SURVIVAL GUIDE FOR ENGINEERING PHYSICS – II

(Semester – II)

For Diploma Students Revision 2015

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CONTENTS

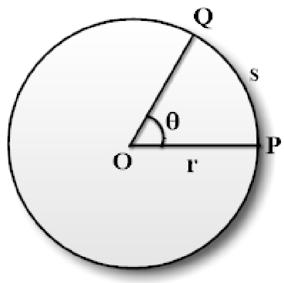
Chapter 1

Circular Motion

1. Define uniform circular motion. Can a body move with uniform velocity along a circular path. Give reason.

   The motion of a body along a circular path with constant speed is called uniform circular motion. In uniform circular motion speed remains a constant, but the velocity keeps on changing. The direction of velocity continuously changes as the body moves in a circular path. Since velocity is a vector quantity, a change in direction implies a variable velocity.

2. Define angular displacement and angular velocity. Derive the relation between linear velocity and angular velocity.



   Consider a body moving around the circumference of a circle with center 'O' and radius 'r'. The linear displacement of the body as it travels from P to Q in 't' seconds is 's'.
   Angular displacement of the body is defined as the angle subtended at the centre of the circle as it moves along the circumference of the circle. The SI unit of angular displacement is radian.

$$\text{Angular displacement, } \theta = \frac{s}{r}$$

   Angular velocity is defined as the rate of change of angular displacement of a body. The SI unit of angular velocity is rad/s.

$$\text{Angular velociy, } \omega = \frac{\theta}{t}$$

   Relation between linear velocity and angular velocity

$$\text{Angular displacement, } \theta = \frac{s}{r}$$

$$s = r\theta \quad (1)$$

$$\text{Angular velociy, } \omega = \frac{\theta}{t} \quad (2)$$

$$\text{Linear velociy, } v = \frac{s}{t}$$

$$\text{Using equation (1), } v = \frac{r\theta}{t}$$

$$\text{Using equation (2), } \boxed{v = r\omega} \quad (3)$$

3. Define angular acceleration. Derive the relation between linear acceleration and angular acceleration.

Angular acceleration is defined as the rate of change of angular velocity. The unit of angular acceleration is rad/s^2. If the angular velocity of a particle changes from ω_1 to ω_2 in t seconds, the angular acceleration is given by

$$\alpha = \frac{\omega_2 - \omega_1}{t}$$

Let v_1 and v_2 are the linear velocities, then

$$\begin{aligned} v_1 &= r\omega_1 \quad \implies \omega_1 = v_1/r \\ v_2 &= r\omega_2 \quad \implies \omega_2 = v_2/r \\ \therefore \quad \alpha &= \frac{(v_2/r) - (v_1/r)}{t} \\ \alpha &= \frac{(v_2 - v_1)}{rt} \end{aligned}$$

But $a = (v_2 - v_1)/t$ is the linear acceleration of the particle. Hence,

$$\alpha = a/r$$
$$\boxed{a = r\alpha}$$

4. Write down three equations of angular motion.

Consider a particle with initial angular velocity ω_1 and angular acceleration α. Let the angular velocity changes from ω_1 to ω_2 in t seconds and the angular displacement be θ. The the three equations of angular motion are:

$$\begin{aligned} \omega_2 &= \omega_1 + \alpha t \\ \theta &= \omega_1 t + \frac{1}{2}\alpha t^2 \\ {\omega_2}^2 &= {\omega_1}^2 + 2\alpha\theta \end{aligned}$$

5. Define and write the expression for centripetal acceleration and centripetal force.

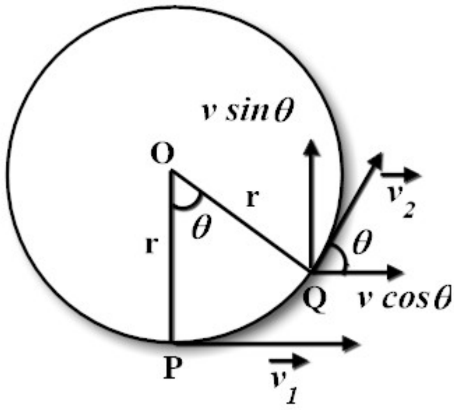
When a particle executes uniform circular motion, the direction of velocity is continuously changing and this change is direction produces an acceleration. The acceleration of a particle moving along a circular path with uniform speed is always directed towards the center of the circle and this acceleration is called centripetal acceleration. If v is the linear speed, w is the angular velocity and r is the radius of the circle, the centripetal acceleration is given by :

$$\boxed{a_c = vw}\ ; \quad \boxed{a_c = \frac{v^2}{r}}\ ; \quad \boxed{a_c = \omega^2 r}$$

Centripetal force is that force which is required to keep a body in a circular path with uniform speed and acting towards the centre of a circular path. If m is the mass of the body then centripetal force is given by:

$$\text{By Newton's second law,} \quad F_c = ma_c$$
$$\boxed{F_c = \frac{mv^2}{r}}\ ; \quad \boxed{F_c = m\omega^2 r}$$

6. Derive an expression for centripetal acceleration for a body in uniform circular motion.



Consider a particle of mass m moving along the circumference of a circle with uniform speed v. Let the particle moves from point P to point Q making an angular displacement θ in a time t seconds. The velocity of the particle at P and Q are $\vec{v_1}$ and $\vec{v_2}$ respectively as shown in the figure. The velocity at every point on the circle is the tangent at the point perpendicular to the radius r of the circle. Hence, the angle between $\vec{v_1}$ and $\vec{v_2}$ is also θ. The magnitude of $\vec{v_1}$ and $\vec{v_2}$ are the same and equal to the speed v, but the direction of the velocities are different. Hence, $\vec{v_1}$ and $\vec{v_2}$ can be represented as

$$\vec{v_1} = v\ \hat{i}$$
$$\vec{v_2} = vcos\theta\ \hat{i} + vsin\theta\ \hat{j}$$

If θ is very small, then $cos\theta \approx 1$ and $sin\theta \approx \theta$. Therefore,

$$\vec{v_2} = v\ \hat{i} + v\theta\ \hat{j}$$
$$\text{Change in velocity, } \vec{\Delta v} = \vec{v_2} - \vec{v_1} = v\theta\ \hat{j}$$
$$\text{magnitude of change in velocity, } \Delta v = v\theta$$
$$\text{Centripetal acceleration, } a_c = \frac{\Delta v}{t} = \frac{v\theta}{t}$$
$$\boxed{a_c = v\omega} \quad \left(\text{Since, angular velocity, } \omega = \frac{\theta}{t}\right)$$
$$\text{We have, } v = r\omega \implies w = \frac{v}{r}$$
$$\therefore \boxed{a_c = r\omega^2} \text{ and } \boxed{a_c = \frac{v^2}{r}}$$

7. Why we say that work done by a centripetal force is zero?.

Centripetal force is that force which is required to keep a body in a circular path with uniform speed and acting towards the centre of a circular path. Centripetal force is always perpendicular to the direction of velocity and hence to the displacement of the particle. Therefore work done by centripetal force is zero.

8. State five examples of circular motion and explain how centripetal force is provided in each case?.

(a) Moon going around the earth or earth moving around the sun - centripetal force is provided by the gravitational force of attraction between Earth and Moon or between Earth and the Sun.

(b) Electron moving around the nucleus - centripetal force is provided by the electrostatic force of attraction between the positively charged nucleus and negatively charged electron.

(c) A stone tied to a string and having uniform circular motion - the centripetal force is provided by the tension on the string.

(d) A vehicle turns round a horizontal curve - centripetal force is provided by the friction between wheel and the road.

(e) A train turning round a horizontal curve - centripetal force is provided by lateral trust exerted by the wheel on the rails.

9. Explain why the outer edge of the road/rail is raised over the inner edge on the curved portion of road/rail. (Or illustrate the role of centripetal force in banking of curves. Or Explain why there is a speed limit for a vehicle going around a curved road)

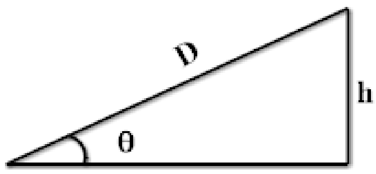
When a moving vehicle takes a turn, it travels along a circular path and for circular motion centripetal force is necessary. If the vehicle is moving long a horizontal curve, the weight of the vehicle is balanced by the normal reaction while the force of friction provides the necessary centripetal force. In order that a vehicle may make a safe turn without depending on the frictional force, the outer portion of the road/rail is raised above the inner portion of the road/rail. This process is called banking of curves. If the curved tracks are banked, a component of normal reaction will contribute to centripetal force in addition to frictional force. This will increase the optimum speed of the vehicle at the curved portion of roads/rails. There is a speed limit for a vehicle going around the curved road even if the road is banked since if both friction and the component of normal reaction together cannot provide the necessary centripetal acceleration, the vehicle will skid away from the curved portion.

10. Define angle of banking and derive the equation for super elevation

Angle of banking (θ) is the angle between horizontal level and elevated surface of the banked road. Angle of banking (θ) depends on the optimum speed (v) of the vehicle and radius of the curve (r). The relation for angle of banking is given by

$$\tan\theta = \frac{v^2}{rg}$$

In the case of curved rail tracks, let the outer rail be laid at a height 'h' above the horizontal level and 'D' be the distance between the rails as shown in the figure.



From the triangle shown in the figure, the height of the outer rail over the inner rail (h) is obtained as

$$\sin\theta = \frac{h}{D}$$

For small angles of banking, $sin\theta$ and $tan\theta$ will be nearly equal. Hence

$$\tan\theta = \frac{h}{D}$$

$$\frac{v^2}{rg} = \frac{h}{D}$$

$$h = \frac{v^2 D}{rg}$$

The height h is called super elevation.

11. Why does a cyclist lean inward while going through a curved path?. Why cyclist must ride slowly in sharp curves?.

When a cyclist is riding through a curved path, sufficient centripetal force has to be provided. Friction alone cannot provide necessary centripetal force if the speed is not very low. Hence, cyclist instinctively leans towards the centre of the curve so that a component of the normal reaction will also contribute to the centripetal force in addition to the frictional force.

If θ is the inclination of the plane of the cycle with the vertical, $tan\theta = v^2/rg$ where r is the radius of the curve, v is the speed of the cycle and g is the acceleration due to gravity. If velocity v of the cycle is very large and r is small, the leaning angle θ becomes large and hence the risk of falling is great. Hence, the cyclist must ride slowly in sharp curves.

12. A body of mass M is attached to a string of length L and is revolved in a horizontal plane. If the string can withstand a tension F, show that the maximum angular velocity with which it can be revolved is given by the equation $\omega = (F/ML)^{1/2}$.

The centripetal force necessary for the circular motion is given by

$$F_c = mr\omega^2$$
$$\omega^2 = \frac{F_c}{mr}$$
$$\omega = (F/mr)^{1/2}$$
$$\text{Here} \quad F_c = F; \quad m = M; \quad \text{and } r = L;$$
$$\therefore \quad \omega = (F/ML)^{1/2}$$

Important Equations to Remember

$$\text{Angular displacement, } \theta = \frac{arc\ length}{radius} = \frac{s}{r}$$
$$\text{Linear velocity, } v = \frac{s}{t}$$
$$\text{Angular velocity, } \omega = \frac{\theta}{t}$$

Relation between linear and angular quantities, $Linear\ quantity = radius \times angular\ quantity$

Relation between linear and angular displacements, $s = r\theta$

Relation between linear and angular velocities, $v = r\omega$

Relation between linear and angular accelerations, $a = r\alpha$

$$\text{Time period of revolution, } T = \frac{2\pi r}{v} = \frac{2\pi}{\omega}$$

Equations of angular motion is obtained from equations of motion by repacing $s \to \theta,\ u \to \omega_0, v \to \omega,\ and$

$$\omega = \omega_0 + \alpha t$$
$$\theta = \omega_0 t + \frac{1}{2}\alpha t^2$$
$$\omega^2 = \omega_0^2 + 2\alpha\theta$$

$$\text{Centripetal acceleration, } a_c = vw;\ a_c = \frac{v^2}{r};\ a_c = rw^2$$

$$\text{Centripetal force, } F_c = \frac{mv^2}{r};\ F_c = mrw^2$$

$$\text{Relation between angle of banking, radius of the curve and optimum speed, } tan\theta = \frac{v^2}{rg}$$

$$\text{Equation for super elevation:} \quad h = \frac{v^2 D}{rg}$$

Chapter 2

Rotational Dynamics

1. Define moment of inertia of a rigid body. What is its SI unit?.

   The inability of a body which is free to rotate about an axis, to change the state of rest or of uniform rotation motion by itself is called rotational inertia or moment of inertia. Moment of inertia is associated with rotational motion and depends on mass of the body and distribution of the mass around the axis of rotation (shape of the body). Moment of inertia of a particle is defined as the product of mass of the particle and square of the distance of the particle from the axis of rotation.

   $$\boxed{I = mr^2}$$

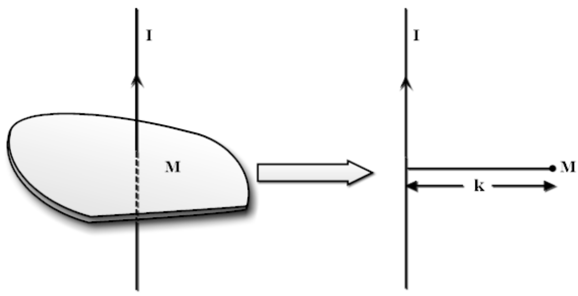
   The SI unit of moment of inertia is kgm^2.

