Chapter 25

Electron, Photon, Photoelectric Effect and X-rays

Electric Discharge Through Gases

At normal atmospheric pressure, the gases are poor conductor of electricity. If we establish a potential difference (of the order of 30 *kV*) between two electrodes placed in air at a distance of few *cm* from each other, electric conduction starts in the form of sparks.

The discharge of electricity through gases can be systematically studied with the help of discharge tube shown below

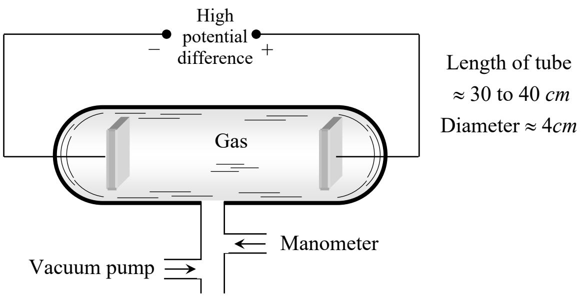


Fig. 25.1

As the pressure inside the discharge tube is gradually reduced, the following is the sequence of phenomenon that are observed.

(1) At normal pressure no discharge takes place.

(2) At the pressure 10 *mm* of *Hg*, a zig-zag thin red spark runs from one electrode to other and cracking sound is heard.

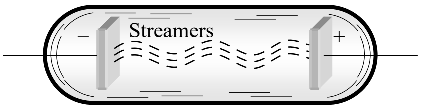


Fig. 25.2

(3) At the pressure 4 *mm.* of *Hg*, an illumination is observed at the electrodes and the rest of the tube appears dark. This type of discharge is called dark discharge.

(4) When the pressure falls below 4 *mm* of *Hg* then the whole tube is filled with bright light called positive column and colour of light depends upon the nature of gas in the tube as shown in the following table.

Table 25.1 : Colour for different gases

Gas	Air	H_2	N_2	Cl_2	CO_2	Neon
Colour	Purple red	Blue	Red	Green	Bluish white	Dark red

(5) At a pressure of 1.65 *mm* of *Hg* :

Sky colour light is produced at the cathode it is called as negative glow. Positive column shrinks towards the anode and the dark space between

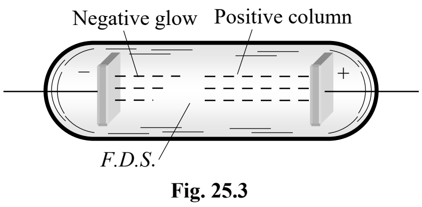


Fig. 25.3

positive column and negative glow is called Faradays dark space (*FDS*).

(6) At a pressure of 0.8 *mm Hg* : At this pressure, negative glow is detached from the cathode and moves towards the anode. The dark space created between cathode and negative glow is called as Crook's dark space. Length of positive column further reduce cathode called cathode glow

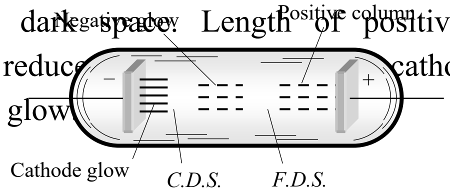


Fig. 25.4

(7) At a pressure of 0.05 *mm* of *Hg* : The positive column splits into dark and bright disc of light called striations.

(8) At the pressure of 0.01 or 10^{-2} *mm* of *Hg* some invisible particles move from cathode which on striking with the glass tube on the opposite side of cathode cause the tube to glow. These invisible rays emerging from cathode are called cathode rays.

(9) Finally when pressure drops to nearly 10^{-4} *mm* of *Hg*, there is no discharge in tube.

Cathode Rays

(1) Cathode rays, discovered by Sir William Crooke

(2) They are streams of fast moving electrons.

(3) They can be produced by using a discharge tube containing gas at a low pressure of the order of 10^{-2} *mm* of *Hg*.

(4) The cathode rays in the discharge tube are the electrons produced due to ionisation of gas and that emitted by cathode due to collision of positive ions.

(5) Cathode rays travel in straight lines.

(6) Cathode rays are emitted normally from the cathode surface. Their direction is independent of the position of the anode.

(7) Cathode rays exert mechanical force on the objects they strike.

(8) Cathode rays produce heat when they strikes a metal surface.

(9) Cathode rays produce fluorescence.

(10) When cathode rays strike a solid object, specially a metal of high atomic weight and high melting point *X*-rays are emitted from the objects.

(11) Cathode rays are deflected by an electric field and also by a magnetic field.

(12) Cathode rays ionise the gases through which they are passed.

(13) Cathode rays can penetrate through thin foils of metal.

(14) Cathode rays are found to have velocity ranging $\frac{1}{30}th$ to $\frac{1}{10}th$ of velocity of light.

J.J. Thomson's Experiment

(1) It's working is based on the fact that if a beam of electron is subjected to the crossed electric field $\vec{E}$ and magnetic field $\vec{B}$, it experiences a force due to each field. In case the forces on the electrons in the electron beam due to these fields are equal and opposite, the beam remains undeflected.

(2) When no field is applied, the electron beam produces illuminations at point *P*.

(3) In the presence of any field (electric and magnetic) electron beam deflected up or down (illumination at P or P')

(4) If both the fields are applied simultaneously and adjusted such that electron beam passes undeflected and produces illumination at point *P*.

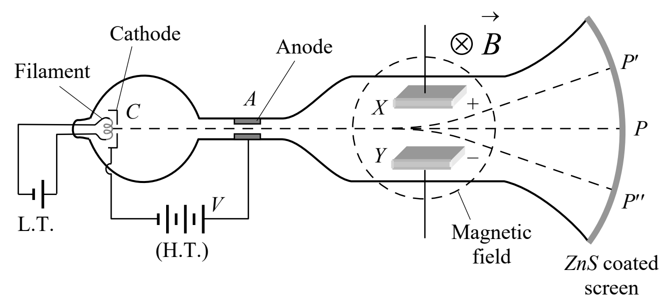


Fig. 25.5

In this case; Electric force = Magnetic force $\Rightarrow$ $eE = evB$

$\Rightarrow v = \frac{E}{B}$; v = velocity of electron

(5) As electron beam accelerated from cathode to anode its loss in potential energy appears as gain in the K.E. at the anode. If suppose V is the potential difference between cathode and anode then, loss in potential energy = eV

And gain in kinetic energy at anode will be K.E. $= \frac{1}{2}mv^2$ *i.e.* $eV = \frac{1}{2}mv^2 \Rightarrow \frac{e}{m} = \frac{v^2}{2V} \Rightarrow \frac{e}{m} = \frac{E^2}{2VB^2}$

Thomson found, $\frac{e}{m} = 1.77 \times 10^{11}\ C/kg.$

If one includes the relativistic variation of mass with speed $(m = m_0/\sqrt{1 - v^2/c^2})$, then specific charge of an electron decreases with the increase in its velocity.

