DAY THIRTY TWO

Photoelectric Effect

Learning & Revision for the Day

- Photon
- Photoelectric Effect
- Laws of Photoelectric Emission Effect
- Energy and Momentum of Photon

Photon

A particle of light called a **photon** has energy E that is related to the frequency f and wavelength λ of light wave.

By the Einstein equation, $E = hf = \dfrac{hc}{\lambda}$ ...(i)

where, c is the speed of light (in vacuum) and h is **Planck's constant**.

$$h = 6.626 \times 10^{-34} \text{ J-s} = 4.136 \times 10^{-15} \text{ eV-s}$$

Since, energies are often given in electron volt $(1\text{eV} = 1.6 \times 10^{-19} \text{ J})$ and wavelengths are in Å, it is convenient to the combination hc in eV-Å. We have,

$$hc = 12375 \text{ eV-Å}$$

Hence, Eq. (i), in simpler form can be written as, $E\,(\text{in eV}) = \dfrac{12375}{\lambda\,(\text{in Å})}$ ...(ii)

The propagation of light is governed by its wave porperties whereas the exchange of energy between, light with matter is governed by its particle properties. The wave-particle duality is a general property of nature. For example, electrons (and other so called particles) also propagate as waves and exchange energy as particles.

Particle Nature of Light

Photoelectric effect gave evidence to the strange fact that light in interaction with matter behaved as if it was made of quanta or packets of energy, each of energy $h\nu$. Einstein stated that the light quantum can also be associated with momentum $\left(\dfrac{h\nu}{c}\right)$.

This particle like behaviour of light was further confirmed, in 1924, by the experiment of A.H. Compton on scattering of X-rays from electrons.

Photoelectric Effect

- Photoelectric effect is the phenomenon of emission of electrons (known as photoelectrons) from the surface of metals when light radiation of suitable frequency are incident on them.
- The minimum energy of incident radiation needed to eject the electrons from metal surface is known as **work function** (ϕ_0) of that surface.
- The frequency or wavelength corresponding to the work function is called **threshold frequency** or **threshold wavelength**. Work function is related to threshold frequency as,

$$\phi_0 = h\nu_0 = \frac{hc}{\lambda_0}$$

where, λ_0 = threshold wavelength.

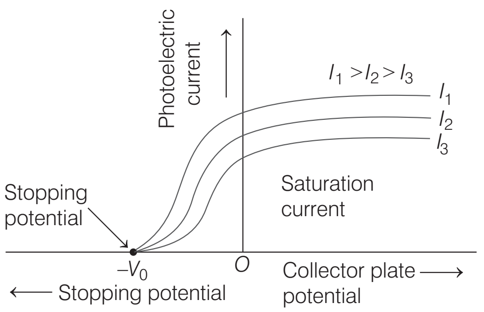
- In electron volt units, $\phi\,(\text{eV}) = \dfrac{hc}{e\lambda_0} = \dfrac{12400}{\lambda\,(\text{Å})}$
- For photoemission to take place energy of incident light (E) is related as, $E \geq p_0$
- According to Einstein's photoelectric equation,

$$h\nu = \phi_0 + K_{\max}$$

where, $K_{\max} = \dfrac{1}{2} mv^2_{\max}$ = maximum kinetic energy of ejected photoelectron.

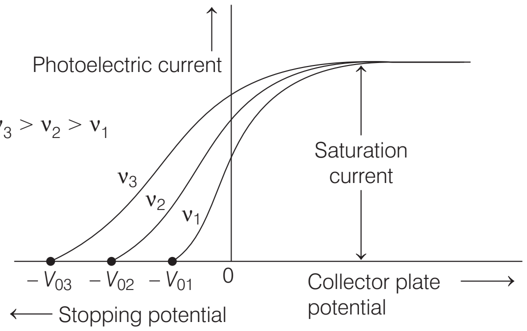
Effect of Intensity on Photoelectric Emission

For a light of given frequency $\nu > \nu_0$ (or given wavelength $\lambda < \lambda_0$), if the intensity of light incident on photosensitive metal surface is increased, the number of photoelectrons and consequently the photoelectric current I increases. However, the stopping potential V_0 remain constant.

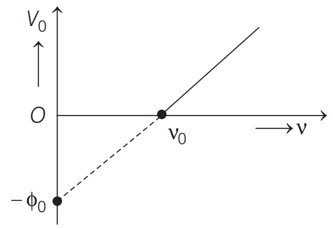


Effect of Frequency on Photoelectric Emission

If keeping the intensity of incident light constant, the frequency of incident light is increased, then the stopping potential V_0 (and hence, $K_{\max}$) increases, but the photoelectric current I remains unchanged.



A photon may collide with a material particle. The total energy and the total momentum remain conserved in such a collision. Photoelectric emission is an instantaneous phenomenon.



Variation of stopping potential V_0 with frequency ν of incident radiation is as shown in above figure.

As, $eV_0 = h(\nu - \nu_0) = h\nu - \phi_0 \Rightarrow V_0 = \dfrac{h}{e}\nu - \dfrac{\phi_0}{e}$

Thus, V_0- ν graph is a straight line whose slope is $\dfrac{h}{e}$ and intercept is $-\phi_0$ eV. The graph meets the ν-axis at ν_0.

Photocurrent $\propto \dfrac{1}{\nu} \propto \lambda$

Energy and Momentum of Photon

- From Einstein's mass-energy relation $E = h\nu = mc^2$

  Kinetic mass of photon is $m = \dfrac{h\nu}{c^2}$

  But $\nu = \dfrac{c}{\lambda}$, where λ is wavelength of the photon.

