The Photoelectric Effect

When light shines on the surface of a metallic substance, electrons in the metal absorb the energy of the light and they can escape from the metal's surface. This is called the photoelectric effect, and it is used to produce the electric current that runs many solar-powered devices.

Using the idea that light is a wave with the energy distributed evenly throughout the wave, classical physicists expected that when using very dim light, it would take some time for enough light energy to build up to eject an electron from a metallic surface. WRONG!!

Experiments show that if light of a certain frequency can eject electrons from a metal, it makes no difference how dim the light is. There is never a time delay.

In 1905, Albert Einstein came up with the solution. If Max Planck's idea that energy comes in clumps (quanta) is correct, then light must consist of a stream of clumps of energy. Each clump of light energy is called a photon , said Einstein, and each photon has an energy equal to

$$E = h f$$

Photon:

A packet or bundle of energy is called a photon.

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

where h is the Planck's constant, v is the frequency of the radiation or photon, c is the speed of light (e.m. wave) and λ is the wavelength.

Properties of photons:

i) A photon travels at a speed of light c in vacuum. (i.e. 3×10^{-8} m/s)

ii) It has zero rest mass. i.e. the photon can not exist at rest.

iii) The kinetic mass of a photon is, $m = \dfrac{E}{c^2} = \dfrac{h}{c\lambda}$

iv) The momentum of a photon is, $p = \dfrac{E}{c} = \dfrac{h}{\lambda}$

v) Photons travel in a straight line.

vi) Energy of a photon depends upon frequency of the photon; so the energy of the photon does not change when photon travels from one medium to another.

vii) Wavelength of the photon changes in different media; so, velocity of a photon is different in different media.

viii) Photons are electrically neutral.

ix) Photons may show diffraction under given conditions.

x) Photons are not deviated by magnetic and electric fields.

What is the Photo – electric effect?

The phenomenon of emission of electrons from metal surface exposed to light (of suitable frequency) is known as **Photo – electric effect**.

- The electrons emitted in this process known as photoelectrons and the current constituted by this electrons known as photoelectric current. This phenomenon also known as photoemission.

- Photo – electric effect was first experimentally verified by H. R Hertz in 1887.

- The classical wave - theory of light could not explain the Photo – electric effect. The failure of classical physics led Max Planck to introduce the Particle-theory (Quantum Physics) of energy. This concept stated that energy is not continuous but discrete.

Work Function (W):

In a metal electrons are bound by attraction force of nucleus. So, a certain minimum energy is require to pull out the electron from the surface of metal. It is called **Work Function** of the metal.

- Work function is a characteristic property of metal.
- The unit of work function is 'eV'.
- 1 eV = $1.6*10^{-19}$

Metal	Symbol	Work Function, eV
Cesium	Cs	1.9
Potassium	K	2.2
Sodium	Na	2.3
Lithium	Li	2.5
Calcium	Ca	3.2
Copper	Cu	4.7
Silver	Ag	4.7
Platinum	Pt	6.4

