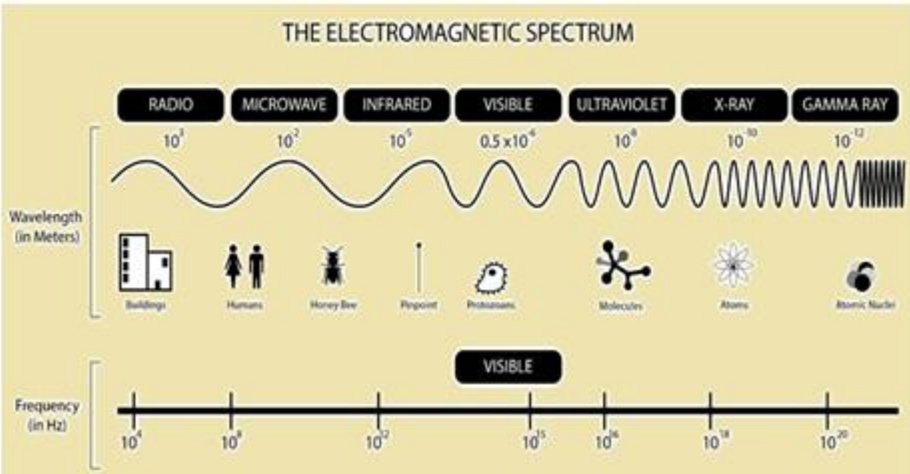
INTRODUCTION:

Do radiations have properties resembling a wave, a particle, or both? Interference, diffraction etc. prove wave nature of radiations. However, photoelectric effect verifies the particle nature of radiations. Same question go for the matters, could matters also possess wave-particle dualism? These are the main arguments we are going to discuss in this chapter notes.

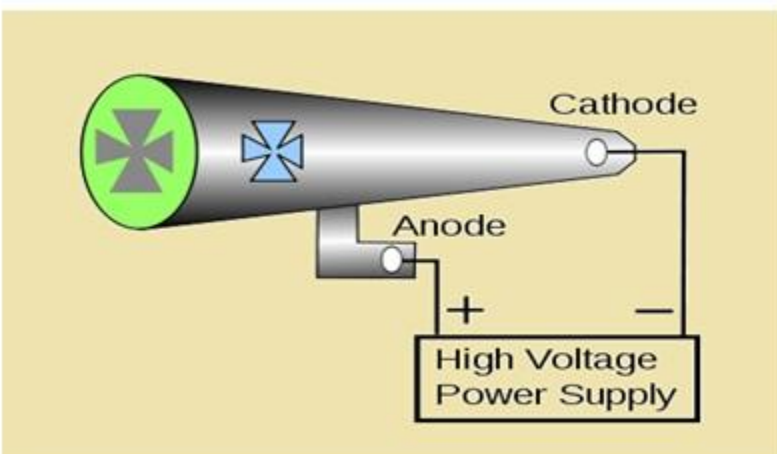


Could radiation possess the wave-particle dualism?

Could the same be said about the matter?

ROADMAP TO THE DISCOVERY OF ELECTRON:

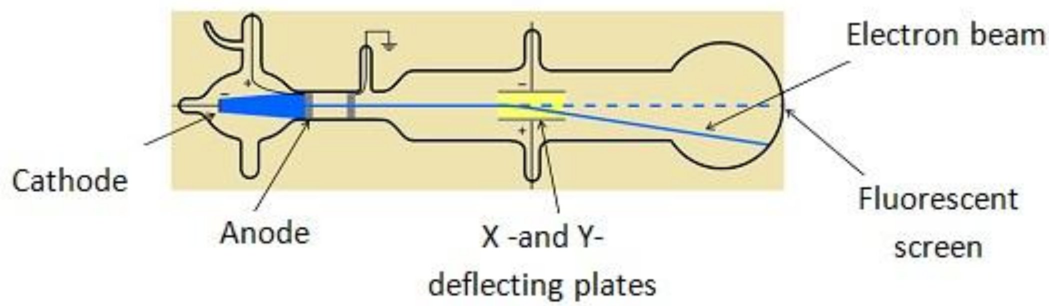
- William Crookes, in 1870, discovered that on applying a strong electric field between cathode and anode (kept under discharge tube at low pressures), some rays were emitted by the cathode. These rays were noticed as a bright fluorescent on the glass adjacent to the cathode
- These rays were called as cathode rays by William Crookes
- In 1879, he proposed that these cathode rays are a bunch of fast moving negatively charged particles



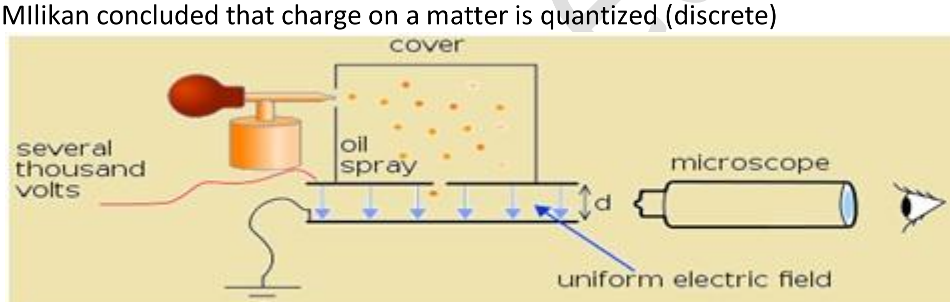
Crookes Tube : Where Cathode rays were discovered

- Then, J. Thomson (1856-1940) validated the above hypothesis. He found that when ultraviolet radiation falls on a metal surface (or when metal surface is heated), few negatively charged particles are released by the metal surface.

- He used electric and magnetic fields (across the discharge tube), mutually perpendicular to each other and the emitted electrons
- He was the first to find the values of; speed(v), and the charge to mass ratio (e/m) of the cathode ray particles, experimentally
- He found the speed of particles to be about 0.1 to 0.2 times the speed of light (), and the charge to mass ratio (e/m)
- He also found that the e/m ratio to be constant, irrespective of the material used as an emitter. This proved the universal nature of cathode ray particles.
- In 1897, he termed this negatively charged cathode ray particles as electron, and this name was used for the first time.



