CHAPTER 11

Dual Nature of Radiation and Matter

EXAM DRILL

ANSWERS

1. **(b) :** Here, $V_0 = 3.5$ V,
Maximum kinetic energy $= eV_0 = 3.5$ eV

2. **(a) :** de Broglie wavelength is given by
$\lambda = \frac{h}{p}$, where p is the momentum

Since, $\hbar = \frac{h}{2\pi}$ $\therefore$ $\lambda = \frac{2\pi\hbar}{p}$

3. **(b) :** The phenomenon of photoelectric emission was discovered by Heinrich Hertz in 1887.

4. **(c) :** de Broglie wavelength of a gas molecule

$$\lambda = \frac{h}{\sqrt{3mk_BT}}$$

where, T = Absolute temperature,
k_B = Boltzmann's constant, m = Mass of gas molecule

For the same temperature, $\lambda \propto \frac{1}{\sqrt{m}}$

As $m_{O_2} > m_{N_2} > m_{He} > m_{H_2}$ $\therefore$ $\lambda_{O_2} < \lambda_{N_2} < \lambda_{He} < \lambda_{H_2}$

5. **(b) :** Since $\lambda = \frac{h}{\sqrt{2mK}}$

Since mass of the particle remains constant,

$$\lambda \propto \frac{1}{\sqrt{K}} \quad \therefore \quad \frac{\lambda'}{\lambda} = \sqrt{\frac{K}{K'}} = \sqrt{\frac{1 \text{ eV}}{1\times10^6 \text{ eV}}} = \frac{1}{10^3}$$

$$\lambda' = \frac{\lambda}{10^3} = \frac{2000}{10^3} \text{ Å} = 2 \text{ Å}$$

6. **(c) :** Millikan's experiment established that electric charge is quantised.

7. **(a) :** de Broglie wavelength associated with an electron is

$$\lambda = \frac{h}{p} \quad \text{or} \quad p = \frac{h}{\lambda} \quad \therefore \quad \frac{\Delta p}{p} = -\frac{\Delta\lambda}{\lambda} \Rightarrow \frac{p}{p_{\text{initial}}} = \frac{0.5}{100}$$

$p_{\text{initial}} = 200p$

8. **(d) :** 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.

9. **(b) :** As $p = \sqrt{2mK}$

$= \sqrt{2\times9\times10^{-31}\times120\times1.6\times10^{-19}} = 5.88 \times 10^{-24}$ kg m s^{-1}

de Broglie wavelength,

$$\lambda = \frac{h}{p} = \frac{6.63\times10^{-34}}{5.88\times10^{-24}} = 1.13 \times 10^{-10} \text{ m} = 1.13 \text{ Å}$$

10. **(d) :** Photoelectric effect can be explained on the basis of quantum theory of light.

11. **(a) :** Equivalent mass of photon (m) is given by equation,

$E = mc^2 = h\upsilon$ $\therefore$ $m = \frac{h\upsilon}{c^2}$

where E is energy, m is mass, c is speed of light, h is Planck's constant, υ is frequency.

$\therefore$ Momentum of photon $= \frac{h\upsilon}{c^2} \times c = \frac{h\upsilon}{c}$

12. **(a)**

13. **(b) :** Photoelectric emission have been adequately explained by Einstein on the basis of photon theory of light.

14. **(c) :** Assertion is correct, but the work function only depends on the photoelectric metal.

15. **(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). **(b) :** $W = \frac{hc}{\lambda_1} - eV_{s_1} = \frac{1240}{550} - 0.19 = 2.07$ eV

16. A photon transfers a part of its energy to the colliding electron, so its energy decreases and consequently wavelength increases.

17. Photoelectric effect shows the quantum nature of electromagnetic radiation. Another one is compton effect.

18. The amount of light energy or photon energy, incident per unit area per unit time is called intensity of radiation.
S.I. Unit : W m^{-2} or J m^{-2} s^{-1}.

OR

Alkali metals have low work function. Even visible radiation can eject out electrons from them. So alkali metals are most suitable photo-sensitive metals.

