Study of Photoelectric Effect

Objectives

After going through the module the learner will be able to:

- Know the factors affecting photoelectric current
- State the laws of photoelectric emission
- Represent the observations of photoelectric effect graphically
- Relate Photoelectric effect and wave theory of light

Content Outline

- Unit syllabus
- Module wise distribution of unit syllabus
- Words you must know
- Introduction
- Photocell -Experimental study of photoelectric effect
- Effect of intensity of light on photoelectric current
- Effect of accelerating potential on photocurrent
- Effect of frequency of incident light on stopping potential
- Photoelectric effect and inadequacy of wave theory
- Summary

Unit Syllabus

Unit 7 Dual Nature of Radiation and matter -

Chapter 11

Dual nature of radiation, photoelectric effect, Hertz and Lenard's observations. Einstein's photoelectric equation, particle nature of light

Matter waves, wave particle duality, nature of particles de Broglie relation, Davisson -Germer experiment (experimental details should be omitted only conclusion should be explained

Module Wise Distribution of Unit Syllabus - 5 Modules

Module 1	• Introduction • Electron emission

	• Photoelectric effect • Hertz's observations • Hallwachs and Lenard's observation • Dual nature of light
Module 2	• Photocell • Experimental study of photoelectric effect • Photocurrent • Effect of intensity of light on photo current • Effect of positive and negative potential on photocurrent • Stopping potential • Effect of frequency of incident radiation on stopping potential • Interpretations from the graphs drawn from above observations • Photoelectric effect and wave theory of light
Module 3	• Einstein's photoelectric equation • Energy quantum of radiation -the photon • Relating Einstein's photoelectric equation and observations from experiments with photocell
Module 4	• Wave nature of matter • De- Broglie's hypothesis • De-Broglie wavelength • Planck's constant • Probability interpretation to matter waves • Davisson and Germer Experiment • Wave nature of electrons
Module 5	• Application of dual nature of radiation and matter • Electron microscope

Module 2

Words You Must Know

- **Atomic structure**: Atomic structure is the positively charged nucleus and the negatively charged electrons circling around it, within an *atom.*
- **Electromagnetic waves**: *Electromagnetic waves* are *waves* that are created as a result of vibrations between an electric field and a magnetic field. In other words, *EM waves* are composed of oscillating magnetic and electric fields.
- **Interference and diffraction of waves**: **interference** is a phenomenon in which two **waves** superimpose to form a resultant **wave** of greater or lower amplitude.
- The **diffraction** phenomenon is described as the apparent bending of **waves** around small obstacles and the spreading out of **waves** past small openings.
- **Effect of electric and magnetic fields on a moving charge**: A **charged** particle **moving** without acceleration **produces** an **electric** as well as a magnetic **field**. It **produces** an **electric field** because it's a **charge** particle. But when it is at rest, it doesn't **produce** a **magnetic field**. All of a sudden when it starts **moving**, it starts producing a magnetic **field**.
- When a **charged** particle moves relative to a **magnetic field**, it will experience a force, unless it is traveling parallel to the **field**. The sign of the **charge**, the direction of the **magnetic field** and the direction the particle is traveling will all affect the direction of the force experienced by the particle.
- **Electric current**: An *electric current* is a flow of *electric* charge.
- **Ionization of atoms**: Is the process by which an **atom** or a molecule acquires a negative or positive charge by gaining or losing electrons to form **ions**, often in conjunction with other chemical changes.
- **Ray and wave optics**: *Ray optics*, describes light propagation in terms of *rays*. The *ray* in *geometric optics* is an abstraction useful for approximating the paths along which light propagates under certain circumstances. Light propagates in straight-line paths as they travel in a homogeneous medium.
- Wave optics is the branch of **optics** that studies interference, diffraction, polarization, and other phenomena for which the **ray** approximation of geometric **optics** is not valid.
- **Plotting and interpreting graphs**: Graphs in the scientific world are between any two physical quantities and show the dependence of one on the other.
- **Analysis and deductions from the graphs** show variations and interpretations can give meaning to the study, for example u-v graphs of experimental observations from

optics experiments, not only show the variation and dependence of one physical quantity on another under the constraints of the study .