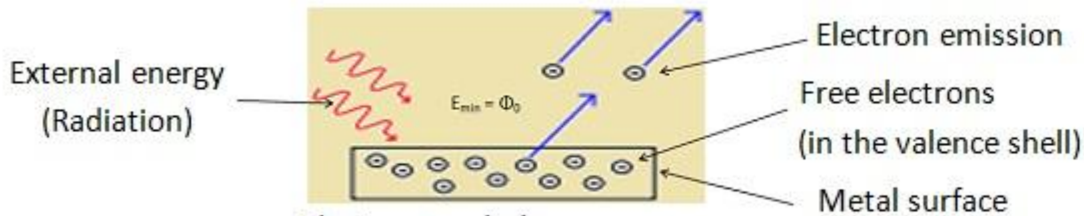
- A. MIlikan, in 1913 performed experiments to calculate the charge on an oil drop (popularly known as Milikan's oil drop experiment)
- He observed that, every time the charge came to be an integral(whole number) multiple of a small charge (), which is actually the charge on an electron
- MIlikan concluded that charge on a matter is quantized (discrete)



Milikan's Oil Drop Experiment

ELECTRON EMISSION:

- The process of emission of electrons from the metal surface when a certain amount of energy is absorbed by the metal, is called electron emission
- There are free electrons on the metal surface, present in the outermost (valence) shell that are loosely bound to the nucleus
- These electrons are emitted when a certain minimum amount of external energy is provided to the metal surface. This least value of energy is called work function of metal (denoted by Φ_0)
- The unit of Φ_0 is electron volt(eV). 1eV is defined as the energy needed to accelerate an electron through the potential difference of 1volt(V).
- Work function of a material depends mainly on the nature of metal, and electronic configuration of metal (meaning the number of valence shell electrons, lesser the number, lesser the work function)

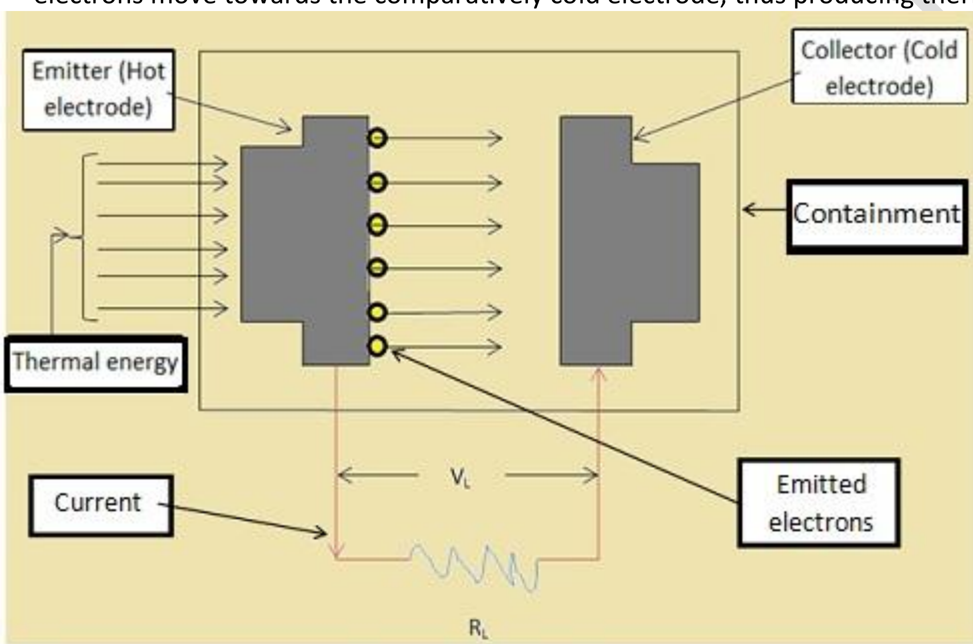


Electron emission process

TYPES OF ELECTRON EMISSION:

There are 3 types of electron emission; a) thermionic emission, b) field emission, and c) photoelectric emission

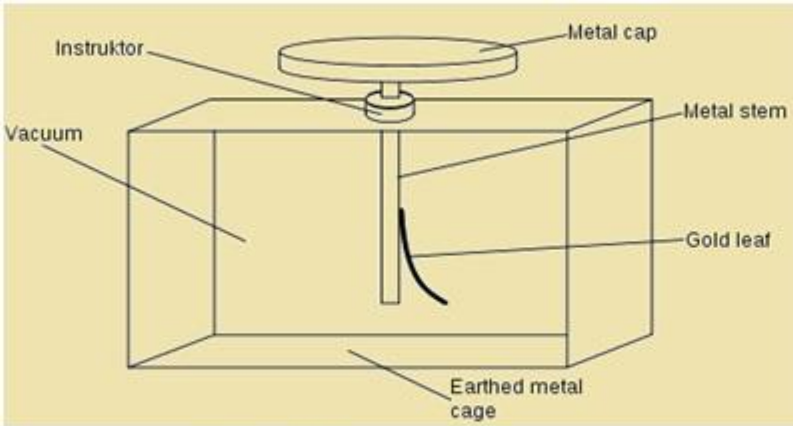
1. Thermionic emission:
- Thermionic emission is the process in which thermal energy is used to overcome the work function of metal in order to force out the free electrons from the metal surface. It is used in thermionic converter
- In thermionic converter, comparatively hot electrode emits electrons on receiving thermal energy. These electrons move towards the comparatively cold electrode, thus producing thermionic current (and power).



Thermeonic Convertor

1. Field Emission:
- Field emission is the process where free electrons are forced out of metal surface using a strong electric field ()
- It is used in field electron microscopes, vacuum nano electronics and other such fields of study.
1. Photoelectric Emission:
- Photoelectric emission is the process where free electrons are removed from a metal surface using a light of certain frequency on that metal
- It is used in image sensor (where optical image is transformed into electric signals), applied mainly in digital cameras.

- It is also used in gold leaf electroscope,used to detect and measure static electricity.