(6) The deflection of an electron in a purely electric field is given by $y = \frac{1}{2}\left(\frac{eE}{m}\right).\frac{l^2}{v^2}$; where l = Length of each plate, y = deflection of electron in the field region, v = speed of the electron.

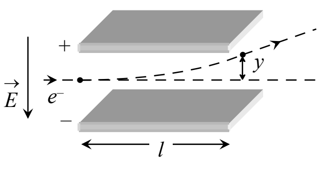


Fig. 25.6

Millikans Oil Drop Experiment

(1) Millikan performed the pioneering oil drop experiment for the precise measurement of the charge on the electron.

(2) By applying suitable electric field across two metal plates, the charged oil droplets could be caused to rise or fall or even held stationary in the field of view for sufficiently long time. He found that the charge on an oil droplet was always an integral multiple of an elementary charge $1.602 \times 10^{-19}\ C$.

(3) In this experiment charge on the drop is given by

$$q = \frac{6\pi\eta(v_1 + v_2)d}{V}\left[\frac{9\eta v_1}{2g(\rho - \sigma)}\right]^{1/2}$$

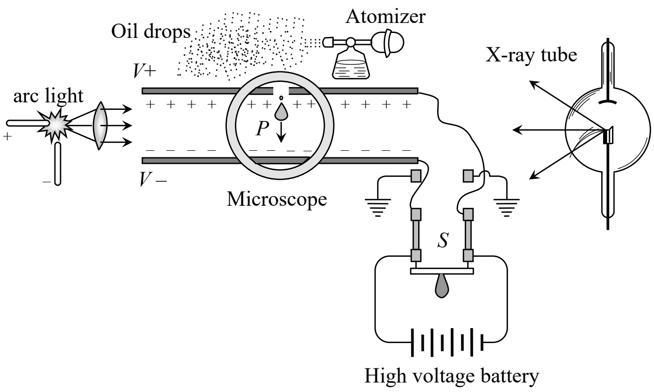


Fig. 25.7: Schematic diagram of Milikan's oil drop experiment

where η = Coefficient of viscosity of air, v_1 = Terminal velocity of drop when no electric field is applied between the plates, v_2 = Terminal velocity of drop when electric field is applied between the plates.

V = Potential difference between the plates, d = Separation between plates, ρ = density of oil, σ = Density of air.

Positive Rays

When potential difference is applied across the electrodes of a discharge tube (10^{-3} *mm* of *Hg*), electrons are emitted from the perforated cathode. As they move towards anode, they gain energy. These energetic electrons when collide with the atoms of the gas in the discharge tube, they ionize the atoms. The positive ions so formed at various places between cathode and anode, travel towards the cathode. Since during their motion, the positive ions when reach the ... ugh the holes in the cathode ... w comes out from each hole on the backside of the cathode. It is called positive rays, which are coming out from the holes.

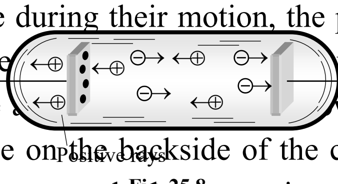


Fig. 25.8

(1) Positive rays are positive ions having same mass if the experimental gas does not have isotopes. However if the gas has isotopes then positive rays are group of positive ions having different masses.

(2) They travel in straight lines and cast shadows of objects placed in their path. But the speed of the positive rays is much smaller than that of cathode rays.

(3) They are deflected by electric and magnetic fields but the deflections are small as compared to that for cathode rays.

(4) They show a spectrum of velocities. Different positive ions move with different velocities. Being heavy, their velocity is much less than that of cathode rays.

(5) q/m ratio of these rays depends on the nature of the gas in the tube (while in case of the cathode rays q/m is constant and doesn't depend on the nature of gas in the tube). q/m for hydrogen is maximum.

(6) They carry energy and momentum. The kinetic energy of positive rays is more than that of cathode rays.

(7) The value of charge on positive rays is an integral multiple of electronic charge.

(8) They cause ionisation (which is much more than that produced by cathode rays).

Thomson's Mass Spectrograph

It is used to measure atomic masses of various isotopes in gas. This is done by measuring q/m of singly ionised positive ion of the gas.

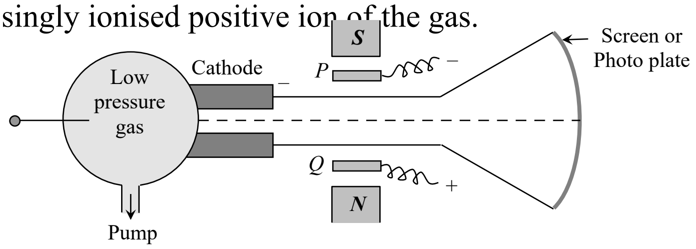


Fig. 25.9

(1) The positive ions are produced in the bulb at the left hand side. These ions are accelerated towards cathode. Some of the positive ions pass through the fine hole in the cathode. This fine ray of positive ions is subjected to electric field E and magnetic field B and then allowed to strike a fluorescent screen ($\vec{E} \parallel \vec{B}$ but $\vec{E}$ or $\vec{B} \perp \vec{v}$).

(2) If the initial motion of the ions is in $+x$ direction and electric and magnetic fields are applied along $+y$ axis then force due to electric field is in the direction of y-axis and due to magnetic field it is along z-direction.

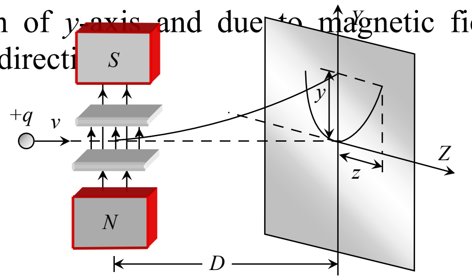


Fig. 25.10

The deflection due to electric field alone $y = \frac{qELD}{mv^2}$ .....(i)

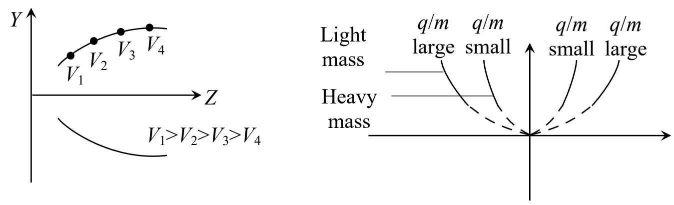
The deflection due to magnetic field alone $z = \frac{qBLD}{mv}$ .....(ii)

From equation (i) and (ii), $z^2 = k\left(\frac{q}{m}\right)y$

where $k = \frac{B^2LD}{E}$; This is the equation of parabola.

It means all the charged particles moving with different velocities but of same q/m value will strike the screen placed in yz plane on a parabolic track as shown in the above figure.

