Particle Nature of Light (The photon).

A definite value of energy as well as momentum gives a strong indication that the light quantum is a particle which was later named as 'photon'.

The particle like behaviour of light was confirmed by A.H. Compton, on scattering of X-rays from electrons.

The photon picture of electromagnetic radiation and the characteristic properties of photons are given below:—

1> In interaction of radiation with matter, radiation behaves as if it is made of particles like photons.

2> Each photon has energy $E = h\nu = \frac{hc}{\lambda}$ and momentum $P \left(= \frac{h\nu}{c} = \frac{h}{\lambda}\right)$, where h = Planck's constant.

3> All the photons of a particular frequency ν or wavelength λ have the same energy $E = (h\nu = hc/\lambda)$ and same momentum $\left(P = \frac{h\nu}{c} = \frac{h}{\lambda}\right)$

4> Photon energy is independent of the intensity of radiations.

5> All the photons emitted from a source of radiations travel through space with the same speed c (equal to speed of light).

6> The frequency of photon gives the radiation, a definite energy which does not change when photon travels through different media.

7> The velocity of photon in different media is is different.

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8> The rest mass of a photon is zero.

$$m = \frac{m_0}{\sqrt{1-v^2/c^2}}$$

or $m_0 = m\sqrt{1-v^2/c^2}$

where, m_0 is rest mass.

$v = c$ for photon.

So, $m_0 = 0$.

9> Photons are not deflected by electric and magnetic fields. Photons are electrically neutral.

10> In a photon-particle collision, the energy and momentum are conserved. However the number of photons may ~~be~~ not be conserved in a collision.

The intensity of light depends upon the no. of photons present in light.

Equivalent mass of a photon $= \frac{h\nu}{c^2}$ or $\frac{h}{\lambda c}$.

The momentum of a photon of energy E is E/c and of wavelength λ is h/λ.

Failure of Wave Theory of light, by Huygen's to explain the photoelectric effect:—

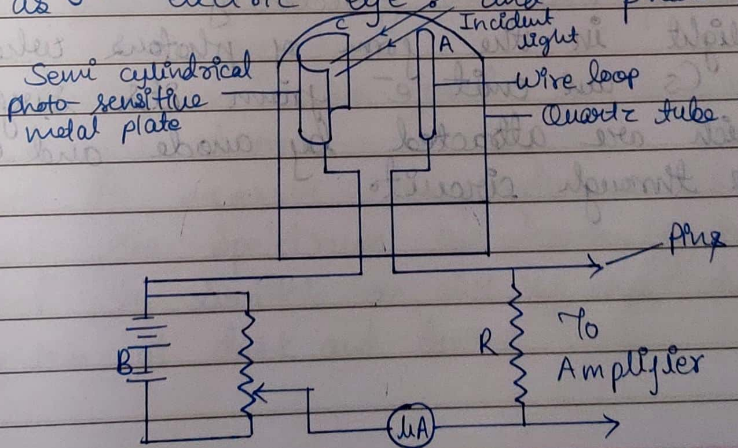
1> According to wave theory, when the waves of light of higher intensity falls on a metal surface it will impart more energy to the electrons in metal. Due to which the kinetic energy of the ejected electrons will increase. This is against the experimental facts that the maximum energy of the ejected photoelectrons is independent of the intensity of incident light.

2> According to the wave theory, by increasing the intensity of the incident wave of light, the energy can be increased and photo-electric emission will take place even if the frequency of the incident light is less than threshold frequency, but it is against the experimental fact that no photoelectric emission takes place from a metal surface if the frequency of the incident light is less than the threshold frequency; no matter whatsoever maybe its intensity.

3> According to wave theory of light, when the wave of lights falls on metal surface, it doesn't go for single e^- but distributes to all e^- presents as a result of which the e^- will take sometime in accumulating the energy required for emission. This is also against the experimental fact that the emission of photoelectrons takes place immediately after the light is incident on the metal.

Photoelectric Cell.

It is a device which converts light energy in electrical energy and also known as 'electric eye' and 'photo tube'.

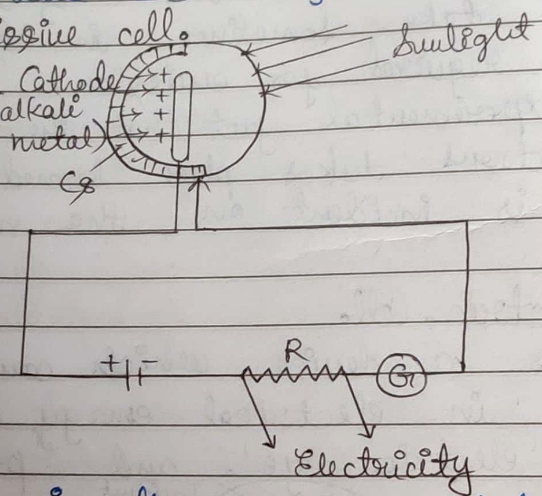


Working.