2. Distinguish between centre of gravity and centre of mass.

   The force of gravity acting on various particles of a rigid body can be represented by a single force which is the weight of the body (Mg) acting at a point. This point is called centre of gravity. The centre of mass of a system of particles is the point associated with the system which moves in the same way in which a single particle having the total mass of the system and acted upon by the same force would move. Centre of mass is a geometrical point and may not be a point on the body. In the same gravitational field, centre of mass and centre of gravity coincide.

3. Define radius of gyration. Give its equation and unit. Determine the radius of gyration of a circular disc of mass m and radius R about an axis pass through its centre and perpendicular to its plane.

   Radius of gyration is the distance from the axis of rotation to the point at which mass of the body is assumed to be concentrated so that moment of inertia will be equal to the moment of inertia of the actual body.



$$I = Mk^2$$
$$k^2 = \frac{I}{M}$$
$$k = \sqrt{\frac{I}{M}}$$

   Radius of gyration is equivalent distance of mass of a body from the axis of rotation. It is a numerical measure of distribution of mass of a body around the axis of rotation. The unit of radius of gyration is meter.

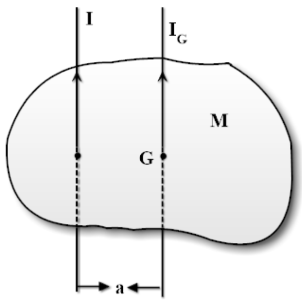
   The moment of inertia of a disc of mass m and radius R about an axis pass through its centre and perpendicular to its plane is given by

$$I = \frac{1}{2}MR^2$$

$$\text{Radius of gyration, } k = \sqrt{\frac{I}{M}}$$
$$= \sqrt{\frac{\frac{1}{2}MR^2}{M}}$$
$$= \sqrt{\frac{1}{2}R^2}$$
$$= \frac{R}{\sqrt{2}}$$

4. State and explain parallel axis theorem and perpendicular axis theorem.

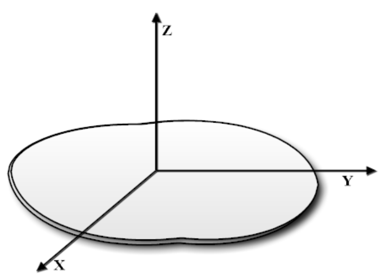
Parallel axis theorem states that the moment of inertia of any rigid body about a given axis is equal to the sum of its moment of inertia about a parallel axis passing through the center of gravity and the product of the mass of the body and square of the distance between the axes.



Let I_G be the moment of inertia of a body of mass M about through the center of gravity and I be the moment of inertia about a parallel axis at a distance 'a' from the center of gravity. Then according to parallel axis theorem,

$$\boxed{I = I_G + Ma^2}$$

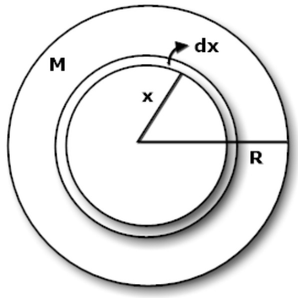
Perpendicular axis theorem (Plane figure theorem) states that the sum of moment of inertia of a plane lamina about two mutually perpendicular axes lying in the plane is equal to the moment of inertia about an axis perpendicular to the plane of the lamina and passing through the intersection of the first two axes.



Consider a plane lamina lies in XY plane and Z-axis is perpendicular to the plane of the lamina. Let I_X, I_Y and I_Z are the moment of inertia of the plane lamina about X,Y and Z axes respectively. Then according to perpendicular axis theorem,

$$\boxed{I_z = I_X + I_Y}$$

5. Derive an expression for moment of inertia of a circular disc about an axis passing through its centre and perpendicular to its plane.



Let M be the mass and R be radius of the disc. the disc can be imagine to be made up of a large number of rings of very small width and gradually increasing radii fro zero to R. Consider a ring of radius x and width dx.

$$\begin{aligned}
\text{Total mass of the disc} &= M \\
\text{Mass per unit area of the disc} &= \frac{M}{\pi R^2} \\
\text{Area of the ring of radius x and width dx} &= 2\pi x dx \\
\text{Mass of the ring} = 2\pi x dx \times \frac{M}{\pi R^2} &= \frac{2Mxdx}{R^2}
\end{aligned}$$

$$\begin{aligned}
\text{Moment of inertial of the ring} &= mass \times (radius)^2 \\
&= \frac{2Mxdx}{R^2} \times x^2 \\
&= \frac{2Mx^3dx}{R^2}
\end{aligned}$$

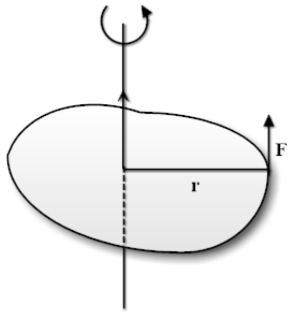
Moment of inertia of the disc about an axis passing through the center and perpendicular its plane is obtained by integrating between the limits $x = 0$ to $x = R$.

$$\begin{aligned}
I &= \int_0^R (\frac{2M}{R^2})x^3dx \\
&= \frac{2M}{R^2}\int_0^R x^3dx \\
&= (\frac{2M}{R^2})[\frac{x^4}{4}]_0^R \\
&= (\frac{2M}{R^2}) \times \frac{R^4}{4} \\
&= \frac{1}{2}MR^2
\end{aligned}$$

$$\boxed{I = \frac{1}{2}MR^2}$$

6. Define torque and angular momentum and derive the relation between them.

The rotating effect of a force acting on a rigid body, about an axis of rotation is called the torque. Torque (τ) is defined as the product of force and the perpendicular distance between the line of action of the force and the axis of rotation.



$$\boxed{\tau = r \times F}$$

Torque is the rotational equivalent of force and moment of inertia is the rotational equivalent of mass. Therefore comparing equation $F = ma$, the equation for torque is given by,

$$\boxed{\tau = I\alpha}$$

Angular momentum of a rigid body is a measure of twisting effect associated with the momentum of the body. Angular momentum (L) about a point is defined the product of momentum of the body and the perpendicular distance the point and axis of rotation of the body.

$$\boxed{L = r \times p}$$

The relation between angular momentum and angular velocity is given by'

$$\boxed{L = I\omega}$$

Consider a body of moment of inertia I rotating about an axis with angular velocity ω_1. When a torque τ is applied for a time t, the angular velocity changes from ω_1 to ω_2. Then, angular acceleration is given by

$$\alpha = \frac{(\omega_2 - \omega_1)}{t}$$

$$\text{But } \tau = I\frac{(\omega_2 - \omega_1)}{t}$$

$$= \frac{(I\omega_2 - I\omega_1)}{t}$$

Since $I\omega_1 = L_1$ is the initial angular momentum and $I\omega_2 = L_2$ is the final angular momentum, then

$$\tau = \frac{(L_2 - L_1)}{t}$$

This shows that rate of change of angular momentum is equal to the torque acting on the body. This is the rotational analog of Newton's second law.

$$\boxed{\tau = \frac{dL}{dt}}$$

7. Define Angular momentum and how it is related to angular velocity. Define rotational kinetic energy and how it is related to angular momentum.

   Angular momentum of a rigid body is a measure of twisting effect associated with the momentum of the body. Angular momentum (L) about a point is defined the product of momentum of the body and the perpendicular distance the point and axis of rotation of the body.

$$\boxed{L = r \times p}$$

The relation between angular momentum and angular velocity is given by

$$\boxed{L = I\omega}$$

The energy of a body by virtue of its rotational motion is called rotational kinetic energy. If I is the moment of inertia and ω is the angular velocity, then rotational kinetic energy is given by

$$\boxed{E_{rot} = \frac{1}{2}I\omega^2}$$

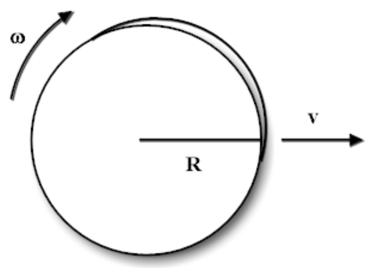
$$\text{We have } L = I\omega$$
$$L^2 = I^2\omega^2$$
$$\therefore \frac{L^2}{2I} = \frac{1}{2}I\omega^2$$

Hence angular momentum and rotational kinetic energy are related by the equation

,

$$\boxed{E_{rot} = \frac{L^2}{2I}}$$

8. Derive an equation for the kinetic energy of a disc rolling on a horizontal surface. What fraction of its total kinetic energy is rotational?.



Consider a disc of radius R and mass M. Let the disc be rolling on a horizontal surface without slipping. Rolling motion of the disc is a combination of a translational motion of the center of mass of the disc with velocity v and a circular motion with angular velocity ω. Hence the disc has two types of kinetic energies - translational and rotational kinetic energies.

$$\text{Translational kinetic energy} = \frac{1}{2}Mv^2$$
$$\text{Rotational kinetic energy} = \frac{1}{2}I\omega^2$$
$$\text{For a disc rolling about its own axis, } I = \frac{1}{2}MR^2$$
$$\text{The relation between v and } \omega \text{ is } v = R\omega$$
$$\therefore \omega = \frac{v}{R}$$
$$\text{Hence rotational kinetic energy} = \frac{1}{2} \times (\frac{1}{2}MR^2) \times (\frac{v}{R})^2$$
$$= \frac{1}{4}Mv^2$$
$$\text{Total kinetic energy of the disc} = \text{Translational K.E} + \text{Rotaional K.E}$$

$$= \frac{1}{2}Mv^2 + \frac{1}{4}Mv^2$$
$$= \frac{3}{4}Mv^2$$

Rotational kinetic energy is only half of the translational kinetic energy and hence,rotational kinetic energy is only one third of the total kinetic energy .

9. If ice on the polar caps of the earth melts, how will it affect the duration of the day?.

   The angular momentum of a rotating body remains conserved if no external torque is acting on it. The angular momentum is given by

   $$\boxed{L = I\omega}$$

   When the ice on the polar caps melts, it flow towards the equator and the effective distance of mass of the earth from the axis of rotation increases. Since moment of inertia $I = mr^2$, the moment of inertia of the earth increases and to conserve angular momentum, the angular velocity of the earth decreases. Hence the rotation of the earth becomes slow and duration of the day increases.

10. Where should the force be applied on a wrench to produce the best screwing effect.

    The rotating effect of a force acting on a rigid body, about an axis of rotation is called the torque. Torque (τ) is defined as the product of force and the perpendicular distance between the line of action of the force and the axis of rotation

    $$\boxed{\tau = r \times F}$$

    If the distance from the axis of rotation increases, torque increases. Hence force must be applied to wrench at the farthest point from the screw to get the best screwing effect.

11. Compare linear kinetic energy and rotational kinetic energy. Prove that for a body rotating with unit angular velocity, its moment of inertia is equal to twice its rotational kinetic energy.

    The energy of a body by the virtue of its linear motion is called linear kinetic energy or translational kinetic energy. If a body of mass m is moving with a velocity v, then its linear kinetic energy is given by

    $$\boxed{E_{lin} = \frac{1}{2}mv^2}$$

    The energy of a body by virtue of its rotational motion is called rotational kinetic energy. If I is the moment of inertia and ω is the angular velocity, then rotational kinetic energy is given by

    $$\boxed{E_{rot} = \frac{1}{2}I\omega^2}$$
    $$\text{If } \omega = 1 \text{ rad/s, then } E_{rot} = \frac{1}{2}I$$
    $$\therefore\ I = 2E_{rot}$$

12. A cycle wheel can be set into rotation easily if force is applied at the rim rather than a point near to the axis of rotation.

    The rotating effect of a force acting on a rigid body, about an axis of rotation is called the torque. Torque (τ) is defined as the product of force and the perpendicular distance between the line of action of the force and the axis of rotation $\boxed{\tau = r \times F}$

If the distance from the axis of rotation increases, torque increases. Hence , it is easier to rotate a cycle wheel if the force is applied at the rim rather than a point near to the axis of rotation.

13. A brass disc and a wooden disc have the same mass and thickness. Which of them has the greater moment of inertia about an axis passing through the centre and perpendicular to its axis?.

    The moment of inertial of a disc about an axis passing through the centre and perpendicular to its axis is given by $I = \frac{1}{2}MR^2$. Since the mass and thickness of the brass and wooden disc are same and wood is less denser than brass, the wooden disc has bigger radius than the brass disc. Hence, wooden disc has greater moment of inertia than the brass disc.

Important Equations to Remember

$$\text{Moment of inertia of a particle, } I = mr^2$$
$$\text{Moment of inertia of a rigid body, } I = \Sigma m_i r_i^2$$
$$\text{Radius of gyration , } k = \sqrt{\frac{I}{M}} \implies I = Mk^2$$
$$\text{Parallel axes therem, } I = I_G + Ma^2$$
$$\text{Perpendicular axes therem, } I_Z = I_X + I_Y$$

Axis of rotation	**M.I. of the ring**	**M.I. of the disc**
Axis passing through the center and perpendicular to its plane	$I = MR^2$	$I = \frac{1}{2}MR^2$
About any diameter	$I = \frac{1}{2}MR^2$	$I = \frac{1}{4}MR^2$
About the tangent	$I = \frac{3}{2}MR^2$	$I = \frac{5}{4}MR^2$

$$\text{Torque, } \tau = r \times F;\ \tau = I\alpha;\ \tau = \frac{(L_2 - L_1)}{t}$$
$$\text{Angular momentum, } L = r \times p;\ L = I\omega$$
$$\text{Rotational kinetic energy, } E_{rot} = \frac{1}{2}I\omega^2$$
$$\text{Total kinetic energy of a rolling disc, } E_{rot} = \frac{3}{4}Mv^2$$

Chapter 3

Law of Gravitation and Motion of Satellites

1. State Newton's universal law of gravitation.

   Newton's universal law of gravitation states that everybody in the universe attracts every other body with a force which is proportional to the product of their masses and inversely proportional to the square of the distance between them.

