DUAL NATURE OF MATTER AND RADIATION PART I

INSTRUCTIONS

1 This is a short and interesting chapter which consists of the following topics as per CBSE syllabus

Dual nature of radiation, Photoelectric effect, Hertz and Lenard's observations; Einstein's photoelectric equation-particle nature of light. Matter waves-wave nature of particles, de-Broglie relation, Davisson-Germer experiment (experimental details should be omitted; only conclusion should be explained)

This section covers **Dual nature of radiation, Photoelectric effect, Hertz and Lenard's observations; Einstein's photoelectric equation**

2 It has small weightage of about 3-4 marks in the CBSE examination.

3 It has a few very important graphs you should do well and numericals on the Einstein equation which need practice

4 To fully prepare this chapter , you can practice previous year question papers of CBSE given along here.

Main points of the chapter

INTRODUCTION

Metals have free electrons which are responsible for electrical conductivity. The free electron is held inside the metal surface by the attractive forces of the ions. The electron can come out of the metal surface only after it has got sufficient energy to overcome the attractive pull of the ions.

The minimum energy required by an electron to escape from the metal surface is called the **work function**. It is denoted by **ϕ_0 or W_0**.

The minimum frequency of the incident radiation at which the photoelectric emission takes place is called **threshold frequency (ν_0).**

The work function is measured in electron- Volt (eV)

1 eV = 1.6×10^{-19} J.

Types of electron emission:

(i) Thermionic Emission: emission of electron when metal surfaces are suitable heated.

(ii) Field Emission: emission of electron when a metal surface is subjected to strong electric field.

(iii) Photo – electric emission: The emission of electrons from a metal surface when radiation of suitable frequency is incident on the metal surface. The electrons generated are called photo – electrons.

Hertz's Observation: The phenomenon of photo electric emission was discovered by Hertz. He observed that a high voltage spark across a detector loop was enhanced when the emitter was illuminated by UV light.

Lenard's Observations and experimental study of Photoelectric effect:

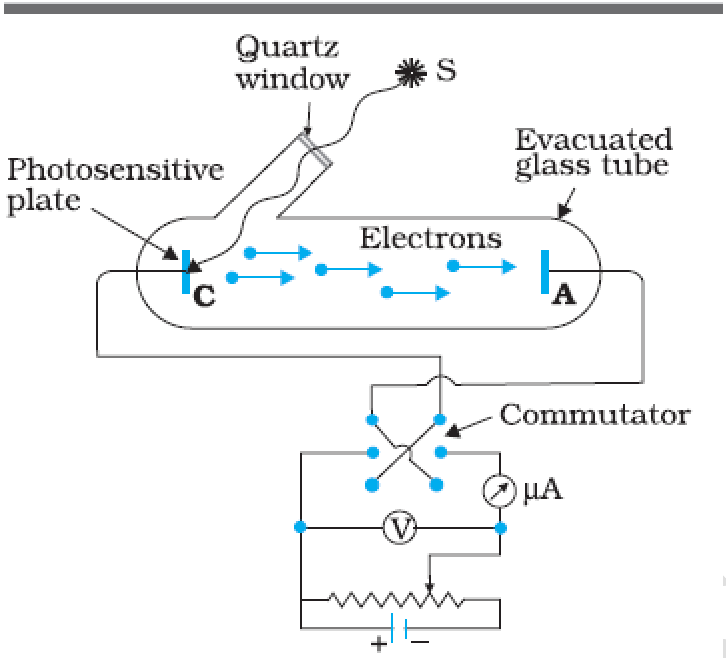


FIGURE 11.1 Experimental arrangement for study of photoelectric effect.

Wilhelm Hallwachs and Philipp Lenard investigated the phenomenon of photoelectric emission in detail during 1886-1902.

Lenard (1862-1947) observed that when ultraviolet radiations were

allowed to fall on the emitter plate of an evacuated glass tube enclosing two electrodes (metal plates), current flows in the circuit. As soon as the ultraviolet radiations were stopped, the current flow also stopped. These observations indicate that when ultraviolet radiations fall on the emitter plate C, electrons are ejected from it which are attracted towards the positive, collector plate A by the electric field. The electrons flow through the evacuated glass tube, resulting in the current flow. Thus, light falling on the surface of the emitter causes current in the external circuit. Hallwachs and Lenard studied how this photo current varied with collector plate potential, and with frequency and intensity of incident light.