When light of suitable frequency is allowed to fall on the cathode, photoelectrons are emitted. These are attracted by anode which is kept at positive potential w.r.t. cathode. So a current starts flowing in the circuit. Due to it, µA shows a deflection. The photoelectric current is very small, so it is to be amplified first before it is used for some useful purpose. When the light is cut-off, no photoelectrons are ejected from the cathode and hence there is no current in the external circuit.

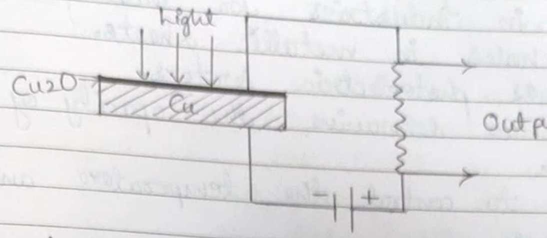
These cells are classified int:—

i> Photoemissive cell.

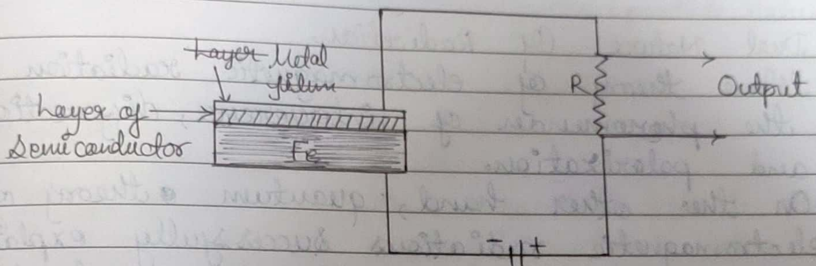


Sunlight in the form of photons when fall on Cs can emit e^- from its surface which are attracted by anode and current flows through circuit.

i> Photovoltaic cell.



ii> Photo conductive cell.



Applications of photoelectric cells.

1> Used in television camera for telecasting scenes and phototelegraphy.

2> Used for the reproduction of sound recorded on films along with pictures in theatres.

3> Photocells are used in counting devices, e.g., to count the persons entering the hall provided they come one by one.

4> Photocells are also used in burglar alarms. and fire alarms.

5> Used to measure temperature of stars and to study the spectrum of heavenly bodies.

6> Used to switch on and off the street lighting system at dusk and dawn.

7) Used in photometry to compare the illuminating powers of two sources.
8) Used in industries for locating minor flaws or holes in metallic sheets.
9) Used as photoelectric sorters.
10) Used to determine the opacity of solids and liquids.
11) Used to control the temperature and chemical reactions.
12) Used for determination of Planck's constant.

Dual Nature Of Radiation
Wave theory of electromagnetic radiation explains the phenomenon of interference, diffraction and polarization.
On the other hand, quantum theory of electromagnetic radiations successfully explained the photoelectric effect, Compton effect, black body radiations, X-ray spectra, etc.
Thus, radiations have dual nature, i.e., wave and particle nature.
In photoelectric effect, emitted electron carries part of the energy of incident photon.
In compton effect, when an X-ray photon is incident on a ~~photon~~ metal of light element, like Al, the free e^- of the metal recoils along a definite direction with some energy depending upon the direction along which the incident photon is scattered.
It was concluded that in photoelectric effect and compton effect, the radiation possesses particle nature.

Radiation has dual nature.
In particular experiment, radiation has particular nature, either wave or particle nature.

Various phenomena related to radiation:

1> Interference, diffraction & polarisation, etc. can be explained on the basis of wave nature.

2> Photoelectric effect, compton effect, etc. can be explained on the basis of particle nature.

3> Rectilinear, reflection, refraction, etc. by either wave nature (Electromagnetic), particle nature (quantum).

De-Broglie Dualistic Hypothesis.

Dual nature of matter.
Louis de Broglie suggested that the particles like electrons, protons, neutrons, etc. have also dual nature, i.e., they ~~can~~ also can have particle as well as wave nature.
His suggestion was based on:-

i> The nature loves symmetry.

ii> The universe is made of particles and radiations and both entities must be symmetrical.