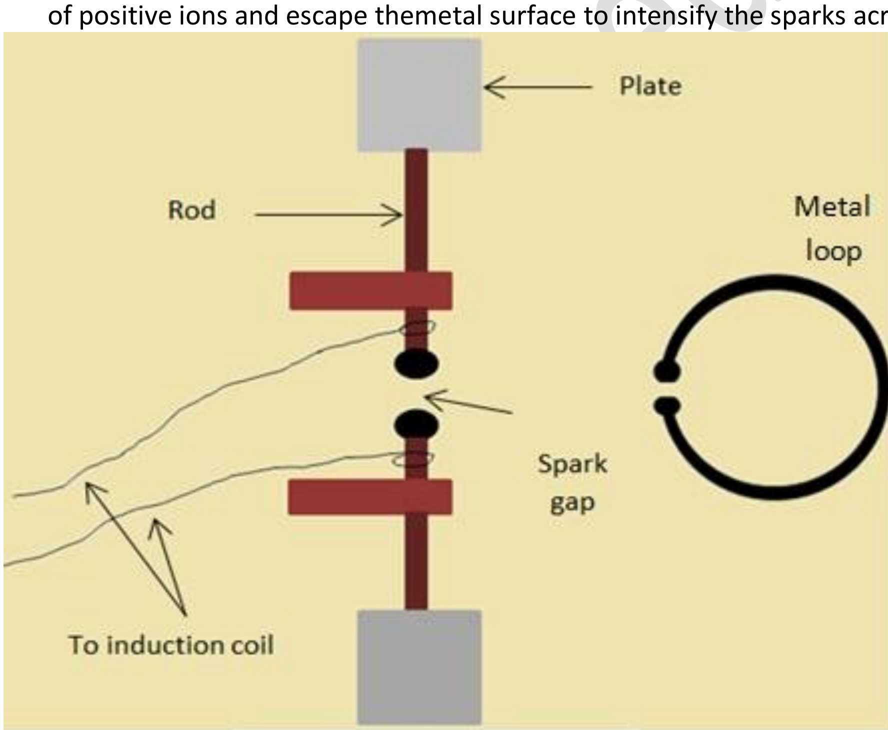


Gold Leaf Electroscope

- Metal cap, on acquiring some charge passes it to the metal stem and the gold leaf inside the evacuated chamber through the instructor. The gold leaf having the same charge as the metal stem gets repelled and move away as shown in the figure.

PHOTOELECTRIC EFFECT- A BRIEF HISTORY:

- Hertz, in 1887 discovered the phenomena of photoelectric effect for the first time
- As he was experimenting on the generation of electromagnetic waves by spark discharge, he noticed that sparks around the detector loop were intensified when ultraviolet radiation fell on the emitter plate
- Radiation falling on the metal surface provided free electrons enough energy to neutralize the attractive force of positive ions and escape themetal surface to intensify the sparks across the metal loop.

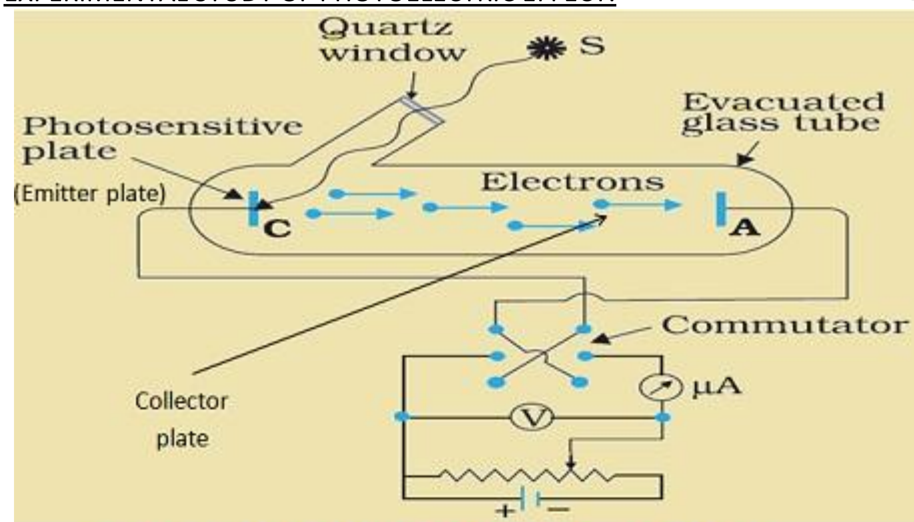


Hertz experiment (1887)

- Hallwach and Lenard during 1886-1902, researched the process of photoelectric emission

- They experimented on negatively charged zinc plate and found that on absorbing ultraviolet light zinc plate became neutral, losing its net positive charge. On further absorption of ultraviolet radiation, neutral zinc plate became negatively charged.
- This proved that electrons are released from the metal surface when ultraviolet radiation is incident on it
- They also observed that electrons are not emitted when the frequency of light incident is less than a specific least value, called the threshold frequency. Threshold frequency depends on the nature of material used as an emitter
- Some metals like zinc, magnesium etc. emitted electrons only by absorbing ultraviolet light. But, alkali metals like sodium potassium etc. could also absorb visible radiation to emit electrons, and so they were called photosensitive materials.
- So, the process in which falling of electromagnetic radiation on the metal surface results in the emission of electrons is called photoelectric effect. And the electrons released due to photoelectric effect are called photoelectrons

EXPERIMENTAL STUDY OF PHOTOELECTRIC EFFECT:



Experimental Set up for PhotoElectric Effect

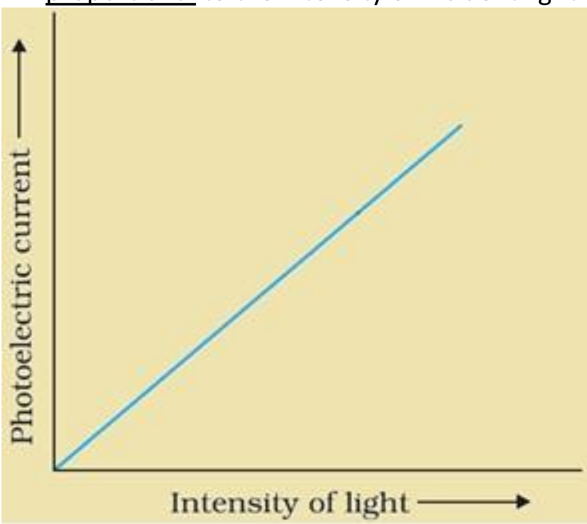
The experimental setup consists of:

- Evacuated tube consist of photosensitive plate (emitter) and the metal plate (collector), so that electrons could freely flow from emitter to collector without any air resistance
- Photosensitive plate (emitter) to absorb visible light and emit electrons
- Metal plate (collector) to receive electrons emitted from the emitter, thus constituting a photoelectric current flow from collector plate to the emitter plate (opposite to the flow of electrons)
- Monochromatic light of short wavelength (meaning high frequency)
- Battery to accelerate emitted electrons through a potential difference
- Voltmeter to measure the potential difference between the emitter and the collector plates due to photoelectric current flow
- Ammeter to measure the value of photoelectric current.

EXPERIMENTAL OBSERVATIONS OF PHOTOELECTRIC EFFECT:

Variation of photoelectric current with intensity of radiation absorbed:

- When the values of photoelectric current were plotted against the different values for intensity of light, it was observed to be a straight line passing through the origin.
- It proved that Photoelectric current, which is number of photoelectrons flowing per unit time, is directly proportional to the intensity of incident light



Variation of photoelectric current with the potential applied:

Case-1-When collector plate was kept at higher potential (accelerating potential) with respect to the emitter.

- As the positive potential of collector rises, photoelectric current rises for a certain period of time because the electrons emitted experience a strong attractive force by the collector
- On further increasing the positive potential, photoelectric current reaches a maximum value, beyond which it remains fixed even when positive potential is increased. This is because number of free electrons in a metal surface is always fixed.
- This maximum value of photoelectric current beyond which it remains fixed, no matter how high the positive potential gets, is called the saturation current.