  $\therefore$Kinetic mass of photon, $m = \dfrac{h}{c^2}\left(\dfrac{c}{\lambda}\right) = \dfrac{h}{c\lambda}$

  Kinetic mass of photon, $m = \dfrac{h\nu}{c^2} = \dfrac{h}{c\lambda}$

- Momentum of photon,

$$p = \text{kinetic mass of photon} \times \text{velocity of photon}$$
$$= \frac{h\nu}{c^2} \times c = \frac{h\nu}{c}$$

  Also, $\nu = \dfrac{c}{\lambda}$

  $\therefore$Momentum of photon, $p = \dfrac{h}{c}\left(\dfrac{c}{\lambda}\right) = \dfrac{h}{\lambda}$

Laws of Photoelectric Emission Effect

Lenard and Millikan gave the following laws on the basis of experiments on photoelectric effect.

- The rate of emission of photoelectrons from the surface of a metal varies directly as the intensity of the incident light falling on the surface.
- The maximum kinetic energy of the emitted photoelectrons is independent of the intensity of the incident light.
- The maximum kinetic energy of the photoelectrons increases linearly with increase in the frequency of the incident light.
- As soon as, the light is incident on the surface of the metal, the photoelectrons are emitted instantly, i.e. there is no time lag between incidence of light and emission of electrons ($\approx 10^{-9}$ s).

DAY PRACTICE SESSION 1

FOUNDATION QUESTIONS EXERCISE

1 Which of the following characteristics of photoelectric effect supports the particle nature of radiations?

(a) Threshold frequency
(b) Dependence of the velocity of photoelectron on frequency
(c) Independence of velocity of photoelectrons of intensity of radiations
(d) Instantaneous photoelectric emission

2 A photocell employs photoelectric effect to convert

(a) change in the frequency of light into a change in electric voltage
(b) change in the intensity of illumination into a change in photoelectric current
(c) change in the intensity of illumination into a change in the work function of the photocathode
(d) change in the frequency of light into a change in the electric current

3 Photoelectric emission occurs only when the incident light has more than a certain minimum ➜ CBSE AIPMT 2011

(a) wavelength (b) intensity
(c) frequency (d) power

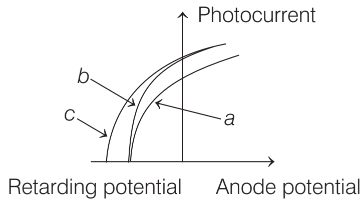
4 The number of photoelectrons emitted for light of a frequency ν (higher than the threshold frequency ν_0) is proportional to ➜ CBSE AIPMT 2009

(a) $\nu - \nu_0$
(b) threshold frequency (ν_0)
(c) intensity of light
(d) frequency of light (ν)

5 What is E in the Einstein's photoelectric equation $E = h\nu - \phi_0$, where ν is the frequency of incident radiations and ϕ_0 is the work function?

(a) Kinetic energy of every photoelectron
(b) Mean kinetic energy of photoelectrons
(c) Minimum kinetic energy of photoelectrons
(d) Maximum kinetic energy of photoelectrons

6 The figure shows a plot of photocurrent *versus* anode potential for a photosensitive surface for three different radiations. Which one of the following is a correct statement ? ➜ CBSE AIPMT 2009



(a) Curves a and b represent incident radiations of different frequencies and different intensities
(b) Curves a and b represent incident radiations of same frequency, but of different intensities
(c) Curves b and c represent incident radiations of different frequencies and different intensities
(d) Curves b and c represent incident radiations of same frequency having same intensity

7 Consider a beam of electrons (each electron with energy E_0) incident on a metal surface kept in an evacuated chamber. Then,

(a) no electrons will be emitted as only photons can emit electrons
(b) electrons can be emitted, but all with an energy E_0
(c) electrons can be emitted with any energy, with a maximum of $E_0 - \phi$ (ϕ is the work function)
(d) electrons can be emitted with any energy, with a maximum of E_0

8 From Einstein's photoelectric equation, the graph of kinetic energy of the photoelectron emitted from the metal *versus* the frequency of the incident radiation gives a straight line graph, whose slope

(a) depends on the intensity of the incident radiation
(b) depends on the nature of the metal and also on the intensity of incident radiation
(c) is same for all metals and independent of the intensity of the incident radiation
(d) depends on the nature of the metal

9 Light of wavelength λ falls on a metal having work function $\frac{hc}{\lambda_0}$. Photoelectric effect will take place only, if

(a) $\lambda \geq \lambda_0$ (b) $\lambda \geq 2\lambda_0$ (c) $\lambda \leq \lambda_0$ (d) $\lambda = 4\lambda_0$

10 The work functions for metals A, B and C are respectively 1.92 eV, 2.0 eV and 5 eV. According to Einstein's equation, the metal (s) which will emit photoelectrons for a radiation of wavelength 4100 Å is/are

(a) Only A (b) A and B
(c) All of these (d) None of these

11 Ultraviolet beam of wavelength 280 nm is incident on lithium surface of work function 2.5eV. The maximum velocity of electron emitted from metal surface is

(a) 8.2×10^5 m/s (b) 10^6 m/s
(c) 7×10^5 m/s (d) 3.8×10^6 m/s

12 A light of wavelength 5000 Å falls on a sensitive plate with photoelectric work function 1.90 eV. Kinetic energy of the emitted photoelectrons will be
(Take, $h = 6.62 \times 10^{-34}$ Js)

(a) 0.1 eV (b) 2 eV (c) 0.58 eV (d) 1.581 eV

13 The photoelectric threshold wavelength of silver is 3250×10^{-10} m. The velocity of the electron ejected from a silver surface by ultraviolet light of wavelength 2536×10^{-10} m is (Take, $h = 4.14 \times 10^{-15}$ eVs and $c = 3 \times 10^8$ ms^{-1}) ➜ NEET 2017

(a) $\approx 6 \times 10^5$ ms^{-1} (b) $\approx 0.6 \times 10^6$ ms^{-1}
(c) $\approx 61 \times 10^3$ ms^{-1} (d) $\approx 0.3 \times 10^6$ ms^{-1}

14 When the energy of the incident radiation is increased by 20%, the kinetic energy of the photoelectrons emitted from a metal surface increased from 0.5 eV to 0.8 eV. The work function of the metal is ➜ CBSE AIPMT 2014

(a) 0.65 eV (b) 1.0 eV (c) 1.3 eV (d) 1.5 eV

15 For photoelectric emission from certain metal, the cut-off frequency is ν. If radiation of frequency 2ν impinges on the metal plate, the maximum possible velocity of the emitted electron will be (where, m is the electron mass) ➜ NEET 2013

(a) $\sqrt{\frac{h\nu}{(2m)}}$ (b) $\sqrt{\frac{h\nu}{m}}$ (c) $\sqrt{\frac{2h\nu}{m}}$ (d) $2\sqrt{\frac{h\nu}{m}}$

16 If a surface has a work function 4.0 eV, what is the maximum velocity of electrons liberated from the surface when it is irradiated with ultraviolet radiation of wavelength 0.2 μm?