(3) All the positive ions of same. q/m moving with different velocity lie on the same parabola. Higher is the velocity lower is the value of y and z. The ions of different specific charge will lie on different parabola.



(A) (B)

Fig. 25.11

(4) The number of parabola tells the number of isotopes present in the given ionic beam.

Bainbridge Mass Spectrograph

In Bainbridge mass spectrograph, field particles of same velocity are selected by using a velocity selector and then they are subjected to a uniform magnetic field perpendicular to the velocity of the particles. The particles corresponding to different isotopes follow different circular paths as shown in the figure.

(1) **Velocity selector :** The positive ions having a certain velocity v gets isolated from all other velocity particles. In this chamber the electric and magnetic fields are so balanced that the particle moves undeflected. For this the necessary condition is $v=\frac{E}{B}$ and E, B and v should be mutually perpendicular to each other.

(2) **Analysing chamber :** In this chamber magnetic field B is applied perpendicular to the direction of motion of the particle. As a result the particles move along a circular path of radius

$$r=\frac{mE}{qBB}\Rightarrow\frac{q}{m}=\frac{E}{BB\,r} \text{ also } \frac{r_1}{r_2}=\frac{m_1}{m_2}$$

In this way the particles of different masses gets deflected on circles of different radii and reach on different points on the photo plate.

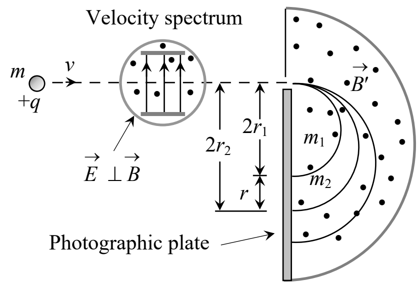


Fig. 25.12

Separation between two traces

$$=d=2r_2-2r_1=\frac{2v(m_2-m_1)}{qB}.$$

Matter Waves (de-Broglie Waves)

According to de-Broglie a moving material particle sometimes acts as a wave and sometimes as a particle.

The wave associated with moving particle is called matter wave or de-Broglie wave and it propagates in the form of wave packets with group velocity.

(1) **de-Broglie wavelength :** According to de-Broglie theory, the wavelength of de-Broglie wave is given by

$$\lambda=\frac{h}{p}=\frac{h}{mv}=\frac{h}{\sqrt{2mE}}\Rightarrow\lambda\propto\frac{1}{p}\propto\frac{1}{v}\propto\frac{1}{\sqrt{E}}$$

Where h = Plank's constant, m = Mass of the particle, v = Speed of the particle, E = Energy of the particle.

The smallest wavelength whose measurement is possible is that of γ -rays.

The wavelength of matter waves associated with the microscopic particles like electron, proton, neutron, α-particle *etc*. is of the order of $10^{-10}\,m$.

(2) **de-Broglie wavelength associated with the charged particles :** The energy of a charged particle accelerated through potential difference V is $E=\frac{1}{2}mv^2=qV$

Hence de-Broglie wavelength $\lambda=\frac{h}{p}=\frac{h}{\sqrt{2mE}}=\frac{h}{\sqrt{2mqV}}$

$$\lambda_{Electron}=\frac{12.27}{\sqrt{V}}\mathring{A},\ \lambda_{Proton}=\frac{0.286}{\sqrt{V}}\mathring{A},$$

$$\lambda_{Deutron}=\frac{0.202}{\sqrt{V}}\mathring{A},\quad \lambda_{\alpha-particle}=\frac{0.101}{\sqrt{V}}\mathring{A}$$

(3) **de-Broglie wavelength associated with uncharged particles :** For *Neutron de*-Broglie wavelength is given as

$$\lambda_{Neutron}=\frac{0.286\times10^{-10}}{\sqrt{E(\text{in } eV)}}m=\frac{0.286}{\sqrt{E(\text{in } eV)}}\mathring{A}$$

Energy of thermal neutrons at ordinary temperature

$\because\ E=kT\Rightarrow\lambda=\frac{h}{\sqrt{2mkT}}$; where T = Absolute temperature, k = Boltzman's constant $=1.38\times10^{-23}$ *Joule/kelvin*,

So,

$$\lambda_{Thermal\,neutron}=\frac{6.62\times10^{-34}}{\sqrt{2\times1.67\times10^{-27}\times1.38\times10^{-23}\,T}}=\frac{30.83}{\sqrt{T}}\mathring{A}$$

(4) **Ratio of wavelength of photon and electron :** The wavelength of a photon of energy E is given by $\lambda_{ph} = \frac{hc}{E}$

While the wavelength of an electron of kinetic energy K is given by $\lambda_c = \frac{h}{\sqrt{2mK}}$. Therefore, for the same energy,

the ratio $\frac{\lambda_{ph}}{\lambda_e} = \frac{c}{E}\sqrt{2mK} = \sqrt{\frac{2mc^2K}{E^2}}$

Characteristics of Matter Waves

(1) Matter wave represents the probability of finding a particle in space.

(2) Matter waves are not electromagnetic in nature.

(3) de-Brogile or matter wave is independent of the charge on the material particle. It means, matter wave of de-Broglie wave is associated with every moving particle (whether charged or uncharged).

(4) Practical observation of matter waves is possible only when the de-Broglie wavelength is of the order of the size of the particles.

(5) Electron microscope works on the basis of de-Broglie waves.

(6) The phase velocity of the matter waves can be greater than the speed of the light.

(7) Matter waves can propagate in vacuum, hence they are not mechanical waves.

(8) The number of de-Broglie waves associated with n^{th} orbital electron is n.

(9) Only those circular orbits around the nucleus are stable whose circumference is integral multiple of de-Broglie wavelength associated with the orbital electron.

Davision and Germer Experiment

(1) It is used to study the scattering of electron from a solid or to verify the wave nature of electron. A beam of electrons emitted by electron gun is made to fall on nickel crystal cut along cubical axis at a particular angle. *Ni* crystal behaves like a three dimensional diffraction grating and it diffracts the electron beam obtained from electron gun.

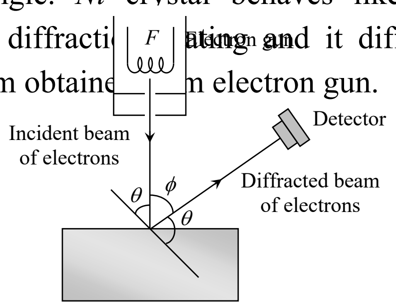


Fig. 25.13

(2) The diffracted beam of electrons is received by the detector which can be positioned at any angle by rotating it about the point of incidence. The energy of the incident beam of electrons can also be varied by changing the applied voltage to the electron gun.

(3) According to classical physics, the intensity of scattered beam of electrons at all scattering angle will be same but Davisson and Germer, found that the intensity of scattered beam of electrons was not the same but different at different angles of scattering. It is maximum for diffracting angle 50° at 54 *volt* potential difference.