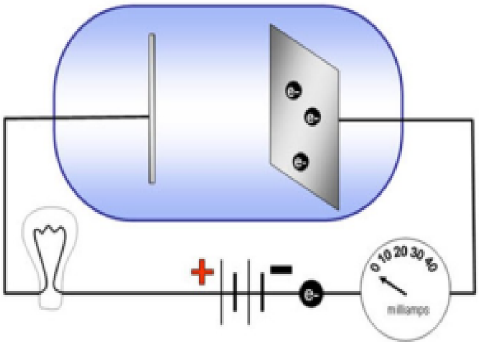
- **Graphs can be linked with a mathematical equation**: All graphs have a mathematical relation. Hence there will always be an equation related to the segment of the graph drawn, the graph could be a **straight line, a curve, a parabola, a hyperbola**.
- **Photoelectric effect:** The emission of electrons from a solid surface when light of suitable frequency is incident on it.
- **Work function**: The minimum amount of energy required by an electron to just escape from the metal surface is known as work function of the metal. This is generally measured in electron volts (eV).
- **Electron volt**: It is the energy gained by an electron when it is accelerated through a potential difference of 1 volt, 1 eV = 1.6×10^{-19} joules
- **Electron emission**: The phenomenon of emission of electrons from a metal surface. this occurs in the following ways
    - **Thermionic emission**: Electrons are emitted from the surface when the surface is heated
    - **Field emission**: Electrons are emitted from a surface when subjected to very high electric field
    - **Photoelectric emission**: Electrons are emitted from a metal surface when electromagnetic radiation of suitable frequency is incident on the surface.
    - **Secondary emission**: Electrons are emitted from the surface by striking it with high energy electrons.
- **Photosensitive material** It was found that certain metals like **zinc, cadmium, magnesium**, etc., responded only to ultraviolet light, having short wavelength, to cause electron emission from the surface. However, some alkali metals such as **lithium, sodium, potassium, caesium and rubidium were sensitive even to visible light.**

Introduction

The phenomenon of emission of electrons from a metal surface if light radiation of appropriate frequency is incident on it. The effect lasts only till the surface is irradiated. This phenomenon was studies in the laboratory using a **Photoelectric cell**

The Photocell

Schematic view of the arrangement used for the experimental study of the photoelectric effect is given below.



Experiments were performed in **evacuated glass tubes**. The electrons ejected from the surface are called **photoelectrons.** They are the same as electrons in every way.

The photoelectrons were ejected when radiations of suitable wavelength were incident on the photosensitive material. The set up stops working when the light is cut off.

The electrons emitted by the plate (emitter) can be collected by the second plate (collector), by the electric field created by the battery.

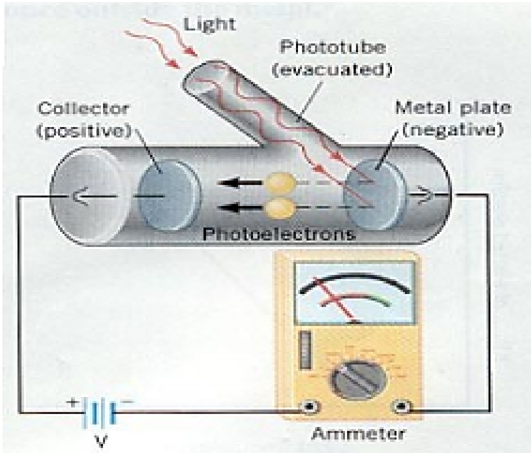
Electric current flows, which can be detected by the deflection in the ammeter.

In order to study photoelectric effect more meaningfully, another arrangement.