(a) 4.4×10^5 m/s (b) 8.8×10^7 m/s
(c) 8.8×10^5 m/s (d) 4.4×10^7 m/s

17 Light of two different frequencies whose photons have energies 1eV and 2.5 eV respectively, illuminate a metallic surface whose work function is 0.5eV successively. Ratio of maximum speeds of emitted electrons will be ➜ CBSE AIPMT 2011

(a) 1 : 2 (b) 1 : 1 (c) 1 : 5 (d) 1 : 4

18 A photoelectric surface is illuminated successively by monochromatic light of wavelength λ and $\frac{\lambda}{2}$. If the maximum kinetic energy of the emitted photoelectrons in the second case is 3 times that in the first case, the work function of the surface of the material is ➜ CBSE AIPMT 2015
(where, h = Planck's constant, c = speed of light)

(a) $\frac{hc}{2\lambda}$ (b) $\frac{hc}{\lambda}$ (c) $\frac{2hc}{\lambda}$ (d) $\frac{hc}{3\lambda}$

19 In an experiment, photoelectrons are emitted when light of wavelength 4000 Å is incident on it. They can be stopped by a retarding potential of 2V. If the wavelength of the incident light be 3000Å, the stopping potential will be

(a) 1 V (b) 1.5 V (c) 2 V (d) 3 V

20 In photoelectric emission process from a metal of work function 1.8 eV, the kinetic energy of most energetic electrons is 0.5 eV. The corresponding stopping potential is ➜ CBSE AIPMT 2011

(a) 1.3 V (b) 0.5 V (c) 2.3 V (d) 1.8 V

21 Photons with energy 5 eV are incident on a cathode C in a photoelectric cell. The maximum energy of emitted photoelectrons is 2 eV. When photons of energy 6 eV are incident on C, no photoelectrons will reach the anode A, if the stopping potential of A relative to C is ➜ NEET 2016

(a) + 3 V (b) + 4 V (c) − 1 V (d) − 3 V

22 A certain metallic surface is illuminated with monochromatic light of wavelength λ. The stopping potential for photoelectric current for this light is $3V_0$. If the same surface is illuminated with light of wavelength 2λ, the stopping potential is V_0. The threshold wavelength for this surface for photoelectric effect is ➜ CBSE AIPMT 2015

(a) 6λ (b) 4λ (c) $\frac{\lambda}{4}$ (d) $\frac{\lambda}{6}$

23 Photons absorbed in matter are converted to heat. A source emitting n photon/s of frequency ν is used to convert 1kg of ice at 0°C to water at 0°C. Then, the time T taken for the conversion

(a) increases with increasing n with ν fixed
(b) increases with n fixed ν increasing
(c) remains constant with n and ν changing such that, $n\nu$ = constant
(d) increases when the product $n\nu$ increases

24 When a monochromatic point source of light is at a distance r from a photoelectric cell, the cut-off voltage is V and the saturation current is I. If the same source is placed at a distance 3 r away from the photoelectric cell, then

(a) no change in saturation current and stopping potential

(b) saturation current will decrease and stopping potential will not change

(c) saturation current will increase and stopping potential will decrease

(d) None of the above

25 A 200 W sodium street lamp emits yellow light of wavelength 0.6 μm. Assuming it to be 25 % efficient in converting electrical energy to light, the number of photons of yellow light it emits per second is ➜ CBSE AIPMT 2012

(a) 1.5×10^{20} (b) 6×10^{18} (c) 62×10^{20} (d) 3×10^{19}

26 A source S_1 is producing 10^{15} photons/s of wavelength 5000 Å. Another source S_2 is producing 1.02×10^{15} photon/s of wavelength 5100 Å. Then, (power of S_2)/ (power of S_1) is equal to ➜ CBSE AIPMT 2010

(a) 1.00 (b) 1.02 (c) 1.04 (d) 0.98

27 Monochromatic light of wavelength 667 nm is produced by a helium-neon laser. The power emitted is 9 mW. The number of photons arriving per second on the average at a target irradiated by this beam is ➜ CBSE AIPMT 2009

(a) 9×10^{17} (b) 3×10^{16}
(c) 9×10^{15} (d) 3×10^{19}

28 A radiation of energy E falls normally on a perfectly reflecting surface. The momentum transferred to the surface is (where, c = velocity of light) ➜ CBSE AIPMT 2015

(a) $\frac{E}{c}$ (b) $\frac{2E}{c}$
(c) $\frac{2E}{c^2}$ (d) $\frac{E}{c^2}$

29 Photon and electron are given same energy $(10^{-20}$ J). Wavelength associated with photon and electron are λ_p and λ_e, the correct statement will be

(a) $\lambda_p > \lambda_e$ (b) $\lambda_p < \lambda_e$
(c) $\lambda_p = \lambda_e$ (d) $\frac{\lambda_e}{\lambda_p} = c$

30 The wavelength λ_e of an electron and λ_p of a photon of same energy E are related by ➜ NEET 2013

(a) $\lambda_p \propto \lambda_e^2$ (b) $\lambda_p \propto \lambda_e$
(c) $\lambda_p \propto \sqrt{\lambda_e}$ (d) $\lambda_p \propto \frac{1}{\sqrt{\lambda_e}}$

