

# Dual Nature of Radiation and Matter

---

## Case Study Based Questions

### Case Study 1

The discovery of the phenomenon of photoelectric effect has been one of the most important discoveries in modern science. The experimental observations associated with this phenomenon made us realise that our, 'till then', widely accepted picture of the nature of light. The electromagnetic (wave) theory of light was quite inadequate to understand this phenomenon. A new picture of light was needed and it was provided by Einstein through his 'photon theory' of light. This theory, regarded light as a stream of particles. Attempts to understand photoelectric effect thus led us to realise that light, which was being regarded as 'waves', could also behave like 'particles'. This led to the idea of 'wave-particle duality' vis-à-vis the nature of light. Attempts to understand this 'duality' and related phenomenon, led to far reaching and very important developments, in the basic theories of Physics.

Read the given passage carefully and give the answer of the following questions:

**Q1. Which of the following phenomenon explain the wave nature of light?**

- a. Interference
- b. Diffraction
- c. Polarisation
- d. All of these

**Q2. Wave-particle duality is shown by:**

- a. light only
- b. matter only
- c. Both a. and b.
- d. None of these

**Q3. The experiment to explain the wave nature of light i.e., electromagnetic wave theory is given by:**

- a. Hertz
- b. Einstein
- c. Lenard
- d. Huygens'

**Q4. The concept of photoelectric effect given by Einstein explains that the light is a:**

- a. photon
- b. wave
- c. particle
- d. Both b. and c.

## Solutions

1. (d) All of these
2. (a) Hertz
3. (c) Both a. and b.
4. (c) particle

## Case Study 2

Lenard observed that when ultraviolet radiations were allowed to fall on the emitter plate of an evacuated glass tube, enclosing two electrodes (metal plates), current started flowing in the circuit connecting the plates. As soon as the ultraviolet radiations were stopped, the current flow also stopped. These observations proved that it was ultraviolet radiation, falling on the emitter plate, that ejected some charged particles from the emitter and the positive plate attracted them.

Read the given passage carefully and give the answer of the following questions:

**Q1. Why do we not observe the phenomenon of photoelectric effect with non-metals?**

- a. For non-metals the work function is high
- b. Work function is low
- c. Work function can not be calculated
- d. For non-metals, threshold frequency is low

**Q2. What is the effect of intensity on photoelectric current?**

- a. It increases
- b. It decreases
- c. There is no change
- d. It varies with the square of intensity

**Q3. Name one factor on which the stopping potential depends.**

- |                  |                     |
|------------------|---------------------|
| a. Work function | b. Frequency        |
| c. Current       | d. Energy of photon |

**Q4. How does the maximum KE of the electrons emitted vary with the work function of metal?**

- a. It doesn't depend on work function
- b. It decreases as the work function increases
- c. It increases as the work function increases
- d. Its value is doubled with the work function

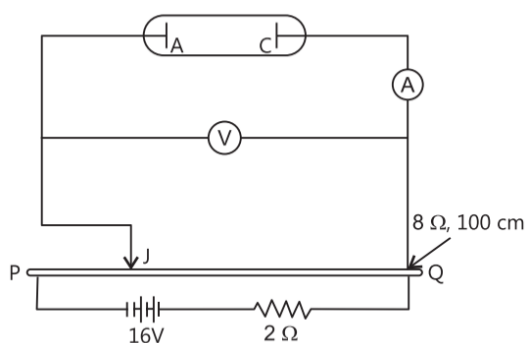
### Solutions

- 1. (a) For non-metals the work function is high
- 2. (a) It increases
- 3. (b) Frequency
- 4. (b) It decreases as the work function increases

### Case Study 3

An experimental setup of verification of photoelectric effect is shown in figure. The voltage across the electrodes is measured with the help of an ideal voltmeter and which can be varied by moving jockey  $J$  on the potentiometer wire. The battery used in potentiometer circuit is of 16V and its internal resistance is  $2\ \Omega$ .

The resistance of 100 cm long potentiometer wire is  $8\ \Omega$ .



The photocurrent is measured with the help of an ideal ammeter. Two plates of potassium oxide of area  $50\text{ cm}^2$  at separation  $0.5\text{ mm}$  are used in the vacuum tube. Photocurrent in the circuit is very small, so we can treat the potentiometer circuit as an independent circuit.

The wavelength for different colours of light are tabulated as:

Light	$\lambda$ (in Å)
Violet	4000-4500
Blue	4500-5000
Green	5000-5500
Yellow	5500-6000
Orange	6000-6500
Red	6500-7000

Read the given passage carefully and give the answer of the following questions:

- Q 1.** When radiation falls on the cathode plate, a current of  $2\mu\text{A}$  is recorded in the ammeter. Assuming that the vacuum tube setup follows Ohm's law, then what is the equivalent resistance of vacuum tube operating in the case when jockey is at end  $P$ ?
- Q 2.** It is found that ammeter current remains unchanged ( $2\mu\text{A}$ ) even when the jockey is moved from the end  $P$  to the middle point of the potentiometer wire. Assuming that all the incident photons eject electrons and the power of the light incident is  $4 \times 10^{-6}\text{ W}$ . Then what is the colour of the incident light?
- Q 3.** Which colour may not give photoelectric effect for this cathode?
- Q 4.** When other light falls on the anode plate, the ammeter reading is zero till jockey is moved from the end  $P$  to the middle point of the wire  $PQ$ . Therefore, the deflection is recorded in the ammeter. What is the maximum kinetic energy of the emitted electron?

## Solutions

1. Equivalent resistance,  $R = \frac{V}{I} = \frac{16}{2 \times 10^{-6}}$   
 $= 8 \times 10^6 \Omega = 8 \text{ M}\Omega$

2. Since  $p = \frac{h\nu}{\lambda e}$

$$\therefore \lambda = \frac{(2 \times 10^{-6})(6.6 \times 10^{-34})(3 \times 10^8)}{(4 \times 10^{-6})(1.6 \times 10^{-19})}$$

$$= \frac{9.9}{1.6} \times 10^{-7} \text{ m} = \frac{9900}{1.6} \text{ \AA} = 6187 \text{ \AA}$$

Which is in the range of orange light.