Case-2-When collector plate was kept at lower potential (retarding potential) with respect to the emitter.

- As the negative potential of collector rises, photoelectric current falls. This is because the electrons emitted will experience a strong repulsive force from the collector
- As the retarding potential is further increased, even the electrons having maximum kinetic energy will be repelled by the repulsive force of the collector, and hence, the photoelectric current becomes zero
- This corresponding minimum value of retarding (negative) potential for which the photoelectric current becomes zero is called stopping potential, or cut-off potential. It is denoted by (V_0).

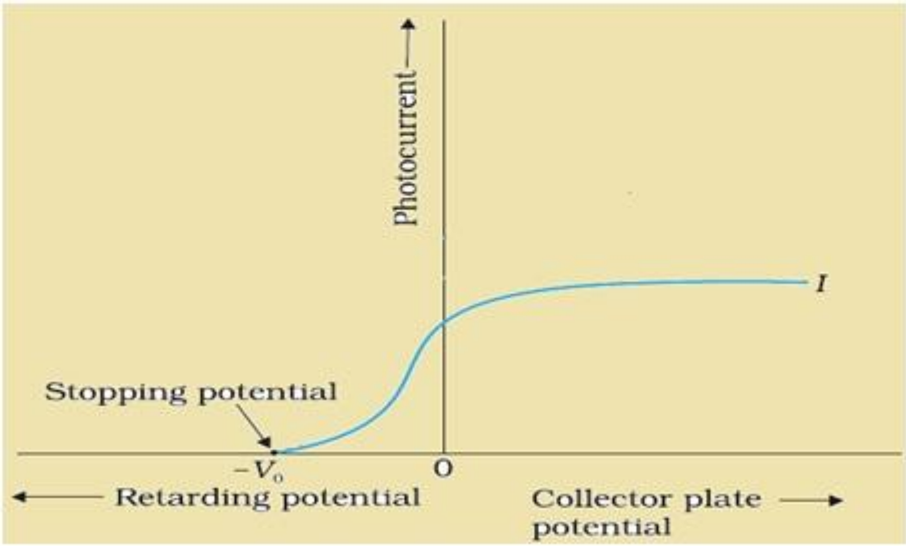
$$K_{max} = eV_o$$

$K_{max} = kinetic\ energy,$

$e = charge\ on\ an\ electron,$

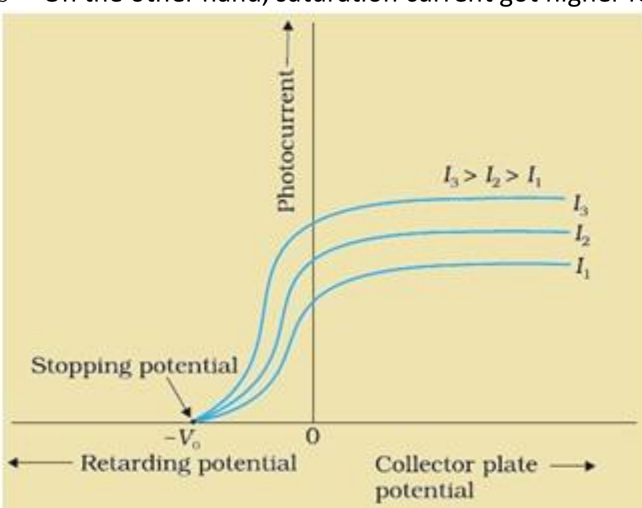
$V_o = stopping\ potential$

- Mathematically, stopping potential could be expressed as



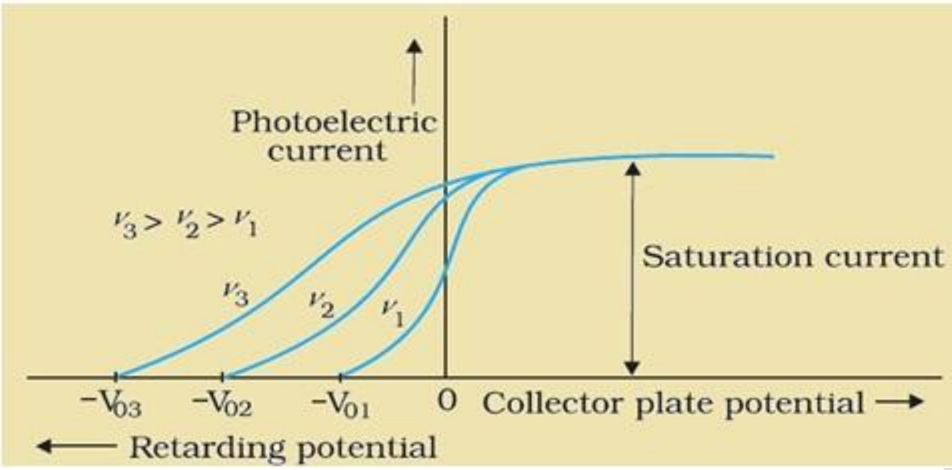
Case-3-When the variation of photoelectric current was plotted against the potential for 3 different values of intensity of incident light (keeping the frequency constant).

- It was observed that stopping potential was constant for all the values of intensity. Thus, stopping potential is independent on the intensity of incident light.
- On the other hand, saturation current got higher for higher values of intensity of absorbed light

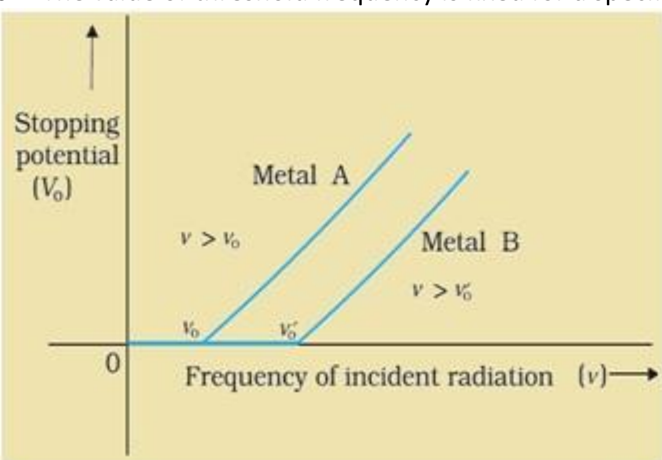


Variation of photoelectric current with the frequency of incident light:

- The variation of photoelectric current was plotted against the potential for 3 different values of frequency of incident light (keeping the intensity constant)
- It was observed that saturation current was constant for all the values of frequency. Thus, saturation current is independent on the frequency of incident light.
- However, stopping potential got higher in the negative direction for higher values of frequency of absorbed light

