1. Details of Module and its structure

Module Detail	
Subject Name	Physics
Course Name	Physics 04 (Physics Part 2, Class XII)
Module Name/Title	Unit-07, Module-03: Einstein's Photoelectric Equation Chapter-11: Dual nature of Radiation and Matter
Module Id	leph_201103_eContent
Pre-requisites	Atomic structure Electromagnetic waves Interference and diffraction of waves Effect of electric and magnetic fields on a moving charge Electric current Ionization of atoms Ray and wave optics; interference and diffraction of waves Plotting and interpreting graphs Analysis and deductions from the graph
Objectives	**After going through the module the learner will be able to:** • Appreciate that light, in interaction, with matter displays particle nature • Write mathematical expression for Einstein's photoelectric equation. • Interpret laws of photoelectric emission on the basis of Einstein's photoelectric equation. • Distinguish between the particle nature and the wave nature of radiation.
Keywords	Photoelectric current, laws of photoelectric emission, factors affecting photo electric effects topping potential, photocell

2. Development Team

Role	Name	Affiliation
National MOOC Coordinator (NMC)	Prof Amarendra P. Behera	Central Institute of Educational Technology, NCERT, New Delhi
Programme Coordinator	Dr. Mohd Mamur Ali	Central Institute of Educational Technology, NCERT, New Delhi
Course Coordinator / PI	Anuradha Mathur	Central Institute of Educational Technology, NCERT, New Delhi
Subject Matter Expert (SME)	Anuradha Mathur	Central Institute of Educational Technology, NCERT, New Delhi
Review Team	Prof. V. B. Bhatia (Retd.) Associate Prof. N.K. Sehgal (Retd.) Prof. B. K. Sharma (Retd.)	Delhi University Delhi University DESM, NCERT, New Delhi

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1. UNIT SYLLABUS

Unit 7

Dual Nature of Radiation and matter

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

2. MODULE WISE DISTRIBUTION OF UNIT SYLLABUS 5 MODULES

Module 1	• **Introduction** • **Electron emission** • **Photo electric 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 photo current** • **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 3

3. 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 propagate 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 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, 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 x 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

Photo electric emission: electrons are emitted from a metal surface when electromagnetic radiations of suitable frequency are 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.**

Photo cell: A device that converts light into electrical energy

Experiments with photocell show

- **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 photo electrons 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**

4. INTRODUCTION

The discovery of phenomenon of photo electric effect led to a number of experiments. The results of the experiments performed on the photo cell could not be explained using the established wave theory of light, which successfully explained the phenomenon of interference, diffraction and polarisation

In 1905, Einstein proposed a radically new picture of electromagnetic radiations to explain photo electric effect.

According to Einstein, photoelectric emission does not take place by continuous absorption of radiations. **Radiations are made up of discrete units, called quanta of energy. It was later named 'Photon'.**

We will now study photoelectric effect in more detail.

5. ENERGY QUANTUM OF RADIATIONS

According to the wave theory, light spreads out from a source in a manner analogous to the spreading out of ripples on the surface of water, that energy of light is distributed continuously throughout the wave pattern. According to quantum theory, proposed by

Einstein, light spreads out from a source as a succession of **localized packets of energy** or **photons**, each sufficiently small to permit it being absorbed by a single electron.

In this particle picture of light, the (quantum) theory requires knowledge of the light frequency, a wave quantity, in order to determine the energy of each photon or quantum of energy. So both ideas of wave and particle were used by Einstein to explain photo electric effect.

Photon energy = hν

where h is Planck's constant .