   If m_1 and m_2 are the two masses separated by a distance d , then according to newton's law of gravitation, the gravitational force between them is

$$F \propto m_1 m_2$$

$$F \propto \frac{1}{d^2}$$
$$F \propto \frac{m_1 m_2}{d^2}$$
$$\boxed{F = G\frac{m_1 m_2}{d^2}}$$

where G is called the universal gravitational constant.

2. Distinguish between 'g' and 'G'.

   The acceleration due to gravity (g) is the acceleration of a body moving under the influence of gravity alone. It is not a universal constant and its value varies from planet to planet. Its dimensional formula is $[LT^{-2}]$ and its unit is m/s^2. On the surface of the earth, the variation of g is small and its average value is 9.8 m/s^2.

   The universal gravitational constant (G) is the proportionality constant appearing in Newton's law of gravitation given by

$$F = G\frac{m_1 m_2}{d^2}$$

   If $m_1 = m_2 = 1$ kg and $d = 1m$, then F is numerically equal to G. Hence universal gravitational constant can be defined as the gravitation force of attraction between two masses of 1 kg each separated by a distance of 1 m.

$$G = \frac{Fd^2}{m_1 m_2}$$

   The dimensional formula of G is $[M^{-1}L^3T^{-2}]$ and its unit is $kg^{-1}m^3s^{-2}$. G is a universal constant and its value is $6.67 \times 10^{-11}\ kg^{-1}m^3s^{-2}$.

3. Derive an equation for acceleration due to gravity on the surface of the earth (Or Calculate the mass of the earth).

   Consider a stone of mass m held at a height above surface of the earth of M and radius R. The distance between the centre of earth and the stone is taken to be R since stone is very close to earth surface. From Newton's law of gravitation, the force of attraction between stone and the earth is

$$F = \frac{GMm}{R^2} \tag{1}$$

   If g is the acceleration due to gravity, then from Newton's Second law of motion

$$F = mg \tag{2}$$

   Equating (1) and (2)

$$\frac{GM\cancel{m}}{R^2} = \cancel{m}g$$
$$\therefore \boxed{g = \frac{GM}{R^2}} \tag{3}$$
$$\text{Also, } M = \frac{gR^2}{G} \tag{4}$$
$$\text{We have, } g = 9.8m/s^2$$
$$G = 6.67 \times 10^{-11}\ kg^{-1}m^3T^{-2}$$
$$R = 6380\ km = 6380 \times 10^3\ m$$

$$\therefore\ M = \frac{9.8 \times (6380 \times 10^3)^2}{6.67 \times 10^{-11}}$$
$$= 5.98 \times 10^{24}\ kg$$

4. Derive the expression for variation acceleration due to gravity with altitude and depth.[Prove that the acceleration due to gravity is maximum at the surface of the earth than at points below or above the earth.]

Variation of g with altitude

Consider a body of mass m situated very close to the surface of earth of mass M and radius R. According to Newton's second law, force experienced by the body towards the centre of the earth is mg. According to Newton's law of gravitation,

$$\frac{GMm}{R^2} = mg$$
$$g = \frac{GM}{R^2} \tag{1}$$

If the body is situated at a height h above the earth, the acceleration due to gravity at the height h is given by

$$g_h = \frac{GM}{(R+h)^2} \tag{2}$$
$$g_h = \frac{GM}{R^2(1+\frac{h}{R})^2}$$

Substituting from equation (1)

$$g_h = \frac{g}{(1+\frac{h}{R})^2} \tag{3}$$

Equation (3) shows that the acceleration due to gravity decreases with altitude h. If h is very small compared to the radius of the earth, by the approximation of binomial expansion, we have

$$(1+\frac{h}{R})^{-2} \approx (1-\frac{2h}{R})$$
$$\therefore g_h = g(1-\frac{2h}{R}) \tag{4}$$

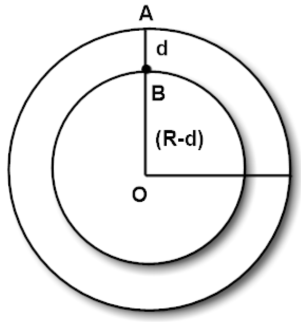
Variation of g with depth

The value of acceleration due to gravity on the surface of the earth is given by

$$g = \frac{GM}{R^2} \tag{1}$$

If ρ is the mean density of earth, then mass of the earth is given by

$$M = \frac{4}{3}\pi R^3 \rho$$
$$\therefore g = \frac{G \times \frac{4}{3}\pi R^3 \rho}{R^2}$$
$$g = \frac{4}{3}\pi G \rho R \tag{2}$$



Consider a point B at a depth d below the surface of the earth as shown in the figure. Since the gravitational force due to the shell of earth of thickness d at any point inside the shell is zero, the acceleration due to gravity g_d at the depth d is obtained by replacing R with (R-d) in equation (2). Thus,

$$g_d = \frac{4}{3}\pi G\rho(R-d)$$

$$g_d = \frac{4}{3}\pi G\rho R(1-\frac{d}{R})$$

Substituting from equation (2)

$$g_d = g(1-\frac{d}{R}) \tag{3}$$

Equation (3) shows that acceleration due to gravity decreases with depth. Hence, it is clear that acceleration due to gravity is maximum on the surface of the earth than at points below or above earth.

5. Discuss the variation of g due to rotation of earth. [Discuss the variation of g with latitude.]

   The earth is rotating about its axis from west to east and due to this rotation, a body situated on the surface of the earth an acceleration which varies with latitude. The effect of this acceleration is to reduce the effective value of g. The effective value of acceleration due to gravity at a latitude θ is given by

   $$g_\theta = g - R\omega^2 cos^2\theta$$

   where $R = 6400 \times 10^3\ m$ is the radius of the earth and $\omega = 7.3 \times 10^{-5}\ rad/s$ is the angular velocity of rotation of earth.

   $$\text{At equator, } \theta = 0^0 \quad \therefore \quad g_\theta = g - R\omega^2$$

   $$\text{At poles, } \theta = 90^0 \quad \therefore \quad g_\theta = g$$

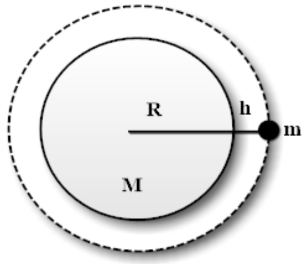
   Hence acceleration due to gravity is greater at the poles compared to that at equator. But the increase in value of acceleration due to gravity in going from equator to pole is $R\omega^2 = 0.034 m/s^2$. Hence variation due to rotation of earth or latitude is very small.

6. Discuss the variation of g due to the shape of earth.

   The shape of earth slightly deviates from a perfect sphere. The earth is slightly flattened at poles and bulged at equator (oblate spheroid shape). The radius in equatorial plane is about 21 km larger than the radius along the poles. Due to this equatorial bulge, acceleration due to gravity is a little smaller than compared to that at poles.

7. Derive the equations for orbital velocity and time period of an artificial satellite. Also obtain expressions for orbital velocity and time period of a artificial satellite revolving close to the surface of the earth.

   Orbital velocity (v) : The velocity with which a satellite moves in a closed orbit is called the orbital velocity.



Consider a satellite of mass m revolving around earth of mass M and radius R. Let the satellite be revolving at a height h with an orbital velocity v, above the surface of the earth. The necessary centripetal force for the circular motion is provided by the gravitational force between earth and the satellite.

$$\text{Centripetal force} = \frac{mv^2}{(R+h)} \tag{1}$$

$$\text{Gravitaional force} = \frac{GMm}{(R+h)^2} \tag{2}$$

$$\text{Equating (1)and (2)} \longrightarrow \frac{mv^2}{(R+h)} = \frac{GMm}{(R+h)^2}$$

$$v^2 = \frac{GM}{(R+h)}$$

$$\boxed{v = \sqrt{\frac{GM}{(R+h)}}} \tag{3}$$

The acceleration due to gravity, g on the surface of the earth is give by

$$g = \frac{GM}{R^2}$$

$$\therefore GM = gR^2 \tag{4}$$

$$\text{Substituting equation (4) in (3)} \longrightarrow v = \sqrt{\frac{gR^2}{(R+h)}}$$

$$\boxed{v = R\sqrt{\frac{g}{(R+h)}}} \tag{5}$$

This is the equation for orbital velocity of a satellite revolving at a height h above the surface of the earth.

Special case: When the satellite revolves close to the earth surface, h is negligibly small compared to the radius of the earth R. In such a case orbital velocity is called first cosmic velocity (v_0).

$$\text{Putting h} = 0 \text{ and } v = v_0 \text{ in equation (3)} \longrightarrow \boxed{v_0 = \sqrt{\frac{GM}{R}}} \tag{6}$$

$$\text{Putting h} = 0 \text{ and } v = v_0 \text{ in equation (5)} \longrightarrow v_0 = R\sqrt{\frac{g}{R}}$$

$$\boxed{v_0 = \sqrt{gR}} \tag{7}$$

Time period of the satellite (T): The time taken by the satellite to complete one revolution is called its period. If the artificial satellite is revolving at a height h above the surface of the earth.

$$\text{Distance covered in time T } = 2\pi(R+h)$$

$$\text{Orbital velocity, } v = \frac{2\pi(R+h)}{T}$$

$$\therefore T = \frac{2\pi(R+h)}{v}$$

$$\text{Substituting the value of } v \text{ from equation (3)} \quad \longrightarrow T = \frac{2\pi(R+h)}{\sqrt{\frac{GM}{(R+h)}}}$$

$$\boxed{T = 2\pi\sqrt{\frac{(R+h)^3}{GM}}} \tag{8}$$

$$\text{Substituting equation (4) in (8)} \quad \longrightarrow \boxed{T = 2\pi\sqrt{\frac{(R+h^3)}{gR^2}}} \tag{9}$$

Special case: When the satellite revolves close to the earth surface, $h <<< R$ and period is T_0.

$$\text{Putting h} = 0 \text{ and T} = T_0 \text{ in equation (8);} \longrightarrow \boxed{T_0 = 2\pi\sqrt{\frac{R^3}{GM}}} \tag{10}$$

$$\text{Putting h} = 0 \text{ and T} = T_0 \text{ in equation (9);} \longrightarrow \boxed{T = 2\pi\sqrt{\frac{R}{g}}} \tag{11}$$

(If the period of the satellite alone is to be derived, first derive the equation for orbital velocity up to equation (3) and then proceed with the derivation of time period.)

8. What are geostationary satellites and mention its use. Deduce the expressions for orbital velocity.

An artificial satellite whose orbital period is same as the rotational period of earth is called geostationary satellite and its orbit is called geostationary orbit. Geostationary satellites appear to remain stationary over the same place on the earth. Geostationary satellite revolves the earth from west to east and its orbital period is 24 hours. The distance between the surface of the earth and a geostationary satellite is about 36,000 km. Geostationary satellites are mainly used for global communication, television broad casting, weather forecasting and a number of defence applications.

[For the derivation of orbital velocity of a geostationary satellite, refer to Question No. 4 upto equation (3)].

9. Deduce the value of height of the geostationary above the surface of the earth (or altitude of the geostationary orbit). [Radius of earth = 6400 km; and g of the earth = 9.8 m/s^2]

$$\text{Radius of the earth, } R = 6400\ km = 6400000\ m$$

$$\text{Acceleration due to gravity, } g = 9.8\ m/s^2$$

$$\text{Period of the geostationary satellite, } T = 24\ hours = 24 \times 60 \times 60 = 84400\ s$$

$$\text{We have, } T = 2\pi\sqrt{\frac{(R+h^3)}{gR^2}}$$

$$T^2 = 4\pi^2\frac{(R+h^3)}{gR^2}$$

$$(R+h)^3 = \frac{gR^2T^2}{4\pi^2}$$

$$R + h = \left(\frac{gR^2T^2}{4\pi^2}\right)^{\frac{1}{3}}$$

$$h = \left(\frac{gR^2T^2}{4\pi^2}\right)^{\frac{1}{3}} - R$$

$$h = \left(\frac{9.8 \times 6400000^2 \times 84400^2}{4 \times 3.14^2}\right)^{\frac{1}{3}} - 6400000$$

$$h = 35954000\ m$$

$$h = 35954\ km$$

10. What is a polar satellite?. Mention its uses,

    A polar satellite is one which orbits the earth in a north-south direction. Polar satellite has a Low Earth Orbit (LEO) of radius about 800-1000 km. Polar satellites take less than 2 hours to go around the earth and it is cable of scanning the entire earth each day as earth rotates below it. The uses of polar satellites are:

    (a) Collecting information about our atmosphere.
    (b) Measurement of humidity and temperature in earth's atmosphere.
    (c) Used to gather information about polar aurora and earth's magnetic field.
    (d) Used as spy satellites.
    (e) Weather forecasting.
    (f) It gives early warnings of storm and other severe atmospheric changes.