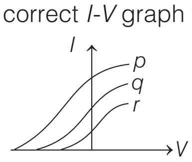
DAY PRACTICE SESSION 2

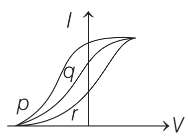
PROGRESSIVE QUESTIONS EXERCISE

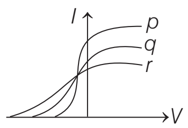
1 A photosensitive metallic surface has work function $h\nu_0$. If photons of energy $2h\nu_0$ fall on this surface, the electrons come out with a maximum velocity of 4×10^6 ms^{-1}. When the photon energy is increased to $5h\nu_0$, then maximum velocity of photoelectrons will be

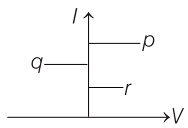
(a) 2×10^6 ms^{-1} (b) 2×10^7 ms^{-1}
(c) 8×10^5 ms^{-1} (d) 8×10^6 ms^{-1}

2 Photoelectric effect experiments are performed using three different metal plates p, q and r having work functions $\phi_p = 2$ eV, $\phi_q = 2.5$ eV and $\phi_r = 3$ eV, respectively. A light beam containing wavelengths of 550 nm, 450 nm and 350 nm with equal intensities illuminates each of the plates.
The correct I-V graph for the experiment is

(a) 

(b) 

(c) 

(d) 

3 When a piece of metal is illuminated by a monochromatic light of wavelength λ, then stopping potential is $3V_s$. When same surface is illuminated by light of wavelength 2λ, then stopping potential becomes V_s. The value of threshold wavelength for photoelectric emission will be

(a) 4λ (b) 8λ (c) $\frac{4}{3}\lambda$ (d) 6λ

4 Two identical photocathodes receive light of frequencies f_1 and f_2. If the velocities of the photoelectrons (of mass m) coming out are respectively v_1 and v_2, then

(a) $v_1^2 - v_2^2 = \frac{2h}{m}(f_1 - f_2)$ (b) $v_1 + v_2 = \left[\frac{2h}{m}(f_1 + f_2)\right]^{1/2}$

(c) $v_1^2 + v_2^2 = \frac{2h}{m}(f_1 + f_2)$ (d) $v_1 - v_2 = \left[\frac{2h}{m}(f_1 - f_2)\right]^{1/2}$

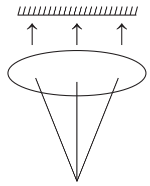
5 In a photoelectric experiment, it was found that the stopping potential decreases from 1.85 V to 0.82 V as the wavelength of incident light is varied from 300 nm to 400 nm. Planck constant from this data is

(a) 6.634×10^{-34} eVs (b) 4.12×10^{-15} eVs
(c) 2×10^{-30} eVs (d) 6.63×10^{-15} eVs

6 A horizontal cesium plate ($\phi = 1.9$ eV) is moved vertically downward at a constant speed v in a room full of radiation of wavelength 250 nm and above. The minimum value of v, so that the vertically upward component of velocity is non-positive for such a photoelectron.

(a) $1.04 \times 10^6\ ms^{-1}$ (b) $3 \times 10^4\ ms^{-1}$
(c) $2 \times 10^3\ ms^{-1}$ (d) None of these

7 A totally reflecting mirror placed horizontally faces a parallel beam of light as shown in figure. The mass of the mirror is 20g. Assume 30% of the light emitted by the source passes through the lens unabsorbed. The power of the source needed to support the mirror



(a) 10^4 W (b) 10^2 W (c) 10^8 W (d) 10^{-1} W

8 Ultraviolet light of wavelength 66.26 nm and intensity $2\ W/m^2$ falls on potassium surface by which photoelectrons are ejected out. If only 0.1% of the incident photons produce photoelectrons and surface area of metal surface is $4\ m^2$, then the number of electrons are emitted per second

(a) 2.67×10^{15} (b) 3×10^{15} (c) 3.33×10^{17} (d) 4.17×10^{16}

9 In a photocell, with exciting wavelength λ, the faster electron has speed v. If the exciting wavelength is changed to $3\lambda/4$, the speed of the fastest electron will be

(a) $v\left(\frac{3}{4}\right)^{1/2}$ (b) $v\left(\frac{4}{3}\right)^{1/2}$
(c) less than $v\left(\frac{4}{3}\right)^{1/2}$ (d) greater than $v\left(\frac{4}{3}\right)^{1/2}$

10 What will be the number of photons emitted per second by a 10 W sodium vapour lamp assuming that 90% of the consumed energy is converted into light?
[Take wavelength of sodium light is 590 nm and $h = 6.63 \times 10^{-34}$ J-s]

(a) 0.267×10^{18} (b) 0.267×10^{19}
(c) 0.267×10^{20} (d) 0.267×10^{17}

11 When the light of frequency $2\nu_0$ (where, ν_0 is threshold frequency), is incident on a metal plate, the maximum velocity of electrons emitted is v_1. When the frequency of the incident radiation is increased to $5\nu_0$, the maximum velocity of electrons emitted from the same plate is v_2. The ratio of v_1 to v_2 is ➜ NEET 2018

(a) 4 : 1 (b) 1 : 4 (c) 1 : 2 (d) 2 : 1

12 When a metallic surface is illuminated with radiation of wavelength λ, the stopping potential is V. If the same surface is illuminated with radiation of wavelength 2λ, the stopping potential is $\frac{V}{4}$. The threshold wavelength for the metallic surface is ➜ NEET 2016

(a) 5λ (b) $\frac{5}{2}\lambda$ (c) 3λ (d) 4λ

13 Monochromatic radiation emitted when electron state on hydrogen atom jumps from first excited state to the ground state irradiates a photosensitive material. The stopping potential is measured to be 3.57 V. The threshold frequency of the material is ➜ CBSE AIPMT 2012