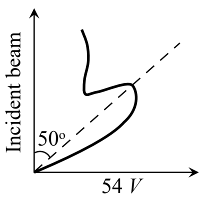


Fig. 25.14

(4) If the de-Broglie waves exist for electrons then these should be diffracted as *X*-rays. Using the Bragg's formula $2d\sin\theta = n\lambda$, we can determine the wavelength of these waves.

where d = distance between diffracting planes, $\theta = \frac{(180-\phi)}{2}$ = glancing angle for incident beam = Bragg's angle.

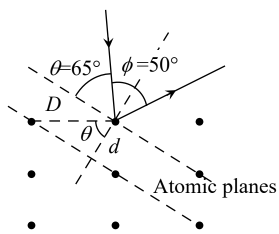


Fig. 25.15

The distance between diffracting planes in *Ni*-crystal for this experiment is d = 0.91$\mathring{A}$ and the Bragg's angle = 65°. This gives for n = 1, $\lambda = 2\times 0.91\times 10^{-10}\sin 65^{o} = 1.65\mathring{A}$

Now the de-Broglie wavelength can also be determined by using the formula $\lambda = \frac{12.27}{\sqrt{V}} = \frac{12.27}{\sqrt{54}} = 1.67\mathring{A}$. Thus the de-Broglie hypothesis is verified.

(5) The Bragg's formula can be rewritten in the form containing interatomic distance D and angle ϕ

$\because\ \theta = 90 - \frac{\phi}{2}$ and $d = D\cos\theta = D\sin\frac{\phi}{2}$

Using $\sin\theta = \cos\frac{\phi}{2}$

$2d\sin\theta = \lambda \Rightarrow 2(D\sin\frac{\phi}{2}).\cos\frac{\phi}{2} = \lambda \Rightarrow D\sin\phi = \lambda$

Heisenberg Uncertainty Principle

(1) According to Heisenberg's uncertainty principle, it is impossible to measure simultaneously both the position and the momentum of the particle.

(2) Let Δx and Δp be the uncertainty in the simultaneous measurement of the position and momentum of the particle, then $\Delta x\Delta p = \hbar$; where $\hbar = \frac{h}{2\pi}$ and h = 6.63 × 10^{-34} *J-s* is the Planck's constant. $(\frac{h}{2\pi} = 1.05\times 10^{-34}\ J\text{-}sec)$

A more rigorous treatment gives $\Delta x.\Delta p \geq \frac{\hbar}{2}\left(\text{or } \frac{h}{4\pi}\right)$.

(3) If $\Delta x = 0$ then $\Delta p = \infty$ and if $\Delta p = 0$ then $\Delta x = \infty$

i.e., if we are able to measure the exact position of the particle (say an electron) then the uncertainty in the measurement of the linear momentum of the particle is infinite. Similarly, if we are able to measure the exact linear momentum of the particle *i.e.*, Δp = 0, then we can not measure the exact position of the particle at that time.

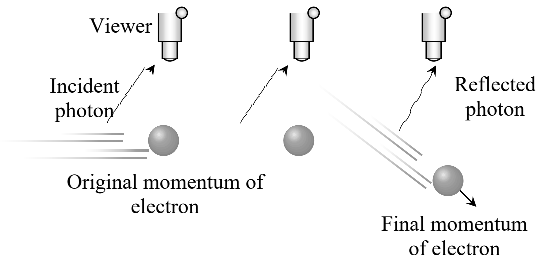


Fig. 25.16

An electron cannot be observed without changing it's momentum

(4) Uncertainty principle successfully explains

(i) Non-existence of electrons in the nucleus

(ii) Finite size of spectral lines.

(5) The Heisenberg uncertainty principle is also applicable to energy and time, angular momentum and angular displacement. Hence $\Delta E.\Delta t \geq \frac{h}{2\pi}$ and $\Delta L.\Delta\theta \geq \frac{h}{2\pi}$

(6) If the radius of the nucleus is r then the probability of finding the electron inside the nucleus is $\Delta x = 2r$ and uncertainty in momentum is $\Delta p = \frac{h}{4\pi r}$

Photon

According to Eienstein's quantum theory light propagates in the bundles (packets or quanta) of energy, each bundle being called a photon and possessing energy.

(1) **Energy of photon :** Energy of photon is given by

$E = h\nu = \frac{hc}{\lambda}$; where c = Speed of light, h = Plank's constant = 6.6 × 10^{-34} *J-sec*, ν = Frequency in *Hz*, λ = Wavelength of light.

In electron volt $E(eV) = \frac{hc}{e\lambda} = \frac{12375}{\lambda(\mathring{A})} \approx \frac{12400}{\lambda(\mathring{A})}$

(2) **Mass of photon :** Actually rest mass of the photon is zero. But it's effective mass is given as

$E = mc^2 = h\nu \Rightarrow m = \frac{E}{c^2} = \frac{h\nu}{c^2} = \frac{h}{c\lambda}$. This mass is also known as kinetic mass of the photon

(3) **Momentum of the photon**

Momentum $p = m\times c = \frac{E}{c} = \frac{h\nu}{c} = \frac{h}{\lambda}$

(4) **Number of emitted photons :** The number of photons emitted per second from a source of monochromatic radiation of wavelength λ and power P is given as $(n) = \frac{P}{E} = \frac{P}{h\nu} = \frac{P\lambda}{hc}$; where E = energy of each photon

(5) **Intensity of light (I) :** Energy crossing per unit area normally per second is called intensity or energy flux

i.e. $I = \frac{E}{At} = \frac{P}{A}$ $\left(\frac{E}{t} = P = \text{radiation power}\right)$

At a distance r from a point source of power P intensity is given by $I = \frac{P}{4\pi r^2} \Rightarrow I \propto \frac{1}{r^2}$

(6) **Number of photons falling per second (n) :** If P is the power of radiation and E is the energy of a photon then $n = \frac{P}{E}$

Photo-Electric Effect

The photo-electric effect is the emission of electrons (called photo-electrons when light strikes a surface. To escape from the surface, the electron must absorb enough energy from the incident radiation to overcome the attraction of positive ions in the material of the surface.

The photoelectric effect was first observed by Heinrich Hertz and it was investigated in detail by Whilelm Hallwachs and Philipp Lenard.

The photoelectric effect is based on the principle of conservation of energy.

(1) **Work function (or threshold energy) (W_0) :** The minimum energy of incident radiation, required to eject the electrons from metallic surface is defined as work function of that surface.