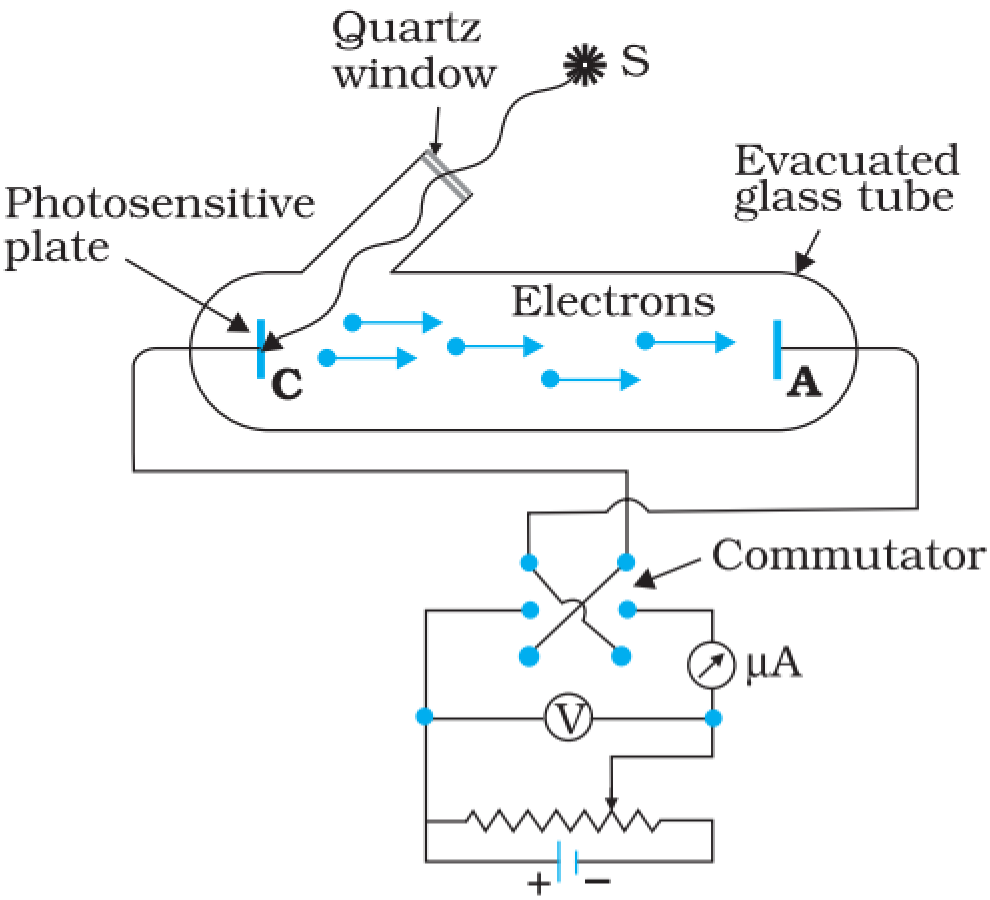
Its schematic diagram is given below.

Notice

The positive and negative terminals of the battery and the connection to the photosensitive plate.



The circuit diagram would be like this



The advantage of the circuit

a) The **rheostat** can change the potential difference between the two plates C (emitter) and A (collector). These may be referred to as the cathode and the anode.

b) The **polarity of the plates** (emitter and collector) can be reversed by a commutator. Thus, the plate A can be maintained at a desired positive, or negative, potential with respect to the emitter C.

c) A micro ammeter is sensitive enough to record small currents.

d) The **quartz window** can be used when the source S is a source of ultraviolet light.

e) Suitable positioning of the circuit or by changing the distance between the source and the plate C, one can alter the intensity of light radiations (from the source) incident on the emitter plate C.

This apparatus is often called a photocell or phototube.

We will now study some important experiments performed using photocells

Effect of Intensity of Light on Photoelectric Current

By 'Intensity of light', we mean brightness of light.The collector A is maintained at a positive potential with respect to emitter C so that electrons ejected from C are attracted towards collector A.