The value of Planck's constant has been obtained and confirmed experimentally. It is equal to 6.63 x 10^{-34} J-s

THE PHOTONS

1) Light spreads out from a source as a succession of **localized packets of energy** or **photons**, each sufficiently small to permit it being absorbed by a single electron
2) A photon is associated with a fixed frequency
3) A photon travels with the speed of light in vacuum (c =3 x 10^{8} m/s)
4) Frequency associated with a photon does not change as it travels from one medium to another
5) The speed of photons changes as it travels from one medium to another as the wavelength (λ) changes v = $\nu\lambda$
6) **The rest mass of a photon is zero i.e. a photon cannot exist at rest**
7) **Energy of a photon E = h ν = $\frac{hc}{\lambda}$**
8) **Momentum of a photon p = m c = $\frac{hc}{\lambda} = \frac{h}{\lambda}$**
9) From Einstein's mass energy relation $E = mc^2 = h\nu$ *or* $m = \frac{h\nu}{c^2}$

6. MAIN FEATURES OF EINSTEIN'S THEORY OF PHOTOELECTRIC EMISSION:

1. Photoelectric emission is a result of interaction of two particles –

one electron of the photosensitive material and the other a photon of the incident radiations.

2. The free electrons are bound within the metal due to attractive forces. There should, therefore, be a minimum energy needed by an electron to escape the surface.

This minimum energy, required to liberate an electron from the metal surface, is called the work function of the metal.

3. Each incident photon interacts with one electron. The energy of the photon is used for two purposes:

a) **Part of the energy of the photon is used in liberating the electron from the metal surface. It is equal to the work function.**

b) The remaining energy of the photon is used in imparting kinetic energy to the ejected electron.

4. Only those few photons whose energies are greater than the work function is likely to eject the photoelectrons.

EINSTEIN'S PHOTOELECTRIC EQUATION:

If the quantum of energy absorbed by an electron exceeds the minimum energy needed for the electron to escape from the metal surface (work function), the electron is emitted with maximum kinetic energy.

$$\mathbf{KE}_{\mathbf{max}} = \mathbf{h}\nu - \emptyset_{\mathbf{0}}$$

Which means

Maximum kinetic energy of emitted electron + work function = energy of the photon

Or

the energy of the incident photon is distributed between

a) Work function - the energy required by the electron of the photosensitive material to escape the surface
b) The maximum kinetic energy of the emitted electron

This equation is known as Einstein's photoelectric equation.

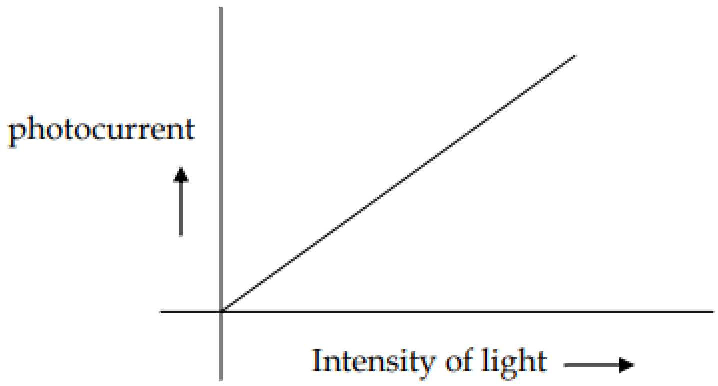
Remember

- **More tightly bound electrons will emerge with kinetic energies less than the maximum value.**
- **The intensity of light of a given frequency is determined by the number of photons incident per second.**
- **Increasing the intensity of radiation will increase the number of emitted electrons per second.**
- **However, the maximum kinetic energy of the emitted photoelectrons is determined by the energy of each photon.**

7. EXPLANATION OF PHOTO ELECTRIC EFFECT ON THE BASIS OF EINSTEIN'S EQUATIONS.

a) EXPLANATION OF EFFECT OF INTENSITY

You will recall the experimental result from the previous module



Intensity of radiation is proportional to the number of energy quanta incident per unit area per unit time.

The greater the number of energy quanta available, the greater is the number of electrons absorbing the energy quanta is greater

Therefore, is the number of electrons coming out of the metal is greater contributing to greater current

This explains why**, photoelectric current is proportional to intensity of incident radiations.**

b) EXPLANATION OF THRESHOLD FREQUENCY

Since K_{max} must be non-negative, it implies that photoelectric emission is possible only if

$$\mathbf{h}\nu > \emptyset_0$$

Or

$$\nu > \nu_0$$

Where

$$\nu_0 = \frac{\emptyset_0}{h}$$

It shows that the greater the work function $\emptyset_0$, the higher the minimum, or threshold frequency, υ_0, needed to emit photoelectrons.