3. The range of wavelength for red light is beyond the wavelength of incident light.
4. Stopping potential,  $V_s = 8\text{V}$   
and  $\text{KE}_{\text{max}} = eV_s$   
 $\therefore \text{KE}_{\text{max}} = 8 \text{ eV}$

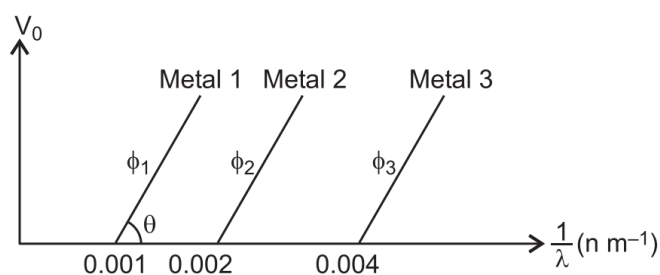
### Case Study 4

According to Einstein, when a photon of light of frequency  $\nu$  and wavelength  $\lambda$  is incident on a photosensitive metal surface of work function  $\phi_0$ , where  $\phi_0 < h\nu$  (here,  $h$  is Planck's constant), then the emission of photoelectrons takes place.

The maximum kinetic energy of the emitted photoelectrons is given by  $K_{\text{max}} = h\nu - \phi_0$ . If the frequency of the incident light is  $\nu_0$  called threshold frequency, the photoelectrons are emitted from metal without any kinetic energy. So,  $h\nu_0 = \phi_0$ .

Read the given passage carefully and give the answer of the following questions:

- Q 1. A metal of work function 3.3 eV is illuminated by light of wavelength 300 nm. What is the maximum kinetic energy of photoelectrons emitted (taking  $h = 6.6 \times 10^{-34} \text{ Js}$ )?
- Q 2. Show the variation of maximum kinetic energy ( $K_{\text{max}}$ ) of the emitted photoelectrons with frequency ( $\nu$ ) of the incident radiations.
- Q 3. The graph between the stopping potential ( $V_0$ ) and  $\left(\frac{1}{\lambda}\right)$  is shown in the figure.



$\phi_1, \phi_2, \phi_3$  are work function. What will be the ratio in  $\phi_1, \phi_2$  and  $\phi_3$ ?

**Q4. Show the graph to represent variation of particle and the associated de-Broglie momentum wavelength?**

### Solutions

**1. Maximum Kinetic Energy,**

$$\begin{aligned}
 K_{\max} &= h\nu - \phi_0 = \frac{hc}{\lambda} - \phi_0 \\
 &= \frac{(6.6 \times 10^{-34}) \times (3 \times 10^8)}{(300 \times 10^{-9})} - 3.3 \times 1.6 \times 10^{-19} \\
 &= 6.6 \times 10^{-19} - 3.3 \times 1.6 \times 10^{-19} \\
 &= 1.6 \times 10^{-19} (4.125 - 3.3) \\
 &= 1.6 \times 10^{-19} \times 0.825 \\
 &= 0.825 \text{ eV}
 \end{aligned}$$

**2. We know,  $K_{\max} = h\nu - \phi_0$ , when  $\nu = \nu_0$ ,  $K_{\max} = 0$**

$$\therefore 0 = h\nu_0 - \phi_0 \text{ or } \phi_0 = h\nu_0$$

If  $\nu < \nu_0$ , then  $K_{\max}$  is negative

i.e., no photoelectric emission takes place.

The variation of maximum kinetic energy ( $K_{\max}$ ) of the emitted photoelectron with frequency ( $\nu$ ) is shown in figure.



**3. From Einstein's photoelectric equation,**

$$K_{\max} = eV_0 = \frac{hc}{\lambda} - \phi$$

$$\text{or } V_0 = \frac{hc}{e} \cdot \frac{1}{\lambda} - \frac{\phi}{e}$$

Graph of  $V_0$  versus  $\frac{1}{\lambda}$  is a straight line.

Slope of straight line,  $\tan \theta = \frac{hc}{e}$

At  $V_0 = 0$ , we have

$$\phi_1 : \phi_2 : \phi_3 = \frac{hc}{\lambda_{01}} : \frac{hc}{\lambda_{02}} : \frac{hc}{\lambda_{03}}$$

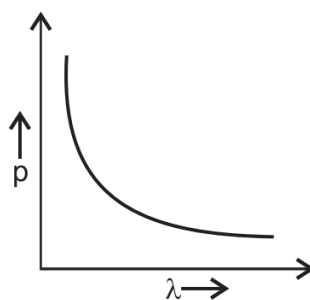
$$= 0.001 hc : 0.002 hc : 0.004 hc$$

$$\therefore \phi_1 : \phi_2 : \phi_3 = 1 : 2 : 4$$

4. de-Broglie wavelength

$$\lambda = \frac{h}{p} \text{ i.e., } \lambda \propto \frac{1}{p}$$

So, the graph between  $\lambda$  and  $p$  is shown in figure:



## Solutions for Questions 5 to 14 are Given Below

### Case Study 5

#### Photoelectric Effect

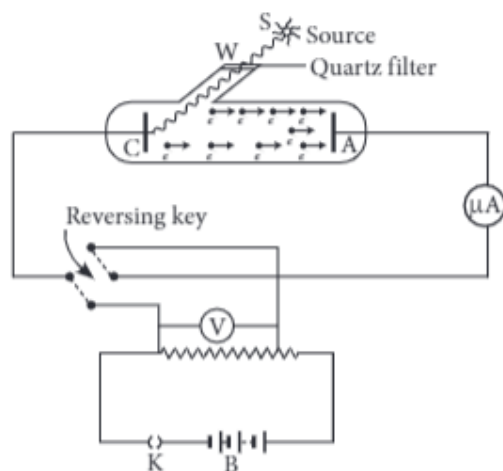
Photoelectric effect is the phenomenon of emission of electrons from a metal surface, when radiations of suitable frequency fall on them. The emitted electrons are called photoelectrons and the current so produced is called photoelectric current.