$W_0 = h\nu_0 = \frac{hc}{\lambda_0}$ *Joules*; ν_0 = Threshold frequency;

λ_0 = Threshold wavelength

Work function in electron volt $W_0(eV) = \frac{hc}{e\lambda_0} = \frac{12375}{\lambda_0(Å)}$

Table 25.2 : Work function of several elements

Element	Work function (eV)	Element	Work function (eV)
Platinum	6.4	Aluminum	4.3
Gold	5.1	Silver	4.3
Nickel	5.1	Sodium	2.7
Carbon	5.0	Lithium	2.5
Silicon	4.8	Potassium	2.2
Copper	4.7	Cesium	1.9

(2) **Threshold frequency (ν_0) :** The minimum frequency of incident radiations required to eject the electron from metal surface is defined as threshold frequency.

If incident frequency $\nu < \nu_0 \Rightarrow$ No photoelectron emission

For most metals the threshold frequency is in the ultraviolet (corresponding to wavelengths between 200 and 300 nm), but for potassium and cesium oxides it is in the visible spectrum (λ between 400 and 700 nm)

(3) **Threshold wavelength (λ_0) :** The maximum wavelength of incident radiations required to eject the electrons from a metallic surface is defined as threshold wavelength.

If incident wavelength $\lambda > \lambda_0 \Rightarrow$ No photoelectron emission

(4) **Einstein's photoelectric equation :** According to Einstein, photoelectric effect is the result of one to one inelastic collision between photon and electron in which photon is completely absorbed

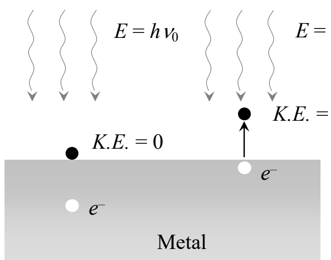


Fig. 25.17

Einstein's photoelectric equation is $\boldsymbol{E = W_0 + K_{max}}$

where $K_{max} = \frac{1}{2}mv_{max}^2$ = maximum kinetic energy of emitted electrons.

Experimental Setup for Photoelectric Effect

(1) Two conducting electrodes, the anode (Q) and cathode (P) are enclosed in an evacuated glass tube as shown

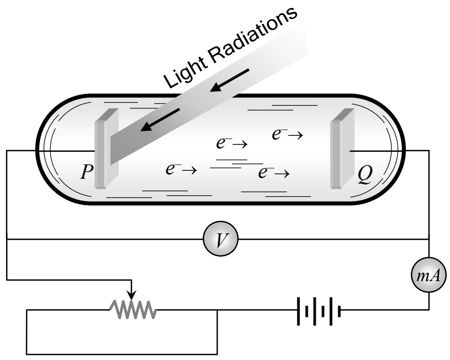


Fig. 25.18

(2) The battery or other source of potential difference creates an electric field in the direction from anode to cathode.

(3) Light of certain wavelength or frequency falling on the surface of cathode causes a current in the external circuit called photoelectric current.

(4) As potential difference increases, photo electric current also increases till saturation is reached.

(5) When polarity of battery is reversed (*i.e.* plate Q is at negative potential *w.r.t.* plate P) electrons start moving back towards the cathode.

(6) At a particular negative potential of plate Q no electron will reach the plate Q and the current will become zero, this negative potential is called **stopping potential** denoted by V_0. Maximum kinetic energy of photo electrons in terms of stopping potential will therefore be $K_{max} = (|V_0|)\ eV$

Effect of Intensity and Frequency of Light

(1) **Effect of intensity :** If the intensity of light is increased (while it's frequency is kept the same) the current levels off at a higher value, showing that more electrons are being emitted per unit time. But the stopping potential V_0 doesn't change *i.e.*

Intensity $\propto$ no. of incident photon $\propto$ no. of emitted photoelectron per time $\propto$ photo current

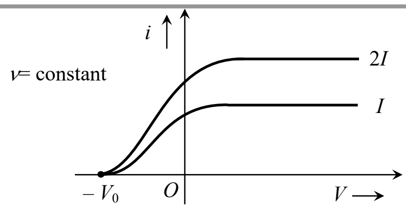


Fig. 25.19

(2) **Effect of frequency :** If frequency of incident light increases, (keeping intensity is constant) stopping potential increases but their is no change in photoelectric current

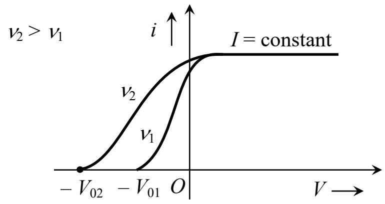


Fig. 25.20

Important Formulae for Photoelectric Effect

(1) $h\nu = h\nu_0 + K_{max}$ and $K_{max} = eV_0$

(2) $K_{max} = eV_0 = h(\nu - \nu_0) \Rightarrow \frac{1}{2}mv_{max}^2 = h(\nu - \nu_0)$

(3) $v_{max} = \sqrt{\frac{2h(\nu - \nu_0)}{m}}$

(4) $K_{max} = \frac{1}{2}mv_{max}^2 = eV_0 = hc\left(\frac{1}{\lambda} - \frac{1}{\lambda_0}\right) = hc\left(\frac{\lambda_0 - \lambda}{\lambda\lambda_0}\right)$

(5) $v_{max} = \sqrt{\frac{2hc}{m}\frac{(\lambda_0 - \lambda)}{\lambda\lambda_0}}$

(6) $V_0 = \frac{h}{e}(\nu - \nu_0) = \frac{hc}{e}\left(\frac{1}{\lambda} - \frac{1}{\lambda_0}\right) = 12375\left(\frac{1}{\lambda} - \frac{1}{\lambda_0}\right)$

Compton Effect

(1) The scattering of a photon by an electron is called Compton effect.

(2) The energy and momentum is conserved.

(3) Scattered photon will have less energy (more wavelength) as compare to incident photon (less wavelength).

(4) The energy lost by the photon is taken by electron as kinetic energy.

(5) The change in wavelength due to Compton effect is called Compton shift. Compton shift $\lambda_f - \lambda_i = \Delta\lambda = \frac{h}{m_0 c}(1 - \cos\phi)$

If $\phi = 0^o$, $\Delta\lambda = 0$

$\phi = 90^o$, $\Delta\lambda = \frac{h}{m_0 c} = 0.24 nm$

$\phi = 180^o, \Delta\lambda = \frac{2h}{m_0 c} = 0.48 nm$ (called Compton wave length)

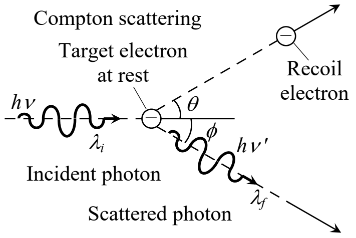


Fig. 25.21

X-Rays

(1) X-rays were discovered by scientist Rontgen thats why they are also called Rontgen rays.

(2) Rontgen discovered that when pressure inside a discharge tube is kept 10^{-3} *mm* of *Hg* and potential difference is kept 25 *kV,* then some unknown radiations (X-rays) are emitted by anode.

(3) There are three essential requirements for the production of X-rays.