After the discovery of the electron in 1897, it became evident that the incident light causes electrons to be emitted from the emitter plate. Due to negative charge, the emitted electrons are pushed towards the collector plate by the electric field. Hallwachs and Lenard also observed that when ultraviolet light fell on the emitter plate, no electrons were emitted at all when the frequency of the incident light was smaller than a certain minimum value, called the *threshold frequency*. This minimum frequency depends on the nature of the material of the emitter plate.

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.

All these *photosensitive substances* emit electrons when they are illuminated by light. After the discovery of electrons, these electrons were termed as ***photoelectrons***. The phenomenon is called ***photoelectric effect.***

TABLE 11.1 WORK FUNCTIONS OF SOME METALS

Metal	Work function ϕ_o (eV)	Metal	Work function ϕ_o (eV)
Cs	2.14	Al	4.28
K	2.30	Hg	4.49
Na	2.75	Cu	4.65
Ca	3.20	Ag	4.70
Mo	4.17	Ni	5.15
Pb	4.25	Pt	5.65

Main features of photoelectric effect

i Effect of intensity of incident Radiation:

With increase in intensity, the photoelectric current increases. i.e. the photoelectric current or number of ejected electrons is directly proportional to the intensity of the incident radiation.

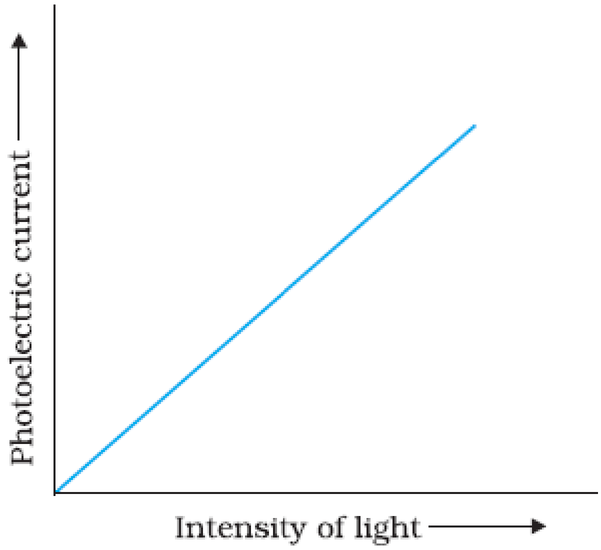
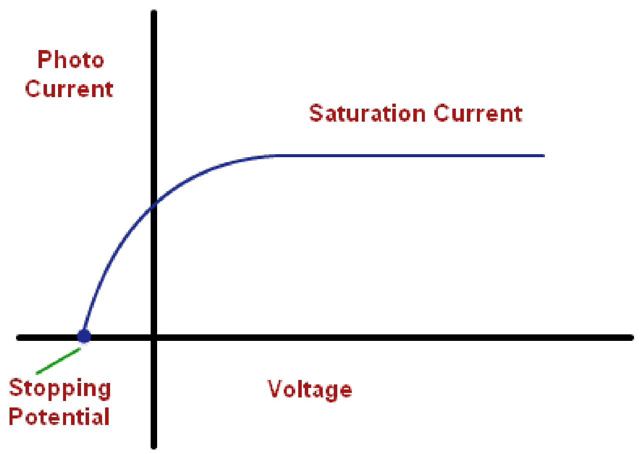


FIGURE 11.2 Variation of Photoelectric current with intensity of light.

ii)Effect of potential:



The graph for potential versus current can be analyzed in three parts. As V is made negative, the plate starts repelling the electrons and thus the photoelectric current decreases.

The current decreases because the electrons with least K.E. are not able to reach the opposite electrode. Since, the current is not decreasing sharply this implies that all electrons do not possess same K.E.

As the negative potential increases, the photoelectric current becomes finally zero at V = – V0 when even the electron with the maximum K.E. is not able to reach the opposite plate.

