CHAPTER 11
DUAL NATURE OF MATTER AND RADIATION

TOPICS TO BE COVERED

ELECTRON EMISSION

Metals have free electrons (negatively charged particles) that are moving randomly inside the metal. However, the free electrons cannot normally escape out of the metal surface. If an electron attempts to come out of the metal, the metal surface acquires a positive charge and pulls the electron back to the metal.

When the electrons absorb sufficient energy from an external source they can come out of the metal surface.

Methods of Electron Emission

1.Thermionic emission: By suitably heating,sufficient thermal energy can be imparted to the free electrons.

2. Field emission: By applying a very strong electric field (of the order of 10 8 V/m) to a metal, electrons can be pulled out of the metal.

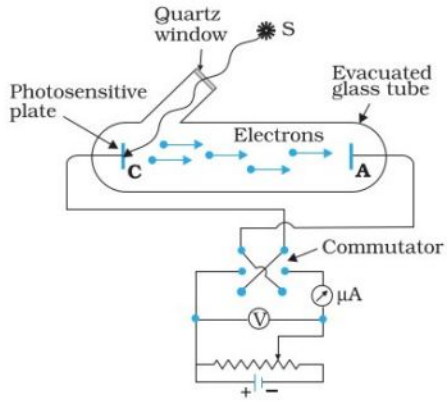
3. Secondary emission: Fast moving electrons on collision with metal atoms; eject electrons by transferring their kinetic energy.

4. Photo-electric emission: When light(radiation) of suitable frequency illuminate on a metal surface, electrons are emitted from the metal surface. This phenomenon is called **photo electric effect**. This was observed by **Heinrich Hertz in 1887.**

Work Function(Φ_0)

The minimum energy required to eject an electron from the metal surface is called the work function. The work function, Φ_0 depends on the properties of the metal and the nature of its surface.

EXPERIMENTAL STUDY OF PHOTO ELECTRIC EFFECT



- It consists of an evacuated glass/quartz tube having a photosensitive plate C and another metal plate A.
- Monochromatic light from the source S passes through the window W and falls on the photosensitive plate C (emitter).
- A transparent quartz window permits ultraviolet radiation to pass through it and irradiate the photosensitive plate C.
- The electrons are emitted by the plate C and are collected by the plate A (collector), by the electric field created by the battery.
- The polarity of the plates C and A can be reversed by a commutator.
- The potential difference between the emitter and collector can be varied and is measured by a voltmeter (V), the resulting photo current flowing in the circuit is measured by a micro ammeter (μA).

Experiment 1:

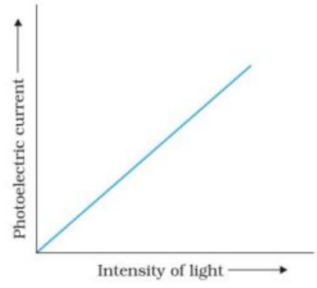
Vary the intensity of incident radiation by keeping frequency fixed.

Observation

Photoelectric current increases with increase in intensity of light.

Explanation

The number of photoelectrons emitted per second is directly proportional to the intensity of incident radiation



Experiment 2

keep the plate A at some positive accelerating potential with respect to plate C and illuminate plate C with uv radiation of fixed frequency, ν

and fixed intensity(I). We next increase the positive potential of the plate 'A' and measure the photocurrent each time.

Observation

It is found that the photo current increases and finally
saturates. This **maximum value of photoelectric current for a particular intensity of incident radiation is called saturation current.**

Explanation

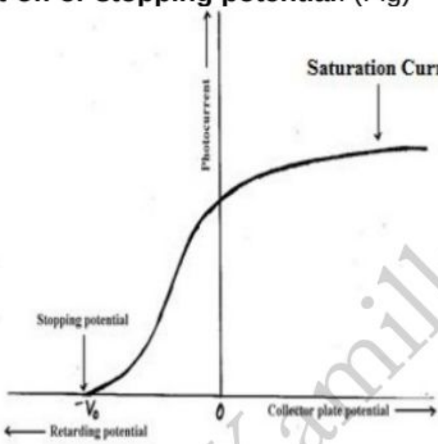
Saturation current corresponds to the case when all the photoelectrons emitted by the emitter plate C reach the collector plate A. (Fig)

Experiment 3

Apply a negative (retarding) potential to the plate A with respect to the plate C and make it increasingly negative gradually.