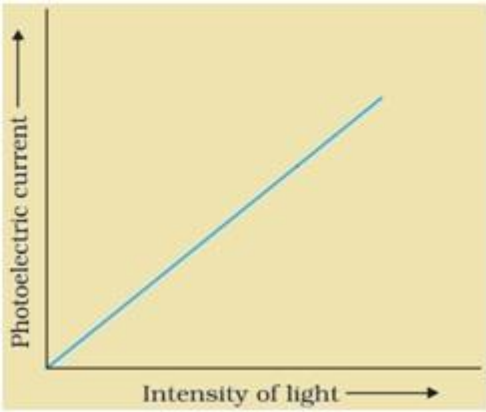


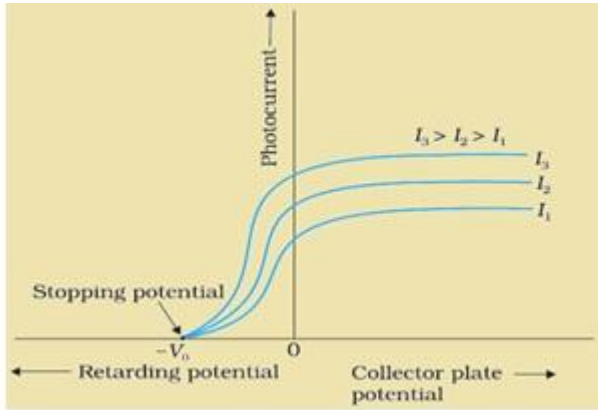
- It was also found that, after reaching a certain minimum frequency value, stopping potential followed a linear relationship with the frequency of incident light.
- This minimum value of frequency of incident light required for photoelectric emission to take place was called as threshold frequency
- The value of threshold frequency is fixed for a specific material, and it changes from one material to another



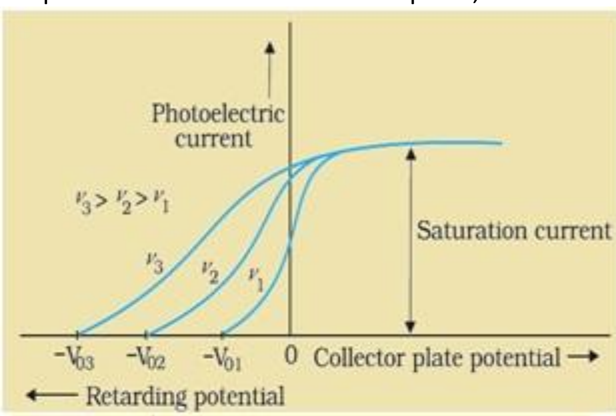
RESULT OF THE EXPERIMENTAL STUDY OF PHOTOELECTRIC EFFECT

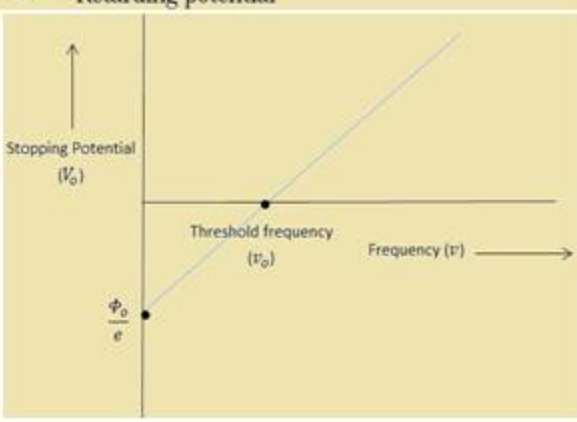
- Photoelectric current is directly proportional to the intensity of incident light
- Saturation current increases if intensity of radiation increases
- Stopping potential doesn't depend on the intensity of light





- Sopping potential, and maximum kinetic energy of photoelectrons, are linearly related to the frequency of incident light
- For every material, there is a minimum value of frequency (threshold frequency) of incident light required for photoelectric emission to take place, below which no photoelectric effect occurs





- Photoelectric emission is an <u>instantaneous process</u>, meaning there is no time lag between the incident light and the emission of free electrons (photoelectrons).

<u>Exercise</u>:

In an experiment of photoelectric effect, the intensity () was <u>doubled</u>. Find the change in the following:a) Photoelectric current (i), b) Stopping potential (V_o), and c) maximum kinetic (K_{max}) energy of the photoelectrons.

Solution:

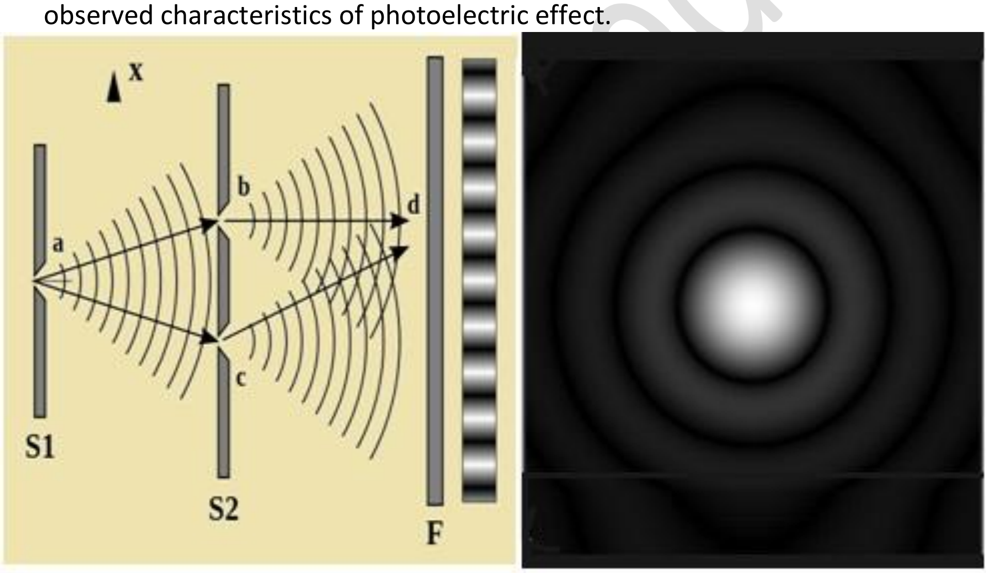
a) From the experiments on photoelectric effect, we know that : i is directly propertion to I. So, photoelectric current gets doubled.
b) We know that stopping potential doesn't depend on the intensity. So, stopping potential remains unchanged
c) We also know that maximum kinetic energy, doesn't change with intensity. So, maximum kinetic energy remains unchanged

Exercise:
In an experiment of photoelectric effect, the frequency () of incident light was tripled. Find the change in the following: a) Saturation current (i), and b) work function of metal.

Solution:
a) Saturation current is independent of frequency. So, saturation current remains unchanged.
b) Work function is always fixed for a given material.