Condition

Keeping the following

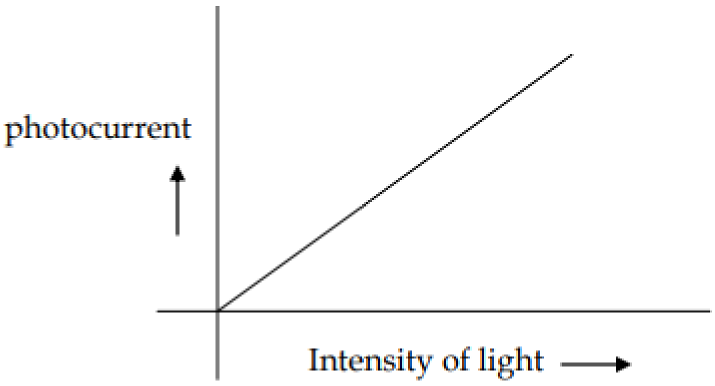
i) The frequency of the incident radiation.

ii) The potential difference between C and A **fixed,**

The intensity of light radiations is varied and the resulting photoelectric current is measured each time.It is observed that the photocurrent increases linearly with increase in the intensity of incident radiations.

The photocurrent is (clearly) directly proportional to the number of photoelectrons emitted per second. This implies that **the number of photoelectrons emitted per second is directly proportional to the intensity of incident radiations**.

Graphical Representation of the Observations



The above indicates that

a) Zero intensity results in zero photocurrent, i.e., no electrons are emitted.
b) Keeping the frequency constant, an increase in the intensity increases the photoelectric current.
c) The number of photoelectrons emitted per second, is proportional to the intensity of incident radiation.

Think About This

- In case the frequency of incident radiations is kept constant and the intensity of incident radiation is increased 'n' times, how would the value of the photo current change?
- If the light of same intensity is incident on another metallic surface, (for which the work function requirement is satisfied), would the value of photo current increase in the same way?

Effect of Accelerating Potential on Photoelectric Current

First keep the plate A at some positive accelerating potential with respect to the plate C and illuminate the plate C with radiations of fixed frequency and a known intensity I_1. Next change the **positive potential of plate** A gradually and measure the resulting photo electric current each time.

It is observed that the photoelectric current increases with increase in accelerating (positive) potential.

At some stage, for a certain **positive potential of plate A**, all the emitted electrons are collected by plate A and the photoelectric current becomes maximum.

If the accelerating potential of plate A is increased further, the photocurrent does not increase. This maximum value of the photoelectric current is called **saturation current.**

Saturation current corresponds to a situation when all the photoelectrons, emitted by the emitter plate C reach the collector plate A.

Now suppose a **negative (retarding) potential is applied to the plate A** with respect to the plate C and make it increasingly negative gradually.

It was observed that when the polarity is reversed, the electrons get repelled and only more energetic electrons are able to reach the collector A.

Hence, the photoelectric current is now observed to decrease rapidly until it drops to zero at a certain sharply defined critical value of the negative potential V_0. For a particular frequency of incident radiations, the minimum negative (retarding) potential V_0, given to the plate A, for which the photocurrent stops (or becomes zero) is called the **cut-off or stopping potential.**

The interpretation of the observation in terms of photoelectrons is straightforward.

- **All the photoelectrons emitted from the metal do not have the same energy.**
- **Photoelectric current is zero when the stopping potential is sufficient to repel even the most energetic photoelectrons, with the maximum kinetic energy (K_{max}), so that**