11. Explain the terms gravitational potential and gravitational potential energy.

    Gravitational potential at a point in the gravitational field due to an object is the amount of work done in moving a unit mass from infinity to that point. The unit of gravitational potential is J/kg. In the case of earth, the gravitational potential at a point is given by

    $$\boxed{V = -GM/r}$$

    where G is the universal gravitational constant, M is the mass of the earth and r is the distance between the centre of the earth and the point. The negative sign for gravitational potential indicates that the work is done by the gravitational force. The gravitational potential is maximum at infinity (chosen reference point of zero potential) and the maximum value is zero.

    Gravitational potential energy of a body is defined as the energy associated with it due to its position in the gravitational field of another body. It is the work done in bringing the body from infinity to that point. In the case of earth, the gravitational potential energy of a mass m placed at a distance r from the centre of the earth is given by

    $$\boxed{E = -GMm/r}$$

    Hence gravitational potential can also be defined as the gravitational potential energy per unit mass at a point in the gravitational field of an object. The gravitational potential energy of a mass m on the surface of the earth is given by

    $$\boxed{E_0 = -GMm/R}$$

    Since $r = R$, where R is the radius of the earth.

12. Define escape velocity. Derive an expression for escape velocity of an object from the surface of the earth.

Escape velocity (v_e) from the earth is defined as the minimum velocity with which a body must be projected so that it may escape from the earth's gravitational field. Consider a body of mass m on the surface of the earth. Then,

$$\text{Potential energy of mass m on the surface of the earth} = \frac{-GMm}{R}$$

When this mass escape from the gravitational field of earth, its potential energy becomes zero. To make the potential energy zero, a kinetic energy ($\frac{1}{2}m{v_e}^2$) equal to $\frac{+GMm}{R}$ must be given to the body. Hence,

$$\frac{1}{2}m{v_e}^2 = \frac{GMm}{R}$$

$${v_e}^2 = \frac{2GM}{R}$$

$$v_e = \sqrt{\frac{2GM}{R}} \qquad (1)$$

$$\text{Since } \frac{GM}{R^2} = g$$

$$\frac{GM}{R} = gR$$

$$\text{Substituting in equation (1)} \quad \boxed{v_e = \sqrt{2gR}}$$

13. How do you account for the lack of atmosphere in moon?.

The escape velocity of the moon (2.38 km/s) is less than the average speed of the molecules of gases in the atmosphere. As a result, all gases escape from the gravitational field of the moon and hence it has no atmosphere.

14. Give the reason why a body weighs more at the poles.

The equation for acceleration due to gravity, g of earth of mass M and radius R is given by

$$g = \frac{GM}{R^2}$$

It is clear that g is inversely proportional to square of the radius of earth. The earth is not a perfect sphere. It is bulged at the equator and flattened at poles. Therefore, radius of the earth at poles is less than that at equator. Hence, the value of g is maximum at the poles. Since weight of a body is the product of its mass and acceleration due to gravity, the weight of a body is maximum at the poles.

Important Equations to Remember

$$\text{Newton's Law of Gravitation, } F = G\frac{m_1 m_2}{d^2}$$

$$\text{Acceleration due to gravity on the surface of the earth, } g = \frac{GM}{R^2}$$

$$\text{Acceleration due to gravity at a heigh h above the earth:} \quad g_h = \frac{g}{(1+\frac{h}{R})^2}$$

Acceleration due to gravity at a heigh h very small compared to the radius of the Earth(R):

$$g_h = g(1 - \frac{2h}{R})$$

Acceleration due to gravity at a depth d below the surface of the Earth: $g_d = g(1 - \frac{d}{R})$

Orbital velocity and period of revolution of a satellite revolving at a height h above the surface of the earth

$$v = \sqrt{\frac{GM}{(R+h)}}$$

$$v = R\sqrt{\frac{g}{(R+h)}}$$

$$T = 2\pi\sqrt{\frac{(R+h)^3}{GM}}$$

$$T = 2\pi\sqrt{\frac{(R+h)^3}{gR^2}}$$

Orbital velocity and time period of revolution of a satellite revolving close to the surface of the earth

$$v_0 = \sqrt{\frac{GM}{R}}$$

$$v_0 = R\sqrt{gR}$$

$$T_0 = 2\pi\sqrt{\frac{R^3}{GM}}$$

$$T_0 = 2\pi\sqrt{\frac{R}{g}}$$

Gravitational potential at a point in the gravitational field of the earth: $V = \frac{-GM}{r}$

Gravitational potential energy of a mass m place at a distance r from the center of the Earth:

$$E = \frac{-GMm}{r}$$

Escape velocity of a mass m from the surface of the Earth: $v_e = \sqrt{2gR}$

Chapter 4

Electromagnetism

1. Explain the terms charge, current and potential difference.

   Charge (Q) is an intrinsic property of certain fundamental particles of matter like electrons, protons etc. The SI unit of charge is coulomb (C). The flow of electric charge constitutes a current (I). The SI unit of current is ampere (A). Current is defined as the time rate of flow of electric charge (I = Q/t).

   The potential difference between two points is numerically equal to the work done in moving a unit test charge from one point to another in the electric filed of another charge. To establish a current in a conductor, it is necessary to maintain a potential difference between its ends. A battery is used for this purpose. The SI unit of potential difference is volt (V). 1 volt = 1 joule/coulomb.

2. State Ohm's law and describe an experiment to verify Ohm's law.

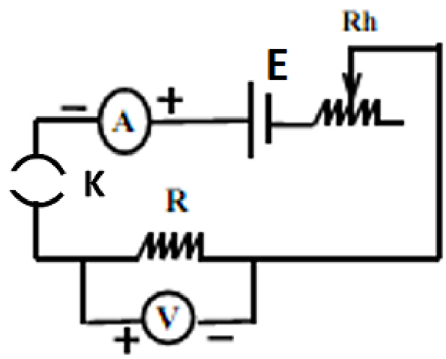
   Ohm's law states that at constant temperature, the current flowing through a conductor is directly proportional to the potential difference between its ends.

$$V \propto I \quad \Longrightarrow V = RI$$
$$R = \frac{V}{I}$$

   where the constant of proportionality R is called resistance of the conductor. The unit of resistance is called ohm (Ω). 1 ohm = 1 volt/ampere. The reciprocal of resistance is called conductance (S). The SI unit of conductance is ohm^{-1} (mho).

$$S = \frac{I}{V}$$

   <u>Verification of Ohm's law</u>



   A cell of emf E is connected in series with a rheostat Rh, key K, ammeter A and the resistance wire R as shown in the figure. A voltmeter V is connected in parallel with the resistance wire. The rheostat is adjusted so that the ammeter reads a convenient reading , say 0.1 A. The corresponding voltmeter meter reading is noted. Rheostat is adjusted for different values of currents and in each case voltmeter reading is measured. In each case, $R = V/I$ is calculated and it can be found that R is a constant. This verifies Ohm's law.

3. Define the term resistivity and how it is related to conductivity?.

   The resistance of a conducting wire is found to be directly proportional to the length l of the wire and inversely proportional to area of cross section A of the wire. Hence,

$$R \propto \frac{l}{A} \quad \Longrightarrow R = \rho \frac{l}{A}$$

   The constant of proportionality ρ is called the resistivity or specific resistance of the material. Resistivity depends on the nature of the material and the temperature. The unit of resistivity is ohm m (Ω m).

$$\boxed{\rho = \frac{RA}{l}}$$

   The reciprocal of resistivity is called conductivity (σ) or specific conductance. The unit of conductivity is $\Omega^{-1}\, m^{-1}$.

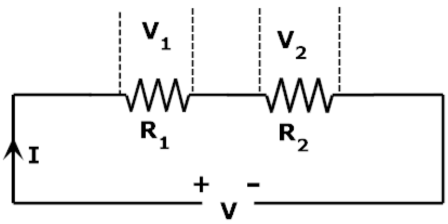
$$\boxed{\sigma = \frac{1}{\rho} = \frac{l}{RA}}$$

4. Why aluminium wires are preferred to copper wires in making overhead power lines?

   Aluminium has a resistivity 1.6 times that of copper. Since the density of aluminium is only one third of that of the copper, aluminium conductors are much lighter as well as cheaper than copper conductors. Hence in spite of its high resistivity, aluminium wires are preferred to copper wires in making overhead power lines.

5. Derive the expressions for the equivalent resistance when two resistors are connected in series and when two resistors are connected in parallel.

Resistors in series



In the figure two resistors R_1 and R_2 are connected in series across the terminals of a source emf V. The current I flowing through both resistors are same.Let V_1 and V_2 be the voltage drops across R_1 and R_2 respectively. Then,

$$V = V_1 + V_2 \qquad (1)$$

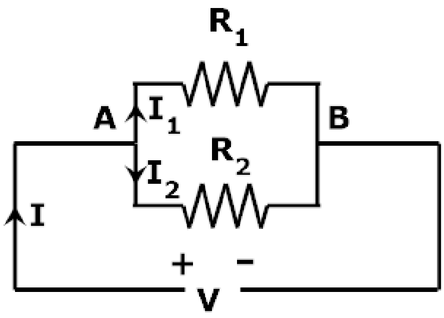
If the effective resistance of R_1 and R_2 in series is R_s, then by Ohm's law, $V = IR_s$ (2)

Also by applying Ohm's law to each resistor, $V_1 = IR_1$ and $V_2 = IR_2$ (3)

Substituting equation (2) and (3) in equation (1), $IR_s = IR_1 + IR_2$

$$\boxed{R_s = R_1 + R_2}$$

Resistors in Parallel



Consider two resistors R_1 and R_2 connected in parallel so that both have the same potential difference V across the points A and B as shown in the figure. At point A the main current I split into two parts - I_1 through R_1 and I_2 through R_2. Hence,

$$I = I_1 + I_2 \tag{1}$$

If the effective resistance of R_1 and R_2 in parallel is R_p, then by Ohm's law,

$$V = IR_p \quad \Longrightarrow I = \frac{V}{R_p} \tag{2}$$

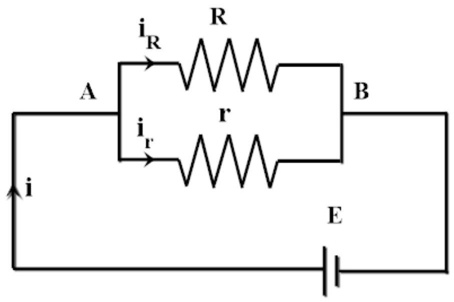
Since the potential difference across R_1 and R_2 are equal, by applying Ohm's law to each resistor,

$$V = IR_1 = IR_2 \quad \Longrightarrow I_1 = \frac{V}{R_1} \text{ and } I_2 = \frac{V}{R_2} \tag{3}$$

Substituting equation (2) and (3) in equation (1) $\frac{V}{R_p} = \frac{V}{R_1} + \frac{V}{R_2}$

$$\boxed{\frac{1}{R_s} = \frac{1}{R_1} + \frac{1}{R_1}} \quad \text{Or } R_p = \frac{R_1 R_2}{R_1 + R_2}$$

6. Explain the principle of shunt resistance.



Consider a large resistance R and a small resistance r connected to a source emf as shown in the figure. Let i_R and i_r be the currents flowing through them. If i is the main current entering the junction A,

$$i = i_R + i_r \implies \quad i_r = i - i_R \tag{1}$$

Since the potential difference across the resistors is same,

$$i_R \times R = i_r \times r$$

Using equation (1), $$i_R R = (i_R - i)r$$

$$i_R R = i_R r - ir$$

$$i_R(R + r) = ir$$

$$\therefore \quad i_R = \frac{ir}{R + r} \tag{2}$$

$$\text{Similarly,} \quad i_r = \frac{iR}{R+r} \tag{3}$$

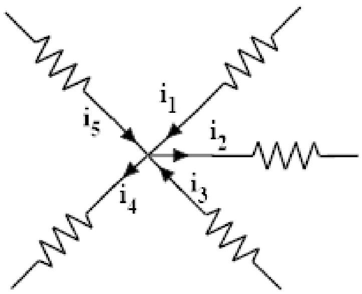
Equation (2) show that current flowing through the large resistance is only a small fraction of the total current. Major portion of the current flows through the small resistance. Such a small resistance connected parallel to a large resistance is called shunt resistance. shunt resistance is usually connected to a sensitive instrument like galvanometer to protect the instrument from heavy currents.

$$\boxed{\text{Current in one branch} = \frac{\text{Main current} \times \text{Resistance of the other branch}}{\text{Sum of both resistances}}}$$

7. State and explain Kirchoff's laws.

Kirchoff's laws

(a) Junction Rule: The algebraic sum of the current meeting at a junction is zero. In other words, the sum of the currents flowing towards a junction is equal to sum of currents flowing out of the junction. Current flowing towards a junction is taken as positive and current flowing out of the junction is taken as negative.



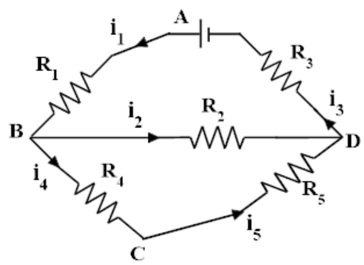
$$i_1 + i_3 + i_5 - i_2 - i_4 = 0$$

$$\text{In general,} \quad \Sigma\, i = 0$$

(b) Loop Rule: In any closed circuit, the algebraic sum of the product of current and resistance of each part of the circuit is equal to the total emf in that circuit.

$$\Sigma\, iR = \Sigma\, E$$

In applying loop rule, positive value of iR is taken when traversed in the direction of current and the emf is taken as positive when traversed fro negative to positive electrode inside the electrolyte of the cell.



