tau particles have a negative electric charge, while neutrinos are electrically neutral.
- **Mass:** The electron is the lightest lepton, followed by the muon and tau particle. Neutrinos have very small masses.

4. Explain the concept of color charge in quarks and its significance in the strong nuclear force. How does the combination of quarks contribute to the color-neutral nature of protons and neutrons?

Color Charge in Quarks

Color charge is a quantum property unique to quarks. It is analogous to electric charge, but it comes in three types: red, green, and blue. Quarks can have any combination of these colors.

The strong nuclear force is mediated by gluons, which are massless bosons that carry color charge. Gluons interact with quarks through their color charges, binding them together to form protons and neutrons.

The combination of quarks in a proton or neutron must be **color-neutral**. This means that the overall color charge of the combination must be zero. For example, a proton is composed of two up quarks and one down quark. The color charges of these quarks must add up to zero to form a color-neutral proton.

5. Describe the structure of a proton and neutron in terms of its quark composition. How do quarks combine to form a proton and a neutron, and what are the specific types of quarks involved?

Structure of Protons and Neutrons

Protons and neutrons are made up of three quarks.

A proton is composed of two up quarks and one down quark, while a neutron is composed of one up quark and two down quarks.

The quarks within a proton or neutron are held together by the strong nuclear force. This force is mediated by gluons, which interact with the color charges of the quarks. The combination of quarks in a proton or neutron must be color-neutral, as explained above.

Section (C) ERQS (Long Answered Questions):

1. Explain the structure of the Standard Model, including the different types of particles and their relationships. How does the model classify fundamental forces?

Notes

2. Describe in detail all fundamental forces and their associated field particles. What is a boson, and why are bosons referred to as field particles?

Notes

3. Describe the operating principle of a Geiger-Müller counter. How does it detect and quantify ionizing radiation, and what are its limitations in terms of measurement range and types of radiation detected?

Notes

4. Discuss the uses of a Wilson cloud chamber in particle physics experiments. How does it visualize charged particle tracks, and what factors can affect its performance?

Mcq's Answers

Chapter # 15

1. **(b)** temperature is directly proportional to average kinetic energy
2. **(a)** 0°C and 1 atm
3. **(a)** Reduced to ½ of the original value
4. **(a)** One mole of a substance
5. **(a)** kT
6. **(a)** 98.6°F (37°C)
7. **(b)** $P = \frac{1}{3}\rho v^2$
8. **(d)** Helium atoms is greater than both Oxygen and Nitrogen molecules
9. **(c)** $\sqrt{3}$ times
10. **(c)** Remains constant

Chapter # 16

1. **(a)** Isothermal process
2. **(b)** Pressure
3. **(a)** Isothermal process
4. **(c)** No heat exchange with the surroundings
5. **(c)** Constant volume
6. **(d)** The total energy contained within the system
7. **(a)** $\Delta U = \Delta Q + \Delta W$
8. **(a)** Temperature only
9. **(b)** Decreases
10. **(a)** $\Delta U = \Delta Q + \Delta W$

Chapter # 17

1. **(c)** 0 K
2. **(a)** Rise
3. **(c)** Sparking Plug
4. **(d)** A chemical explosion
5. **(c)** Not possible
6. **(a)** $\Delta S = \Delta Q / T$
7. **(a)** Positive
8. **(a)** Greater than petrol engine
9. **(d)** Entropy increases over time
10. **(d)** Heat flowing from cold to hot

Chapter # 18

1. **(b)** reversed
2. **(b)** magnetic levitation trains
3. **(a)** At right angles to each other
4. **(a)** doubled
5. **(a) Increasing number of turns** and **(c) increasing the current through the solenoid**
6. **(b)** uniform
7. **(a)** Magnetic effect of current
8. **(a)** Increase it

9. **(c)** Perpendicular to the magnetic field and the proton's velocity
10. **(c)** Zero, since the electron is moving parallel to the field

Chapter # 19

1. **(c)** the movement of conductors within magnetic fields.
2. **(c)** Applicable to both cases.
3. **(c)** the increase in the number of turns in the coil.
4. **(b)** that the induced e.m.f. is directly proportional to the rate of change of magnetic flux.
5. **(b)** by stating that the induced current will oppose the change causing it.
6. **(c)** magnetic fields that oppose the inducing field and cause heating in conductors.
7. **(c)** minimize eddy current losses and reduce heating.
8. **(b)** a changing magnetic field within a coil induces an emf in the same coil.
9. **(b)** the magnetic field within its coil.
10. **(b)** electromagnetic induction between primary and secondary coils.