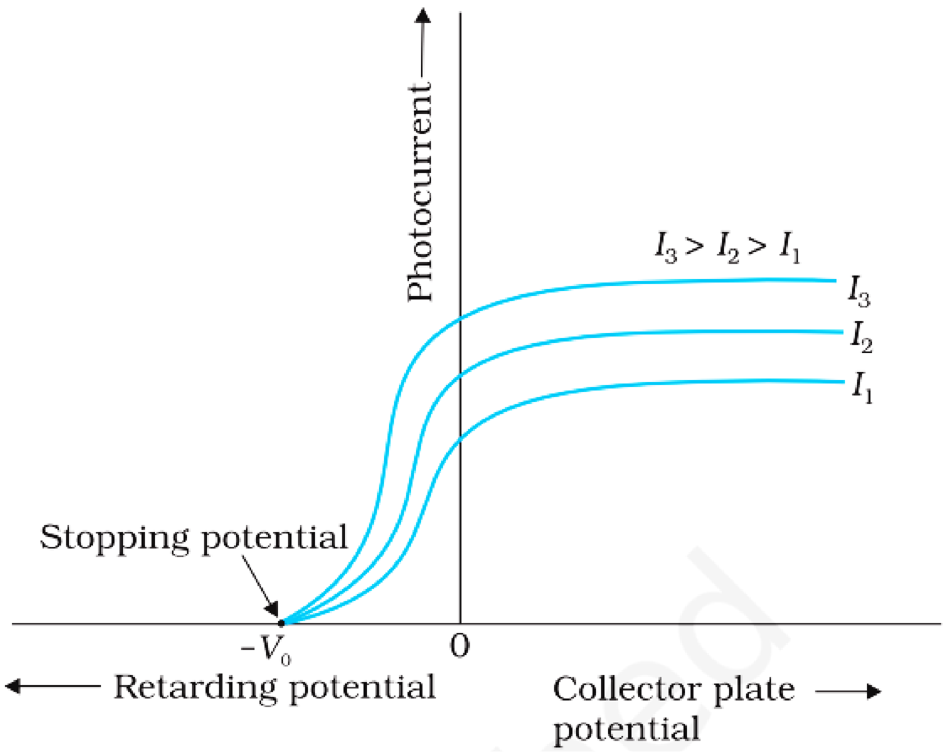
$$K_{max} = eV_0$$

With incident radiations of the same frequency, but of higher intensity, say I_2 and I_3, (i.e., it is observed that the saturation current has higher values.

This shows that more electrons are being emitted per second, in proportion to the intensity of incident radiations.

- **However, the stopping potential remains the same as that for the incident radiations of intensity. Thus, for a given frequency of the incident radiations, the stopping potential is independent of its intensity.**
- **In other words, the maximum kinetic energy of photoelectrons depends on the nature of the light source and the emitter plate material but is independent of the intensity of incident radiation.**

Graphical Representation



Variation of photocurrent with collector plate potential for different intensity of incident radiation.

Interpretation of the graph

- **For a given frequency, the photocurrent increases with an increase in intensity. Even when collector potential is zero, there is some photo electric current.**
- **As the collector potential increases, photoelectric current does not continue increasing. It soon becomes constant.**
- **On applying reverse potential, photoelectric current decreases and becomes zero at a certain value of this negative potential.**
- **On increasing the intensity keeping the same frequency, the photoelectric current increases but the stopping potential remains the same.**
- **For a given frequency of the incident radiation, the stopping potential is independent of its intensity.**

Think About These

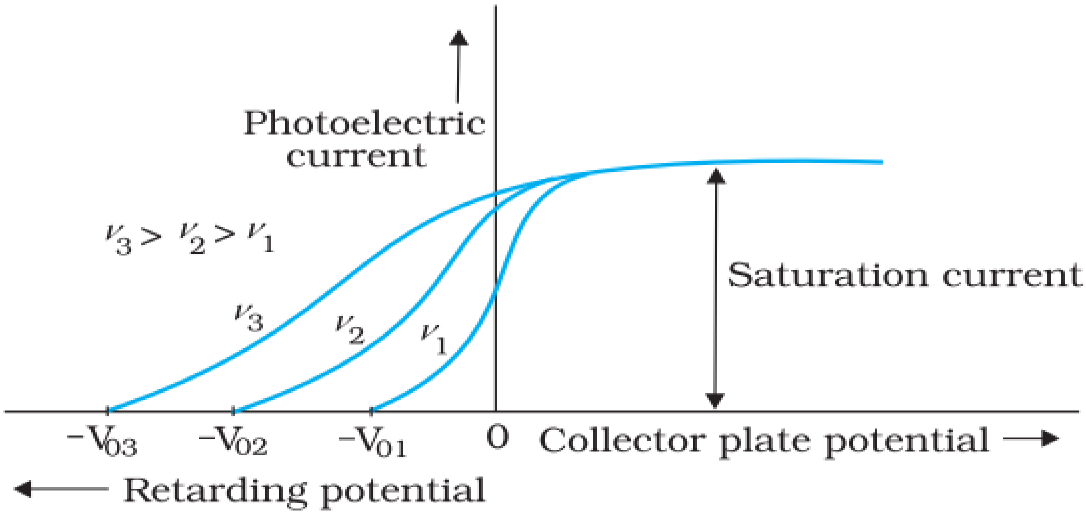
- **The value of photoelectric current and its saturation value is greater for greater intensity. Do you think intensity is related to the number of electrons emitted?**