Observation

The photo current is found to decrease. And at a particular retarding potential V_0 photocurrent is completely stopped. **The minimum retarding potential of the collector plate at which the photocurrent stops or becomes zero is called the cut-off or stopping potential**. (Fig)



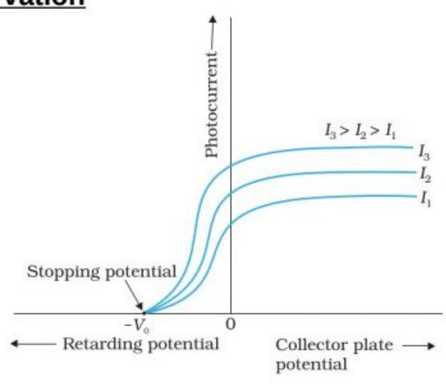
Explanation

At stopping potential, $eV_0 = KE_{max}$

Experiment 4

Potential –photo current graph (for different intensities with fixed frequency)

Observation

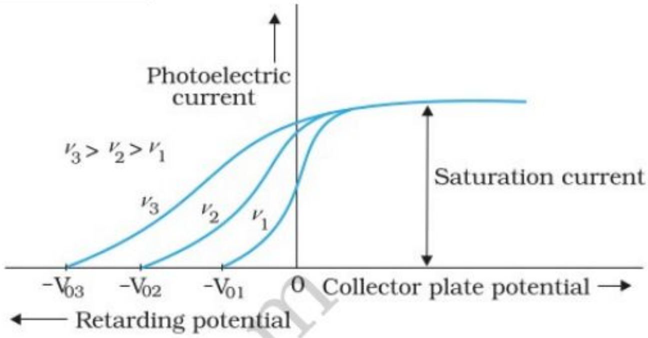


stopping potential is independent of the intensity of incident light. But the photoelectric current (saturation current) increases with intensity of incident light.

Experiment 5

Potential –photo current graph (for fixed intensity with different frequencies)

Observation



The stopping potential increases with increase in frequency of incident light.

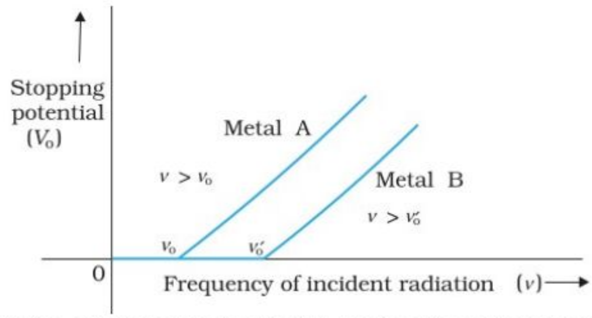
Explanation

The K.E. of the emitted photoelectrons increases with increase in frequency of incident radiation. As the K.E. of the photoelectrons increases, the stopping potential increases. $eV_0 = KE_{max}$

Experiment 6

Variation of Stopping Potential with frequency of incident light

Observation



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

(ii) There exists a minimum cut-off frequency ν_0 for which the stopping potential is zero.

Explanation

There exist a minimum frequency(cut off frequency) for incident radiation below which no photo electric effect occur.

Laws of photoelectric emission

- The photoelectric current is directly proportional to the intensity of incident light and is independent of the frequency.

- Kinetic energy (stopping potential) of emitted photo electrons depends on the frequency and does not depend on intensity of radiation.
- For each metal there is a threshold frequency, below which no photoelectron emission is possible.
- The photoelectric emission is an instantaneous process.

PHOTO ELECTRIC EFFECT AND WAVE THEORY OF LIGHT

Photoelectric effect cannot be explained using wave theory due to following reasons.

1. Greater the intensity of incident radiation, greater will be the amplitude of the wave. When amplitude of wave increases the energy density of the wave increases. Thus a high intensity light contains high energy waves and can emit photoelectrons of greater kinetic energy. Therefore, by the wave concept the K.E. of the photoelectrons should depend on the intensity of incident radiation. But experiments show that KE of photoelectron does not depend on the intensity of incident radiation but depends on the frequency.

2. When we consider the wave concept, even low frequency wave can produce photoelectric effect if the intensity is greater. Thus threshold frequency should not exist. But experiments show that there is a threshold frequency.

3. If light is a wave, the electron in the metal surface can absorb energy continuously from the wave front. But the energy absorbed per unit time is very small. Therefore, it takes a long time (hours) for a single electron to absorb sufficient energy to escape from the metal surface. But experimental observations show that photoelectric effect is instantaneous.

EINSTEIN'S EXPLANATION OF PHOTO ELECTRIC EFFECT

Einstein explained photoelectric effect based on Max Planck's quantum theory. According to quantum theory, light contain photons having energy hν.

- When a photon of energy hν is incident on a metal surface, electrons are emitted.
- A part of the photon energy is used as the work function and the remaining part of the photon energy appears as the kinetic energy of photoelectrons.

Einstein's photoelectric equation

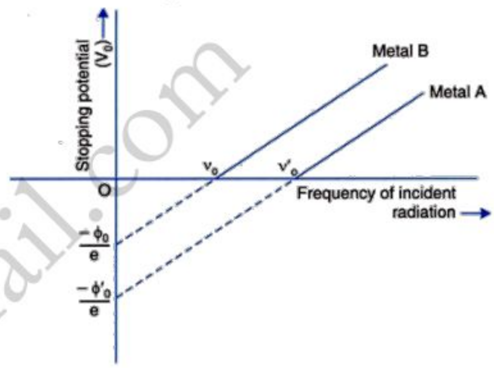
Photon Energy = Work function + maximum K.E. of photoelectron.