***Stopping Potential (V0)**: The value of the negative potential at which the photoelectric current becomes zero is called the stopping potential.*

K. E. max = e V0 *(Energy= charge X Potential)*

*The value of stopping potential is same for different intensities, it means the **stopping potential does not depend upon the intensity** and since the value of stopping potential is the measure of the maximum K.E. of the ejected electrons – it means the **K.E. of ejected electrons does not depend upon the intensity of the incident radiation.***

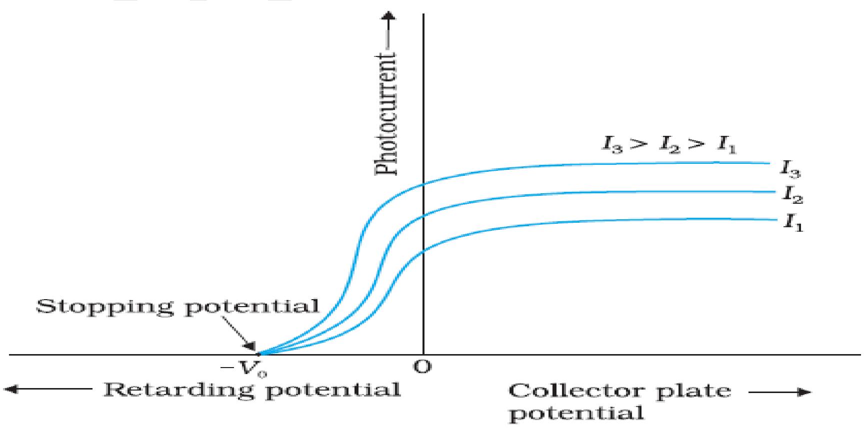


FIGURE 11.3 Variation of photocurrent with collector plate potential for different intensity of incident radiation.

iii)Effect of Frequency:

As explained earlier, for positive potential the current increases and then becomes constant. The maximum value of current for an intensity is called the saturation current. With increase in the frequency of the incident radiation, the value of stopping potential also increases. Since, the stopping potential is a measure of the K.E. of the ejected electrons this implies that the K.E. of the ejected electrons is directly proportional to the frequency of the incident radiation

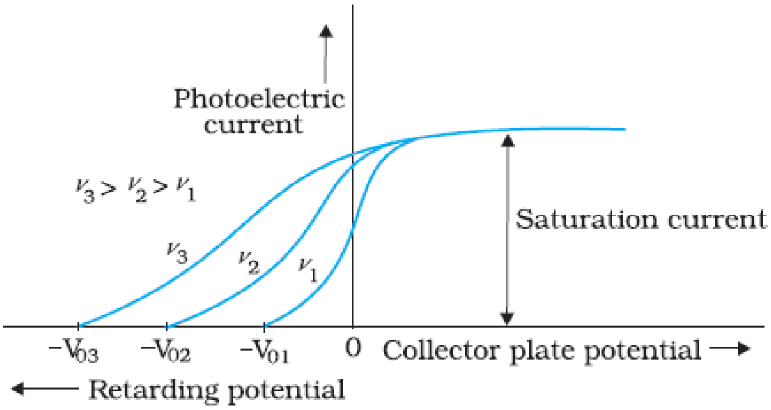


FIGURE 11.4 Variation of photoelectric current with collector plate potential for different frequencies of incident radiation

iv)Relation between stopping potential and frequency

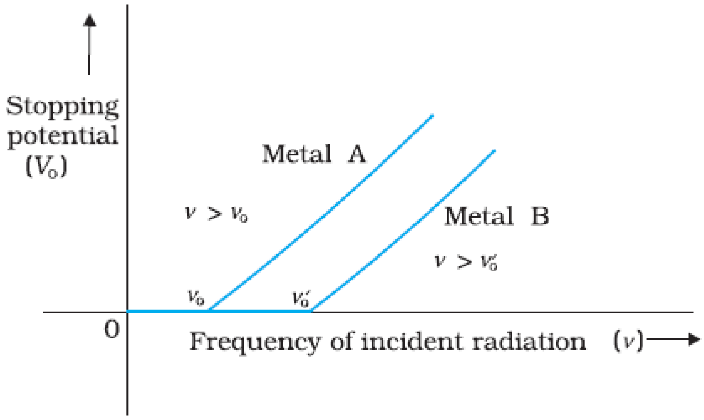


FIGURE 11.5 Variation of stopping potential V_0 with frequency ν of incident radiation for a given photosensitive material.

Stopping potential is directly proportional to frequency of incident light. Of course below the threshold frequency, there is no emission and hence no stopping potential is required!