- **Why is the value of photocurrent and saturation current greater for a higher intensity, for the same frequency of incident radiation? Do you think this could be due to a greater number of emitted electrons or an increase in the kinetic energy of the electrons?**
- **Which section of the graph suggests that all photoelectrons are not emitted with the same kinetic energy?**
- **What would the graph look like if all the photoelectrons were emitted with the same kinetic energy?**
- **What would happen if the collector is made more negative, i.e. its potential is made less than V_0?**
- **Think of factors that would change the value of V_0?**

Effect of Frequency of Incident Radiations on Stopping Potential

To study the relation between the frequency υ of the incident radiations and the stopping potential V_0, the intensity of light radiations for various frequencies is adjusted to have the same value and variation of photocurrent with collector plate potential is measured.

The resulting variation is shown in the graph.



Variation of photoelectric current with collector plate potential for different frequencies of incident radiation

Different values of stopping potential are obtained but the same value of the saturation current for incident radiation of different frequencies.

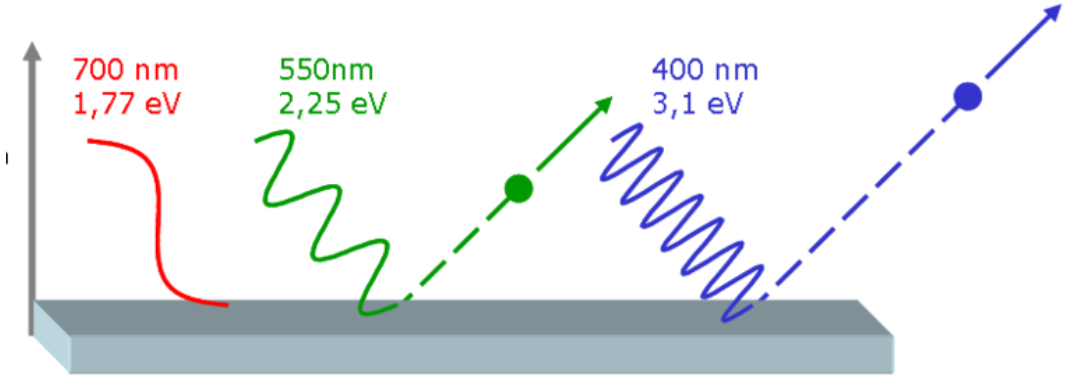
The energy of the emitted photoelectrons is thus seen to depend on the frequency of the incident radiations. The stopping potential is more negative for higher frequencies of incident radiations.

It is observed that:

- **The stopping potential $V_{03} > V_{02} > V_{01}$ for frequencies $\nu_3 > \nu_2 > \nu_1$.**

  This means that greater the frequency of incident radiations, greater is the maximum kinetic energy of the photo electrons. That is why a greater retarding potential is required to stop them completely.
- **The value of saturation current remains the same, if and only if, the intensity remains the same for all three values of frequency in this case.**

Example



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Study the given diagram.

There are three incident light radiations of different frequencies corresponding to red, green and violet colours on a plate of potassium

a) Why is there no emission of photoelectrons when a red light is incident?

b) For which colour the stopping potential will be higher?

c) In terms of the maximum velocity of the emitted photoelectrons, which one of the two, green or violet, will show greater current when collector voltage is zero?