Ie, $$\boxed{h\nu = \phi_0 + KE_{max}}$$

=> $$h\nu = h\nu_0 + KE_{max}$$

=> $$\boxed{KE_{max} = h\nu - h\nu_0}$$

Frequency - stopping potential(KE_{max}) graph (for different metals)



We know $KE_{max} = h\nu - \phi_0$ => $eV_0 = h\nu - \phi_0$

=> $$V_0 = \frac{h\nu}{e} - \frac{\phi_0}{e}$$

It predicts that the V 0 versus ν curve is a straight line with slope = (h/e), independent of the nature of the material and y intercept $\frac{-\phi_0}{e}$

PARTICLE NATURE OF LIGHT

In interaction of radiation with matter, radiation behaves as if it is made up of particles called photons.

Properties of Photons

- Each photon has energy $\boxed{E = h\nu}$ and momentum $\boxed{p = \frac{h\nu}{c}}$ and speed c, the speed of light.
- All photons of light of a particular frequency ν, or wavelength λ, have the same energy E (=hν = hc/λ) and momentum p (= hν/c = h/λ), independent of intensity of light.

- By increasing the intensity of light of given wavelength, there is only an increase in the number of photons per second crossing a given area, with each photon having the same energy.

- The photon energy is independent of intensity of radiation.

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

Example 11.1 NCERT

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

$E = h\nu$ = (6.63×10^{-34} J s) (6.0×10^{14} Hz)

= 3.98×10^{-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

$$N = \frac{P}{E} = \frac{2.0 x 10^3 W}{3.98 x 10^{-19} J}$$

= 5.0×10^{15} photons per second.

Example 11.2 NCERT

The work function of caesium is 2.14 eV. Find (a) the threshold frequency for caesium

Solution

(a) For the cut-off or threshold frequency, the energy $h\nu_0$ of the incident radiation must be equal to work function, ϕ_0 so that $\nu_0 = \frac{\phi_0}{h}$

=> $$\nu_0 = \frac{2.14 eV}{6.63 x 10^{-34} J s}$$

=> $$\nu_0 = \frac{2.14 x 1.6 x 10^{-19} J}{6.63 x 10^{-34} J s} = 5.6 x 10^{34} Hz$$

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

Dual nature of radiation

Radiation has wave nature as well as particle nature. This is called the dual nature of radiation.

WAVE NATURE OF MATTER

De Broglie wave (Matter wave)

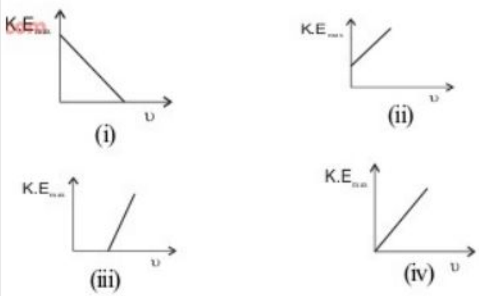
Louis De Broglie guessed that particles have wave nature.The waves associated with material particles are called matter waves or De Broglie waves.

The wave length λ associated with a particle of momentum p is given as $\lambda = \frac{h}{p} = \frac{h}{mv}$

The above equation is known as the de Broglie relation and the wavelength λ of the matter wave is called de Broglie wavelength.

PREVIOUS QUESTIONS

1.	The work function of caesium metal is 2.14 eV. When light of frequency 6×10^{14} Hz is incident on the metal surface, photoemission of electrons occurs. (h=6 .6 x 10^{-34}Js)	
a)	Define work function.	1
b)	Calculate the maximum kinetic energy of the emitted electrons.	1
c)	Calculate the stopping potential.	2
2.a)	Write Einstein's photoelectric equation.	1
b)	Using this equation show that, "photoelectric emission is not possible if the frequency of incident radiation is less than threshold frequency".	2
3.	Explain work function.	2
4.a)	Write Einstein's photoelectric equation.	1
b)	Monochromatic light of frequency 6×10^{14} Hz is produced by a Laser. The power emitted is 2×10^{-3} W. How many photons per second on an average are emitted by the source ? (h=6 .6 x 10^{-34}Js).	2
5.	The minimum energy required by an electron to escape from the metal surface is called	
6.	What is stopping potential ?	2
7.a)	State any two laws of photoelectric	2

b)	emission. What is work function ?	1
8.a)	A photosensitive surface has a work function of 2.00 eV. Find the maximum kinetic energy of electrons ejected from this surface by radiation of wavelength 300 nm. ($h=6.6 \times 10^{-34}$Js).	2
b)	Which one of the following is the correct graph showing the variation between the maximum kinetic energy (K.E.max) of the emitted photoelectrons and the frequency of incident radiation (ν) for a givenphotosensitive surface ? 	1