- (i) With the increase of intensity of incident radiations on photoelectrons emitted by a photo tube, the number of photoelectrons emitted per unit time is
  - (a) increases
  - (b) decreases
  - (c) remains same
  - (d) none of these
- (ii) It is observed that photoelectron emission stops at a certain time  $t$  after the light source is switched on. The stopping potential ( $V$ ) can be represented as
  - (a)  $2(KE_{\max}/e)$
  - (b)  $(KE_{\max}/e)$
  - (c)  $(KE_{\max}/3e)$
  - (d)  $(KE_{\max}/2e)$
- (iii) A point source of light of power  $3.2 \times 10^{-3}$  W emits monoenergetic photons of energy 5.0 eV and work function 3.0 eV. The efficiency of photoelectron emission is 1 for every  $10^6$  incident photons. Assume that photoelectrons are instantaneously swept away after emission. The maximum kinetic energy of photon is
  - (a) 4 eV
  - (b) 5 eV
  - (c) 2 eV
  - (d) Zero
- (iv) Which of the following device is the application of Photoelectric effect?
  - (a) Light emitting diode
  - (b) Diode
  - (c) Photocell
  - (d) Transistor
- (v) If the frequency of incident light falling on a photosensitive metal is doubled, the kinetic energy of the emitted photoelectron is
  - (a) unchanged
  - (b) halved
  - (c) doubled
  - (d) more than twice its initial value

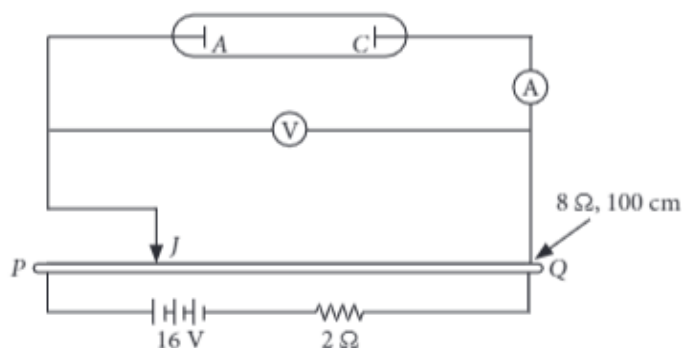
## Case Study 6

### Photocurrent

When a monochromatic radiations of suitable frequency obtained from source  $S$ , after being filtered by a filter attached on the window  $W$ , fall on the photosensitive place  $C$ , the photo electrons are emitted from  $C$ , which get accelerated towards the plate  $A$  if it is kept at positive potential. These electrons flow in the outer circuit resulting in photoelectric current. Due to it, the microammeter shows a deflection. The reading of micrommeter measures the photoelectric current.



An experimental setup of verification of photoelectric effect is shown in figure. The voltage across the electrodes is measured with the help of an ideal voltmeter, and which can be varied by moving jockey  $J$  on the potentiometer wire. The battery used in potentiometer circuit is of 16 V and its internal resistance is  $2\ \Omega$ . The resistance of 100 cm long potentiometer wire is  $8\ \Omega$ .



The photocurrent is measured with the help of an ideal ammeter. Two plates of potassium oxide of area  $50\text{ cm}^2$  at separation  $0.5\text{ mm}$  are used in the vacuum tube. Photocurrent in the circuit is very small, so we can treat the potentiometer circuit as an independent circuit.

Light	1 Violet	2 Blue	3 Green	4 Yellow	5 Orange	6 Red
$\lambda$ (in $\text{\AA}$ )	4000 – 5000	4500 – 5000	5000 – 5500	5500 – 6000	6000 – 6500	6500 – 7000

- (i) When radiation falls on the cathode plate, a current of  $2\ \mu\text{A}$  is recorded in the ammeter. Assuming that the vacuum tube setup follows Ohm's law, the equivalent resistance of vacuum tube operating in the case when jockey is at end  $P$  is

- (a)  $8 \times 10^8\ \Omega$       (b)  $16 \times 10^6\ \Omega$       (c)  $8 \times 10^6\ \Omega$       (d)  $10 \times 10^6\ \Omega$

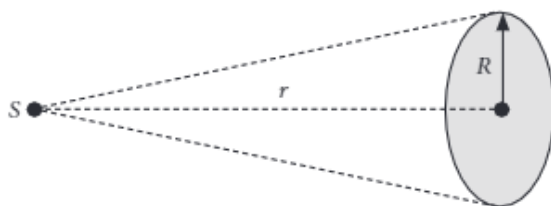


- (ii) It is found that ammeter current remains unchanged ( $2\ \mu\text{A}$ ) even when the jockey is moved from the end  $P$  to the middle point of the potentiometer wire. Assuming that all the incident photons eject electrons and the power of the light incident is  $4 \times 10^{-6}\ \text{W}$ . Then, the color of the incident light is
- (a) Green (b) Violet (c) Red (d) Orange
- (iii) Which of the following colors may not give photoelectric effect for this cathode?
- (a) Green (b) Violet (c) Red (d) Orange
- (iv) When other light falls on the anode plate, the ammeter reading zero till jockey is moved from the end  $P$  to the middle point of the wire  $PQ$ . Therefore, the deflection is recorded in the ammeter. The maximum kinetic energy of the emitted electron is
- (a) 16 eV (b) 8 eV (c) 4 eV (d) 10 eV
- (v) If the intensity of incident radiation is increased twice, the number of photoelectrons emitted per second will be
- (a) halves (b) double (c) remain same (d) four times

## Case Study 7

### Experimental Study of Photoelectric Effect

A point source  $S$  of power  $6.4 \times 10^{-3}\ \text{W}$  emits mono energetic photons each of energy 6.0 eV. The source is located at a distance of 0.8 m from the centre of a stationary metallic sphere of work function 3.0 eV and of radius  $1.6 \times 10^{-3}\ \text{m}$  as shown in figure. The sphere is isolated and initially neutral and photoelectrons are instantly taken away from sphere after emission. The efficiency of photoelectric emission is one for every  $10^5$  incident photons.