Thus**, there exists a threshold frequency for the metal surface, below** which no photoelectric emission is possible**, no matter how intense the incident radiation may be or how long it falls on the surface.**

c) EXPLANATION OF KINETIC ENERGY OF EMITTED ELECTIONS

According to the equation, K_{max} depends linearly on υ, and is independent of intensity of radiation; this is in agreement with observations.

This is because in Einstein's picture, photoelectric effect arises from the absorption of a single quantum of radiation by a single electron.

The intensity of radiation (that is proportional to the number of energy quanta per unit area per unit time), only decides the number of electrons emitted by the photosensitive surface.

d) EXPLANATION OF NO TIME LAG

In Einstein's picture, the basic elementary process involved in photoelectric effect is the absorption of a light quantum by an electron. This process is **instantaneous.**

Thus, whatever may be the intensity i.e., the number of quanta of radiations per unit area per unit time, photoelectric emission is instantaneous.

Low intensity does not mean delay in emission, since the basic elementary process is the same.

Intensity only determines how many electrons are able to participate in the elementary process (absorption of a light quantum by a single electron) and, therefore, the photoelectric current.

e) DETERMINATION OF PLANCK'S CONSTANT AND WORK FUNCTION

We have Einstein's photo electric equation

$$\mathbf{KE}_{\mathbf{max}} = \mathbf{h}\nu - \emptyset_0$$

or

$$\mathbf{KE}_{\mathbf{max}} = \frac{1}{2} m_e v^2 = \mathbf{h}\nu - \emptyset_0$$

$$\mathbf{KE}_{\mathbf{max}} \text{ is also equal to } \mathbf{e}V_0$$

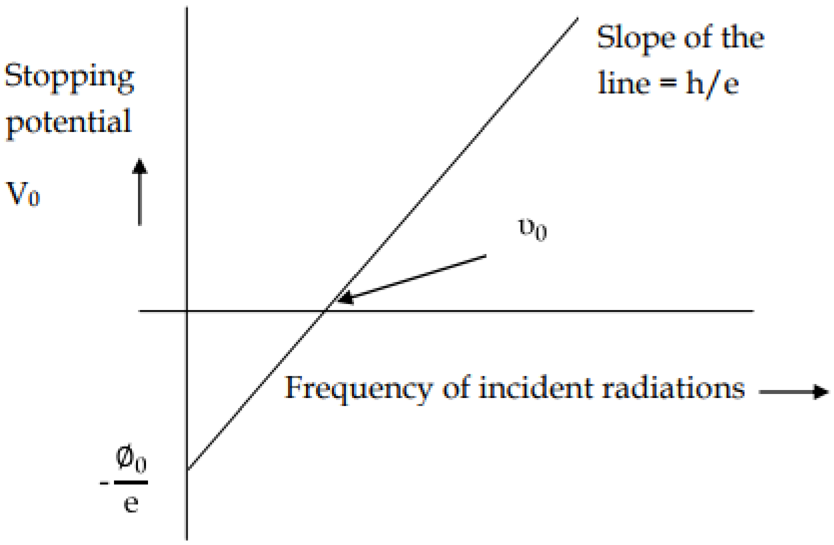
V_0 is the stopping potential eV_0 is the energy gained by an electron when subjected to a potential difference of V_0

The maximum kinetic energy must be equal to this such that the electron is completely stopped by the retarding potential difference applied in the photocell

$$\mathbf{e}V_0 = \mathbf{h}\nu - \emptyset_0$$

For

$$\nu \geq \nu_0$$



$$\therefore V_0 = \left(\frac{h}{e}\right)\nu - \frac{\emptyset_0}{e}$$

This is our equation of the line obtained in the graph

Notice

- **the physical quantities on y and x axis**
- **the slope of the line**
- **the intercept**
- **the sign of the intercept (negative)**
- **the magnitude of frequency for $V_0 = 0$**

It is an **important result**.