Consider a cell of emf E is connected in a network as shown in the figure. Applying Kirchoff's loop rule,

For the loop ABDA:

$$i_1R_1 + i_2R_2 + i_3R_3 = E$$

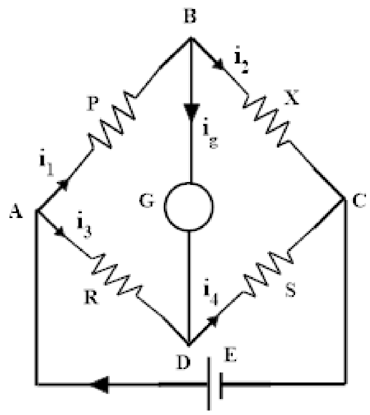
For the loop BCDB:

$$i_4R_4 + i_5R_5 - i_2R_2 = 0$$

For the loop ABCDA:

$$i_1R_1 + i_4R_4 + i_5R_5 + i_3R_3 = E$$

8. Applying Kirchoff's laws, derive the balancing condition of a Wheatstone's bridge.



Wheatstone's bridge is a network of four resistances commonly used for the measurement of resistance. Three resistance boxes P, R and S and an unknown resistance X are connected as shown in figure. A cell of emf E is connected between A and C and a galvanometer between B and D. Let the resistance of the galvanometer be G and the current through it be i_g. The currents in various branches are as shown in figure. Applying junction rule at the junctions B and D,

$$i_1 - i_g - i_2 = 0 \quad (1)$$
$$i_3 + i_g - i_4 = 0 \quad (2)$$

Applying loop rule to the closed circuits ABDA and BCDB,

$$i_1P + i_gG - i_3R = 0 \quad (3)$$
$$i_2X - i_4S - i_gG = 0 \quad (4)$$

By adjusting the resistances P, R and S , the current through the galvanometer can be made equal to zero and hence galvanometer shows no deflection. This condition is called balancing condition of the Wheatstone's bridge. Putting $i_g = 0$;

$$\text{From equation (1) : } i_1 - i_2 = 0 \implies i_1 = i_2 \quad (5)$$
$$\text{From equation (2) : } i_3 - i_4 = 0 \implies i_3 = i_4 \quad (6)$$
$$\text{From equation (3) : } i_1P - i_3R = 0 \implies i_1P = i_3R \quad (7)$$
$$\text{From equation (4) : } i_2X - i_4S = 0 \implies i_2X = i_4S \quad (8)$$

Dividing equation (7) by (8):

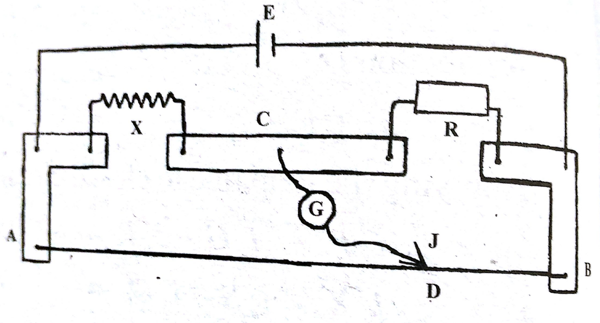
$$\frac{i_1P}{i_2X} = \frac{i_3R}{i_4S}$$

Since $i_1 = i_2$ and $i_3 = i_4$, we get:

$$\boxed{\frac{P}{X} = \frac{R}{S}}$$

This is the balancing condition of a Wheatstone's bridge.

9. With the help of a neat diagram, explain the working of metre bridge.



Meter bridge is convenient form of Wheatstone's Bridge used for the practical measurement of resistance. It consists of a uniform wire AB of length 1 meter stretched on a wooden base parallel to a meter scale. Two L shaped copper strips and a straight copper strip are fixed on the wooden base so as to form two gaps as shown in the figure. The strips are provided with terminal to fix connecting wires. A resistance box R and the given resistance wire X are connected in the gaps. A cell E is connected between A and B. A galvanometer G is connected between the central terminal C and a jockey J which can slide over the wire.

A suitable resistance R is introduced in the resistance box. The jockey is moved along the wire and its position is adjusted to get null deflection in the galvanometer. Let l_x be the balancing length adjacent to the unknown resistance X. Let r be the resistance per unit length of the meter bridge wire. Since the total length of the wire is 100 cm, applying the balancing condition for a Wheatstone's Bridge,

$$\frac{X}{R} = \frac{l_x r}{(100 - l_x)r}$$

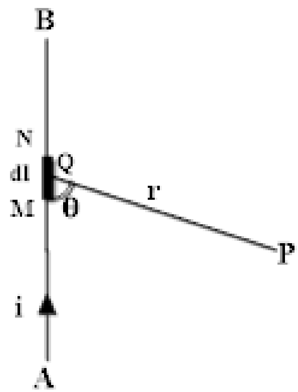
$$\frac{X}{R} = \frac{l_x}{(100 - l_x)}$$

$$X = \frac{l_x R}{(100 - l_x)}$$

The experiment is repeated for different values of R and mean value of X is calculated. If the unknown resistance X is in the form of a wire, its length L is measured with a meter scale. the diameter and hence the radius r of the wire is determined using a screw gauge. The resistivity ρ is calculated using the formula

$$\rho = \frac{X\pi r^2}{L}$$

10. On what factors does the magnetic field intensity due to a current carrying element of a conductor depend (Or State and explain Biot-Savart law Or State the law by which we can calculate the magnetic filed intensity at a point due to an elementary current carrying conductor of very small length).



Biot-Savart law help us to determine the magnetic field intensity at a point due to a small current carrying element of the conductor. Let AB represents a conductor through which a current i flows. MN is a very small segment of length dl of the conductor. P is a point at a distance r from the mid point Q of the segment. θ is angle between dl and r. Biot-Savart law states that the magnetic field dB produced by an elementary length dl of a current carrying conductor at a point P is

(a) directly proportional to the current i ($dB \propto i$)

(b) directly proportional to elementary length dl ($dB \propto dl$)

(c) directly proportional to the sine of the angle between dl and the line joining midpoint of dl and the point P ($dB \propto sin\theta$)

(d) inversely proportional to the square of the distance r between the midpoint of dl and the point P ($dB \propto \frac{1}{r^2}$)

Biot-Savart law can be mathematically expressed as

$$dB = k\frac{idlsin\theta}{r^2}$$

where k is a constant. If SI sytem is employed , it is convenient to write the constnat k in different form as $k = \frac{\mu_0}{4\pi}$ where $\mu_0 = 4\pi \times 10^{-7}$ is the permeability of the free space.

$$\therefore \quad \boxed{dB = \frac{\mu_0}{4\pi}\frac{idlsin\theta}{r^2}}$$

11. What is the SI unit of magnetic field intensity?. What is the relation between tesla and gauss?.

Tesla is the SI unit of magnetic field intensity and gauss is the CGS unit of magnetic filed intensity.

$$1 \ tesla = 1 \ newton/amp.\ meter$$
$$\boxed{1 \ gauss = 10^{-4} \ tesla}$$

12. State right hand grip rule (Right hand palm rule). Write down the expression for magnetic field due to a straight conductor carrying current.

Right hand grip rule state that if a current carrying conductor is held in right hand with thumb pointing in the direction of current, the remaining fingers encircling the conductor shows the direction of the magnetic field. For a straight conductor carrying current, the magnetic filed lines are circular around the conductor and tangent at a point on the circle gives the direction of the magnetic field at the point.

The magnetic field due to a straight conductor carrying a current i at a perpendicular distance a from the conductor of finite length is given by

$$B = \frac{\mu_0 i}{4\pi a}[sin\phi_1 + sin\phi_2]$$

where ϕ_1 and ϕ_2 are the angles subtended at the point by the end points of the conductor. For a conductor of infinite length, ϕ_1 and ϕ_2 will be nearing 90^0. Therefore,

$$sin\phi_1 + sin\phi_2 = 2$$
$$B = \frac{\mu_0 i}{2\pi a}$$

13. State and explain Biot-Savart law and derive the expression magnetic field intensity at the centre of a circular coil carrying current.

Biot-Savart law states that the magnetic filed dB produced by an elementary length dl of a current carrying conductor at a point P is

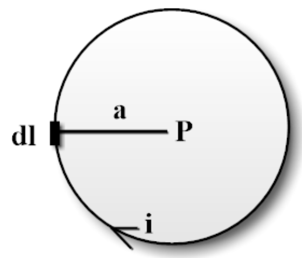
(a) directly proportional to the current i
(b) directly proportional to elementary length dl
(c) directly proportional to the sine of the angle between dl and the line joining midpoint of dl and the point P
(d) inversely proportional to the square of the distance r between the midpoint of dl and the point P

Biot-Savart law can be mathematically expressed as

$$\boxed{dB = \frac{\mu_0}{4\pi}\frac{idl sin\theta}{r^2}}$$

where μ_0 is the permeability of the free space.

Magnetic field due to a circular coil carrying current



Consider a single turn of a circular coil of radius 'a' carrying a current i. From Biot-Savart law the magnetic field dB at the centre of the coil due to an elementary length dl is

$$dB = \frac{\mu_0}{4\pi}\frac{idl sin\theta}{a^2}$$

The angle between dl and a is 90°

$$\therefore \ dB = \frac{\mu_0}{4\pi}\frac{idl}{a^2}$$

For all elementary lengths of the coil, the angle between dl and a is 90°. Hence total magnetic field due to the coil at the centre is

$$B = \Sigma \left(\frac{\mu_0 idl}{4\pi a^2}\right)$$

For all elements a is a constant

$$; \ B = \left(\frac{\mu_0 i}{4\pi a^2}\right) \ \Sigma \ dl$$

But $\Sigma \ dl = 2\pi a$ is the circumference of the coil and hence

$$B = \left(\frac{\mu_0 i}{4\pi a^2}\right) \times 2\pi a = \frac{\mu_0 i}{2a}$$

If the coil has n number of turns, the magnetic field at the centre of the coil is

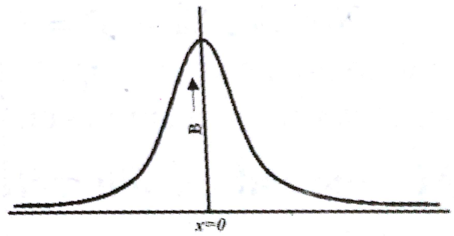
$$\boxed{B = \frac{\mu_0 ni}{2a}}$$

14. Write down the expression for magnetic field intensity due to a current carrying circular coil at the axial point and deduce magnetic field intensity at its centre. Draw a graph showing the variation of magnetic field intensity along the axial line of a circular coil carrying current.

The magnetic field intensity due to a circular coil at an axial point at a distance x from the centre is

$$B_x = \frac{\mu_0 n a^2 i}{2(a^2 + x^2)^{\frac{3}{2}}}$$

At the centre of the coil, $x = 0$ and $B_x = B$; $\therefore \quad B = \frac{\mu_0 n i}{2a}$



15. State Fleming's left hand rule (Or State the rule which gives the direction of force in the case of a current carrying conductor placed in a magnetic field). Write down the expression for the force on a current carrying conductor placed in a magnetic field. Name an instrument in which this is used as the working principle.

Fleming's left hand rule gives the direction of the force in the case of a current carrying conductor placed in a magnetic field. Fleming's left hand rule states that if the thumb, forefinger and the middle finger of the left hand are held mutually at right angles and forefinger is pointed in the direction of magnetic field while the middle finger in the direction of the current, then thumb gives the direction of the force.

When a conductor of length l carrying a current i is placed in a magnetic field B, the force experienced by the conductor is given by $F = Bilsin\,\theta$

where θ is the angle between the direction of the magnetic field and the direction of the current. This principle is used as the working principle of moving coil galvanometer.

16. Describe the principle, construction and working of a moving coil galvanometer.

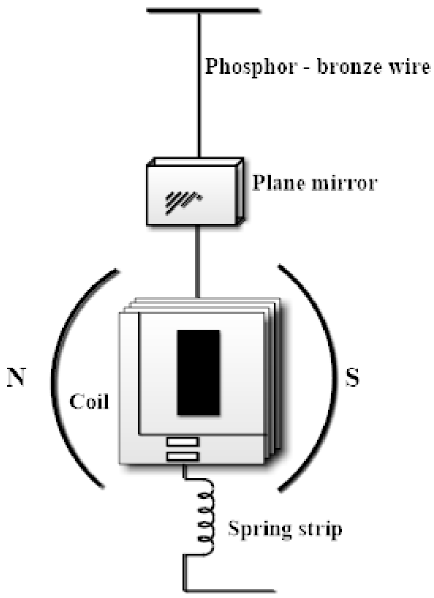
The moving coil galvanometer is a very sensitive instrument used for the detection and measurement of small electric current.

<u>Principle</u>

When a conductor carrying a current is placed in a uniform magnetic field, it experiences a mechanical force. If a conductor of length l carrying current i is placed perpendicular to a uniform magnetic field B, then force on the conductor is given by $F = Bil$. The direction of the force is given by Fleming's left hand rule.

<u>Construction</u>

A galvanometer essentially consists of a flat coil of insulated copper wire wound on an aluminium frame. It is suspended by a phosphor bronze wire between the pole pieces of a powerful magnet. The magnet is provided with concave pole pieces. In order to make the field radial and arrange that it is always parallel to the plane of the coil for all position, a soft iron block is placed at the centre of the coil. The current to be measured enters the coil through the suspension wire and leaves through a spring strip below the coil. A small mirror is attached to the suspension wire.