- (i) The power received by the sphere through radiations is
- (a)  $\frac{4R^2}{Pr}$  (b)  $\frac{PR^2}{4r^2}$  (c)  $\frac{P^2R}{2\pi r}$  (d)  $\frac{PR}{4r}$
- (ii) Number of photons striking the metal sphere per second is
- (a)  $6.7 \times 10^9$  (b)  $3.3 \times 10^9$  (c)  $6.7 \times 10^{10}$  (d)  $3.3 \times 10^{10}$
- (iii) The number of photoelectrons emitted per second is about
- (a)  $3.3 \times 10^4$  (b)  $6.7 \times 10^4$  (c)  $6.7 \times 10^{15}$  (d)  $3.3 \times 10^{15}$
- (iv) The photoelectric emission stops when the sphere acquires a potential about
- (a) 2 V (b) 3 V (c) 4 V (d) 6 V
- (v) If the distance of source becomes double from the centre of the metal sphere then the power received by the sphere
- (a)  $\frac{PR^2}{4r^2}$  (b)  $\frac{PR^2}{16r^2}$  (c)  $\frac{PR^2}{4r}$  (d)  $\frac{P^2R^2}{16r^2}$

## Case Study 8

### Einstein Theory

According to Einstein, when a photon of light of frequency  $\nu$  or wavelength  $\lambda$  is incident on a photosensitive metal surface of work function  $\phi_0$ , where  $\phi_0 < h\nu$  (here,  $h$  is Planck's constant), then the emission of photoelectrons takes place. The maximum kinetic energy of the emitted photoelectrons is given by  $K_{\max} = h\nu - \phi_0$ . If the frequency of the incident light is  $\nu_0$  called threshold frequency, the photoelectrons are emitted from metal without any kinetic energy. So  $h\nu_0 = \phi_0$ .

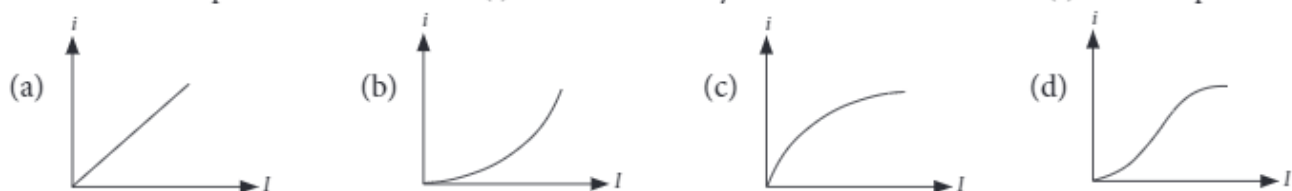
- (i) A metal of work function 3.3 eV is illuminated by light of wavelength 300 nm. The maximum kinetic energy of photoelectrons emitted is (taking  $h = 6.6 \times 10^{-34}$  Js)

(a) 0.413 eV                      (b) 0.825 eV                      (c) 1.65 eV                      (d) 1.32 eV

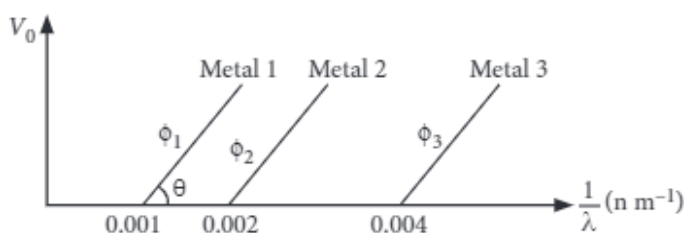
- (ii) The variation of maximum kinetic energy ( $K_{\max}$ ) of the emitted photoelectrons with frequency ( $\nu$ ) of the incident radiations can be represented by



- (iii) The variation of photoelectric current ( $i$ ) with the intensity of the incident radiation ( $I$ ) can be represented by



- (iv) The graph between the stopping potential ( $V_0$ ) and  $\left(\frac{1}{\lambda}\right)$  is shown in the figure.  $\phi_1, \phi_2, \phi_3$  are work function. Which of the following options is correct?



- (a)  $\phi_1 : \phi_2 : \phi_3 = 1 : 2 : 3$   
 (b)  $\phi_1 : \phi_2 : \phi_3 = 4 : 2 : 1$   
 (c)  $\phi_1 : \phi_2 : \phi_3 = 1 : 2 : 4$   
 (d) Ultraviolet light can be used to emit photoelectrons from metal 2 and metal 3 only
- (v) Which of the following figures represent the variation of particle momentum and the associated de-Broglie wavelength?



## Case Study 9

### Photoelectric Emission

When light of sufficiently high frequency is incident on a metallic surface, electrons are emitted from the metallic surface. This phenomenon is called photoelectric emission. Kinetic energy of the emitted photoelectrons depends on the wavelength of incident light and is independent of the intensity of light. Number of emitted photoelectrons depends on intensity.  $(h\nu - \phi)$  is the maximum kinetic energy of emitted photoelectrons (where  $\phi$  is the work function of metallic surface). Reverse effect of photo emission produces X-ray. X-ray is not deflected by electric and magnetic fields. Wavelength of a continuous X-ray depends on potential difference across the tube. Wavelength of characteristic X-ray depends on the atomic number.