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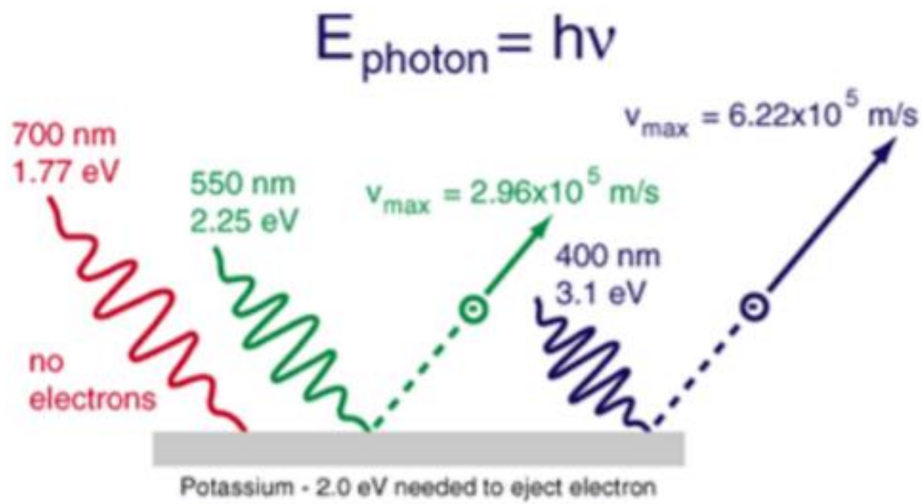
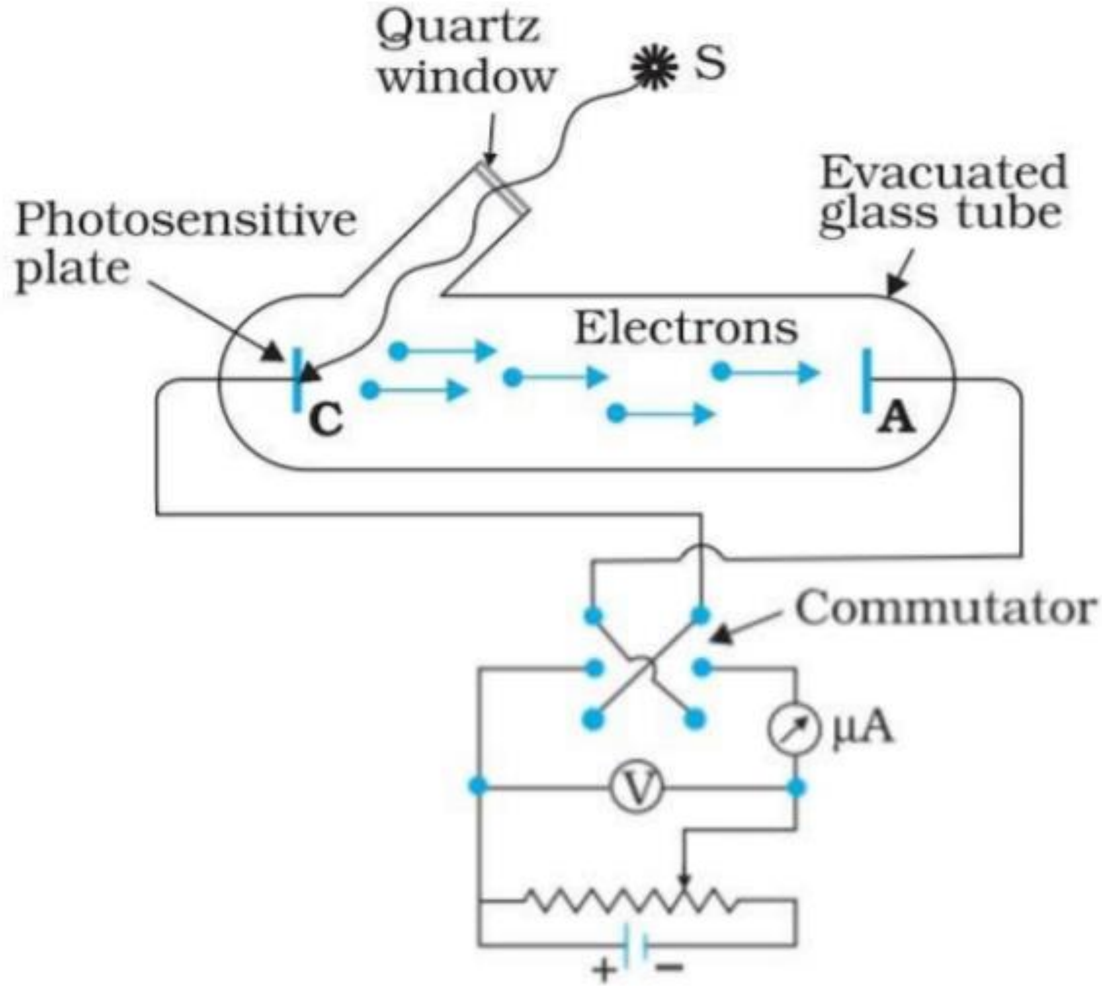


Photoelectric effect

Experimental Set-up to study Photo – electric effect:



'V': Potential applied between Emitter (C) and collecter (A). When A is cennected to (+ve) and C is (–ve), it is called Accelerating potential and reverse is known as Retarding potential.

Observations of Photo-electric Effect:

- The photoelectric current starts flowing as soon as the light supply is turned on. Actually the time lag between the shining of light and emission of electrons is less than $3*10^{-9}$ second.