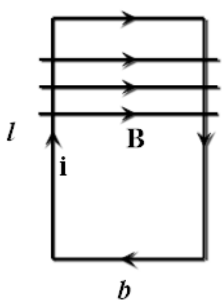
Working

When current to be measured flows through the coil which is placed in a magnetic field, the coil experiences a deflecting couple. This couple rotates the coil and as a result, the suspension wire is twisted. The suspension wire opposes the deflecting couple with a restoring couple and the deflection θ of the coil is such that deflecting couple is equal to the restoring couple. In this condition, relation between the current through the coil i and deflection θ of the coil is given by

$$i = \frac{\alpha\theta}{nBA}$$

where α is the couple per unit twist of the wire, A is the area of the coil, B is the magnetic field strength and n is the number of turns of the coil. Since α, n, A, B are constants for a given arrangement, the current i is directly proportional to deflection, θ. The deflection can be measured using a lamp and scale arrangement. Instead of lamp and scale, a pointer fixed at the lower end of the suspension wire can also be used to indicate the current.

17. Explain the theory behind the working of a moving coil galvanometer.



Let l and b are the length and breadth of the coil. Let the current passing though the coil be i. If B is the intensity of the magnetic field, the force experienced on each vertical side of the coil is

$$F = Bil$$

According to Fleming's left hand rule, the force on the two vertical sides are in opposite directions. These two equal and opposite forces constitute a couple of moment C_l given by

$$C_l = Bil \times b = BiA$$

where $A = lb$ is the area of the coil. If there are n turns in the coil, the total deflecting couple is given by

$$C_d = nBiA$$

Due to this deflecting couple, the coil rotates and suspension wire is twisted. As a result, a restoring couple is produced in the suspension wire. Let θ be the twist produced in the wire and if α is the couple per unit twist of the wire, then restoring couple is given by

$$C_r = \alpha\theta$$

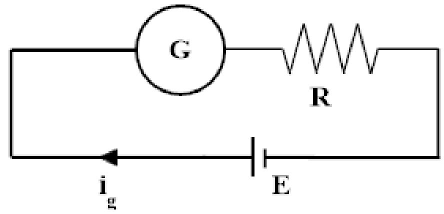
At the equilibrium position of the coil, deflecting couple = restoring couple.

$$nBiA = \alpha\theta$$

Since α, n, A, B are constants for a given arrangement, the current i is directly proportional to deflection, θ.

18. How will you convert a galvanometer into a voltmeter and ammeter?.

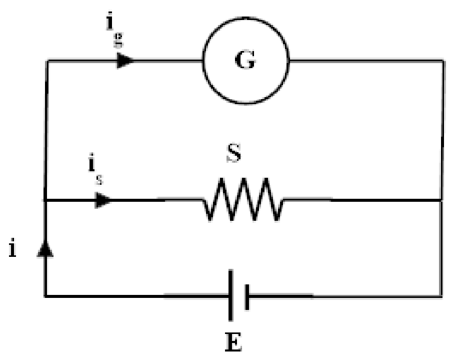
A galvanometer can be converted into a voltmeter by connecting a suitable high resistance in series with it. The value of high resistance is chosen in such a way that the current through the galvanometer should not be greater than the maximum current for which it is designed.



Let G be the resistance of the galvanometer and i_g be the maximum current which produces full scale deflection in the galvanometer. Let E be the maximum potential to be measured. The value of high resistance, R can be calculated using the formula:

$$\boxed{R = \left[\frac{E}{i_g}\right] - G}$$

A galvanometer can be converted into an ammeter by connecting a suitable shunt. Shunt is a low resistance connected in parallel with a sensitive galvanometer to reduce its sensitiveness and to protect the instrument from heavy currents.



Let G be the resistance of the galvanometer and S is the shunt resistance. If i is the current to be measured, i_s is the current through the shunt and i_g is the maximum current which produces full scale deflection in the galvanometer.

$$i = i_s + i_g$$

The value of shunt resistance, $\boxed{S = \frac{i_g G}{i - i_g}}$

Important equations to Remember

Ohm's Law: $V = IR$

Resistivity (specific resistance): $\rho = \frac{RA}{l}$

conductivity (specific conductance): $\sigma = \frac{1}{\rho} = \frac{l}{RA}$

Effective resistance of two resistors connected in series: $R_s = R_1 + R_2$

Effective resistance of two resistors connected in parallel: $\frac{1}{R_p} = \frac{1}{R_1} + \frac{1}{R_2}$ Or $R_p = \frac{R_1 R_2}{R_1 + R_2}$

Biot-savart law : $dB = \frac{\mu_0}{4\pi} \frac{idlsin\theta}{r^2}$

Permeability of the free space : $\mu_0 = 4\pi \times 10^{-7}\ N/A^2 \quad \therefore \quad \frac{\mu_0}{4\pi} = 10^{-7}$

Magnetic field due to a straight conductor carrying current : $B = \frac{\mu_0 i}{4\pi a}[sin\phi_1 + sin\phi_2]$

Magnetic field due to very long or infinite conductor carrying current : $B = \frac{\mu_0}{4\pi} \frac{2i}{a}$

Magnetic field at the centre of a coil carrying current : $B = \frac{\mu_0 n i}{2a}$

Magnetic field along axial line at a distance x from the center of the coil carrying current : $B = \frac{\mu_0 n a^2 i}{2(a^2 + x^2)^{\frac{3}{2}}}$

Force on a current carrying conductor placed in a magnetic field : $F = Bilsin\theta$

Kirchoff's junction rule : $\Sigma\, i = 0$

Kirchoff's loop rule : $\Sigma\, iR = \Sigma\, E$

Balancing condition for a Wheatstone's bridge : $\frac{P}{X} = \frac{R}{S}$

Relation between current i and Deflection θ of a moving coil galvanometer : $i = \frac{\alpha\theta}{nBA}$

Value of shunt resistance to convert a galvanometer to ammeter : $S = \frac{i_g G}{i - i_g}$

Value of high resistance to convert a galvanometer to voltmeter : $R = \frac{E}{i_g} - G$

Chapter 5

Quantum Theory and Photoelectric Effect

1. Explain the quantum theory of light.

   In 1901, Max Planck put forward a new theory of light called quantum theory. According to quantum theory, light is radiated in the form of tiny packets of energy called quantum or photon. If ν is the frequency of a photon,the its energy is given by

   $$\boxed{E = h\nu}$$

   Here h is a universal constant called Planck's constant and its value is $6.63 \times 10^{-34}\ Js$. If c is the velocity of light ($c = 3 \times 10^8\ m/s$), the wavelength λ is related to frequency ν by the relation

   $$c = \nu\lambda \quad \Longrightarrow \nu = \frac{c}{\lambda}$$
   $$\therefore \quad \boxed{E = \frac{hc}{\lambda}}$$

2. What is electron volt? Define electron volt. Give the relation between electron volt and joule.

   Electron volt (eV) is a unit of energy used in atomic and quantum physics. It is a convenient unit to represent small energy in particle physics. One electron volt is defined as the energy gained by an electron in accelerating through a potential difference of one volt.

   $$\boxed{1\ eV = 1.6 \times 10^{-19}\ J}$$

3. What is photoelectric effect?. Explain the laws of photoelectric effect.

   The emission of light from a metal surface when irradiated by light is called photoelectric effect and electrons ejected from the surface are called photo electrons. Millikan conducted a number of experiments and arrived at the following laws.

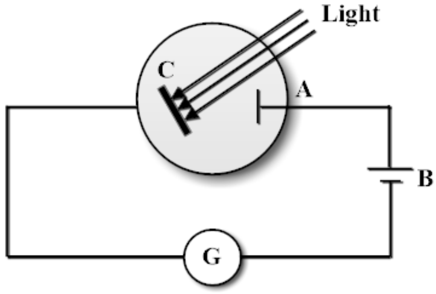
   (i) Photoelectric effect is frequency dependant. It is experimentally proved that for a given material, there is a minimum frequency required for the light to initiate photoelectric effect even if the intensity of light used is very large. The minimum frequency required for the incident light to initiate photoelectric effect is called the threshold frequency (ν_0).

   (ii) The number of ejected photoelectrons (photo current) depends on the intensity of light provided the frequency of the incident light is greater than the threshold frequency.

   (iii) The photoelectric effect is an instantaneous phenomenon. There is no time lag between the incidence of photon and the emission of electrons.

4. Explain an experiment to demonstrate photoelectric effect.

   The photoelectric effect can be demonstrated with the help of a photoelectric cell. A simple arrangement is shown in figure.



It consists of a silver plate C coated with cesium and another metal plate A both enclosed in an evacuated glass tube. C acts as cathode and A acts as anode. The negative of the battery B is connected to the cathode and positive to the anode. A galvanometer G is also is included in the circuit for the detection of current. When light falls on the cathode, electron are ejected from the surface of cesium . The flow of electrons from the cathode towards the anode constitutes an electric current and galvanometer shows a deflection. Photoelectric effect will be observed only if the incident light frequency is above a threshold value. The magnitude of electric current depends on the intensity of incident light.

5. Define the terms threshold frequency and threshold wavelength

   The minimum frequency required for the incident light to initiate photoelectric effect is called the threshold frequency (ν_0). The wavelength corresponding to threshold frequency is called threshold wavelength. Threshold wavelength can be defined as the largest wavelength above which there will not be the liberation of photoelectrons from a material.

6. Discuss Einstein's explanation of photoelectric effect. State Einstein's photoelectric equation.

   Einstein explained photoelectric effect using Planck's quantum theory. According to quantum theory, light consists of small packets of energy called quantum or photon. If ν is the frequency of light, the enegy of the photon is

$$E = h\nu$$

   where h is the Planck's constant. When a photon of energy $h\nu$ is incident on a metal surface, its energy is used for two purposes.

   (1) Energy required to remove electron from the metal surface called phtoelectric work function (ϕ).

   (2) Kinetic energy of the emitted photo electrons. If m is the mass of the electron and v is its velocity, then

$$\text{Kinetic enegy of the emitted electron} = \frac{1}{2}mv^2$$

   Therefore Einstein's photo electric equation can be written as

$$E = \phi + K.E.$$
$$h\nu = \phi + \frac{1}{2}mv^2$$

   Work function ϕ is a constant for a given material. Hence, if the frequency ν of the incident photon is decreased, the kinetic energy of the electron will be reduced. The frequency ν_0 at which kinetic energy of the electron becomes zero is the threshold frequency. Thus,

$$\phi = h\nu_0 = \frac{hc}{\lambda_0}$$

$$\therefore \text{ Einstein's photoelectric equation:} \quad h\nu = h\nu_0 + \frac{1}{2}mv^2$$

$$\boxed{h(\nu - \nu_0) = \frac{1}{2}mv^2}$$

$$\boxed{h(\frac{c}{\lambda} - \frac{c}{\lambda_0}) = \frac{1}{2}mv^2}$$

7. What are the different types of photoelectric cells?. List the practical applications of photoelectric effect.

   Photoelectric cell is a device used for converting light energy into electrical energy by employing photoelectric effect. There are three types of photoelectric cells.

   (i) Photo emissive cell: Based on the emission of photoelectrons from a metal surface when light is incident on it.

   (ii) Photo voltaic cell (solar cell): Based on the transition of electrons from valence band to conduction band in semiconducting materials when light fall on it.

   (iii) Photo conductive cell (Photo resistor): Based on the change in conductivity or resistivity of certain semiconducting materials, when light fall on it.

   Applications of photoelectric effect

   (a) Photoelectric cell is used as an illumination meter to measure the illuminating power of light sources.

   (b) A burglar alarm is constructed with a photoelectric cell.

   (c) Photoelectric cell is used in relay circuits.

   (d) A photo conductive cell is used for detecting infra-red light.

   (e) Photoelectric cell is used to reproduce sound recorded in a talkie film.

   (f) An array of photoelectric cell is used in television cameras for the conversion of light into electric signals.

   (g) Photo voltaic cells is used as a source of electricity.

Important Equations to Remember

Energy of a photon : $E = h\nu = \dfrac{hc}{\lambda}$

Relation between velocity, wavelength and frequency of light : $c = \nu\lambda$

$h = 6.63 \times 10^{-34}\ Js; \quad c = 3 \times 10^8\ m/s$

If E is in eV and λ in nanometers, then $E = \dfrac{1243}{\lambda}$

$1\ eV = 1.9 \times 10^{-19}\ J$

Einstein's photoelectric equation : $E = \phi + K.E.$

Photoelectric work function of a metal : $\phi = h\nu_0 = \dfrac{hc}{\lambda_0}$

Einstein's photoelectric equation in terms of frequency : $h\nu = h\nu_0 + \dfrac{1}{2}mv^2$

Einstein's photoelectric equation in terms of wavelength : $\dfrac{hc}{\lambda} = \dfrac{hc}{\lambda_0} + \dfrac{1}{2}mv^2$

Chapter 6

Laser

1. Explain the principle of laser action. What are the characteristics that made the LASER light different from ordinary light?.

   An atomic system can exist in different energy levels. The energy level of an atom with lowest energy is called ground state and levels of higher energy are called exited states. An atom in ground state can absorb energy and undergo transition to exited states. This process is called absorption. An atom in exited state can come down to ground state by emitting a photon in two ways. If the emission of light is without any external stimulation, it is called spontaneous emission. A photon striking an exited atom can induce a transition from exited state to the ground state by emitting a photon. This process is called stimulated emission. The major feature of the stimulated emission is that the emitted radiation has the same phase and frequency as that of the stimulating photon.