(a) 4×10^{15} Hz (b) 5×10^{15} Hz
(c) 1.6×10^{15} Hz (d) 2.5×10^{15} Hz

ANSWERS

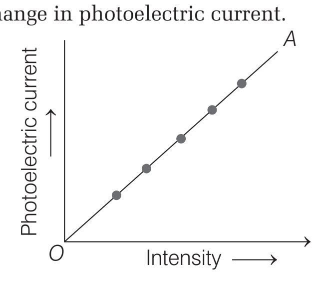
SESSION 1	**1** (a)	**2** (b)	**3** (c)	**4** (c)	**5** (d)	**6** (b)	**7** (d)	**8** (c)	**9** (c)	**10** (b)
	11 (a)	**12** (c)	**13** (a,b)	**14** (b)	**15** (c)	**16** (c)	**17** (a)	**18** (a)	**19** (d)	**20** (b)
	21 (d)	**22** (b)	**23** (c)	**24** (b)	**25** (a)	**26** (a)	**27** (b)	**28** (b)	**29** (a)	**30** (a)
SESSION 2	**1** (d)	**2** (c)	**3** (a)	**4** (a)	**5** (b)	**6** (a)	**7** (c)	**8** (a)	**9** (b)	**10** (c)
	11 (c)	**12** (c)	**13** (c)							

Hints and Explanations

SESSION 1

1 Threshold characteristics of photoelectric effect supports the particle nature of radiations.

2 Using the incident radiations of a fixed frequency, it is found that the photoelectric current increases linearly with intensity of incident light as shown in figure. Hence, a photocell employs photoelectric effect to convert change in the intensity of illumination into a change in photoelectric current.

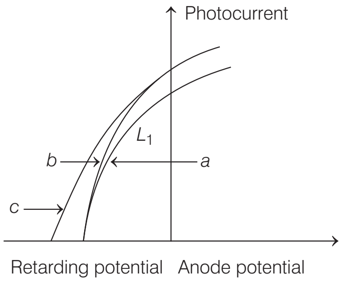


3 By the concept of threshold minimum frequency needed for photoelectric emission.

4 Independent of frequency (ν) of light, it only depends on the intensity of incident light. If intensity increases, number of photoelectrons increases.

5 In the Einstein's photoelectric equation $(E = h\nu - \omega_0)$, E is maximum kinetic energy of photoelectrons.

6

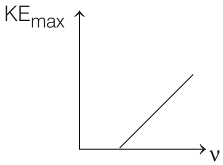


Since, in the graph, retarding potential is same in curves (a) and (b) and photocurrent is different, so for curves, they have same frequency, but different intensity of light.

7 When a beam of electrons of energy E_0 is incident on a metal surface kept in an evacuated chamber, electrons can be emitted with maximum energy E_0 (due to elastic collision) and with any energy less than E_0, when part of incident energy of electron is used in liberating the electrons from the surface of metal.

8 From Einstein's photoelectric equation, $KE_{max} = h\nu - \phi_0$

Comparing with the equation of straight line $y = mx + c$



$\Rightarrow$ Slope is h which is same for all metals and independent of the intensity of the incident radiation.

9 The energy of photon, $E = \dfrac{hc}{\lambda}$

Work function of metal, $W = \dfrac{hc}{\lambda_0}$

For photoelectric effect,

$$E > W \;\Rightarrow\; \frac{hc}{\lambda} > \frac{hc}{\lambda_0} \Rightarrow \lambda \le \lambda_0$$

10 Work function for wavelength of 4100 Å is

$$W = \frac{hc}{\lambda} = \frac{6.62 \times 10^{-34} \times 3 \times 10^8}{4100 \times 10^{-10}}$$

$$= 4.8 \times 10^{-19}\text{ J}$$

$$= \frac{4.8 \times 10^{-19}}{1.6 \times 10^{-19}}\text{ eV} = 3\text{ eV}$$

Now, we have $W_A = 1.92$ eV,

$W_B = 2.0$ eV, $W_C = 5$ eV

Since, $W_A < W$.

and $W_B < W$, hence A and B will emit photoelectrons.

11 From Einstein's equation,

$$\frac{hc}{\lambda} = \phi + \frac{1}{2} mv^2_{max}$$

$$v_{max} = \sqrt{\frac{2\left(\frac{hc}{\lambda} - \phi\right)}{m}}$$

$$= \sqrt{\frac{2\left(\frac{1242\text{ meV}}{280\text{ nm}} - 2.5\text{ eV}\right)}{9.1 \times 10^{-31}}}$$

$$= \sqrt{\frac{2 \times 1.9 \times 1.6 \times 10^{-19}}{9.1 \times 10^{-31}}}$$

$$= 8.2 \times 10^5\text{ m/s}$$

12 From photoelectric equation, $E_k = E - W$

where, E_k is kinetic energy of emitted photoelectrons,

W is the work function and E is the energy supplied.

$$E = h\nu = \frac{hc}{\lambda}$$

$$\therefore \quad E = \frac{6.6 \times 10^{-34} \times 3 \times 10^8}{5000 \times 10^{-10}}$$

$$= 3.96 \times 10^{-19}\text{ J}$$

Also, 1 eV $= 1.6 \times 10^{-19}$J

$$\therefore \quad E = \frac{3.96 \times 10^{-19}}{1.6 \times 10^{-19}} = 2.48\text{ eV}$$

Hence, $E_k = 2.48 - 1.90 = 0.58$ eV

13 Applying Einstein's photoelectric equation, we have

$$E = K + \phi_0 \Rightarrow h\nu = \frac{1}{2} m_e v^2 + h\nu_0$$

$$\Rightarrow \frac{1}{2} m_e v^2 = h\nu - h\nu_0 = hc\left(\frac{1}{\lambda} - \frac{1}{\lambda_0}\right)$$