- The minimum frequency of light required to eject an electron from the metal surface, is called **Threshold Frequency (υ_0)**. '$h\upsilon_0$' is the minimum energy required for electron emission therefore,

$$\mathbf{W = h\upsilon_0}$$

The corresponding wave-length is known as **cut-off wavelength** (λ_c)

$$\lambda_c = (c / \upsilon_0) = (h\, c / W)$$

('c' is velocity of light in vacuum)

- The kinetic energy (**K**) of the photoelectrons is **independent of the light intensity** and only **depends on the frequency** of the light.

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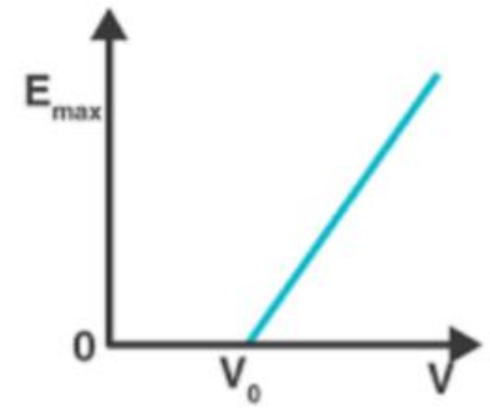
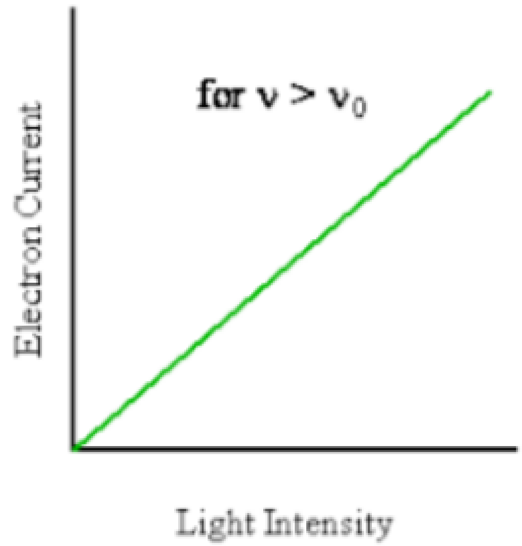
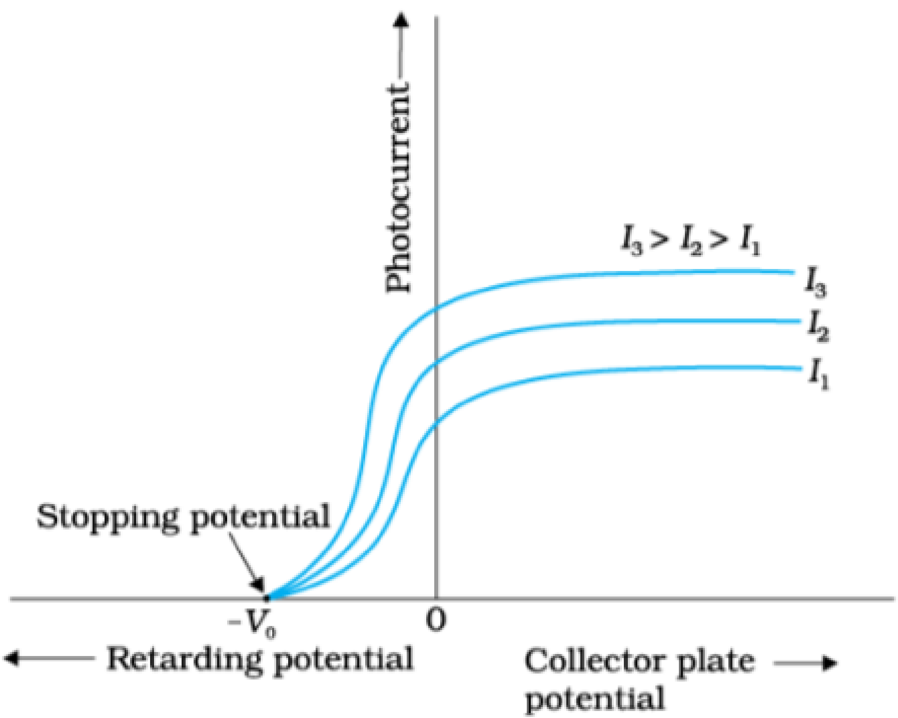


Kinetic energy V/s frequency

- For a fixed frequency (υ)of light, the numbers of emitted photoelectrons is proportional to the intensity of light. So, photo-electric current increases linearly with the Intensity (I) of the incident light.