(i) Einstein's photoelectric equation is

(a)  $E_{\max} = h\nu - \phi$       (b)  $E = mc^2$       (c)  $E^2 = p^2c^2 + m_0^2c^4$       (d)  $E = \frac{1}{2}mv^2$

(ii) Light of wavelength  $\lambda$  which is less than threshold wavelength is incident on a photosensitive material. If incident wavelength is decreased so that emitted photoelectrons are moving with some velocity then stopping potential will

- (a) increase      (b) decrease      (c) be zero      (d) become exactly half

(iii) When ultraviolet rays incident on metal plate then photoelectric effect does not occur, it occur by incident of

- (a) Infrared rays      (b) X-rays      (c) Radio wave      (d) Micro wave

(iv) If frequency ( $\nu > \nu_0$ ) of incident light becomes  $n$  times the initial frequency ( $\nu$ ), then K.E. of the emitted photoelectrons becomes ( $\nu_0$  threshold frequency).

- (a)  $n$  times of the initial kinetic energy  
(b) More than  $n$  times of the initial kinetic energy  
(c) Less than  $n$  times of the initial kinetic energy  
(d) Kinetic energy of the emitted photoelectrons remains unchanged

(v) A monochromatic light is used in a photoelectric experiment. The stopping potential

- (a) Is related to the mean wavelength      (b) Is related to the shortest wavelength  
(c) Is not related to the minimum kinetic energy of emitted photoelectrons  
(d) Intensity of incident light

## Case Study 10

### Electromagnetic Radiation

If we allow radiations of a fixed frequency to fall on plate and the accelerating potential difference between the two electrodes is kept fixed, then the photoelectric current is found to increase linearly with the intensity of incident radiation. Here, radiation pressure is  $P = \left(\frac{1+e}{C}\right)I$ . As, atmosphere pressure at sea level is  $10^5\text{Pa}$ .

If the intensity of light of a given wavelength, is increased, there is an increase in the number of photons incident on a given area in a given time. But the energy of each photon remain the same.

(i) The number of photons hitting the cone second

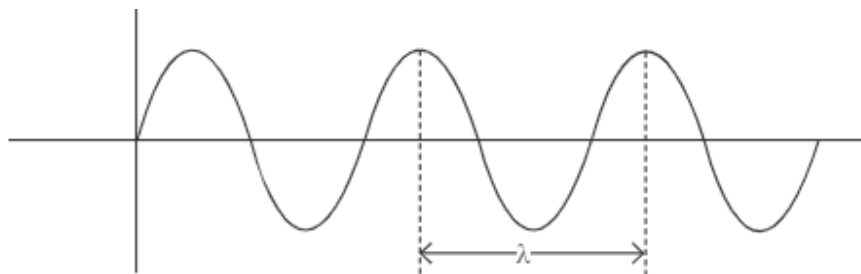
- (a)  $\pi R^2 I / 2E$       (b)  $2\pi R^2 I / E$       (c)  $\pi R^2 I / 4E$       (d)  $\pi R^2 I / E$

- (ii) A radiation of energy  $E$  falls normally on a perfect reflecting surface. The momentum transferred to the surface is
- (a)  $\frac{E}{c}$  (b)  $\frac{2E}{c}$  (c)  $Ec$  (d)  $\frac{E}{c^2}$
- (iii) Which one is correct?
- (a)  $E^2 = p^2 c^2$  (b)  $E^2 = p^2 c$  (c)  $E^2 = p^2$  (d)  $E^2 = \frac{p^2}{c^2}$
- (iv) The incident intensity on a horizontal surface at sea level from the Sun is about  $1 \text{ k W m}^{-2}$ . Assuming that 50% of this intensity is reflected and 50% is absorbed, determine the radiation pressure on this horizontal surface.
- (a)  $8.2 \times 10^{-2} \text{ Pa}$  (b)  $5 \times 10^{-6} \text{ Pa}$  (c)  $3 \times 10^{-5} \text{ Pa}$  (d)  $6 \times 10^{-5} \text{ Pa}$
- (v) Find the ratio of radiation pressure to atmospheric pressure  $P_0$  about  $1 \times 10^5 \text{ Pa}$  at sea level.
- (a)  $5 \times 10^{-11}$  (b)  $4 \times 10^{-8}$  (c)  $6 \times 10^{-12}$  (d)  $8 \times 10^{-11}$

## Case Study 11

### de-Broglie Wavelength

According to de-Broglie, a moving material particle sometimes acts as a wave and sometimes as a particle or a wave associated with moving material particle which controls the particle in every respect. The wave associated with moving particle is called matter wave or de-Broglie wave where wavelength called de-Broglie wavelength, is given by  $\lambda = \frac{h}{mv}$ .



- (i) If a proton and an electron have the same de Broglie wavelength, then
- (a) kinetic energy of electron < kinetic energy of proton  
 (b) kinetic energy of electron = kinetic energy of proton  
 (c) momentum of electron = momentum of proton  
 (d) momentum of electron < momentum of proton
- (ii) Which of these particles having the same kinetic energy has the largest de Broglie wavelength?
- (a) Electron (b) Alpha particle (c) Proton (d) Neutron
- (iii) Two particles  $A_1$  and  $A_2$  of masses  $m_1, m_2$  ( $m_1 > m_2$ ) have the same de Broglie wavelength. Then
- (a) their momenta are the same. (b) their energies are the same.  
 (c) momentum of  $A_1$  is less than the momentum of  $A_2$ . (d) energy of  $A_1$  is more than the energy of  $A_2$ .
- (iv) When the velocity of an electron increases, its de Broglie wavelength
- (a) increases (b) decreases  
 (c) remains same (d) may increase or decrease
- (v) Proton and  $\alpha$ -particle have the same de-Broglie wavelength. What is same for both of them?
- (a) time period (b) energy (c) frequency (d) momentum



## Case Study 12

### Wave Theory of Light

According to wave theory, the light of any frequency can emit electrons from metallic surface provided the intensity of light be sufficient to provided necessary energy for emission of electrons, but according to experimental observations, the light of frequency less than threshold frequency can not emit electrons; whatever be the intensity of incident light. Einstein also proposed that electromagnetic radiation is quantised.