19. Let λ_0 is the threshold wavelength, the work function is

$\phi = \frac{hc}{\lambda_0}$

Now, by photoelectric equation, $eV_s = \frac{hc}{\lambda} - \frac{hc}{\lambda_0}$

$$ex = \frac{hc}{\lambda} - \frac{hc}{\lambda_0} \quad \text{...(i)}$$

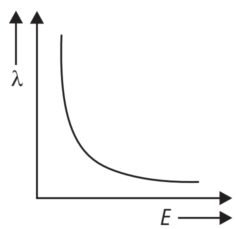
$$\frac{ex}{n+1} = \frac{hc}{n\lambda} - \frac{hc}{\lambda_0} \quad \text{...(ii)}$$

From (i) and (ii), $\frac{hc}{\lambda} - \frac{hc}{\lambda_0} = (n+1)\frac{hc}{n\lambda} - (n+1)\frac{hc}{\lambda_0}$

or $\frac{nhc}{\lambda_0} = \frac{hc}{n\lambda} \Rightarrow \lambda_0 = n^2\lambda$

20. de Broglie wavelength, $\lambda = \frac{h}{p} = \frac{h}{\sqrt{2mKE}}$

$\Rightarrow \lambda^2 \, KE$ = constant.



OR

(i) Photoelectric cell are used in television camera for telecasting scenes and in photo telegraphy.
(ii) Photocells are used for the reproduction of sound recorded on films along with pictures in the movie theatre.
(iii) Photocells are used in counting devices *e.g.*, to count the persons entering the hall provided they come one by one.
(iv) Photocells are also used in burglar alarm and fire alarms.
(v) They are used for the determination of Planck's constant.
(vi) They are used to determine the opacity of solids and liquids.
(vii) It is used to control the temperature and chemical reactions, to measure the temperature of stars and to study the spectrum of the heavenly body.
(viii) It is used to switch on and off the street lighting system at dusk and down without any manual attention.
(ix) They are used in photometry to compare the illuminating powers of two sources.
(x) It is used to sort out the material of different shades.

21. (i) No, the stopping potential does not depend on the intensity of the incident radiation.
(ii) Yes, the stopping potential depends on the frequency of incident radiation.

22. The stopping potential is still V_0. As the distance is decreased from 50 cm to 25 cm (*i.e.*, the distance is halved), the intensity of light becomes four times the original intensity. But the stopping potential is independent of the intensity and depends on frequency which remains unchanged.

23. An electron microscope exploits the wave nature of an accelerated beam of electrons to provide high magnifying and resolving powers.

24. Here $W_0 = 3.3 \times 10^{-19}$ J, $h = 6.6 \times 10^{-34}$ J s

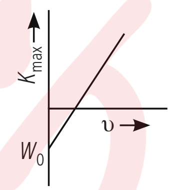
Threshold frequency,

$$\upsilon_0 = \frac{W_0}{h} = \frac{3.3 \times 10^{-19}}{6.6 \times 10^{-34}} = 5 \times 10^{14} \text{ Hz.}$$

25. According to Einstein's photoelectric equation,

$K_{max} = h\upsilon - W_0$

So the graph between K_{max} and υ is a straight line as shown in figure.



(i) Slope of K_{max}-υ graph $= \frac{\Delta K_{max}}{\Delta \upsilon} = h$

∴ Slope of K_{max}-υ graph gives the value of Planck's constant.

(ii) Intercept on the negative K_{max} axis $= W_0$

∴ Intercept on the negative K_{max} axis gives the value of work function.