Solution

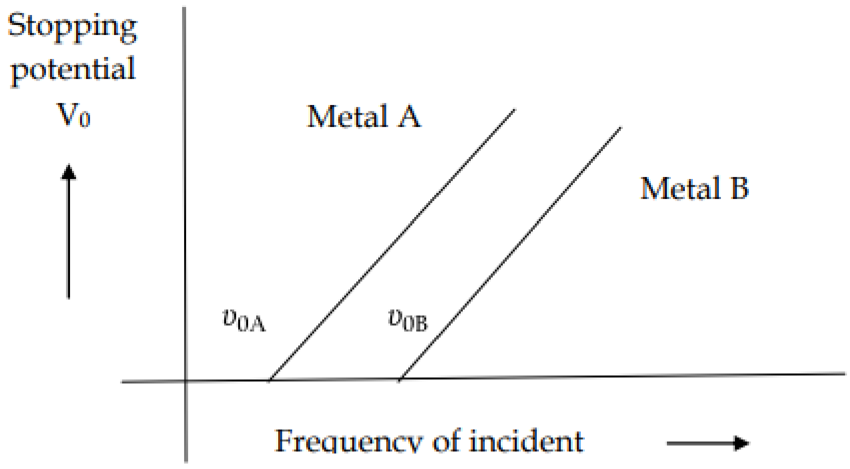
a) the photon energy is less than the work function for potassium

b) violet

c) violet

Variation of Stopping Potential V_0 with frequency υ of incident radiation for a given photosensitive material

When a graph between the frequency of radiation and corresponding stopping potential for a given metal is plotted, a straight line is obtained. A similar straight line is obtained when a different metal is used as an emitter.



Interpretation Of Graph

a) The stopping potential V_0 varies linearly with frequency of incident radiation for a given photosensitive material.

b) There exists a minimum cut-off frequency ν_0 for which the stopping potential is zerofor metal A.

c) It appears the threshold frequency for metal B is greater than that for A but the graph for B is parallel to that for A.

One can conclude from the above inferences that the **maximum kinetic energy of the photoelectrons varies linearly with frequency of incident radiation, but is independent of intensity.**

One can also deduce that for a frequency ν of incident radiations, lower than the cut off frequency ν_0, no photoelectric emission is possible even if the intensity is large.

It is now known that the emission starts in time of the order of 10^{-9} s or less.

What We Have Learnt from Experimental Observations

- **For a given photosensitive material and frequency of incident radiations (above threshold frequency), the photoelectric current is directly proportional to the intensity of incident light**.

- **For a given photosensitive material and frequency of incident radiations, saturation current is observed to be proportional to the intensity of incident radiations, but the stopping potential depends only on incident frequency.**
- **For a given photosensitive material, there exists a certain minimum cut-off frequency of incident radiation(called the threshold frequency), below which no emission of photoelectrons takes place no matter how intense the incident light is. However, above the threshold frequency, the stopping potential, or equivalently the maximum kinetic energy of the emitted photoelectrons increases linearly with the frequency of the incident radiations but is independent of its intensity**.
- **The photoelectric emission is an instantaneous process without any apparent time lag (10^{-9}s or less), even when the intensity of incident radiations (of frequency greater than the threshold frequency) is very small.**

Photoelectric Effect and Inadequacy of Wave Theory

Wave theory was well established when the photoelectric effect was observed. The phenomenon of interference, diffraction and polarization could be explained satisfactorily by using it. According to the wave model, light is an electromagnetic wave consisting of electric and magnetic fields with continuous distribution of energy over the region of space over which the wave is extended.