(i) A source of electron

(ii) An arrangement to accelerate the electrons

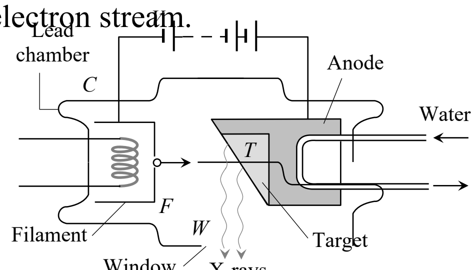
(iii) A target of suitable material of high atomic weight and high melting point on which these high speed electrons strike.

Coolidge X-Ray Tube

(1) It consists of a highly evacuated glass tube containing cathode and target (also known as filament type X-ray tube). The cathode consist of a tungsten filament. The filament is coated with oxides of barium or strontium to have an emission of electrons even at low temperature. The filament is surrounded by a molybdenum cylinder kept at negative potential *w.r.t.* the target.

(2) The target (It is a material of high atomic weight, high melting point and high thermal conductivity) made of tungsten or molybdenum is embedded in a copper block.

(3) The face of the target is set at 45° to the incident electron stream.



(4) The filament is heated by passing the current through it. A high potential difference (≈ 10 *kV* to 80 *kV*) is applied between the target and cathode to accelerate the electrons which are emitted by filament. The stream of highly energetic electrons are focussed on the target.

(5) Most of the energy of the electrons is converted into heat (above 98%) and only a fraction of the energy of the electrons (about 2%) is used to produce X-rays.

(6) During the operation of the tube, a huge quantity of heat is produced in this target, this heat is conducted through the copper anode to the cooling fins from where it is dissipated by radiation and convection.

(7) **Control of intensity of X-rays** : Intensity implies the number of X-ray photons produced from the target. The intensity of X-rays emitted is directly proportional to the electrons emitted per second from the filament and this can be increased by increasing the filament current. So *intensity of X-rays* ∝ *Filament current*

(8) **Control of quality or penetration power of X-rays :** Quality of X-rays implies the penetrating power of X-rays, which can be controlled by varying the potential difference between the cathode and the target.

For large potential difference, energy of bombarding electrons will be large and hence larger is the penetration power of X-rays.

Table 25.3 : Types of X-rays

Hard X-rays	Soft X-rays
More penetration power	Less penetration power
More frequency of the order of ≈	Less frequency of the order of ≈

10^{19} Hz	10^{16} Hz
Lesser wavelength range (0.1Å – 4Å)	More wavelength range (4Å – 100Å)

Properties of X-Rays

(1) X-rays are electromagnetic waves with wavelength range 0.1Å – 100Å.

(2) The wavelength of X-rays is very small in comparison to the wavelength of light. Hence they carry much more energy (This is the only difference between X-rays and light)

(3) X-rays are invisible.

(4) They travel in a straight line with speed of light.

(5) X-rays are measured in Rontgen (measure of ionization power).

(6) X-rays carry no charge so they are not deflected in magnetic field and electric field.

(7) $\lambda_{Gama\ rays} < \lambda_{X\text{-}rays} < \lambda_{UV\ rays}$

(8) They used in the study of crystal structure.

(9) They ionise gases

(10) X-rays do not pass through heavy metals and bones.

(11) They affect photographic plates.

(12) Long exposure to X-rays is injurious for human body.

(13) Lead is the best absorber of X-rays.

(14) For X-ray photography of human body parts, $BaSO_4$ is the best absorber.

(15) They produce photoelectric effect and Compton effect

(16) X-rays are not emitted by hydrogen atom.

(17) These cannot be used in Radar because they are not reflected by the target.

(18) They show all the important properties of light rays like; reflection, refraction, interference, diffraction and polarization *etc*.

Absorption of X-Rays

X-rays are absorbed when they incident on substance.

Intensity of emergent X-rays $I = I_0 e^{-\mu x}$

So intensity of absorbed X-rays

$I' = I_0 - I = I_0(1 - e^{-\mu x})$

where x = thickness of absorbing medium, μ = absorption coefficient

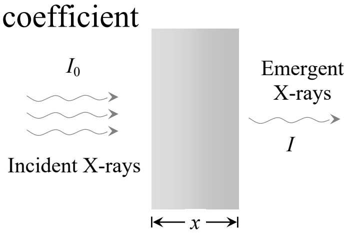


Fig. 25.23

$\mu \propto \lambda^3$; (λ = Wavelength of X-ray)

$\mu \propto \bar{\nu}^3$ (ν = Frequency of X-ray)

$\mu \propto Z^4$ (Z = Atomic number of target)

Classification of X-Rays

In X-ray tube, when high speed electrons strikes the target, they penetrate the target. They loses their kinetic energy and comes to rest inside the metal. The electron before finally being stopped makes several collisions with the atoms in the target. At each collision one of the following two types of X-rays may get formed.

(1) Continuous X-rays

(2) Characteristic X-rays

Continuous X-Rays

As an electron passes close to the positive nucleus of atom of the target, the electron is deflected from it's path as shown in figure. This results in deceleration of the electron. The loss in energy of the electron during deceleration is emitted in the form of X-rays.

The X-ray photons so emitted form the continuous X-ray spectrum.

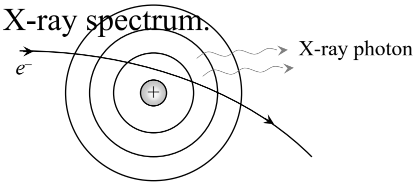


Fig. 25.24

(1) **Minimum wavelength :** When the electron looses whole of it's energy in a single collision with the atom, an X-ray photon of maximum energy $h\nu_{max}$ is emitted *i.e.* $\frac{1}{2}mv^2 = eV = h\nu_{\max} = \frac{hc}{\lambda_{\min}}$

where v = velocity of electron before collision with target atom, V = potential difference through which electron is accelerated, c = speed of light = 3 × 10^8 *m/s*

Maximum frequency of radiations (X-rays) $\nu_{\max} = \frac{eV}{h}$

Minimum wavelength = cut off wavelength of X-ray

$$\lambda_{\min} = \frac{hc}{eV} = \frac{12375}{V} \mathring{A}$$

(2) **Intensity wavelength graph :** The continuous X-ray spectra consist of all the wavelengths over a given range. These wavelength are of different intensities. Following figure shows the intensity variation of different wavelengths for various accelerating voltages applied to X-ray tube.

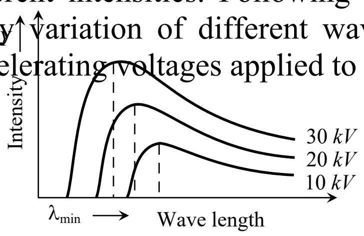


Fig. 25.25

For each voltage, the intensity curve starts at a particular minimum wavelength (λ_{min}). Rises rapidly to a maximum and then drops gradually.