   In atomic system, under normal conditions, the number of atoms in the ground state is much higher than that in the exited states. By supplying energy from outside, atoms in the ground state undergo transition to exited states. As a result of this, the number of atoms in the exited state becomes higher than that at the ground state. This condition is called population inversion. The process of exiting an atomic system leading to population inversion is called optical pumping. Population inversion is an essential condition for lasing action.

   The first step to achieve lasing action is the optical pumping of a suitable atomic system with very intense light sources like flash tubes. As a result, the number of atoms in the exited state increases and population inversion is achieved. Under this condition, a spontaneously emitted photon can induce exited atom to emit an identical photon. These two photons will stimulate two more and so on. Since there are a large number of atoms in exited state, an intense beam of light of same frequency and phase is produced. Such an intense coherent beam of light is called LASER light.

   Characteristics of laser light

   (a) Laser light is monochromatic (single wavelength or colour).

   (b) Laser light is highly coherent (same phase and frequency)

   (c) Laser light is highly intense.

   (d) Laser light is highly directional and has low divergence.

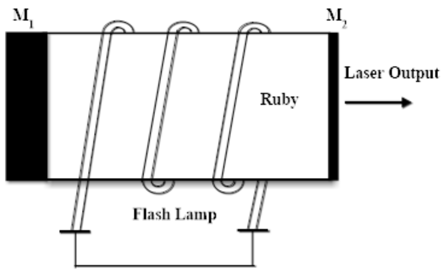
2. Distinguish between spontaneous emission and stimulated emission.

   An atomic system can exist in different energy levels. The energy level of an atom with lowest energy is called ground state and levels of higher energy are called exited states. An atom in ground state can absorb energy and undergo transition to exited states. This process is called absorption. An atom in exited state can come down to ground state by emitting a photon in two ways. If the emission of light is without any external stimulation, it is called spontaneous emission. A photon striking an exited atom can induce a transition from exited state to the ground state by emitting a photon. This process is called stimulated emission. The major feature of the stimulated emission is that the emitted radiation has the same phase and frequency as that of the stimulating photon.

3. What is the essential condition for lasing action (Explain population inversion).

An atomic system can exist in different energy levels. The level of an atom with with lowest energy is called ground state and levels of higher energy are called exited states. In atomic system, under normal conditions, the number of atoms in the ground state is much higher than that in the exited states. By supplying energy from outside, atoms in the ground state undergo transition to exited states. As a result of this, the number of atoms in the exited state becomes higher than that at the ground state. This condition is called population inversion. The process of exiting an atomic system leading to population inversion is called optical pumping. Population inversion is an essential condition for lasing action.

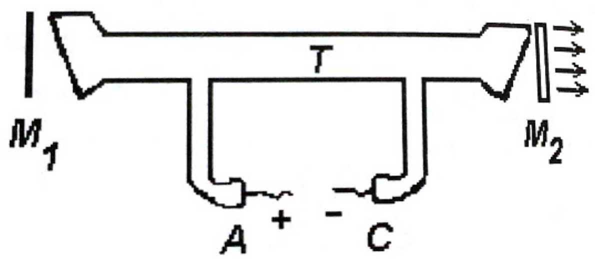
4. With the help of a neat diagram, explain the working of a Ruby laser.



The working element of a Ruby laser is a pink ruby rod exited by intense light from a flash lamp. Ruby consists of Al_2O_3 (Sapphire) with some of the aluminium atoms replaced by chromium. Sapphire serves as a transparent medium to include chromium ions. Usually the concentration of chromium in ruby is about 0.05 % to 1 %. Figure shows the configuration of a Ruby laser. The ruby rod has a length 10 cm and diameter about 1 cm. The end faces are perfectly flat and one end is completely silvered (M_1). The other end face M_2 is partially silvered. The ruby rod is surrounded by the coil of a flash lamp.

When the flash lamp is triggered, it emits intense beam of light. The chromium ions in the ruby absorb this light and make transitions to exited states. Since flash lamp is sufficiently intense, most of the chromium atoms are exited to higher energy states and thus population inversion is achieved. Population inversion is an essential requirement for lasing action. The spontaneously emitting photon travelling through the ruby rod will stimulate additional photon. Since the end faces are reflecting surfaces, radiation produced in the rod bounces back and forth between the mirrors M_1 and M_2. In this way, it gets amplified. The intense beam of photons thus developed emerges through the partially silvered mirror M_2. The output of the Ruby laser has a wavelength 694.3 nm.

5. With the help of a diagram, explain the working of a He-Ne Laser. What are the advantages of gas laser over solid lasers?.



Helium-Neon laser is gas laser. The essential parts of He-Ne laser are shown in the figure.The working substance of this laser is a mixture of helium and neon in the ratio 10:1. The gas mixture is placed in a long discharge tube, typically 50 cm long and 0.5 cm diameter. The pressure inside the tube is nearly 1 mm of mercury. The anode A and cathode C are attached to the side arms. The tube is placed between two mirrors M_1 and M_2 for feedback. The mirror M_1 is highly reflective whereas M_2 is partially transparent.

When the discharge is maintained in the tube by an electric field, electrons are produced. Electrons collide with atoms in the tube. The helium atoms are soon raised to higher energy states by electrons collisions. When the excited helium atoms collide with the neon atoms in the ground state, the excitation energy of helium is transferred to the neon atoms. In this way, a large number of neon atoms are raised to the the excited states and population inversion is achieved . Under this condition, a spontaneously emitted photon can trigger laser action. The output of He-Ne laser has a wavelength 632.8 nm.

Advantages of Gas lasers over solid state lasers

(a) Cost of gas laser is less
(b) Gas laser is more compact
(c) Gas laser is more monochromatic due to the absence of imperfections
(d) Gas laser can be operated continuously for a long time
(e) Cooling of materials can be done easily in gas lasers

6. List a few application of laser.

(a) Laser can be used as tool for surgery (Ophthalmic surgery).
(b) Laser is used for cutting, drilling and welding.
(c) Laser beam can be used as a carrier of information (telephone signal through optical fibre cables).
(d) Laser based methods are used to guide missiles and pilot-less fighter planes.
(e) Laser is used for range finding (measurement of distance of far away objects).
(f) Laser is used in Holography or 3D imaging.
(g) Laser is used to initiate fusion reaction.
(h) Laser is used to read and write data in CD/DVD systems.
(i) Laser is used in printing technology (Laser printer).
(j) Laser is used in textile industry to perfectly cut many layers of cloths together .

Chapter 7

Nuclear Physics and Nuclear Reactor

1. Discuss various forms of energy sources associated with electricity production.

Energy is the most reliable indicator of a country's progress and developing country like India has a long way to go up in energy production. The following are the major conventional and non-conventional energy sources associated with electrical energy production.

(a) Hydroelectric power is the most cheap and clean energy source for electricity production. But sites for hydroelectric projects must be provided by nature. Moreover, hydroelectric dams will flood a lot of land and reduce biodiversity.
(b) Wind energy : Turbines driven by wind can be used for electricity production. Thousands of large windmills extending over thousands of hectares of land are need to substitute a single hydroelectric plant. This will create serious environmental problems like noise pollution and interference with birds.

(c) Solar energy:Solar energy is a good non-polluting renewable energy source available in nature. It is difficult to store electricity and batteries are very costly and space consuming. hence electricity must be used as and when it is produced. The availability of solar energy is very low in rainy and winter seasons when compared to the same in summer seasons. Moreover, we cannot produce electricity during night. Photovoltaic cells or solar cells can be used to produce electricity directly from sunlight. It is an expensive option and the pollution due to poisonous chemicals like boron trifluoride, arsenic, cadmium, tellurium, selenium etc is of great concern.

(d) Thermoelectric power: Turbines can be driven by the expanding steam which can be produced by burning fossils fuels like coal, oils and natural gases. But thermal power plants contribute substantially to green house gases like carbon dioxide which can cause global warming. The compounds of nitrogen and sulphur produced by the combustion of fossil fuels may lead to acid rain. Moreover the supply of fossil fuels is limited and they have many applications including its use in automobiles. Hence it makes no sense in using fossil fuels for electricity production.

(e) Nuclear energy: Nuclear reactors are used to produce electricity by using nuclear fuels like uranium and plutonium. Radioactive waste materials produced in the nuclear reactor is a serious threat to humanity. Nuclear energy is a promising source of electricity for India and recently two Russian reactors called VVER-1000 have started functioning at Kudankulam which give 2000 mega watt power.

2. Define atomic number and mass number of a nucleus or atom. How a nucleus is symbolically represented? What are isotopes?

   The nucleus of an atom has an inner structure consists of positively charged particles called protons and neutral particles called neutrons. Atomic number (Z) is the total number of protons in the nucleus and mass number (A) is the total number of protons and neutrons in the nucleus. A nucleus X is symbolically represented as $_ZX^A$. Isotopes are atoms with same atomic number and different mass number. For example, $_{92}U^{235}$ and $_{92}U^{238}$ are isotopes of uranium.

3. State Einstein's mass energy relation. What are the units used in nuclear physics to express mass and energy.

   According to Einstein's special theory of relativity, mass and energy are equivalent and are mutually convertible.Einstein's mass energy relation is given by

$$E = mc^2$$

   where E represents the energy equivalent of mass m and c is the velocity of light.

   In atomic and nuclear physics, mass of the atom or nucleus is usually expressed in a unit called atomic mass unit (u). This unit is defined by taking the mass of $_6C^{12}$ isotope to be exactly 12 u. The relation between kilogram and atomic mass unit is $1\ u = 1.66 \times 10^{-27}\ kg$.

   In nuclear physics, energy is usually expressed in electron volt (eV) and million electron volt (MeV).

$$1\ eV = 1.6 \times 10^{-19}\ J$$
$$1\ MeV = 1.6 \times 10^{-13}\ J$$
$$1\ u = 931\ MeV$$

4. Explain nuclear fission reaction of uranium nucleus. What are the other fissionable isotopes?.

   The process of splitting a heavy nucleus into two nearly equal fragments together with the release of a large amount of energy is called nuclear fission. When a heavy nucleus like $_{92}U^{235}$ undergoes fission by the capture of a slow neutron, it splits into two fragments of intermediate mass number together with the release of two or three neutrons and about 200 MeV energy. Two possible nuclear reactions with ${}_{92}U^{235}$ when bombarded with a slow neutron can be written as

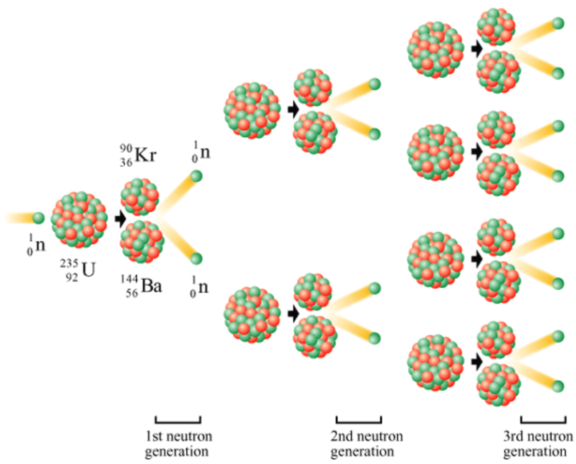
$$
\begin{aligned}
{}_{92}U^{235} + {}_{0}n^{1} &\rightarrow {}_{56}Ba^{141} + {}_{36}Kr^{92} + 3\,{}_{0}n^{1} + Energy \\
{}_{92}U^{235} + {}_{0}n^{1} &\rightarrow {}_{54}Xe^{140} + {}_{38}Sr^{94} + 2\,{}_{0}n^{1} + Energy
\end{aligned}
$$

A single fission reaction will release 200 MeV energy and on average 2.5 neutrons. Measurements have shown that the total mass of the products is less than the total mass of the reactants and this mass defect is converted into energy according Einstein's mass energy relation. ${}_{92}U^{235}$ is the only naturally occurring material which can undergo fission by neutrons of all energies, but fission probability is very high with slow neutrons of energy as low as 0.05 eV. Such low energy neutrons are called thermal neutrons. Natural uranium contains only 0.7% of ${}_{92}U^{235}$ and the remaining is non fissionable ${}_{92}U^{238}$.

${}_{92}U^{233}$ and ${}_{94}Pu^{239}$ are the two other isotopes which will undergo fission easily with neutrons of all energy. They are not naturally occurring materials, but they are produced artificially by nuclear reactions. Highly radioactive spent fuel in a uranium reactor contains a lot of plutonium which can be separated by careful chemical reprocessing. ${}_{92}U^{233}$ is produced by neutron irradiation of thorium (${}_{90}Th^{232}$).

5. What is meant by chain reaction as applied to nuclear fission. What is neutron multiplication factor and explain its importance.

The process of splitting a heavy nucleus into two nearly equal fragments together with the release of a large amount of energy is called nuclear fission. When a heavy nucleus like ${}_{92}U^{235}$ undergoes fission by the capture of a neutron, it splits into two fragments together with the release of two or three neutrons and about 200 MeV energy. Since only one neutron is required for the fission of a nucleus, the newly created neutrons can initiate fission in other nuclei releasing more neutrons. Each of these neutrons causes fission producing more neutrons in the next generation. The nuclear fission reaction proceeds like a chain and hence it is called chain reaction.