If photoelectrons are ejected from a surface when light of wavelength  $\lambda_1 = 550 \text{ nm}$  is incident on it. The stopping potential for such electrons is  $V_s = 0.19 \text{ V}$ . Suppose the radiation of wavelength  $\lambda_2 = 190 \text{ nm}$  is incident on the surface.

- (i) Photoelectric effect supports quantum nature of light because
- (A) there is a minimum frequency of light below which no photoelectrons are emitted.
  - (B) the maximum K.E. of photoelectric depends only on the frequency of light and not on its intensity.
  - (C) even when the metal surface is faintly illuminated, the photo electrons leave the surface immediately.
  - (D) electric charge of the photoelectrons is quantized.
- (a) A, B, C                      (b) B, C                      (c) C, D                      (d) A, D, C
- (ii) In photoelectric effect, electrons are ejected from metals, if the incident light has a certain minimum
- (a) wavelength                      (b) frequency                      (c) amplitude                      (d) angle of incidence
- (iii) Calculate the stopping potential  $V_{s_2}$  of surface.
- (a) 4.47                      (b) 3.16                      (c) 2.76                      (d) 5.28
- (iv) Calculate the work function of the surface.
- (a) 3.75                      (b) 2.07                      (c) 4.20                      (d) 3.60
- (v) Calculate the threshold frequency for the surface.
- (a)  $500 \times 10^{12} \text{ Hz}$                       (b)  $480 \times 10^{13} \text{ Hz}$                       (c)  $520 \times 10^{11} \text{ Hz}$                       (d)  $460 \times 10^{13} \text{ Hz}$

## Case Study 13

### Particle Nature of Light

The photon picture of electromagnetic radiations and the characteristic properties of photons are as follows :  
In the interaction of radiation with matter, radiation behaves as if it is made of particles like photons.

Each photon has energy  $E (= h\nu = hc/\lambda)$  and momentum  $p \left( = \frac{h\nu}{c} = \frac{h}{\lambda} \right)$ , where  $h$  is Planck's constant,  $\nu$  and  $\lambda$  are the frequency and wavelength of radiation and  $c$  is the velocity of light.

The photon energy is independent of the intensity of radiations.

All the photons emitted from a source of radiations travel through space with the same speed  $c$ .

The frequency of photon gives the radiation, a definite energy (or colour) which does not change when photon travels through different media.

Photons are not deflected by electric and magnetic fields. This shows that photons are electrically neutral.

- (i) Which one among the following shows particle nature of light?
- (a) Photoelectric effect      (b) Interference                      (c) Refraction                      (d) Polarization

(ii) Which of the following statements about photon is incorrect?

- (a) Photons exert no pressure. (b) Momentum of photon is  $\frac{h\nu}{c}$ .  
(c) Rest mass of photon is zero. (d) Energy of photon is  $h\nu$ .

(iii) The rest mass of photon is

- (a)  $\frac{h\nu}{c}$  (b)  $\frac{h\nu}{c^2}$  (c)  $\frac{h\nu}{\lambda}$  (d) zero

(iv) In a photon-particle collision (such as photon-electron collision), which of the following may not be conserved?

- (a) Total energy (b) Number of photons (c) Total momentum (d) Both (a) and (b)

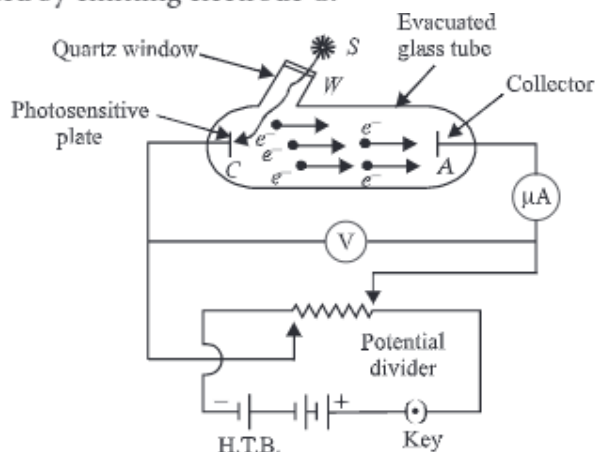
(v) 'n' photons of wavelength ' $\lambda$ ' are absorbed by a black body of mass 'm'. The momentum gained by the body is

- (a)  $\frac{h}{m\lambda}$  (b)  $\frac{mnh}{\lambda}$  (c)  $\frac{nh}{m\lambda}$  (d)  $\frac{nh}{\lambda}$

## Case Study 14

### Hertz Observations

To study photoelectric effect, an emitting electrode C of a photosensitive material is kept at negative potential and collecting electrode A is kept at positive potential in an evacuated tube. When light of sufficiently high frequency falls on emitting electrode, photoelectrons are emitted which travel directly to collecting electrode and hence an electric current called photoelectric current starts flowing in the circuit, which is directly proportional to the number of photoelectrons emitted by emitting electrode C.



While demonstrating the existence of electromagnetic waves, Hertz found that high voltage sparks passed across the metal electrodes of the detector loop more easily when the cathode was illuminated by ultraviolet light from an arc lamp. The ultraviolet light falling on the metal surface caused the emission of negatively charged particles, which are now known to be electrons, into the surrounding space and hence enhanced the high voltage sparks.

(i) Cathode rays were discovered by

- (a) Maxwell Clerk James (b) Heinrich Hertz  
(c) William Crookes (d) J. J. Thomson

(ii) Cathode rays consists of

- (a) photons (b) electrons (c) pistons (d)  $\alpha$ -particles.

(iii) Who discovered the charge on an electron for the first time?

- (a) Millikan (b) Thomson (c) Kelvin (d) Coulomb

(iv) The dual nature of light is exhibited by

- (a) diffraction and photoelectric effect (b) photoelectric effect  
(c) refraction and interference (d) diffraction and reflection

(v) In the phenomenon of electric discharge through gases at low pressure, the coloured glow in the tube appears as a result of

- (a) collisions between the charged particles emitted from the cathode and the atoms of the gas  
(b) collision between different electrons of the atoms of the gas  
(c) excitation of electrons in the atoms  
(d) collision between the atoms of the gas.