The graph shows that

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

(ii) There exists a certain minimum cut-off frequency ν_0 for which the stopping potential is zero. These observations have two implications:

- **(i)** The **maximum kinetic energy of the photoelectrons varies linearly with the frequency of incident radiation, but is independent of its intensity.**
- (ii) For a frequency ν of incident radiation, lower than the cut-off frequency ν_0, no photoelectric emission is possible even if the intensity is large.
- (iii) This minimum, cut-off frequency ν_0, is called the **threshold frequency**. It is different for different metals. Different photosensitive materials respond differently to light.

Selenium is more sensitive than zinc or copper. The same photosensitive substance gives different response to light of different wavelengths. For example, ultraviolet light gives rise to photoelectric effect in copper while green or red light does not.

Note

That in all the above experiments, it is found that, if frequency of the incident radiation exceeds the threshold frequency, the photoelectric emission starts instantaneously without any apparent time lag, even if the incident radiation is very dim. It is now known that emission starts in a time of the order of 10^{-9} s or less.

Using Einstein's equation, we can

a) **Prove that the slope is independent of nature of material -V_0 versus υ (frequency) curve is a straight line with slope = (h/e)**

b) Calculate Work function from the intercept.

c) Calculate Planck's constant from the slope

8. LAWS OF PHOTOELECTRIC EMISSION.

1. **For a given metal, and a given frequency of incident radiation. (Above threshold frequency), the number of photoelectrons emitted per second is proportional to the intensity of incident radiations.**
2. **For a given metal, no photoelectrons are emitted if the incident frequency is less than threshold frequency.**
3. **Above the threshold frequency, the maximum kinetic energy of emitted photoelectrons is directly proportional to the frequency of incident radiations but is independent of the intensity of incident radiations.**
4. **Photoelectric emission is an instantaneous process with a time lag of 10^{-9} s or less.**

9. SOLVING PROBLEMS USING EINSTIEN'S EQUATION

It is important to read the question well and then use the equation

$$KE_{max} = h\nu - \emptyset_0$$

EXAMPLE

Sodium has a work function of 2.3 eV. Calculate

a) **its threshold frequency**
b) **the maximum velocity of photoelectrons produced when sodium is illuminated with light of wavelength 5 x 10^{-7}m**
c) **maximum velocity of emitted electron, when the source is brought close to the sodium surface**
d) **stopping potential with light of this wavelength**

SOLUTION

a) the threshold frequency is given by

$$h\upsilon_0 = \emptyset_0$$

$$6.6 \times 10^{-34}\upsilon_0 = 2.3 \times 1.6 \times 10^{-19}$$

Or

$$\upsilon_0 = 5.6 \times 10^{14}\text{Hz}$$

b) By Einstein's photoelectric equation

$$\text{h}\upsilon = \text{h}\upsilon_0 + \frac{1}{2}\text{mv}^2$$

$$\text{h}\frac{\text{c}}{\lambda} = \emptyset_0 + \frac{1}{2}\text{mv}^2$$

$$\frac{6.6 \times 10^{-34} \times 3 \times 10^8}{5 \times 10^{-7}} = 2.3 \times 1.6 \times 10^{-19} + \frac{1}{2}\text{mv}^2$$

$$\frac{1}{2}\text{mv}^2 = 0.28 \times 10^{-19}$$

Therefor the maximum velocity v of photo electrons is given by

$$\text{v} = \sqrt{\frac{2 \times 0.28 \times 10^{-19}}{9.1 \times 10^{-31}}}$$

$$\text{v} = 2.5 \times 10^5 \text{ m/s}$$

c) Maximum velocity remains the same. Since only intensity increases, the number of electrons per second increases.

d) The stopping potential is given by

$$eV_0 = \frac{1}{2}mv^2$$

$$1.6 \times 10^{-19}V_0 = 0.28 \times 10^{-19}$$

$$\mathbf{V_0 = 0.18V}$$

EXAMPLE

The photoelectric work function for copper is 4.5 eV. Find the maximum energy of the photoelectrons when ultraviolet light of 1.5x 10^{15} Hz falls on copper surface