The figure shows a schematic representation of a nuclear chain reaction assuming that two neutrons are produced in a single fission event. A chain reaction will be self sustaining only if every neutron absorbed will produce at least one neutron to bombard with another nucleus. This condition can be expressed in terms of a parameter called neutron multiplication factor (k). The neutron multiplication factor can be defined as the ratio of average number of neutrons produced in one generation to the number of neutrons produced in the immediately preceding generation. The maximum value of k for the fission reaction of ${}_{92}U^{235}$ is about 2.5. Depending on the value of k, there are three conditions in a chain reaction.

(a) Critical (k=1): In this case reaction will be self sustaining at a controlled rate and it is a suitable condition for the operation of a nuclear reactor.

(b) Sub critical (k<1): In this case the fission process die out soon.

(c) Super critical (k>1):In this case, chain reaction proceeds in an uncontrollable rate, releasing huge amount of energy and results in a terrible explosion. This is the principle behind an atom bomb.

6. What is meant by a nuclear reactor?. What are the different types of nuclear reactors?

A nuclear reactor is a device in which fission reaction takes place at a controlled rate. There are mainly three different types of nuclear reactors depending upon the use.

(a) Power reactors used for electricity production

(b) Research reactors for producing neutron beams and radio isotopes for research purpose.

(c) Fast Breeder reactors for generating fissile materials from non fissionable materials.

7. What are the essential components of a nuclear reactor (Power reactor)?

Power reactor is used for generating electricity based on the phenomenon of controlled self sustaining nuclear fission. The essential components of a power reactor based on thermal neutrons are given below:

(a) **Fuel**: The material used for fission is called fuel. The fuel may be natural uranium or enriched uranium.

(b) **Moderator**: Neutrons produced in the fission are fast moving with kinetic energy of the order of 2 MeV. But fission is induced most effectively by slow neutrons of energy less than 0.5 MeV. In a Nuclear reactor, neutrons have to be slowed down to sustain chain reaction. The materials used for slowing down neutrons are called moderators. An ideal moderator should have the following properties.

   i. It should be cheap and abundant
   ii. It should be stable
   iii. It should have low mass number to absorb maximum amount of energy in a collision with neutrons.
   iv. It should be capable of reducing the velocity of neutrons without absorbing it.

   Commonly used moderators are heavy water (D_2O), Graphite and ordinary water. D_2O is the best available moderator, but it is expensive and requires complicated procedures for manufacture. In the case of graphite, the reduction in neutron energy in a single collision is comparatively small. Ordinary water has a disadvantage because the protons in water have a great chance for capturing a neutron. Hence when water is used as a moderator, enriched uranium must be used as the fuel.

(c) **Control rods**: A nuclear reactor is designed to allow a controlled chain reaction to take place. If neutron multiplication factor exceeds unity, the chain reaction will proceed in an uncontrolled rate. In such a situation, some neutrons should be removed from the system. Control rods used in the reactor can absorb neutrons and hence it can control chain reaction. Commonly cadmium and boron are used as control rods. They readily absorb neutrons. Fission reaction can be controlled by pushing the control rods in or out of the reactor core.

(d) **Coolant**: When fission goes on, a large amount of energy is produced in the form of heat.A coolant is used to remove heat produced as fast as it is liberated. The hot coolant is used to boil water and the resulting steam is used to rotate the turbine to produce electricity. Usually water is used as a coolant in most reactors operating with thermal neutrons. A good coolant should have a large thermal capacity to absorb the heat quickly. Since the steam is having a small heat capacity, reactors using water as a coolant is kept at high pressure (150 atm) so that coolant remains in liquid state. This the principle of a Pressurized Water Reactor (PWR). If heavy water is used as a coolant, the reactor is called Pressurized Heavy Water Reactor (PHWR). In Fast Breeder Reactors (FBR) using fast neutrons, molten sodium is used as the coolant. But sodium is highly corrosive and susceptible to radioactivity. Sodium has a high heat capacity and high boiling point. Hence a pressurizer is not required in fast breeder reactor.

(e) **Containment Structure**: The containment is the structure that separates the reactor from the environment. it is usually a dome shaped and is made of steel reinforced concrete. A typical containment is constructed of a 90 cm thick concrete walls heavily reinforced by thick steel rods welded into a tight net around which the concrete is poured. Usually inside of the containment is lined with thick steel plates welded to form a tight chamber which can withstand very high pressure. The contaminant also provides protection to reactor from external forces.

8. What is a moderator?. what are the properties of an ideal moderator?. Name three substances used a moderators in a reactor.

Neutrons produced in the fission are fast moving with kinetic energy of the order of 2 MeV. But fission is induced most effectively by slow neutrons of energy less than 0.5 MeV. In a Nuclear reactor, neutrons have to be slowed down to sustain chain reaction. The materials used for slowing down neutrons are called moderators. An ideal moderator should have the following properties.

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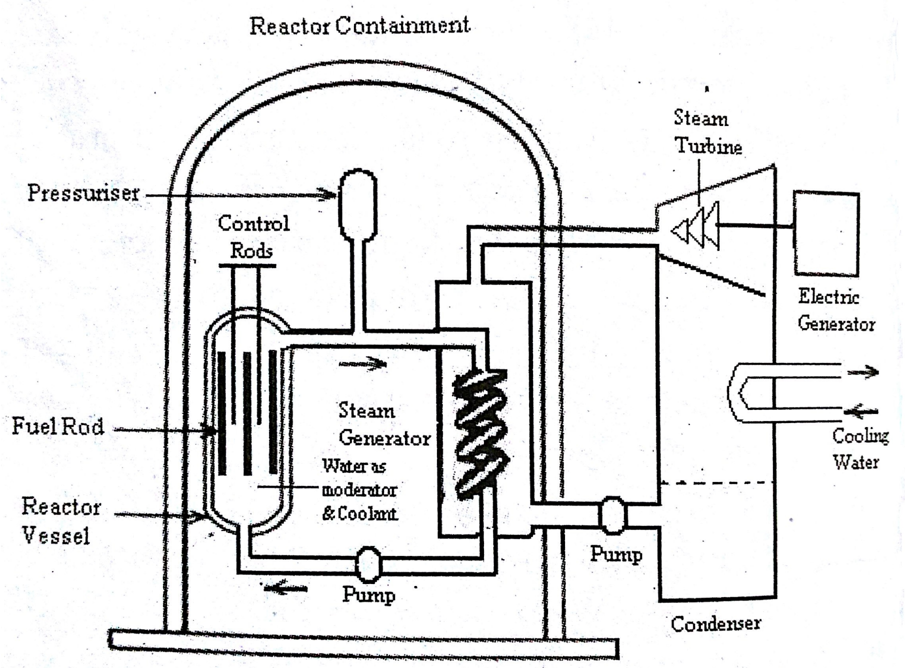
(d) It should be capable of reducing the velocity of neutrons without absorbing it.

Commonly used moderators are heavy water (D_2O), Graphite and ordinary water.

9. What is the role of control rods in a fission reactor. Give two examples of materials which are used as control rods.

A nuclear reactor is designed to allow a controlled chain reaction to take place. If neutron multiplication factor exceeds unity, the chain reaction will proceed in an uncontrolled rate. In such a situation, some neutrons should be removed from the system. Control rods used in the reactor can absorb neutrons and hence it can control chain reaction. Commonly cadmium and boron are used as control rods.

10. With the help of a neat diagram, explain the working of nuclear reactor (Pressurized Water Reactor)



A highly simplified design of a pressurized water reactor (PWR)is shown in the figure. The main component of the reactor is a cylindrical reactor vessel which housed a reactor core containing fuel rods. The head of the reactor vessel is removable to allow refuelling. The fuel is in the form of uranium oxide pellets stacked in sealed cladding tubes made of zirconium alloy. The cladding tubes protect the fuel from the coolant and prevent the escape of radioactive fission products into the coolant. The control rod driving mechanism is located at the top of the reactor vessel. Control rods are made up of cadmium rods which is a good absorber of neutrons. Pushing the control rods into the reactor core slows down the reaction while pulling them out increases the rate of fission.

In the PWR, water is used as a coolant. Since enriched uranium (up to 4% of U^{235}) is used, the coolant functions as a moderator also. When fission takes place, heat is evolved and water is heated to a high temperature. Using a pressuriser, pressure up to 150 atmospheres is applied to keep the coolant water in the liquid state without boiling. The coolant transfers the heat to a steam generator. It is then pumped back into the reactor vessel forming a closed primary cycle. The water in the steam generator boils vigorously, thereby producing steam under high pressure. the steam from the steam generator passes out of the containment through strong pressure tubes to drive the turbine. The turbine drives an electric generator to produce electricity. After passing through the turbine, steam is routed to the condenser. Cold water passing through the tubes in the condenser condenses the steam and condensed water is pumped back to the steam generator for reuse. This flow system is called secondary flow cycle.

11. What are the advantages and disadvantages of Pressurized Water Reactor (PWR) over other reactor types?

Advantages of PWR

(a) The PWR turbine cycle loop is separate from the primary coolant loop so that water in that loop is not contaminated with radioactive materials.
(b) PWR is very stable against temperature rise.
(c) Since the coolant water has moderating properties, no separate moderator is required.

Disadvantages of PWR

(a) Coolant water must be at high pressure to keep it in the liquid state. Hence high strength pipes are required to transport it to steam generator.

(b) Enriched uranium must be used as the fuel and hence fuel cost increases.

12. What are the uses of nuclear reactors?

    (a) Nuclear reactors are mainly used for the production of electricity.

    (b) A reactor is a good source of neutrons and radioisotopes are produced by irradiating different chemical elements by neutrons.

    (c) Fissile materials like Pu^{239} and U^{233} are produced in large quantities by using breeder reactors.

    (d) Nuclear submarine is powered by an inbuilt nuclear reactor.

13. Distinguish between nuclear fission and fusion.

    Nuclear fission is the process of splitting a heavy nucleus into two fragments with the release of large amount of energy. When a heavy nucleus like ${}_{92}U^{235}$ undergoes fission by the capture of a neutron, it splits into two fragments together with the release of two or three neutrons and about 200 MeV energy. Nuclear fission reactions proceeds like a chain and hence it is called chain reaction. Nuclear fusion is a nuclear reaction in which two or more light nuclei combined to form a heavier nucleus. Fusion reaction takes place only at a very high temperature of about 10^7 K and hence fusion reaction is called a thermonuclear reaction. Nuclear fusion releases more energy than fission reaction. Fusion reactions are the main source of energy in sun and stars.

14. Write a note on energy production in sun.

    The basic energy producing process in the sun is the fusion of hydrogen nuclei (proton) into helium nuclei. The sun consists of about 70% of hydrogen, 28% helium and 2% of other elements. The core of the sun is believed to be at a temperature of about 15 million kelvin which is enough to produce fusion reaction. The main fusion reaction takes place in the sun is called proton-proton cycle. The net result of this sequence is the combination of 4 hydrogen nuclei to form a helium together with the liberation of two positrons. The total energy evolved in the fusion event is 25 MeV. Proton-proton cycle is responsible for energy production in stars like sun and other cooler stars.

15. Which is the most promising fusion reaction for controlled nuclear fusion reaction. The most promising nuclear reaction is a D-T reaction in which a deuteron(${}_1H^2$)and a tritium ${}_1H^3$ fuse together to form a helium nucleus and a neutron. The fusion reaction is

    $${}_1H^2 + {}_1H^3 \rightarrow {}_2He^4 + {}_0n^1 + Energy$$

    The energy released in this fusion is about 17.6 MeV per fusion. Extremely high temperature of about 10^8 kelvin is required to initiate this fusion reaction.

16. What is plasma. Mention briefly two approaches for plasma confinement in fusion reaction.

    Plasma is the forth state of matter consists of fully ionized gas. This aggregate of ions and electrons behave quite differently from other three states of matter - solid, liquid and gas. Nuclear fusion reactions requires high temperature of the order of 10^8 and hence nuclear fuel will be in plasma state. The major problem arising in the attempt to produced controlled fusion is the confinement of plasma for a long time. There are basically two schemes are considered for confinement. But still plasma loses a lot of energy by radiation. In one scheme, a suitable designed magnetic filed can be used to confine plasma. This is called magnetic confinement. In the second scheme called inertial confinement, a pellet of solid deuterium and tritium is bombarded from all sides by an intense lase beam. This compresses the pellets and also heat it. But the beam energy require is well beyond the capacity of ordinary lasers.

Important Equations to Remember

Einstein's Mass - Energy relation: $E = mc^2$

Conversion of atomic mass unit into kg: $1\ u = 1.66\ \times\ 10^{-27}$ kg

Energy equivalent of one atomic mass unit: $1\ u = 931$ MeV

Conversion of electron volt into joule: $1\ eV = 1.6\ \times\ 10^{-19}$ J

Conversion of million electron volt into joule: $1\ MeV = 1.6\ \times\ 10^{-13}$ J

Nuclear fission of ${}_{92}U^{235}$ with a neutron capture:

$${}_{92}U^{235} +_0 n^1 \ \rightarrow\ {}_{56}Ba^{141} +_{36} Kr^{92} + 3\ {}_0n^1 + \text{Energy}$$

$${}_{92}U^{235} +_0 n^1 \ \rightarrow\ {}_{54}Xe^{140} +_{38} Sr^{94} + 2\ {}_0n^1 + \text{Energy}$$

Nuclear fusion of deuteron with a tritium nucleus into helium nucleus:

$${}_1H^2 +_1 H^3 \ \rightarrow\ {}_2He^4 +_0 n^1 + \text{Energy}$$