## HINTS & EXPLANATIONS

5. (i) (a): With the increase of intensity of the incident radiation the number of photoelectrons emitted per unit time increases.

(ii) (b): As  $eV = KE_{\max}$

$$\therefore V = \left( \frac{KE_{\max}}{e} \right)$$

(iii) (c): From Einstein's photoelectric equation,

$$KE_{\max} = h\nu - \phi = (5 - 3) = 2\text{ eV}$$

(iv) (c): A photocell is a technological application of the photoelectric effect.

(v) (d): According to Einstein's photoelectric equation, the kinetic energy of the emitted photoelectron is

$$K = h\nu - \phi_0 \quad \dots (i)$$

where  $\nu$  is the frequency of incident radiation and  $\phi_0$  is a work function of the metal.

If the frequency of incident radiation is doubled, then  $K' = 2h\nu - \phi_0 = 2(h\nu - \phi_0) + \phi_0 = 2K + \phi_0$  (Using (i))  
 $K' > 2K$

6. (i) (c): Equivalent resistance

$$R = \frac{V}{I} = \frac{16\text{ V}}{2 \times 10^{-6}\text{ A}} = 8 \times 10^6 \Omega$$

(ii) (d):  $P = \frac{hc}{e\lambda}$

$$\lambda = \frac{(2 \times 10^{-6})(6.6 \times 10^{-34})(3 \times 10^8)}{(4 \times 10^{-6})(1.6 \times 10^{-19})}$$

$$= \frac{9.9}{1.6} \times 10^{-7}\text{ m} = \frac{9900}{1.6} \text{ \AA} = 6187 \text{ \AA}$$

Which is in the range of orange light.

(iii) (c): The range of wavelength for red light is beyond the wavelength of incident light.

(iv) (b): Stopping potential,  $V_s = 8\text{ V}$

$$\text{and K.E.} = eV_s$$

$$\therefore \text{K.E.} = 8\text{ eV}$$

(v) (b): Photoelectric current varies linearly with the intensity of the incident radiation.

7. (i) (b): Let  $R$  be the radius of the metallic sphere and  $r$  be its distance from the source  $S_0$ . The power received at the sphere is

$$P' = \frac{P \times \pi R^2}{4\pi r^2} = \frac{PR^2}{4r^2}$$

(ii) (a): Number of photons striking the metal sphere per second is

$$n' = \frac{P'}{E} = \frac{6.4 \times 10^{-9}}{6.0 \times 1.6 \times 10^{-19}} = 6.7 \times 10^9 \text{ s}^{-1}$$

(iii) (b): Number of photoelectrons emitted from

$$\text{metal sphere, } \frac{n'}{10^5} = \frac{6.7 \times 10^{-9}}{10^5} = 6.7 \times 10^4$$

(iv) (b): Kinetic energy of the fastest photoelectrons is  
 $K_{\max} = 6.0 - 3.0 = 3.0 \text{ eV}$

$$\therefore \text{Stopping potential, } V_s = \frac{K_{\max}}{e} = \frac{3.0 \text{ eV}}{e} = 3.0 \text{ V}$$

(v) (b): When  $r = 2r_1$ , then power received by the sphere

$$P'' = \frac{P\pi R^2}{4\pi(2r)^2} = \frac{1}{4} \left( \frac{PR^2}{4r^2} \right)$$

$$\begin{aligned} 8. \quad (i) \quad (b): K_{\max} &= h\nu - \phi_0 = \frac{hc}{\lambda} - \phi_0 \\ &= \frac{(6.6 \times 10^{-34}) \times (3 \times 10^8)}{(300 \times 10^{-9}) \times (1.6 \times 10^{-19})} - 3.3 \\ &= 4.125 \times 3.3 = 0.825 \text{ eV} \end{aligned}$$

(ii) (c):  $K_{\max} = h\nu - \phi_0$ , When  $\nu = \nu_0$ ,  $K_{\max} = 0$   
 $\therefore 0 = h\nu_0 - \phi_0$  or  $\phi_0 = h\nu_0$

If  $\nu < \nu_0$ , then  $K_{\max}$  is negative, i.e., no photoelectric emission takes place. Thus, graph (c) is possible.

(iii) (a): Photoelectric current ( $i$ ) is proportional to the intensity of the emission light. Thus, graph (a) is possible.

(iv) (c): From Einstein's photoelectric equation,

$$K_{\max} = eV_0 = \frac{hc}{\lambda} - \phi$$

$$\text{or } V_0 = \frac{hc}{e} \cdot \frac{1}{\lambda} - \frac{\phi}{e}$$

Graph of  $V_0$  versus  $\frac{1}{\lambda}$  is a straight line

$$\text{Slope of straight line, } \tan\theta = \frac{hc}{e}$$

At  $V_0 = 0$ , we have

$$\phi_1 : \phi_2 : \phi_3 = \frac{hc}{\lambda_{01}} : \frac{hc}{\lambda_{02}} : \frac{hc}{\lambda_{03}}$$

$$0.001 \text{ hc} : 0.002 \text{ hc} : 0.004 \text{ hc}$$

$$\therefore 1 : 2 : 4$$

(v) (d): de-Broglie wavelength

$$\lambda = \frac{h}{p} \text{ i.e., } \lambda \propto \frac{1}{p}$$

So the graph between  $\lambda$  and  $p$  is of the type shown is option (d).

9. (i) (a)

(ii) (a): According to Einstein's photoelectric equation,

$$eV_0 = \frac{hc}{\lambda} - \frac{hc}{\lambda_0}$$

As  $\lambda_0$  is constant, so when  $\lambda$  is decreased, stopping potential ( $V_0$ ) increases.

(iii) (b): It indicates that threshold frequency is greater than that of ultraviolet light. As X-rays have greater frequency than ultraviolet rays, so they can cause photoelectric effect.