$\therefore$ Velocity of electron

$$v = \sqrt{\frac{2hc}{m_e}\left(\frac{1}{\lambda} - \frac{1}{\lambda_0}\right)}$$

$$= \sqrt{\frac{2 \times 4.14 \times 10^{-15} \times 1.6 \times 10^{-19} \times 3 \times 10^8}{9.1 \times 10^{-31}}\left(\frac{3250 - 2536}{3250 \times 2536}\right)}$$

$$\approx 0.6 \times 10^6\text{ ms}^{-1} \approx 6 \times 10^5\text{ ms}^{-1}$$

14 $KE = h\nu - \phi \Rightarrow 0.5 = h\nu - \phi$ ...(i)

Again, $0.8 = 1.2 = h\nu - \phi$ ...(ii)

Solving Eqs. (i) and (ii), we get

$\phi = 1$ eV

15 As, $\frac{1}{2} mv^2{}_{max} = h\nu \Rightarrow v^2{}_{max} = \frac{2h\nu}{m} \Rightarrow$

$$v_{max} = \sqrt{\frac{2h\nu}{m}}$$

16 Work function, $W = 4$ eV

$$= 4 \times 1.6 \times 10^{-19}\text{ J} = 6.4 \times 10^{-19}\text{ J}$$

Wavelength of incident radiation,

$\lambda = 0.2\mu\text{m} = 0.2 \times 10^{-6}$m

Maximum Kinetic energy of liberated electron, $(KE)_{max} = \dfrac{hc}{\lambda} - W$

$$\frac{1}{2} mv^2_{max} = \frac{hc}{\lambda} - W$$

$$\frac{1}{2} \times 9.1 \times 10^{-31}\, v^2_{max}$$

$$= \frac{6.6 \times 10^{-34} \times 3 \times 10^8}{0.2 \times 10^{-6}} - 6.4 \times 10^{-19}$$

$$= 9.9 \times 10^{-19} - 6.4 \times 10^{-19} = 3.5 \times 10^{-19}$$

$$\therefore v_{max} = \sqrt{\frac{3.5 \times 10^{-19} \times 2}{9.1 \times 10^{-31}}}$$

$$= \sqrt{\frac{7}{9.1} \times 10^{12}} = 8.8 \times 10^5\text{m/s}$$

17 Kinetic energy, $KE = \phi - \phi_0$

Here, $KE_1 = 1 - 0.5 = 0.5$ eV

$KE_2 = 2.5 - 0.5 = 2$ eV

$$\therefore \quad \frac{KE_1}{KE_2} = \frac{0.5}{2} = \frac{1}{4} \text{ or } \frac{v_1^2}{v_2^2} = \frac{1}{4}$$

$$\text{or} \quad \frac{v_1}{v_2} = \sqrt{\frac{1}{4}} = \frac{1}{2}$$

18 According to Einstein's photoelectric equation, $K_{max} = E - \phi = h\nu - \phi$

$$K_{max} = \frac{hc}{\lambda} - \phi \qquad \text{...(i)}$$

Similarly, in second case, maximum kinetic energy of emitted electron is 3 times that in first case, we get

$$3K_{max} = \frac{hc}{\frac{\lambda}{2}} - \phi \qquad \text{...(ii)}$$

Solving Eqs. (i) and (ii), we get work function of an emitted electron from a metal surface.

$$\phi = \frac{hc}{2\lambda}$$

19 $\dfrac{hc}{\lambda_1} - \omega_0 = eV_1$, $\dfrac{hc}{\lambda_2} - \omega_0 = eV_2$

Hence, $e(V_2 - V_1) = hc\left[\dfrac{1}{\lambda_2} - \dfrac{1}{\lambda_1}\right]$

$$= hc\left[\frac{\lambda_1 - \lambda_2}{\lambda_1\lambda_2}\right]$$

This gives, $V_2 = 3$ V

20 Stopping potential

= Maximum kinetic energy

$$eV = KE_{max} \text{ or } V = \frac{KE_{max}}{e}$$

Here, $KE_{max} = 0.5\,eV$

$$\therefore \quad V = \frac{0.5eV}{e} = 0.5\text{ V}$$

21 Using Einstein's photoelectric equation,

We know that, $E = (KE)_{max}$ + Work function (ϕ)

$$(KE)_{max} = \frac{1}{2} mv_0^2$$

$\Rightarrow \quad (KE)_{max} = h\nu - \phi$

$\Rightarrow \quad 2\text{ eV} = 5\text{eV} - \phi$ (given)

$\Rightarrow \quad \phi = 3\text{ eV}$

Thus, $V_{cathode} - V_{anode} = 3\text{ V}$

$\Rightarrow \quad V_{anode} - V_{cathode} = -3\text{ V}$

22 From photoelectric equation,

$h\nu = W + eV_0$

(where, W = work function)

So, $\frac{hc}{\lambda} = W + 3eV_0$ ...(i)

Also, $\frac{hc}{2\lambda} = W + eV_0$

$\Rightarrow \frac{hc}{\lambda} = 2W + 2eV_0$ ...(ii)

Subtracting Eq. (i) from Eq. (ii),

we get $0 = W - eV_0 \Rightarrow W = eV_0$

From Eq. (i), we get

$\frac{hc}{\lambda} = eV_0 + 3eV_0 = 4eV_0$

The threshold wavelength is given by

$\lambda_{th} = \frac{hc}{W} = \frac{4eV_0\lambda}{eV_0} = 4\lambda$

23 Energy spent to convert ice into water $= mL = (1000\text{ g}) \times (40\text{ cal/g}) = 80000\text{ cal}$

Energy of photons used

$= nT \times E = nT \times h\nu \quad [\because E = h\nu]$

$\therefore \quad nTh\nu = mL$ or $T = \frac{mL}{nh\nu}$

$\therefore \quad T \propto 1/n$ when ν is constant; $T \propto 1/\nu$ when n fixed; $T \propto 1/n\nu$. Thus, T is constant, if $n\nu$ is constant.

24 When the distance is increased, frequency of incident light and hence the stopping potential does not change, but the intensity and hence saturation current decreases nine times.