(iv) Existence of Threshold Frequency:

With increase in frequency, the K.E. of ejected electrons increases and thus, the value of stopping potential also increases. However, no photoelectric emission takes place if the incident radiation is less than a minimum frequency called threshold frequency (v0)

(v) The photoelectric effect is an instantaneous phenomenon.

***Failure of Wave theory**: According to wave theory, the energy of the wave depends upon the intensity but in photoelectric effect the energy is actually dependent on the frequency of the incident radiation and is independent of the intensity. In wave theory, the energy of a wave is distributed over the entire wave front and no electron will get sufficient energy for the photoelectric emission to be instantaneous.*

Laws of Photoelectric emission:

(i) It is an instantaneous phenomenon.

(ii) The photoelectric effect takes place only if the frequency of the incident radiation is greater than the threshold frequency.

(iii) The maximum kinetic energy of the ejected electrons is dependent only on the frequency of the incident radiation and is independent of the intensity of the radiation.

(iv) The number of ejected electrons i.e. photoelectric current is directly proportional to the intensity of the incident radiation and is independent of the frequency of the radiation.

Einstein's Explanation of Photoelectric Effect:

Einstein proposed that light consist of tiny packets of energy called photons which travel with the speed of light. Each photon has energy E = hν, where h = Planck's Constant and ν = frequency of the light wave. The photoelectric effect is basically a collision between an electron and a photon and obeys the simple law of conservation of energy. When a photon of energy E = hν strikes the metal surface, a part of this incident energy is used up in detaching the electron from the surface of the metal this energy is called work function ($W_0 = h\nu_0$) and the remaining energy is converted into the K.E. of the ejected electron.

Thus we have

$$E = W_0 + K.E._{max}$$

$$\text{Or, } h\nu = h\nu_0 + KE_{max}$$

$$\text{Or, } KE_{max} = h\nu - h\nu_0$$

This equation is called Einstein's photoelectric equation.

Explanations: (i) In photon picture, the intensity can be imagined as the number of photons per unit area per unit time striking the metal surface thus as intensity increases, more photons strikes the metal surface and more electrons are ejected and the photoelectric current increases.

(ii) As seen from the photoelectric equation, with increase in the incident frequency, the energy of the incident photon will increase and this will increase the K.E. of the ejected electron.

(iii) No photoelectric emission occurs for $\nu < \nu_0$, because from the photoelectric equation, for $\nu < \nu_0$, the K.E. will become negative which is not possible. This explains the existence of threshold frequency.

(iv) Since, the photoelectric emission is a collision, it is an instantaneous phenomenon.

5 Remember: For photoelectric emission to take place the photon must have energy > work function of the metal. It has to be a one photon – one electron collision. The K.E. max is for an electron on the surface of the metal. For electrons inside the metal surface the energy is a little less than what we get from the equation.

The photoelectric equation can be further written as:

$$KEmax = h\nu - h\nu 0 = eV0$$

Also

$$eV0 = h\nu - h\nu 0$$

or

$eV0 = hc/\lambda - hc/\lambda 0$ ***where*** λ ***is wavelength***

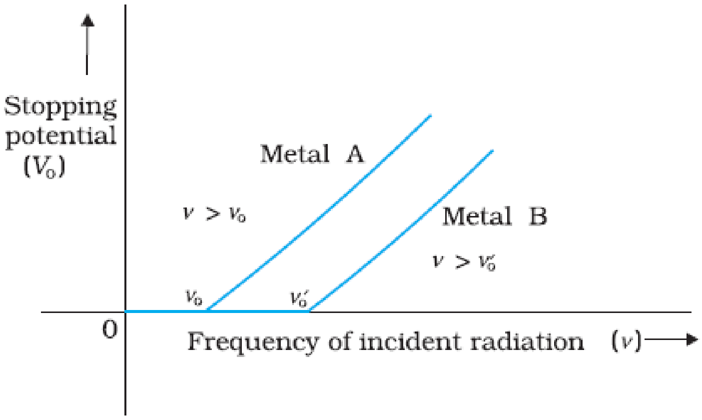


FIGURE 11.5 Variation of stopping potential V_0 with frequency ν of incident radiation for a given photosensitive material.