Wave theory of light is inadequate to explain photoelectric effect due to the following reasons:

- The energy carried by a light beam is measured by its intensity. Thus, by increasing intensity (irrespective of wavelength or frequency) one can increase the energy of the light beam. This will lead to greater energy absorbed by each electron. So the energy of photoelectrons should also increase. But kinetic energy of electrons is observed to be independent of the intensity.
- As per wave nature photoemission should take place from a metal surface for all frequencies because no matter what the frequency of radiation is, a sufficiently intense beam of radiation over sufficient time should be able to impart enough energy to the electrons. After all, objects get hot when left out in the sun for sufficient duration! But in reality, no emission takes place for frequency values below threshold frequency.
- Further, one should note that in the wave picture, the absorption of energy by electrons takes place continuously over the entire wave front of the radiation. Since a

large number of electrons absorb energy, the energy absorbed per electron per unit time turns out to be quite small. Explicit calculations estimate that it can take hours, or more, for a single electron to pick up sufficient energy to overcome the work function and come out of the metal. This conclusion is again in striking contrast to the observation that photoelectric emission is an instantaneous phenomenon.

In short, the wave picture is unable to explain the most basic features of photo emission.

Answer These

1. **How can photons displace electrons from metals? Why not from non- metals?**
2. **What happens when light is incident on a metal surface? What is this phenomenon called?**
3. **If the _____ of the incoming light is too small, no electrons will be ejected from the metal surface.**
   a) wavelength
   b) frequency
   c) amplitude
   d) exposure time
4. **What is the threshold frequency?**
   a) the maximum frequency that would allow electrons to be ejected from the metal
   b) the minimum frequency that would allow electrons to be ejected from the metal
   c) the highest frequency of visible light
   d) the lowest frequency of visible light

5. **Work function and threshold frequency are related**
   a) always equal
   b) work function is energy
   c) work function =h threshold frequency
   d) work function =h/threshold frequency
6. **If light behaved only as a wave, what would happen when light below the threshold frequency illuminated the metal surface?**
   a) No electrons would ever be ejected.
   b) Electrons would be ejected at a very slow speed.
   c) Electrons in the metal would be stabilized by the addition of energy.

d) Electrons would eventually be ejected when the light was shined onto the surface for a long time.

7. Suppose that the threshold frequency in a photoelectric effect experiment corresponds to yellow light. Would the following colors of light cause electrons to be ejected from the metal surface? (Answer yes or no for each.)

a) blue–

b) red–

c) green–

d) violet–

8. Suppose that the incoming light is above the threshold frequency. What happens as the frequency is increased even further?

a) More electrons are ejected, but the electrons move at the same speed as before.

b) The number of ejected electrons is the same, but the electrons move faster.

c) More electrons are ejected and the electrons move faster.

d) There is no effect on either the number of ejected electrons or their speed.

9. An increase in the _____ of the incoming light causes an increase in the number of ejected electrons.

a) intensity

b) frequency

c) wavelength

d) speed

10. What does the photoelectric cell in a calculator do?

11. Stopping potential is

a) potential of cathode of a phototube for which photoelectric current stops

b) potential of anode of a phototube for which photoelectric current stops

12. Draw graphs to show

a) the effect of intensity on photocurrent

b) the effect of frequency on photocurrent

c) the effect of time of exposure on photocurrent

Summary

- **Photocell** device that converts light into electrical energy
- **Experimental study of photoelectric effect and the factors affecting the Photocurrent**

- **For a given photosensitive material and frequency of incident radiations (above threshold frequency), the photoelectric current is directly proportional to the intensity of incident light**.
- **For a given photosensitive material and frequency of incident radiations, saturation current is observed to be proportional to the intensity of incident radiations, but the stopping potential depends only on incident frequency.**
- **For a given photosensitive material, there exists a certain minimum cut-off frequency of incident radiation, (called the threshold frequency), below which no emission of photoelectrons takes place no matter how intense the incident light is. However, above the threshold frequency, the stopping potential, or equivalently the maximum kinetic energy of the emitted photoelectrons increases linearly with the frequency of the incident radiations but is independent of its intensity**.
- **The photoelectric emission is an instantaneous process without any apparent time lag (10^{-9}s or less), even when the intensity of incident radiations (of frequency greater than the threshold frequency) is very small.**