- The photocurrent increases with accelerating potential and for some certain positive potential of collector A all the emitted electrons are collected by A. Then the current becomes maximum and known as **Saturation Current.**



Saturation current increase with the Intensity (I) of the incident light but independent of frequency of light.

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Einstein's Photoelectric Equation:

When a photon of energy $h\nu$ falls on a metal surface, the energy of the photon is absorbed by the electron and is used in two ways:

i) A part of energy is used to overcome the surface barrier and come out of the metal surface. This part of the energy is called 'work function' ($\Phi = h\nu_0$).

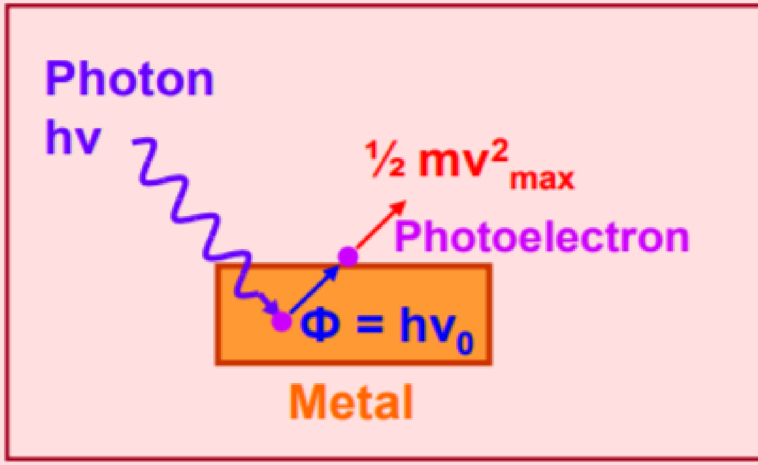
ii) The remaining part of the energy is used in giving a velocity 'v' to the emitted photoelectron. This is equal to the maximum kinetic energy of the photoelectrons ($\frac{1}{2} mv^2_{max}$) where 'm' is mass of the photoelectron.

According to law of conservation of energy,

$$h\nu = \Phi + \frac{1}{2} mv^2_{max}$$

$$= h\nu_0 + \frac{1}{2} mv^2_{max}$$

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



Dual Nature of Radiation and Matter:

Wave theory of electromagnetic radiations explained the phenomenon of interference, diffraction and polarization.

On the other hand, quantum theory of e.m. 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.

Louis de Broglie suggested that the particles like electrons, protons, neutrons, etc have also dual nature. i.e. they also can have particle as well as wave nature.

Note: In no experiment, matter exists both as a particle and as a wave simultaneously. It is either the one or the other aspect. i.e. The two aspects are complementary to each other.