De-Broglie hypothesis.
According to de-broglie, a moving material particles sometimes acts as a wave and some acts as a particle or a wave is associated with moving material particle which controls the particle in every respect. The wave associated with the moving particle is called matter wave or de-broglie wave whose wavelength called de broglie wavelength, is given by

$$\boxed{\lambda = h/mv}$$

Derivation of de-Broglie ~~hypothesis~~ wavelength.
According to Planck's quantum theory,

$$E = h\nu$$

According to Einstein's mass-energy relation,

$$E = mc^2$$

Comparing,

$$h\nu = mc^2$$

$$\frac{hc}{\lambda} = mc^2$$

$$\lambda = \frac{h}{mc}$$

or $$\lambda = \frac{h}{p}$$

where, $p = mc$ is momentum of a photon.

If instead of a photon, we have a material particle of mass m and velocity v, then the equation becomes :—

$$\boxed{\lambda = \frac{h}{mv} = \frac{h}{p}}$$

This is de-broglie wave eq..

Conclusion :—

i) λ is inversely $\propto$ to velocity of particle.

ii) If the particle is at rest, $\lambda = \infty$.

iii) $\lambda \propto \frac{1}{m}$.

iv) λ is independent of charge on the particle.

Matter waves, like electromagnetic waves, can travel in vacuum and hence, they are not mechanical waves.

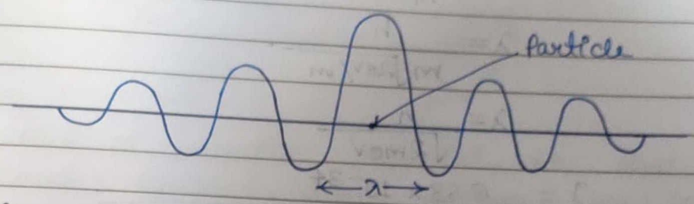
Matter waves are not electromagnetic waves, because they are not produced by accelerated charges.

Matter waves are probability waves, amplitude of which gives the probability of existence of particle at the point.

from de-broglie hypothesis, we conclude:—

i) If $v = 0$, $\lambda = \infty$ and, if $v = \infty$, then $\lambda = 0$. de-broglie waves cannot be electromagnetic in nature because electromagnetic waves are produced by motion of charged particles.

ii) The wavelength of a wave associated with moving particle defines a region of uncertainty, within which the whereabouts of particle are unknown.



Relation for de-broglie wavelength and temperature
from kinetic ~~en~~ theory of matter, the average kinetic energy of particle at a given temperature T kelvin is,

$$K = \frac{3}{2} kT$$

k = Baltzmann constant

$$K.E. = \frac{1}{2} mv^2$$

Momentum of particle,

$$p = mv = \sqrt{2mK}$$

$$p = \sqrt{\frac{2m \times 3kT}{2}}$$

$$p = \sqrt{3mkT}$$

de-broglie wavelength,

$$\lambda = \frac{h}{p}$$

$$\boxed{\lambda = \frac{h}{\sqrt{3mkT}}}$$

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De-Broglie wavelength of an electron:-

Gain in K.E. of $e^- = \frac{1}{2} mv^2$

Work done on $e^- = eV$

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

$$v = \sqrt{\frac{2eV}{m}}$$

$$\lambda = \frac{h}{mv}$$

$$\lambda = \frac{h}{m\sqrt{2eV/m}}$$

$$\lambda = \frac{h}{\sqrt{2meV}}$$

$$\lambda = \frac{6.63 \times 10^{-34}}{\sqrt{2 \times 9.1 \times 10^{-31} \times 1.6 \times 10^{-19} \times V}}$$

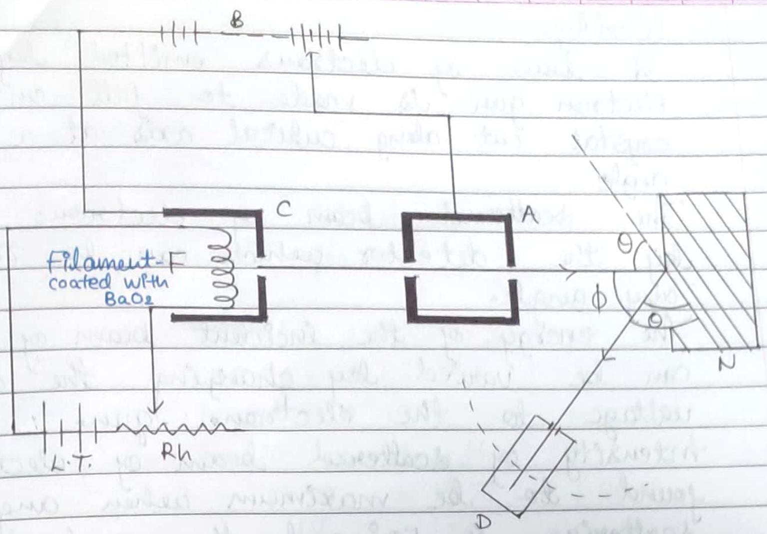
$$\lambda = \frac{12.27 \times 10^{-10}}{\sqrt{V}} m$$

$$\boxed{\lambda = \frac{12.27}{\sqrt{V}} A^{\circ}}$$

DAVISSON AND GERMER EXP. DEMO. OF WAVE NATURE OF ELECTRON.