25 Efficient power,

$P = \frac{N}{t} \times \frac{hc}{\lambda} = 200 \times 0.25$

$\frac{N}{t} = 50 \times \frac{\lambda}{hc}$

$= \frac{50 \times 0.6 \times 10^{-6}}{6.6 \times 10^{-34} \times 3 \times 10^{8}} = 1.5 \times 10^{20}$

26 Number of photons emitted per second is given by

$n = \frac{P}{\left(\frac{hc}{\lambda}\right)}$ $\left[\text{where, } P = \text{Power}, \frac{hc}{\lambda} = \text{Energy}\right]$

So, $P = \frac{nhc}{\lambda}$

So, for two different situations,

$\frac{P_2}{P_1} = \frac{n_2\lambda_1}{n_1\lambda_2}$

$= \frac{1.02 \times 10^{15} \times 5000}{10^{15} \times 5100} = 1$

27 Here, $\lambda = 667 \times 10^{-9}$ m,

$P = 9 \times 10^{-3}$ W

$\therefore$ Power $= \frac{\text{energy }(E)}{\text{time }(t)} = \frac{nhc}{\lambda t} = \frac{Nhc}{\lambda}$

$\left[\begin{array}{l} E = \frac{hc}{\lambda}, \\ n = \text{total number of photons,} \\ N = \text{number of photons emitted per second} = \frac{n}{t} \end{array}\right]$

So, $N = \frac{P \times \lambda}{hc}$

$= \frac{9 \times 10^{-3} \times 667 \times 10^{-9}}{6.6 \times 10^{-34} \times 3 \times 10^{8}}$

$= 3 \times 10^{16}$

28 The radiation energy is given by

$E = \frac{hc}{\lambda}$

Initial momentum of the radiation is

$\mathbf{p}_i = \frac{h}{\lambda} = \frac{E}{c}$

The reflected momentum is

$\mathbf{p}_r = -\frac{h}{\lambda} = -\frac{E}{c}$

So, the change in momentum of light is

$\Delta\mathbf{p}_{light} = \mathbf{p}_r - \mathbf{p}_i = -\frac{2E}{c}$

Thus, the momentum transferred to the surface is

$\Delta\mathbf{p}_{light} = \frac{2E}{c}$

29 Wavelength of photon will be greater than that of electron, because mass of photon is less than that of electron.

$\Rightarrow \quad \lambda_p > \lambda_e$

30 Wavelength of electron, $\lambda_e = \frac{h}{\sqrt{2mE}}$

and proton,

$\lambda_p = \frac{h_c}{E} \Rightarrow \lambda_e^2 = \frac{h^2}{2mE}$ or $E = \frac{h_c}{\lambda_p}$

$\therefore \quad \lambda_e^2 = \frac{h^2}{2m\frac{\lambda_c}{\lambda_p}}, \quad \lambda_e^2 = \frac{h^2}{2m\lambda_c}\lambda_p$

$\Rightarrow \quad \lambda_e^2 \propto \lambda_p$

SESSION 2

1 Einstein's photoelectric equation can be written as

$\frac{1}{2}mv^2 = h\nu - W_0$

$\Rightarrow \frac{1}{2}m \times (4 \times 10^6)^2 = 2h\nu_0 - h\nu_0$ ...(i)

and $\frac{1}{2}m \times v^2 = 5h\nu_0 - h\nu_0$ ...(ii)

On dividing Eq. (ii) by Eq. (i), we get

$\frac{v^2}{(4 \times 10^6)^2} = \frac{4h\nu_0}{h\nu_0}$

or $\quad v^2 = 4 \times 16 \times 10^{12} = 64 \times 10^{12}$

$\therefore \quad v = 8 \times 10^6\text{ ms}^{-1}$

2 $K_p = E_p - \phi_p = \frac{1240}{550} - 2 = 0.2545\text{ eV}$

$K_q = E_q - \phi_q = \frac{1240}{450} - 2.5 = 0.255\text{ eV}$

$K_r = E_r - \phi_r = \frac{1240}{350} - 3 = 0.543\text{ eV}$

K has maximum kinetic energy of photoelectrons and E is the energy of incident radiation.

From above equation, it is clear that,

$|V_r| > |V_q| > |V_p|$

their intensities are equal, but energy of individual photon of r is maximum. Hence, number of photons incident on r can be assumed to be least. Hence, saturation current of r is minimum. Hence, option (c) is true.

3 According to Einstein's photoelectric equation, $eV = hc\left[\frac{1}{\lambda} - \frac{1}{\lambda_0}\right]$

***Case* I** $\quad 3eV_s = hc\left[\frac{1}{\lambda} - \frac{1}{\lambda_0}\right]$ ...(i)

***Case* II** $\quad eV_s = hc\left[\frac{1}{2\lambda} - \frac{1}{\lambda_0}\right]$ ...(ii)

From Eqs. (i) and (ii), we get $\lambda_0 = 4\lambda$

4 Photon energy, $hf = hf_0 + \frac{1}{2}mv^2$

Hence, $\quad v_1^2 = \frac{2hf_1}{m} - \frac{2hf_0}{m}$,

$v_2^2 = \frac{2hf_2}{m} - \frac{2hf_0}{m}$

$\therefore \quad v_1^2 - v_2^2 = \frac{2h}{m}(f_1 - f_2)$

5 Change in stopping potential,

$V_{s_1} - V_{s_2} = \frac{h\nu_1}{e} - \frac{\phi}{e} - \left(\frac{h\nu_2}{3} - \frac{\phi}{e}\right)$

$= \frac{hc}{e}\left[\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right]$

$h = \frac{e(V_{s_1} - V_{s_2})}{c\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right)}$

$= \frac{1.03\text{ eV}}{3 \times 10^8 \times \left(\frac{1}{12} \times 10^7\right)}$

$= 4.12 \times 10^{-15}$ eVs

6 Energy, $E(N) = \frac{1242}{50} = 4.97$ eV,

$(KE)_{max} = 4.97 - 1.9 = 3.07$ eV

$\frac{1}{2}mv^2 = 3.07 \times 1.6 \times 10^{-19}$

$\Rightarrow \quad v = \sqrt{\frac{3.07 \times 1.6 \times 10^{-19} \times 2}{9.1 \times 10^{-31}}}$