SOLUTION:

The quantum energy of incident photons, in eV, is

$$hv = \frac{6.63 \times 10^{-34}Js \times 1.5 \times 10^{15}H_z}{1.6 \times 10^{-19}J(eV)^{-1}}$$

$$= 6.2\text{eV}$$

Hence the maximum photoelectron energy is

$$= hv - hv_0 = (6.2 - 4.5)eV = 1.7\ eV$$

EXAMPLE

Find the maximum frequency and wavelength of X-rays produced by 30 kV electrons

SOLUTION

$$\nu_{max} = \frac{E}{h} = \frac{eV}{h} = \frac{1.6 \times 10^{-19} \times 30 \times 10^{3}}{6.63 \times 10^{-34} Js} = 7.24 \times 10^{15} s^{-1}$$

EXAMPLE

Monochromatic light of wavelength 632.8 nm is produced by helium–neon laser. The power emitted is 9.42 mW

a) Find the energy and momentum of each photon in the light beam

b) How many photons arrive at the target in one second?

c) How fast does a hydrogen atom have to travel in order to have the same momentum as the photon?

SOLUTION

a) Energy of each photon =

$$E = \frac{hc}{\lambda} = \frac{6.6 \times 10^{-34} \times 3 \times 10^{8}}{6.328 \times 10^{-7}} = 3.14 \times 10^{-19} J$$

And momentum of each photon

$$p = \frac{E}{c} = \frac{3.14 \times 10^{-19} J}{3 \times 10^{8}} = 1.05 \times 10^{-27} kg - m - s^{-1}$$

b) Number of photon arriving per second at the target

$$n = \frac{power}{energy\ of\ one\ photon} = \frac{9.42 \times 10^{-3}}{3.14 \times 10^{-19}} = 3 \times 10^{16}\ \ photon/second$$

c) We know the mass of hydrogen atom = $1.6 \times 10^{-27} kg$

If the velocity of the atom is v, its momentum = momentum of photon

$= 1.05 \times 10^{-27} kgms^{-1}$

Therefore

$$v = \frac{1.05 \times 10^{-27} kgms^{-1}}{1.6 \times 10^{-27} kg} = 0.63 ms^{-1}$$

EXAMPLE

In an experiment on photoelectric effect, the slope of the cut - off voltage versus frequency of incident light is found to be 4.12x10 $^{-15}$ Vs.

Calculate the value of the Planck's constant

SOLUTION

$$k_{max} = eV_0 = h(\nu - \nu_0)$$

Or

$$V_0 = \frac{h}{e}(\nu - \nu_0)$$

$$\frac{h}{e} = 4.12 \times 10^{-15}$$

$$h = 4.12 \times 10^{-15} \times 1.6 \times 10^{-19} = 6.59 \times 10^{-34} Js$$

EXAMPLE

Monochromatic light of frequency 6.0 ×10^{14} Hz is produced by a laser. The power emitted is 2.0 ×10^{-3} W.

(a) What is the energy of a photon in the light beam?

(b) How many photons per second, on an average, are emitted by the source?

SOLUTION

(a) Each photon has an energy

$$E = h\nu = (6.63 \times 10^{-34} Js)(6.0 \times 10^{14} Hz) = 3.98 \times 10^{-19} J$$

(b) If N is the number of photons emitted by the source per second, the power P transmitted in the beam equals N times the energy per photon E, so that P = N E. Then

$$N = \frac{P}{E} = \frac{2.0 \times 10^{-3} W}{3.98 \times 10^{-19} J} = 5.0 \times 10^{15}\ photons\ per\ second$$

EXAMPLE

The work function of caesium is 2.14 eV. Find

(a) the threshold frequency for caesium, and

(b) the wavelength of the incident light if the photocurrent is brought to zero by a stopping potential of 0.60 V.