The wave nature of slow moving e^- has been experimentally established by Davisson and Germer in 1927.

The apparatus consists of a filament F of tungsten coated with barium oxide, which on heating with current from low tension battery emits large number of electrons. C is a hollow metallic cylinder with a hole along the axis, it surrounds the filament and



is kept at negative potential, so that the electrons emitted from filament may form a convergent beam of electrons. It acts as a cathode. A is a cylinder with fine hole along its axis. It is kept at positive potential w.r.t. cathode and is called anode. The cathode and anode form an electron gun, by which a fine beam of electrons can be obtained under different accelerating potentials applied between cathode and anode. N is a nickel crystal cut along cubical diagonal. D is an electron detector. It can be rotated on a circular scale and is connected to a sensitive galvanometer which records the current.

Working.

A beam of electrons emitted by the electron gun is made to fall on Nickel crystal cut along cubical axis at a particular angle.

The scattered beam of electrons is received by the detector which can be rotated at any angle.

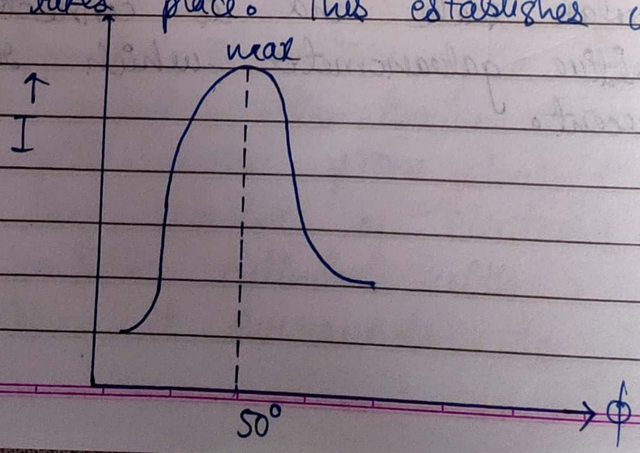
The energy of the incident beam of electrons can be varied by changing the applied voltage to the electron gun.

Intensity of scattered beam of electrons is found to be maximum when angle of scattering is 50° and the accelerating patential is 54 V.

The intensity of the scattered beam is measured for different values of scattering angle ϕ, the angle between the incident and the scattered electron beam.

The experiment was performed by varying the accelerating voltage from 44 V to 68 V. It was noticed that at accelerating voltage 54 V, there is a sharp peak in the intensity of the scattered electrons for scattering angle $\phi = 50°$.

Apperance of peak is due to constructive interference of electrons scattered i.e., diffraction of e^- takes place. This establishes wave nature of e^-.



$\theta + \phi + \theta = 180°$

$2\theta = 180° - \phi$

$2\theta = 180° - 50°$

$2\theta = 130°$

$\theta = 65°$

for nickel crystal, interatomic separation $d = 0.91 A°$

According Bragg's eq.,

$$2d\sin\theta = 1 \times \lambda$$

$$2 \times 0.91 \times \sin 65° = \lambda$$

$$\lambda = 1.65\ A°.$$

According de-broglie wavelength,

$$\lambda = \frac{12.27}{\sqrt{V}} = \frac{12.27}{\sqrt{54}} = 1.66 A°$$

This proves the existence of de Broglie waves for slow moving e^-.

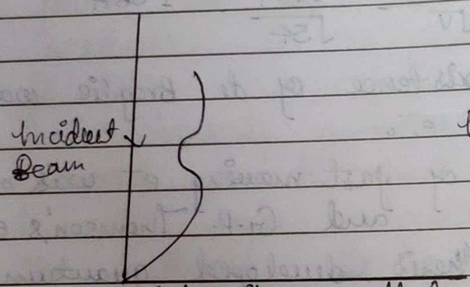
The wave nature of fast moving e^- was established by G.P. Thomson and G.P. Thomson's exp.

de-Broglie hypothesis developed quantum mechanics. Many classical mechanics were solved. It also led to the field of electron optics which helped in preparing electron microscope. with higher resolution as compared to optical microscope.