Comparing with y = mx + c, we find that this is the equation of a straight line where y = V0 and x = ν, the graph is what we have drawn in figure (5), The slope of this graph is h/e. The intercept on y –axis is hν0/e This is also one of the methods to determine the value of Planck's constant or the charge of electron. Since, the values of both h and e are constants; the slope is a constant for all metal

Video links

https://www.youtube.com/watch?v=byEaU9ILHmw

https://www.youtube.com/watch?v=-fKdjBokGVo

https://www.youtube.com/watch?v=oJaw7wMnTpc

https://www.youtube.com/watch?v=ubkNGwu_66s

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Assignment on the topic

DUAL NATURE ASSIGNMENT (questions from previous year CBSE papers)

1It is easier to remove an electron from sodium than from copper, which has a higher value of threshold wavelength. Why?

2 What is the value of stopping potential between the cathode and anode of photocell? If the max K.E of electrons emitted is 5eV?

3 A metal emits photoelectrons when red light falls on it. Will this metal emit photoelectrons when blue light falls on it?

4 The photoelectric cut off voltage in a certain photoelectric experiment is 1.5V. What is the max kinetic energy of photoelectrons emitted?

5 The work function of the following metal is given Na = 2.75 eV, K = 2.3 eV, Mo = 4.17 eV,Ni = 5.15 eV which of these metal will not give a photoelectric emission for radiation of wave length 3300 A° from a laser source placed at 1 m away from the metal. What happens if the laser is brought nearer and placed 50 cm away.

6 Why photoelectrons ejected from a metal surface have different kinetic energies although the frequency of incident photons are same?

7What is Einstein's explanation of photo electric effect? Explain the laws of photo electric emission on the basis of quantum nature of light.

8 Explain the effect of increase of (i) frequency (ii) intensity of the incident radiation on photo electrons emitted by a metal.

9 A metal surface illuminated by 8.5×10^{14} Hz light emits electrons whose maximum energy is 0.52 eV the same surface is illuminated by 12.0×10^{14} Hz light emits elections whose maximum energy is 1.97eV. From these data find work function of the surface and value of Planck's constant.

10 If the frequency of incident light in photoelectric experiment is doubled then does the stopping potential become double or more than double, Justify?
If the intensity oincident radiation on a metal is doubled what happens to the K.E of electrons emitted?

10What is the effect on the velocity photo electrons, if the wavelength of incident light is decreased?

11Show graphically how the stopping potential for a given metal varies with a frequency of the incident radiation.

12 Work functions 2ev and 5ev for two metals x and y respectively. Which metal will emit electrons,when it is irradiated with light and wave length 400nm and why?

13Following table gives values of work function for a few photosensitive metal.

S.NO	Metal	Work function(ev)
1	Na	1.92

2	K	2.15
3	Mo	4.17

If each metal is exposed to radiation of wavelength 300nm which of them will not emit photoelectron.

14 Visible light can not eject photo electrons from copper surface, whose work function is 4.4 ev , why? Prove mathematically.

15 The threshold frequency for a certain metal is $3.3X10^{14}$ Hz. If light of frequency $8.2X10^{14}$ Hz is incident on the metal. Predict the velocity of ejected electrons and cut-off voltage.

16The work function of two metals A and B are respectively 1.2 eV and 2.4 eV. Light of wavelength 600nm falls on these metals.

(i) Which metal / metals will give photoelectric emission?

(ii) What is the maximum velocity and cut-off potential?

(iii) If the source is moved away, how does it affect the stopping potential?

17 The work function of cesium is 2.14 eV. Find (i) threshold frequency (ii) wavelength of light if the photoelectrons are stopped with stopping potential 0.6V.

18 In a plot of photoelectric current versus anode potential, how does

a. the saturation current vary with anode potential for incident radiations of different frequencies but same intensity.

b. The stopping potential varies for incident radiations of different intensities but same frequency?

c. Photoelectric current vary for different intensities but same frequency of incident radiations?

Justify your answer in each case.

19 The radiations of frequency 10^{15} Hz are incident on two photosensitive surfaces A and B. Following observations are recorded:

Surface A: no photo electric emission takes place.

Surface B: Photoemission takes place photo electrons have zero energy.

Explain the above observations on the basis of Einstein’s photoelectric equations. How will the observations with surface B change when the wavelength of incident radiations is decreased?

20 Light of frequency 2.5 n0 is incident on surface of threshold frequency n0 and the photoelectric current is 1 mA. If frequency of light is halved and intensity is doubled, find new photoelectric current.