SOLUTION

(a) For the cut-off or threshold frequency, the energy $h\nu_0$ of the incident radiation must be equal to work function $\emptyset_0$, so that

$$\nu_0 = \frac{\emptyset_0}{h} = \frac{2.14eV}{6.63 \times 10^{-34}Js}$$

$$= \frac{2.14 \times 1.6 \times 10^{-19}}{6.63 \times 10^{-34}Js} = 5.16 \times 10^{14}Hz$$

Thus, for frequencies less than this threshold frequency, no photoelectrons are ejected.

(b) Photocurrent reduces to zero, when maximum kinetic energy of the emitted photoelectrons equals the potential energy e V_0 by the retarding potential V_0.

Einstein's photoelectric equation is

$$eV_0 = h\nu - \emptyset_0 = \frac{hc}{\lambda} - \emptyset_0$$

Or

$$= \frac{(6.63 \times 10^{-34}Js) \times (3 \times 10^{8}m/s)}{(0.60eV + 2.14eV)}$$

$$= \frac{19.89 \times 10^{-26}J\,m}{(2.74eV)}$$

$$\lambda = \frac{19.89 \times 10^{-26}J\,m}{2.74 \times 1.6 \times 10^{-19}J} = 454\,nm$$

Example

The wavelength of light in the visible region is about 390 nm for violet colour, about 550 nm (average wavelength) for yellow green colour and about 760 nm for red colour.

(a) What are the energies of photons in (eV) at the (i) violet end, (ii) average wavelength, yellow-green colour, and (iii) red end of the visible spectrum? (Take h = 6.63×10–34 J s and 1 eV = 1.6×10 –19J.)

(b) From which of the photosensitive materials with work functions according to the given table

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

and using the results of (i), (ii) and (iii) of (a),

can you build a photoelectric device that operates with visible light?

SOLUTION

(a) Energy of the incident photon, E = hν = hc/λ

$$E = (6.63 \times 10^{-34} Js)(3 \times 10^{8} m/s)/\lambda$$

$$= \frac{1.989 \times 10^{-25}}{\lambda}$$

(i) For violet light, $\lambda_1 = 390\ nm\ (lower\ wavelength\ end)$

Incident photon energy,

$$E_1 = \frac{1.989 \times 10^{-25} Jm}{390 \times 10^{-9} m}$$

$$= 5.10 \times 10^{-19} J$$

$$= \frac{5.10 \times 10^{-19} J}{1.6 \times 10^{-19} J/eV}$$

$$= 3.19\ eV$$

(ii) For yellow-green light, $\lambda_2 = 550\ nm$ (average wavelength)

Incident photon energy,

$$E_2 = \frac{1.989 \times 10^{-25} Jm}{550 \times 10^{-9} m}$$

$$= 3.62 \times 10^{-19} J = 2.26\ eV$$

(iii) For red light $\lambda_3 = 760\ nm$ (higher wavelength end)

Incident photon energy,

$$E_3 = \frac{1.989 \times 10^{-25} Jm}{760 \times 10^{-9} m}$$

$$= 2.62 \times 10^{-19} J = 1.64 eV$$

(a) For a photoelectric device to operate, we require incident light energy E to be equal to or greater than the work function φ0 of the material.

Thus, the photoelectric device will operate with violet light (with E = 3.19 eV) photosensitive material

Na (with φ0 = 2.75 eV),
K (with φ0 = 2.30 eV) and
Cs (with φ0 = 2.14 eV).
It will also operate with yellow-green light (with E = 2.26 eV) for Cs (with φ0 = 2.14 eV) only.
However, it will not operate with red light (with E = 1.64 eV) for any of these photosensitive materials.

EXAMPLE

Light of frequency 7.21x 10^{14} Hz is incident on a metal surface. Electrons with a maximum speed of 6 x 10^{5} m/s are ejected from the surface. What is the threshold frequency for the surface?

SOLUTION

$$k_{max} = eV_0 = h(\nu - \nu_0)$$

$$\nu - \nu_0 = \frac{mv_{max}^2}{2h} = \frac{9.11 \times 10^{-31} \times (6 \times 10^5)^2}{2 \times 6.63 \times 10^{-34}} = 2.48 \times 10^{14}$$

$$\nu_0 = (7.21 \times 10^{14} - 2.48 \times 10^{14})Hz = 4.73 \times 10^{14} Hz$$

One can easily calculate the wavelength of light as well.