PHOTOELECTRIC EFFECT AND WAVE THEORY OF LIGHT:

- As per the wave theory, the maximum kinetic energy of the photoelectron should be affected by the change in intensity. But, the experiments on photoelectric effect showed that maximum kinetic energy doesn't depend on the change in intensity. So, this was the first inconsistency of the wave theory with the experiments.
- Wave theory didn't talk about the relation between stopping potential and the threshold frequency.It said only increasing the intensity could overcome the stopping potential. Here came the second inconsistency of wave theory with the experimental results.
- According to the wave theory, photoelectric effect was not aninstantaneous process, it was time taking. This was the third inconsistency with the experiments.
- The above three inconsistencies showed that wave theory of light could not explain the experimentally observed characteristics of photoelectric effect.

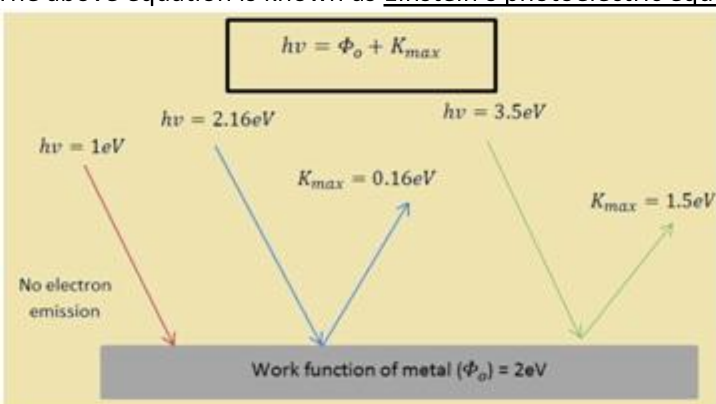


Interference experiment and diffraction pattern of a point light source

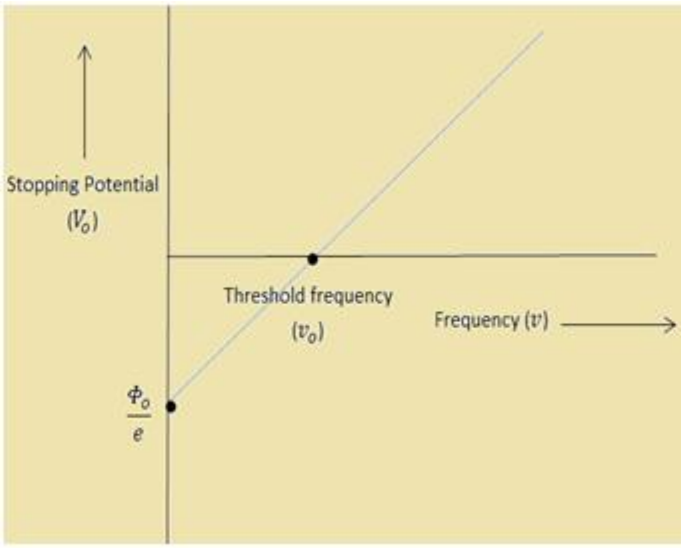
Showing the wave nature of light

EINSTEIN'S PHOTOELECTRIC EQUATION:

- Since wave theory could not explain the photoelectric effect, Einstein proposed a particle theory of light for the first time

- He said that radiations are made up of specific and discrete packets of energy called as <u>quanta</u> of radiation energy. Each energy quantum has a value equal to <u>*hv*</u>, where *h = Planck's constant*, and *v = frequency of incident light*
- These specific packets of quanta of energy are known as <u>photons</u>
- When a light of frequency(v) (having energyhv) is incident on a metal surface of work function(Φ_o), 3 cases could be possible
- <u>Case-1</u>-When ($hv < \Phi_o$), i.e., energy of photon is less than the work function of metal , no photoelectric emission occurs
- <u>Case-2</u>- When ($hv = \Phi_o$), i.e., energy of photon is exactly same as the work function of metal, then electrons get enough energy to just escape the metal surface.
- <u>Case-3</u>- When ($hv > \Phi_o$),e., energy of photon is greater than the work function of metal. Then electron, apart from getting energy to escape the metal surface, the remaining energy is provided to the electron as kinetic energy. Mathematically, it can be expressed as:
- $hv = \Phi_o + K_{max}$
- Here, K_{max} is the maximum kinetic energy of a photoelectron
- The above equation is known as <u>Einstein's photoelectric equation</u>
- 

- From the Einstein's photoelectric equation, following points are clear:
- Photoelectric current (i) is directly proportional to the intensity (I) of radiation. As the intensity rises, number of photons received by metal surface in a unit area per unit time rises, so number of electrons emitted rises, and hence, photoelectric current increases
- $\boldsymbol{I \propto I}$
- Since saturation current is just a maximum value of photoelectric current, saturation current gets higher with increasing intensity of incident light
- For every metal, there exists a certain minimum frequency below which no photoelectric effect occurs. This frequency is called threshold frequency.
- $HV_O = \Phi_O$
- Here, v_o = *frequency of incident light*, Φ_o = *work function of metal*
- Stopping potential (V_o) and Maximum kinetic energy (K_{max}) doesn't depend upon the intensity. Because intensity is the number of photons in unit area and unit time, and the photoelectric effect take place when one electron takes one photon
- Stopping potential (V_o) and Maximum kinetic energy (K_{max}) is directly proportional to the frequency (v)
- $K_{MAX} \propto V \quad V_O \propto V$
- The relation between stopping potential, maximum kinetic energy and the frequency of incident light could be expressed mathematically as follows: using Einstein's photoelectric equation
- $\boldsymbol{hv = \Phi_o + K_{max}}$

- ***$K_{max} = hv - \Phi_o$***
- ***Also, $K_{max} = eV_o$***
- ***$\therefore eV_o = hv - \Phi_o$***
- On rearranging the above equation:
- **$V_o = (h/e)v + (\Phi_o/e)$**
- Plotting the above equation graphically, we get:
- 

- Photoelectric emission is an <u>instantaneous process</u>, meaning that there is no time gap between incident radiation and electron emission.
-
- **<u>Numerical Problems:</u>**
- 1)**Question**: Caesium metal has work function of 2.14eV. Photoelectric emission takes place when a light of frequency 6×10^{14} Hz is incident on the metal surface. Calculate the following: a) maximum kinetic energy of the electrons emitted, b) stopping potential, and c) maximum speed of the emitted electrons.
- ***Solution***:
- Given, $\Phi_o = 2.14\text{eV} = 2.14\times10^{-19}\text{J}$, and $v = 6\times10^{14}\text{Hz}$
- a) Using Einstein's photoelectric equation:
- *$hv = \Phi_o + K_{max}$*
- *$K_{max} = hv - \Phi_o = (6.6\times10^{-34}\times6\times10^{14})J - (2.14\times10^{-19})J$*
- *$\therefore K_{max} = 1.82\times10^{-19}J$ (ans)*
- b) Stopping potential is given by the equation:
- *$eV_o = K_{max}$*
- *$V_o = K_{max}/e = 1.82\times10^{-19} = 1.1375V$ (ans)*
- c) Maximum speed of emitted electrons can be found using maximum kinetic energy equation:
- *$K_{max} = (1/2)mv_{max}^2$*
- $$\therefore v_{max} = \sqrt[2]{\frac{2K_{max}}{m}} = \sqrt[2]{\frac{2\times1.82\times10^{-19}}{9.1\times10^{-31}}} = 6.32\times10^5 ms^{-1}$$
- 2)**Question**: Light of wavelength 488nm is incident on an emitter plate. The photoelectrons have a stopping (cut-off) potential of 0.38V. Calculate the work function of the emitter plate.
- ***Solution***:

- Given, $\lambda = 488\times10^{-9}$m, $V_o = 0.38V$
- Using Einstein's photoelectric equation:
- $hv = hc/\lambda = \Phi_o + K_{max}$
- and,
- $K_{max} = eV_o$
- $$\Phi_o = h\frac{c}{\lambda} - eV_o = \frac{6.6\times10^{-34}\times3\times10^{8}}{488\times10^{-9}} - (1.6\times10^{-19}\times0.38)$$
  $$\therefore \Phi_o = 3.45\times10^{-19}J = 3.45eV\ (ans)$$

PHOTON PICTURE OF RADIATION:

- Radiation can behave as a wave as well as a particle under different situations. And while interacting with matter, it behaves as a particle
- Energy (E) of a photon is given by: $E = hv = hc/\lambda$

Here, v = *frequency*, λ = *wavelength*, c = *speed of light*, and h = *Planck's constant*

- Momentum (p) of a photon is given by: $p = hv/c = h/\lambda$

Here symbols have their usual meaning.

- Photons of similar frequencies possess equal energies and equal momentums
- Photons are electrically neutral (not having a net positive or negative charge)
- In a photon-particle collision:

1. Total energy remains constant
2. Total momentum remains constant
3. Total number of photons may or may not be constant.

The photoelectric effect proves the particle nature of radiation. Whereas, the phenomena like interference, diffraction, and polarization proves the wave nature of light. Hence, we can say that radiation displays both, wave nature, and particle nature, meaning a radiation possesses wave-particle dualism.

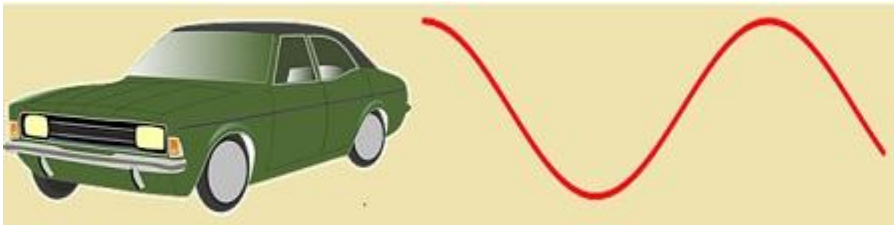
WAVE NATURE OF MATTER: DE BROGLIE'S HYPOTHESIS:

- De Broglie proposed that if the radiations could possess dual nature, matters could also possess dual nature.
- A particle of mass (m), moving with velocity (v) could behave like a wave under suitable conditions. And the corresponding wave related to that matter is called matter wave
- De Broglie's wavelength for matter wave is given by: $\boldsymbol{\lambda = h/p}$

Case-1- (Macroscopic object)

If we take an example of a car of mass= 900kg, moving with the velocity of 36km/hr (10m/s).
The wavelength associated with the car will be:

$$\lambda = \frac{h}{p} = \frac{6.6\times10^{-34}}{1000\times10} = 6.6\times10^{-30}m = 6.6\times10^{-21}nm$$



We can observe that the wavelength associated with the car is insignificant and can't be detected experimentally.

Hence, for the macroscopic objects, the mass is so large that the matter wave associated with them becomes insignificant and negligible

Case-2- (Microscopic object)

If we take an electron, mass=9.1 X 10^{-31} kg, moving with the speed of light (3 X 10^{8} m/s).

The wavelength associated with an electron will be:

Kinetic energy K = (1/2)mv² = (mv)²/(2m) = p²/2m

$$p = \sqrt[2]{2mK} = \sqrt[2]{2meV}$$

Using De-Broglie's Hypothesis:

$$\lambda = \frac{h}{p} = \frac{h}{\sqrt[2]{2meV}} = \frac{6.6 \times 10^{-34}}{\sqrt[2]{2 \times 9.1 \times 10^{-31} \times 1.6 \times 10^{-19} \times V}} = \frac{1.223}{\sqrt[2]{V}} nm$$

Putting the value of V = 50V

$$\lambda = \frac{1.223}{\sqrt[2]{V}} nm = 0.173 nm$$

The wavelength associated with electron is quite large and is experimentally observable. This is because the mass of a microscopic object is very small, so wavelength becomes sufficiently large andhence, observable.

Numerical Problems:

Question: Monochromatic light of wavelength 632.8nm is generated by a helium-neon laser having power of 9.42mW. Evaluate the following: a) energy and momentum of each photon, b) The number of photons emitted per second, and c) speed of a hydrogen atom to have momentum equal to that of an emitted photon by the laser.

Solution:

Given, $\lambda = 632\times10^{-9}nm$, $P = 9.42\times10^{-3}W$

1. Energy of a photon is given by: ***E = hv = hc/λ***

$$E = 6.6 \times 10^{-34} \frac{3 \times 10^{8}}{632.8 \times 10^{-9}} = 3.13 \times 10^{-19} J = 3.13 eV\ (ans)$$

Momentum of the photon is given by: ***p = hv/c = h/λ***

$$p = \frac{6.6 \times 10^{-34}}{632.8 \times 10^{-9}} = 1.043 \times 10^{-27} kgms^{-1}\ (ans)$$

b. Number of photons emitted per second (n) will be given by the equation:

Power = n×energy of a photon

$9.42\times10^{-3}W = n\times3.13\times10^{-19}J$

$$\therefore n = \frac{9.42\times10^{-3}}{3.13\times10^{-19}} = 3\times10^{16}\frac{photons}{second}(ans)$$

To find the speed of a hydrogen atom (v) to have momentum same as a photon:

$v = p/m$

Here, p = *momentum of photon* $=1.043\times10^{-27}kgm/s$, and

m=*mass of a hydrogen atom*= $1.67\times10^{-24}kg$

$$\therefore v = \frac{1.043\times10^{-27}kgms^{-1}}{1.67\times10^{-24}} = 6.25\times10^{-4}ms^{-1}\ (ans)$$