The wavelength at which the intensity is maximum depends on the accelerating voltage, being shorter for higher voltage and vice-versa.

Characteristic X-Rays

Few of the fast moving electrons having high velocity penetrate the surface atoms of the target material and knock out the tightly bound electrons even from the inner most shells of the atom. Now when the electron is knocked out, a vacancy is created at that place.

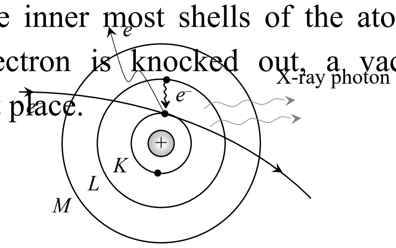


Fig. 25.26

To fill this vacancy electrons from higher shells jump to fill the created vacancies, we know that when an electron jumps from a higher energy orbit E_1 to lower energy orbit E_2, it radiates energy ($E_1 - E_2$). Thus this energy difference is radiated in the form of X-rays of very small but definite wavelength which depends upon the target material. The X-ray spectrum consists of sharp lines and is called characteristic X-ray spectrum.

(1) ***K, L, M, …… series* :** If the electron striking the target eject an electron from the *K*-shell of the atom, a vacancy is created in the *K*-shell. Immediately an electron from one of the outer shell, say *L*-shell jumps to the *K*-shell, emitting an X-ray photon of energy equal to the energy difference between the two shells. Similarly, if an electron from the *M*-shell jumps to the *K*-shell, X-ray photon of higher energy is emitted. The X-ray photons emitted due to the jump of electron from the *L*, *M*, *N* shells to the K-shells gives K_α, K_β, K_γ lines of the *K*-series of the spectrum.

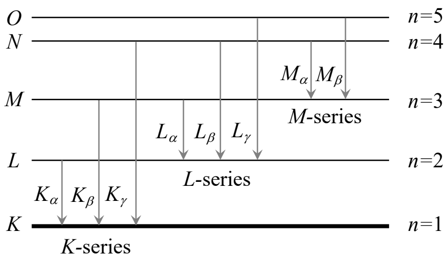


Fig. 25.27

If the electron striking the target ejects an electron from the *L*-shell of the target atom, an electron from the *M*, *N* ….. shells jumps to the *L*-shell so that X-rays photons of lesser energy are emitted.

These photons form the *L*-series of the spectrum. In a similar way the formation of *M* series, *N* series *etc*. may be explained.

(2) **Intensity-wavelength graph :** At certain sharply defined wavelengths, the intensity of X-rays is very large as marked K_α, K_β …. as shown in figure. These X-rays are known as characteristic X-rays. At other wavelengths the intensity varies gradually and these X-rays are called continuous X-rays.

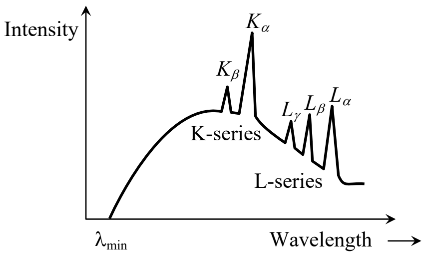


Fig. 25.28

Mosley's Law

Mosley studied the characteristic *X*-ray spectrum of a number of a heavy elements and concluded that the spectra of different elements are very similar and with increasing atomic number, the spectral lines merely shift towards higher frequencies.

He also gave the following relation $\sqrt{\nu} = a(Z-b)$

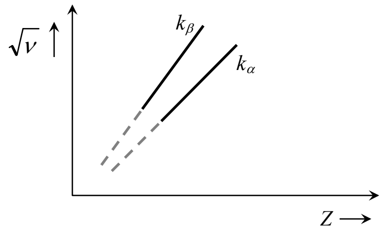


Fig. 25.29

where ν = Frequency of emitted line, Z = Atomic number of target, a = Proportionality constant, b = Screening constant or Shielding constant.

$(Z-b)$ = Effective atomic number

a and b doesn't depend on the nature of target. Different values of b are as follows

$b = 1$	for	*K*-series
$b = 7.4$	for	*L*-series
$b = 19.2$	for	*M*-series

(1) Mosley's law supported Bohr's theory

(2) It experimentally determined the atomic number (Z) of elements.

(3) This law established the importance of ordering of elements in periodic table by atomic number and not by atomic weight.

(4) Gaps in Moseley's data for A = 43, 61, 72, 75 suggested existence of new elements which were later discovered.

(5) The atomic numbers of *Cu*, *Ag* and *Pt* were established to be 29, 47 and 78 respectively.

(6) When a vacancy occurs in the *K*-shell, there is still one electron remaining in the *K*-shell. An electron in the *L*-shell will feel an effective charge of $(Z-1)e$ due to $+Ze$ from the nucleus and $-e$ from the remaining *K*-shell electron, because *L*-shell orbit is well outside the *K*-shell orbit.

(7) Wave length of characteristic spectrum $\frac{1}{\lambda} = R(Z-b)^2\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right)$ and energy of X-ray radiations.

$$\Delta E = h\nu = \frac{hc}{\lambda} = Rhc(Z-b)^2\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right)$$

(8) If transition takes place from $n_2 = 2$ to $n_1 = 1$ (K_α - line)

(i) $a = \sqrt{\frac{3RC}{4}} = 2.47 \times 10^{15}\ Hz$

(ii) $\nu_{K\alpha} = RC(Z-1)^2\left(1 - \frac{1}{2^2}\right) = \frac{3RC}{4}(Z-1)^2$

$= 2.47 \times 10^{15}(Z-1)^2\ Hz$

(iii) In general the wavelength of all the *K*-lines are given by $\frac{1}{\lambda_K} = R(Z-1)^2\left(1 - \frac{1}{n^2}\right)$ where n = 2, 3, 4, ….

While for K_α line $\lambda_{K\alpha} = \frac{1216}{(Z-1)^2}\ \mathring{A}$

(iv) $E_{K\alpha} = 10.2(Z-1)^2\ eV$

Uses of X-Rays

(i) In study of crystal structure : Structure of DNA was also determined using X-ray diffraction.

(ii) In medical science

(iii) In radiography

(iv) In radio therapy

(v) In engineering

(vi) In laboratories

(vii) In detective department

(viii) In art the change occurring in old oil paintings can be examined by X-rays.