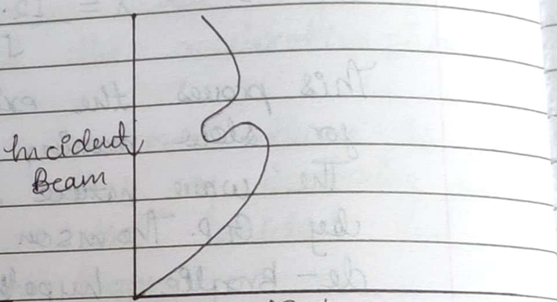
Probability Interpretation of Matter Waves :-

The concept of matter waves associated with a moving material particle was accounted by quantum mechanics, which involves probability interpretation of matter waves.

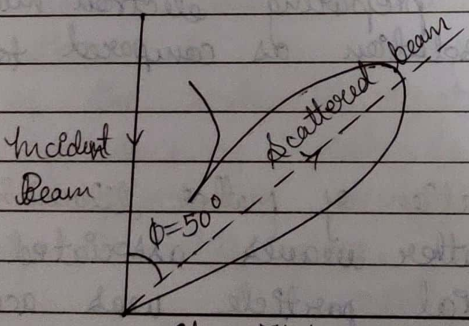
Max Born, proposed the prob. inter. to the matter wave amplitude, stating that the intensity of the matter waves at a point determines the probability density of the particle at that point. Probability density means probability per unit volume. If at a point A, then probability of the particle being found in a small volume dv around that point is = $|A|^2 \Delta V$. It means, if the intensity of the matter wave is large in a certain region, there is a greater probability of the particle being found there as compared to the region where intensity is less.



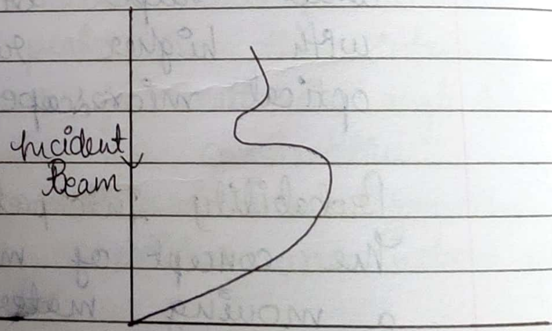
Intensity of scatted beam at 44V



at 48V

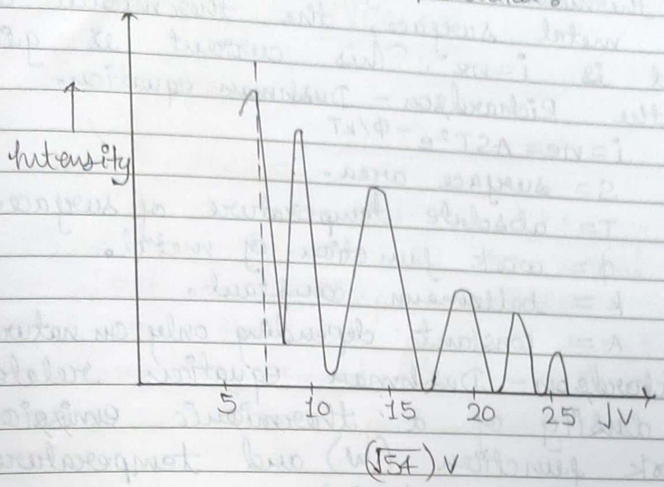


at 54V



at 64V

Intensity vs $\sqrt{}$ Anode Potential :



Application of Photoelectric Effects :—

1> Automatic fire alarm.
2> " burglar " .
3> Scanners in TV transmission.
4> Reproduction of sound in cinema film.
5> In paper industry to measure the thickness of paper.
6> To locate flaws or holes in the finished goods.
7> In astronomy.
8> To determine opacity of solids and liquids.
9> Automatic switching of street lights.
10> To control the temperature of furnace.
11> Photometry.
12> Beauty meter— To measure the fair complexion of skin.
13> Light meters used in cinema industry to check the light.
14> Photoelectric sorting.
15> Photo counting.
16> Meteorology.

If n thermions are ejected per unit time by a metal surface, the thermionic current is $i = ne$. This current is given by the Richardson - Dushman equation.

$$i = ne = AST^2 e^{-\phi/kT}$$

S = surface area.

T = absolute temperature of surface.

ϕ = work function of metal.

k = boltzmann constant.

A = constant depending only on nature of metal.

The Richardson - Dushman equation relates the current density of a thermionic emission to the work function (W) and temperature (T) of the emitting material.