(iv) (b):  $K.E._1 = h\nu - \phi$

$$K.E._2 = n h\nu - \phi = n(h\nu - \phi) + (n-1)\phi$$

$$K.E._2 = n K.E._1 + (n-1)\phi$$

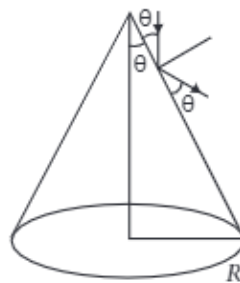
$$K.E._2 > n K.E._1$$

(v) (b): Stopping potential is the measurement of maximum kinetic energy of emitted photoelectrons and kinetic energy of emitted photoelectrons is linearly related with the frequency of incident light corresponding (i.e., corresponding to shortest wavelength, K.E. is maximum).

Stopping potential is independent of intensity.

10. (i) (d): Power of light received by the cone  
 $= I(\pi R^2)$

Let number of photons hitting the cone per second is  $n$ .



$$\text{Then, } nE = I\pi R^2 \Rightarrow n = \pi R^2 I/E$$

(ii) (b): Initial momentum,  $p_i = \frac{E}{c}$

For a perfectly selecting surface,

$$\text{Final momentum, } p_f = \frac{-E}{c}$$

$$\Delta p = p_f - p_i = \frac{-E}{c} - \frac{E}{c} = \frac{-2E}{c}$$

Hence a momentum  $\frac{2E}{c}$  is transferred to the reflecting surface.



(iii) (a): According to the theory of relatively,

$$E = mc^2 = mc \cdot c = pc$$

$$\text{or } E^2 = p^2 c^2$$

where  $p$  is the momentum of a photon.

(iv) (b):  $I = 1 \text{ kWm}^{-2}$

As, 50% of light is reflected, thus  $e = 0.5$

$$\text{Radiation pressure, } P = \frac{(1+e)I}{c}$$

$$\therefore P = \frac{(1+0.5) \times 1000}{3 \times 10^8} = 5 \times 10^{-6} \text{ Pa}$$

$$(v) (a): \frac{P_{\text{rad}}}{P_0} = \frac{5 \times 10^{-6}}{1 \times 10^5} = 5 \times 10^{-11}$$

11. (i) (c): de Broglie wavelength,  $\lambda = \frac{h}{p}$

where  $p$  is the momentum of the particle

$$\text{For electron, } \lambda_e = \frac{h}{p_e}$$

$$\text{For proton, } \lambda_p = \frac{h}{p_p}$$

$$\text{As } \lambda_e = \lambda_p \Rightarrow p_e = p_p \quad (\text{Given})$$

or Momentum of electron = Momentum of proton

$$(ii) (a): \text{As } \lambda = \frac{h}{\sqrt{2mK}} \text{ so } \lambda \propto \frac{1}{\sqrt{m}}$$

Out of the given particles  $m$  is least for electron, therefore electron has the largest value of de Broglie wavelength.

$$(iii) (a): \text{As } \lambda = \frac{h}{p} \text{ or } p = \frac{h}{\lambda} \text{ or } p \propto \frac{1}{\lambda}$$

$$\therefore \frac{p_1}{p_2} = \frac{\lambda_2}{\lambda_1} = \frac{\lambda}{\lambda} = 1 \text{ or } p_1 = p_2$$

$$\text{Also } E = \frac{1}{2} \frac{p^2}{m} = \frac{1}{2m} \frac{h^2}{\lambda^2} \quad \left( \because p = \frac{h}{\lambda} \right)$$

$$\text{or } E \propto \frac{1}{m} \therefore \frac{E_1}{E_2} = \frac{m_2}{m_1} < 1 \text{ or } E_1 < E_2$$

(iv) (b): The de Broglie wavelength is given by

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

So if the velocity of the electron increases, the de Broglie wavelength decreases.

$$(v) (d): \lambda = \frac{h}{p}, \text{ when } \lambda \text{ is same, } p \text{ is also same.}$$

12. (i) (a): The existence of the frequency and the instantaneous emission of photo electrons support the quantum nature of light.

(ii) (b): For photoelectric emission, the incident light must have a certain minimum frequency, called threshold frequency.

(iii) (a): From Einstein's relation

$$eV_s = h\nu - W$$

As work function is a constant for a surface.

$$e(V_{s2} - V_{s1}) = h(\nu_2 - \nu_1)$$

$$V_{s2} = V_{s1} + \frac{h}{e}(\nu_2 - \nu_1)$$

$$= 0.19 + 1240 \left( \frac{1}{190} - \frac{1}{550} \right) = 4.47 \text{ V}$$

$$(iv) (b): W = \frac{hc}{\lambda_1} - eV_{s1} = \frac{1240}{550} - 0.19 = 2.07 \text{ eV}$$

$$(v) (a): h\nu_c = W$$

$$\nu_c = \frac{W}{h} = \frac{(2.07)(1.602 \times 10^{-19})}{6.626 \times 10^{-34}} \approx 500 \times 10^{12} \text{ Hz}$$

13. (i) (a): Particle nature of light was established by photoelectric effect.

(ii) (a): Photons move with velocity of light and have energy  $h\nu$ . Therefore, they also exert pressure.

(iii) (d): The rest mass of photon is zero.

(iv) (b): In a photon-particle collision, (such as photon electron collision), the total energy and total momentum are conserved. However, the number of

photons may not be conserved in photon-particle collision. The photon may be absorbed or a new photon may be created.

$$(v) (d): \text{Energy of } n \text{ photons, } E = \frac{nhc}{\lambda}$$

$$\text{Momentum gained by the body, } p = \frac{E}{c} = \frac{nhc}{\lambda c} = \frac{nh}{\lambda}$$

14. (i) (c)

(ii) (b)

(iii) (a)

(iv) (a)

(v) (c): In discharge tube, collision between charged particles emitted from cathode and atoms of the gas results to colorless glow in the tube.