10. PHOTOELECTRIC EFFECT AND WAVE THEORY OF LIGHT

The wave nature of light was well established by the end of the nineteenth century. The phenomena of interference, diffraction and polarisation were explained in a natural and satisfactory way by the wave picture of light. According to this picture, 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.

Let us now see if this wave picture of light can explain the observations on photoelectric emission given in the previous section. According to the wave picture of light, the free electrons at the surface of the metal (over which the beam of radiation falls) absorb the radiant energy continuously. The greater the intensity of radiation, the greater are the amplitude of electric and magnetic fields. Consequently, the greater the intensity, the greater should be the energy absorbed by each electron. In this picture, the maximum kinetic energy of the photoelectrons on the surface is then expected to increase with increase in intensity. Also, 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, so that they exceed the minimum energy needed to escape from the metal surface. A threshold frequency, therefore, should not exist. These expectations of the wave theory directly contradict observations.

Further, we should note that in the wave picture, the absorption of energy by electron takes place continuously over the entire wavefront of the radiation. Since a large number of electrons absorb energy, the energy absorbed per electron per unit time turns out to be 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 observation that the photoelectric emission is instantaneous. In short, the wave picture is unable to explain the most basic features of photoelectric emission.

Millikan's first precise measurements confirmed the Einstein's photoelectric equation and obtained an accurate value of Planck's constant h. This led to the acceptance of particle or photon description (nature) of electromagnetic radiation, introduced by Einstein.

11. SUMMARY

In this module we have learnt

- The minimum energy needed by an electron to come out from a metal surface is called the work function of the metal.
- Photoelectric effect is the phenomenon of emission of electrons by metals when illuminated by light of suitable frequency. Certain metals respond to ultraviolet light while others are sensitive even to the visible light.
- Photoelectric effect involves conversion of light energy into electrical energy.
- It follows the law of conservation of energy.
- The photoelectric emission is an instantaneous process and possesses certain special features.
- Photoelectric current depends on
  the intensity of incident light,
  the potential difference applied between the two electrodes, and
  the nature of the emitter material.
- The stopping potential (Vo) depends on $V_0 = \left(\frac{h}{e}\right)\nu - \frac{\phi_0}{e}$
  The frequency of incident light, and the nature of the emitter material for a given frequency of incident light, it is independent of its intensity.
  The stopping potential is directly related to the maximum kinetic energy of electrons emitted
- Below a certain frequency (threshold frequency) ν_0, characteristic of the metal, no photoelectric emission takes place, no matter how large the intensity may be.
- The classical wave theory could not explain the main features of photoelectric effect. Its picture of continuous absorption of energy from radiation could not explain the

independence of K_{max} on intensity, the existence of ν o and the instantaneous nature of the process.

- Einstein explained these features on the basis of photon picture of light. According to this, light is composed of discrete packets of energy called quanta or photons
- Each photon carries an energy E (= h ν) and momentum p (= h/λ), which depend on the frequency (ν) of incident light and not on its intensity.
- Photoelectric emission from the metal surface occurs due to absorption of a photon by an electron.
- Einstein's photoelectric equation is in accordance with the energy conservation law as applied to the photon absorption by an electron in the metal.
- The maximum kinetic energy

KE_{max} is equal to the photon energy (hν) minus the work function φ_0 (= $h\nu_0$) of the

target metal:

$$\mathbf{KE}_{\mathbf{max}} = \frac{1}{2} m_e v^2 = \mathbf{h\nu} - \emptyset_0$$

- This photoelectric equation explains all the features of the photoelectric effect.
- **Millikan's first precise measurements confirmed the Einstein's photoelectric equation and obtained an accurate value of Planck's constant h. This led to the acceptance of particle or photon description (nature) of electromagnetic radiation, introduced by Einstein.**