Question: An electron has a kinetic energy of 120eV. Calculate: a) momentum, b) speed, and c) De Broglie wavelength of the electron

Solution:

Given, $K_{max} = 120\times10^{-19}J$

a) The momentum is given by:

$$p = \sqrt[2]{2mK} = \sqrt[2]{2\times9.1\times10^{-31}\times120\times10^{-19}} = 4.67\times10^{-24}kgms^{-1}$$

b) Speed of electron (v) will be:

$$v = \frac{p}{m} = \frac{4.67\times10^{-24}}{9.1\times10^{-31}} = 5.13\times10^{6}ms^{-1}$$

c) De Broglie wavelength of electron is given by:

$$\lambda = \frac{h}{p} = \frac{6.6\times10^{-34}}{4.67\times10^{-24}} = 1.413\times10^{-10}m = 0.143nm$$

HEISENBERG'S UNCERTAINTY PRINCIPLE:

- This principle was in favor of the wave nature of matter
- It stated that it is impossible to simultaneously evaluate the precise position and momentum of particle. There is always some probability in predicting the position and momentum of a particle. Mathematically, it can be written as:

  $(\Delta x)(\Delta p) \geq h/(2\pi)$

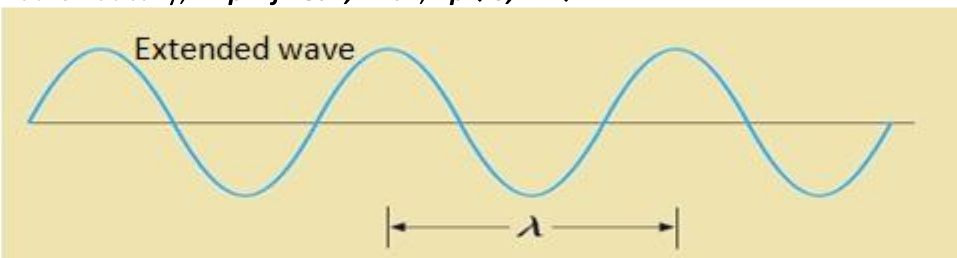
Considering the above equation, 2 cases are possible:

- Case-1- If precise momentum(p) of an electron is known, then its wavelength by De Broglie's hypothesis will be constant:

λ = h/p

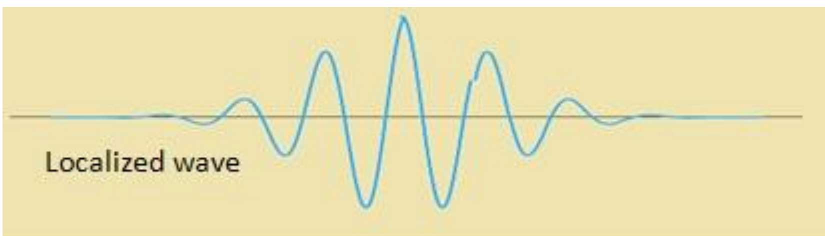
It means that the wavelength has a fixed value and the wave is extended infinitely throughout the wave. Hence, it is impossible to find the position of the wave.

Mathematically, if ***p = fixed*** **,** Then, ***Δp→0, Δx→∞***



- Case-2- If the wave is localized, having finite end points

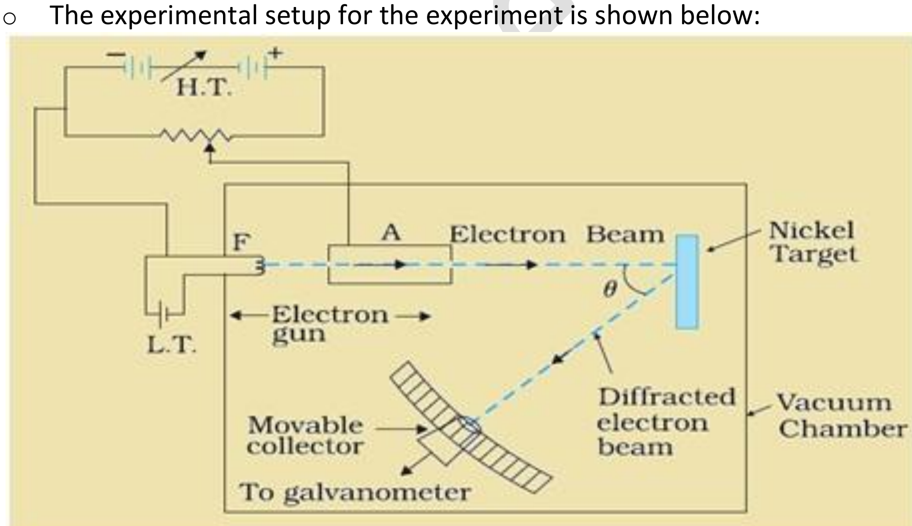
A localized wave is shown below:



As we can see in the diagram, the wavelength (λ) is not fixed, so the momentum (*p*) is also not fixed. Hence, there is uncertainty in both, momentum (*p*) and position (*x*).

DAVISSON AND GERMER EXPERIMENT:

- Davisson and Germer experiment showed the wave nature of electron for the first time
- They studied the diffraction effects of electron in crystal diffraction experiment
- The experimental setup for the experiment is shown below:



The experimental setup consists of:

- Evacuated chamberfor the free movement of electron without any air resistance
- Electron gunfor the emission of electron
- BatteryUsed for the acceleration of electrons inside the cylinder

- Cylinder with fine hole along its axisconnected to the battery so that electrons entering it could be accelerated to high speed
- Nickel Targetused to deflect electron beam towards the detector
- Movable detector(collector)to detect the intensity and scattering of electrons deflected by the nickel crystal at varying voltage supplies(44 to 68 V)
- Galvanometerto measure the small values of current
- Observations:
- Strong peak was detected at 55V, and the angle of scattering was observed to be 50°
- The pattern of deflected electrons was quite similar to the diffraction pattern of waves
- The wavelength corresponding to the electron (matter wave) was found to be $\lambda = 0.165$nm
- The experiment was in strong agreement with De Broglie's hypothesis
- According to De Broglie's hypothesis, matter wave is given by:

$$\lambda = \frac{h}{p} = \frac{1.223}{\sqrt[2]{V}} nm$$

- The experiment proved that electrons behave as a wave under specific conditions as the scattering of electron gave rise to the diffraction pattern
- On putting the value of V= 55V (the value at which a strong peak was detected), we get

$$\lambda = \frac{1.223}{\sqrt[2]{V}} nm = 0.165 nm$$

- The wavelength calculated above using De Broglie's hypothesis is equal to the wavelength observed in the Davisson and Germer experiment. So, Davisson and Germer experiment was consistent with De Broglie's hypothesis.
- Hence, this experiment proved that electron behaves as a wave under specific conditions.