Light has a dual nature

- Wave (electromagnetic) – Interference
  – Diffraction

- Particle (photons) – Photoelectric effect
  – Compton effect

Wave – Particle Duality for light

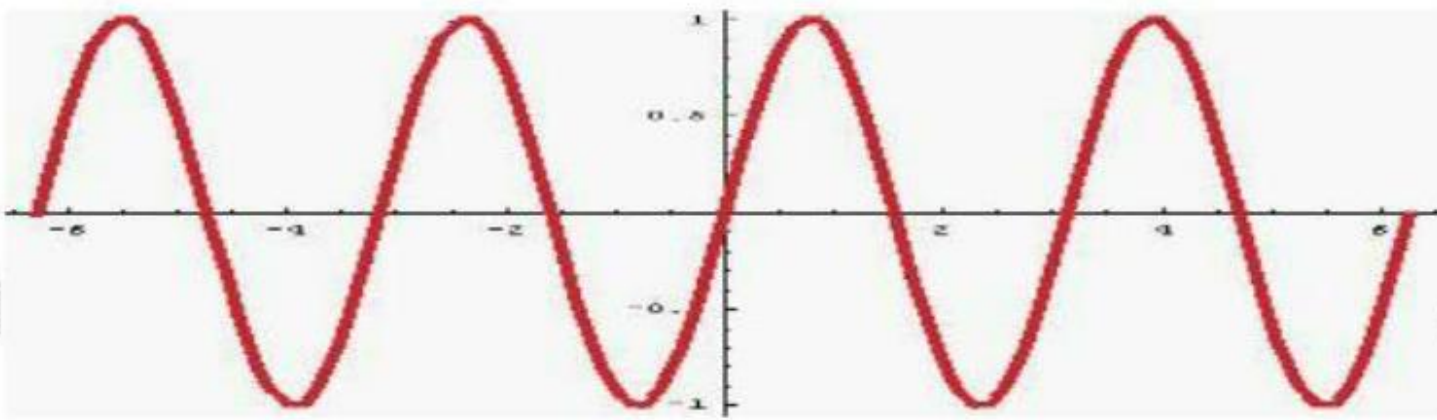
Particle

Our traditional understanding of a particle…

“Localized” – definite position, momentum, confined in space

Wave

Our traditional understanding of a wave....



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Waves and Particles:

Wavelength

Frequency

Waves

Spread in space and time

Can be superposed – show interference effects

Pass through each other

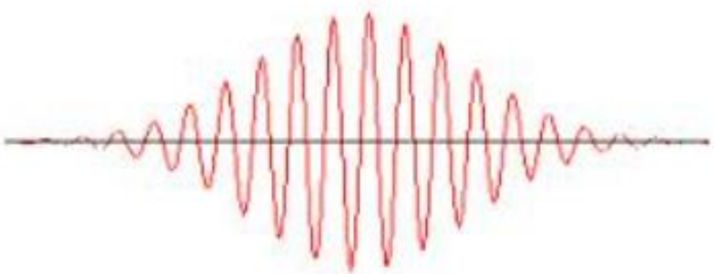
Particles

Localized in space and time

Cannot pass through each other - they bounce or shatter.

Constructing a wave packet by adding up several waves …………

If several waves of different wavelengths (frequencies) and phases are superposed together, one would get a resultant which is a localized wave packet



A wave packet describes a particle

- A wave packet is a group of waves with slightly different wavelengths interfering with one another in a way that the amplitude of the group (envelope) is non-zero only in the neighbourhood of the particle

- A wave packet is localized – a good representation for a particle!

de-Broglie concept of matter waves

- Electromagnetic radiation displays a dual character, behaving as a wave and a particle.
- Louis de Broglie in 1923 extended the wave-particle dualism to all fundamental particles such as electrons, protons, neutrons, atoms and molecules etc..
- According to de Broglie hypothesis, a moving particle is associated with a wave which is known as de Broglie wave or a matter wave. These waves are associated with particles like electrons , protons, neutrons etc.

Louis de Broglie's hypothesis

The dual nature of matter

A particle with momentum p has a *matter wave* associated with it, whose wavelength is given by

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

The connecting link – Planck's constant

Dual Nature

Radiation

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

Matter

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

Why isn't the wave nature of matter more apparent to us...?

$$h = 6.6\text{x}10^{-34}\,\text{J.s}$$

Planck's constant is so small that we don't observe the wave behaviour of ordinary objects – their de Broglie wavelengths could be many orders of magnitude smaller than the size of a nucleus!

de Broglie wavelength of a material particle moving with momentum p is given by

$$\lambda = \quad h / \sqrt{2mE}$$

In the case of electrons accelerated by a potential V volts from rest to velocity v

$$\lambda = h / \sqrt{2\, m_0 V e}$$

Because of the smallness of h, we observe the wave nature only for particles of atomic or nuclear size . For ordinary objects the de Broglie wavelength is very small and so it is not possible to observe wave nature of these macroscopic objects

For electrons, the de-Broglie wavelength $\lambda = 12.26 / \sqrt{V} \quad {}^{o}A$

Properties of de-Broglie waves or matter waves

- Matter waves consists of group of waves or a wave packet each having the wavelength λ , is associated with the particle. This group travels with the particle velocity v.
- Each wave of the group of matter waves travels with a velocity known as phase velocity of the wave $v_{phase} = c^2 / v$
- Lighter is the particle, greater is its wavelength. Smaller is the velocity, greater is the wavelength associated with it. When $v = 0$ then $\lambda = \infty$ which means that the wave becomes indeterminate. This shows that matter waves are generated by the motion of the particles.
- The wave and particle aspects of a moving body can never appear together in the same experiment
- The wave nature of matter introduces an uncertainty in the location of the particle because the wave is spread out in space.