Tips & Tricks

- Discovery of positive rays helps in discovering of isotopes.
- The de-Broglie wavelength of electrons in first Bohr orbit of an atom is equal to circumference of orbit.
- A particle having zero rest mass and non zero energy and momentum must travels with a speed equal to speed of light.
- de-Broglie wave length associates with gas molecules is given as $\lambda = \frac{h}{mv_{rms}} = \frac{h}{\sqrt{3\,mkT}}$ (Energy of gas molecules at temperature T is $E = \frac{3}{2}kT$)
- A photon is not a material particle. It is a quanta of energy.
- When a particle exhibits wave nature, it is associated with a wave packet, rather then a wave.
- By coating the metal surface with a layer of barium oxide or strontium oxide it's work function is lowered.
- We must remember that intensity of incident light radiation is inversely proportional to the square of distance between source of light and photosensitive plate P *i.e.*, $I \propto \frac{1}{d^2}$ so $I \propto i \propto \frac{1}{d^2}$)
- The photoelectric current can be increased by filling some inert gas like Argon into the bulb. The photoelectrons emitted by cathode ionise the gas by collision and hence the current is increased.
- Compton effect shows that photon have momentum.
- Production of X-ray is the reverse phenomenon of photoelectric effect.
- The thickness of medium at which intensity of emergent X-rays becomes half *i.e.* $I' = \frac{I_0}{2}$ is called half value thickness ($x_{1/2}$) and it is given as $x_{1/2} = \frac{0.693}{\mu}$.
- Continuos X-rays are produced due to the phenomenon called "Bremsstrahlung". It means slowing down or braking radiation.
- The wavelength of characteristic X-ray doesn't depend on accelerating voltage. It depends on the atomic number (Z) of the target material.
- In characteristic X-ray spectrum $\lambda_{K\alpha} < \lambda_{L\alpha} < \lambda_{M\alpha}$ and $\nu_{K\alpha} > \nu_{L\alpha} > \nu_{M\alpha}$ also $\lambda_{K\alpha} > \lambda_{K\beta} > \lambda_{K\gamma}$
- Nearly all metals emits photoelectrons when exposed to UV light. But alkali metals like lithium, sodium, potassium, rubidium and cesium emit photoelectrons even when exposed to visible light.
- Oxide coated filament in vacuum tubes is used to emit electrons at relatively lower temperature.
- Conduction of electricity in gases at low pressure takes because colliding electrons acquire higher kinetic energy due to increase in mean free path.
- Kinetic energy of cathode rays depends on both voltage and work function of cathode.
- Photoelectric effect is due to the particle nature of light.
- Hydrogen atom does not emit X-rays because it's energy levels are too close to each other.
- The essential difference between X-rays and of γ-rays is that, γ-rays emits from nucleus while X-rays from outer part of atom.
- There is no time delay between emission of electron and incidence of photon *i.e.* the electrons are emitted out as soon as the light falls on metal surface.
- If light were wave (not photons) it will take about an year to eject a photoelectron out of the metal surface.
- Doze of X-ray are measured in terms of

produced ions or free energy via ionisaiton.

✍ Safe doze for human body per week is one Rontgen (One Rontgon is the amount of X-rays which emits 2.5 × 10^4 *J* free energy through ionization of 1 *gm* air at NTP

✍ The photoelectrons emitted from the metallic surface have different kinetic energies even when the incident photons have same energy. This happens because all the electrons do not exist in the surface layer.

Those coming from below the surface loose more energy in getting themselves free.

✍ Einstein was awarded Nobel prize for explaining the photoelectric effect.

✍ Uncertainty in the measurement of momentum of photon within the nucleus is $\Delta p = \frac{h}{2\pi d}$

where *d* = diameter of the nucleus and $\Delta x = d$ = uncertainty in the measurement of position of proton.

Ordinary Thinking

Objective Questions

Cathode Rays and Positive Rays

1. In the Millikan's experiment, the distance between two horizontal plates is 2.5 *cm* and the potential difference applied is 250 *V*. The electric field between the plates will be

(a) 900 *V/m* (b) 10000 *V/m*

(c) 625 *V/m* (d) 6250 *V/m*

2. The cathode rays have particle nature because of the fact that **[CPMT 1986; MNR 1986]**

(a) They can propagate in vacuum

(b) They are deflected by electric and magnetic fields

(c) They produced fluorescence

(d) They cast shadows

3. In Millikan's experiment for the determination of the charge on the electron, the reason for using the oil is

(a) It is a lubricant (b) Its density is higher

(c) It vapourises easily (d) It does not vapourise

4. The mass of a particle is 400 times than that of an electron and the charge is double. The particle is accelerated by 5 *V*. Initially the particle remained in rest, then its final kinetic energy will be **[MP PMT 1990]**

(a) 5 *eV* (b) 10 *eV*

(c) 100 *eV* (d) 2000 *eV*

5. An electron (charge $= 1.6 \times 10^{-19}\ C$) is accelerated through a potential of 100,000 *V*. The energy acquired by the electron is **[MP PET 1989]**

(a) $1.6 \times 10^{-24}\ J$ (b) $1.6 \times 10^{-14}\ erg$

(c) $0.53 \times 10^{-17}\ J$ (d) $1.6 \times 10^{-14}\ J$

6. While doing his experiment, Millikan one day observed the following charges on a single drop

(i) $6.563 \times 10^{-19}\ C$ (ii) $8.204 \times 10^{-19}\ C$

(iii) $11.50 \times 10^{-19}\ C$ (iv) $13.13 \times 10^{-19}\ C$

(v) $16.48 \times 10^{-19}\ C$ (vi) $18.09 \times 10^{-19}\ C$

From this data the value of the elementary charge (*e*) was found to be **[MP PMT 1993]**

(a) $1.641 \times 10^{-19}\ C$ (b) $1.630 \times 10^{-19}\ C$

(c) $1.648 \times 10^{-19}\ C$ (d) $1.602 \times 10^{-19}\ C$

7. When electron beam passes through an electric field, they gain kinetic energy. If the same beam passes through magnetic field, then

(a) Their energy increases

(b) Their momentum increases

(c) Their potential energy increases

(d) Energy and momentum both remains unchanged

8. Which of the following law is used in the

Millikan's method for the determination of charge **[DPMT 2002]**

(a) Ampere's law (b) Stoke's law

(c) Fleming's left hand rule (d) Fleming's right hand rule

9. The mass of the electron varies with

(a) The size of the cathode ray tube

(b) The variation of *'g'*

(c) Velocity

(d) Size of the electron

10. When the speed of electrons increases, then the value of its specific charge **[MP PMT 1994]**

(a) Increases

(b) Decreases

(c) Remains unchanged

(d) Increases upto some velocity and then begins to decrease

11. An electron is accelerated through a potential difference of 1000 *volts*. Its velocity is nearly **[MP PMT 1985; Pb. PET 2003]**

(a) $3.8 \times 10^7 \, m/s$ (b) $1.9 \times 10^6 \, m/s$

(c) $1.9 \times 10^7 \, m/s$ (d) $5.7 \times 10^7 \, m/s$

12. In an electron gun the control grid is given a negative potential relative to cathode in order to **[NCERT 1988]**

(a) Decelerate electrons

(b) Repel electrons and thus to control the number of electrons passing through it

(c) To select electrons of same velocity and to converge them along the axis

(d) To decrease the kinetic energy of electrons