Chapter # 20

1. **(c)** Cycle
2. **(a)** 50 Hz
3. **(b)** Frequency
4. **(a)** 0°
5. **(d)** AVO meter
6. **(c)** Capacitive and inductive opposition to current flow
7. **(d)** Resonant
8. **(d)** The difference between the positive and negative peak voltages
9. **(c)** 1
10. **(b)** To step up or step down voltage

Chapter # 21

1. **(a)** Elasticity
2. **(b)** Ductile
3. **(b)** Yield point
4. **(a)** Compressibility
5. **(d)** I and II
6. **(c)** Metallic
7. **(c)** Conduction and valence bands
8. **(a)** Between conductor and insulator
9. **(a)** All the domains get oriented in the direction of the magnetic field.
10. **(b)** By heating, hammering, and spinning it in an external magnetic field

Chapter # 22

1. **(a)** Four
2. **(b)** Intrinsic
3. **(b)** Trivalent atom
4. **(d)** Boron
5. **(b)** Equals the line frequency
6. **(d)** Gallium arsenide
7. **(c)** One-half of the line frequency
8. **(b)** Low

9. **(d)** Common emitter circuit
10. **(d)** Amplified

Chapter # 23

1. **(b)** 0 volts
2. **(a)** Low state
3. **(c)** Analyze output states based on input combinations
4. **(b)** OR
5. **(b)** ON
6. **(b)** ON
7. **(b)** 0
8. **(b)** 0
9. **(b)** 0
10. **(c)** OR + NAND

Chapter # 24

1. **(b)** gravity
2. **(b)** 1.2 kg
3. **(a)** The equivalence of inertial and gravitational mass
4. **(c)** Gravitational waves
5. **(b)** They are indistinguishable for an observer
6. **(a)** Gravitational lensing
7. **(d)** their immense gravity traps light
8. **(a)** Their mass becomes infinite
9. **(b)** It violates the constancy of the speed of light
10. **(b)** A train moving smoothly at constant speed

Chapter # 25

1. **(d)** h/2p
2. **(d)** the electric potential that causes the electron current to vanish
3. **(b)** 0.60 V
4. **(a)** higher frequency radiation
5. **(d)** X-rays
6. **(d)** 180°
7. **(c) 2.1×10^{-11}m**
8. **(a)** Electrons
9. **(b)** Minimum
10. **(c)** Minimum

Chapter # 26

1. **(b)** Line spectra
2. **(c)** 1:2
3. **(a)** increases
4. **(b)** Highly coherent photons
5. **(a)** Optical pumping
6. **(a)** Three energy levels
7. **(a)** Active medium
8. **(a)** Energy

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9. **(b)** Electric fields
10. **(d)** Quadruples the intensity

Chapter # 27

1. **(c)** neutron
2. **(d)** ${}_{0}^{1}n$
3. **(c)** Charged particles emitted by the nucleus
4. **(a)** 8 and 6
5. **(b)** 75%
6. **(d)** remains the same
7. **(d)** First increases and then decreases with increase of mass number
8. **(d)** all of the above
9. **(a)** Increases by 1
10. **(c)** 2g

Chapter # 28

1. **(b)** Fermions and Bosons
2. **(c)** Electron
3. **(c)** +2/3e
4. **(a)** Quarks cannot exist as free particles outside of hadrons.
5. **(b)** Providing mass to other particles
6. **(b)** Charge property of quarks
7. **(c)** Meson
8. **(b)** Quark
9. **(b)** Detect and count ionizing radiation
10. **(c)** Argon