$= 1.04 \times 10^6\text{ ms}^{-1}$

7 Weight, $F = \frac{2P}{c} = mg$

$$\Rightarrow \frac{2(0.3P)}{3 \times 10^8} = 20 \times 10^{-3} \times 10$$

$$\Rightarrow \quad P = \frac{3 \times 10^8 \times (0.2)}{0.6} = 10^8 \text{ W}$$

8 Number of photons falling on metal surface,

$$n_p = \frac{\text{Intensity} \times \text{Area}}{\text{Energy per quanta}}$$

$$n_p = \frac{(2 \text{ Wm}^{-2})(4\text{m}^2)}{\left\{\frac{(6.62 \times 10^{-34})(3 \times 10^8)}{66.26 \times 10^{-9}}\right\}}$$

$n_p = 2.67 \times 10^{18}$ per second

$n_e = 0.1\%$ of n_p

$= \frac{0.1}{100} \times 2.67 \times 10^{18}$

$= 2.67 \times 10^{15}$ per second

9 According to Einstein's photoelectric equation,

$$\frac{hc}{\lambda_1} = W_0 + \frac{1}{2} m v_1^2$$

and $\frac{hc}{\lambda_2} = W_0 + \frac{1}{2} m v_2^2$

These expression show that,

$$v^2 \propto \left(\frac{1}{\lambda}\right)$$

$$\therefore \quad \frac{v_1}{v_2} = \sqrt{\frac{\left(\frac{1}{\lambda_1}\right)}{\left(\frac{1}{\lambda_2}\right)}}$$

$$= \sqrt{\frac{\lambda_2}{\lambda_1}}$$

$$= \sqrt{\frac{3\lambda / 4}{\lambda}}$$

$$\therefore \quad v_2 = v_1 \left(\frac{4}{3}\right)^{1/2}$$

10 Energy of photon,

$$E = \frac{hc}{\lambda} = \frac{6.63 \times 10^{-34} \times 3 \times 10^8}{590 \times 10^{-9}}$$

$$= \frac{6.63 \times 3}{59} \times 10^{-18}$$

Light energy produced per second

$$= \frac{90}{100} \times 10 = 9 \text{ W}$$

Number of photons emitted per second

$$= \frac{9 \times 59}{6.63 \times 3 \times 10^{-18}}$$

$$= 2.67 \times 10^{19} = 0.267 \times 10^{20}$$

11 According to the Einstein's photoelectric equation,

$$K_{\text{max}} = \frac{1}{2} m v_{\text{max}}^2 = h\nu - \phi_0$$

$$= h\nu - h\nu_0 \qquad \ldots\text{(i)}$$

When incident frequency of light, $\nu = 2\nu_0$

Substituting the value of ν in Eq. (i), we get

$$\frac{1}{2} m v_1^2 = h(2\nu_0) - h\nu_0$$

$$= 2h\nu_0 - h\nu_0 = h\nu_0 \qquad \ldots\text{(ii)}$$

If incident frequency of radiation,

$$\nu = 5\nu_0$$

Substituting the value of ν in Eq. (i), we get

$$\frac{1}{2} m v_2^2 = h(5\nu_0) - h\nu_0$$

$$= 5h\nu_0 - h\nu_0 = 4h\nu_0 \qquad \ldots\text{(iii)}$$

On dividing Eq. (ii) by Eq (iii), we get

$$\frac{\frac{1}{2} m v_1^2}{\frac{1}{2} m v_2^2} = \frac{h\nu_0}{4h\nu_0}$$

$$\Rightarrow \quad \frac{v_1^2}{v_2^2} = \frac{1}{4}$$

$$\text{or} \quad \frac{v_1}{v_2} = \frac{1}{2}$$

$$\therefore \quad v_1 : v_2 = 1 : 2$$

12 In first case, when a metallic surface is illuminated with radiation of wavelength λ, the stopping potential is V.

So, photoelectric equation can be written as

$$eV = \frac{hc}{\lambda} - \frac{hc}{\lambda_0} \qquad \ldots\text{(i)}$$

In second case, when the same surface is illuminated with radiation of wavelength 2λ, the stopping potential is $\frac{V}{4}$. So, photoelectric equation can be written as

$$\frac{eV}{4} = \frac{hc}{2\lambda} - \frac{hc}{\lambda_0}$$

$$\Rightarrow \quad eV = \frac{4hc}{2\lambda} - \frac{4hc}{\lambda_0} \qquad \ldots\text{(ii)}$$

From Eqs. (i) and (ii), we get

$$\Rightarrow \quad \frac{hc}{\lambda} - \frac{hc}{\lambda_0} = \frac{4hc}{2\lambda} - \frac{4hc}{\lambda_0}$$

$$\Rightarrow \quad \frac{1}{\lambda} - \frac{1}{\lambda_0} = \frac{2}{\lambda} - \frac{4}{\lambda_0}$$

$$\Rightarrow \quad \lambda_0 = 3\lambda$$

13 *Concept* When an electron in hydrogen atom jumps from first excited state $(n = 2)$ to ground state $(n = 1)$, energy is released and is given by

$$E = E_{(n=2)} - E_{(n=1)}$$

where, $E_n = -\frac{13.6}{n^2}\text{eV}$

Energy released from emission of electron is given by

$$E = -3.4 - (-13.6)$$

$$= 10.2 \text{ eV}$$

Now, from photoelectric equation, work function,

$$\phi = E - eV = h\nu$$

$$\nu = \frac{E - eV}{h} = \frac{(10.2 - 3.57)e}{6.67 \times 10^{-34}}$$

$$\Rightarrow \nu = \frac{6.63 \times 1.6 \times 10^{-19}}{6.67 \times 10^{-34}} = 1.6 \times 10^{15}\text{Hz}$$