26. The kinetic energy gained by a particle when accelerated through potential difference V is

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

or $m^2v^2 = 2mqV$

∴ Momentum, $p = mv = \sqrt{2mqV}$

$$\therefore \frac{p_\alpha}{p_p} = \sqrt{\frac{2m_\alpha q_\alpha V}{2m_p q_p V}}$$

$$= \sqrt{\frac{2 \times 4m_p \times 2e \times V}{2 \times m_p \times e \times V}} = 2\sqrt{2} : 1$$

OR

de-Broglie wavelength,

$$\lambda = \frac{h}{\sqrt{2mqV}} = \frac{h}{\sqrt{2mq}} \cdot \frac{1}{\sqrt{V}}$$

∴ λ versus $\frac{1}{\sqrt{V}}$ graph is a straight line with slope

$$= \frac{h}{\sqrt{2mq}}$$

For the particles of same charge q, slope $\propto \frac{1}{\sqrt{m}}$.

As $m_2 < m_1$, the line B with larger slope than that of line A represents the graph for smaller mass m_2.

27. Momentum, $p = \frac{h}{\lambda}$

As both electron and photon have same wavelength, so they have equal momentum.

Relativistic energy of particle, $E = \sqrt{m_0^2 c^4 + p^2 c^2}$

But for a photon, $m_0 = 0$ and for an electron, $m_0 > 0$.
Hence the electron has more energy than the photon.

28. Like an eye, a photo-cell can distinguish between a weak and an intense light. But a photocell gives a measure of light intensity in terms of photoelectric current. So it is also called an electric eye.

29. (i) Here $\lambda = 300$ nm $= 3 \times 10^{-7}$ m

$V_0 = 0.54$ V

$$E = \frac{hc}{\lambda} = \frac{6.63 \times 10^{-34} \times 3 \times 10^8}{3 \times 10^{-7}} = 6.63 \times 10^{-19} \text{ J}$$

$$= \frac{6.63 \times 10^{-19}}{1.6 \times 10^{-19}} \text{ eV} = 4.14 \text{ eV}.$$

(ii) $K_{max} = eV_0 = 0.54$ eV.

(iii) Again, $K_{max} = h\upsilon - W_0$

$W_0 = h\upsilon - K_{max} = 4.14 - 0.54 = 3.6$ eV.

30. Einstein's photoelectric equation is

$eV_0 = h\upsilon - W_0$

On differentiation, we get

$e\Delta V_0 = h\Delta\upsilon$

$$\therefore \quad h = \frac{\Delta V_0}{\Delta \upsilon} \cdot e = \frac{1.23 - 0}{(8-5) \times 10^{14}} \times 1.6 \times 10^{-19} \text{ J s}$$

$= 6.56 \times 10^{-34}$ J s.

31. The basic features of the photon picture of e.m. radiation are as follows :

(i) Light is composed of discrete packets of energy called quanta or photons.

(ii) Each photon carries an energy $E(= h\upsilon)$ and momentum $p(= h/\lambda)$, which depend on the frequency υ of the incident radiation and not on its intensity.

(iii) During the collision of a photon with an electron, the total energy of the photon gets absorbed by the electron.

(iv) Photoelectric emission from the metal surface occurs due to the absorption of a photon by an electron.

32. (i) Cut-off voltage or stopping potential :

The minimum negative potential given to the anode of a photocell for which the photoelectric current becomes zero is called cut-off voltage or stopping potential.

(ii) Threshold frequency: The minimum value of the frequency of incident radiation below which the photoelectric emission stops is called threshold frequency.

According to Einstein's photoelectric equation, the maximum K.E. of a photoelectron is given by

$K_{max} = h\upsilon - W_0$

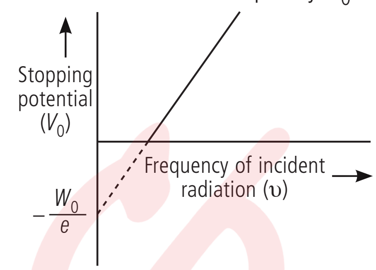
If V_0 is the stopping potential, then

$K_{max} = eV_0$

$\therefore \quad eV_0 = h\upsilon - W_0$

or $\quad V_0 = \left(\frac{h}{e}\right)\upsilon - \frac{W_0}{e}$ ...(i)

So the graph of V_0 versus υ is a straight line as shown in figure. We can read the value of threshold frequency υ_0 from the graph.



From equation (i), we can find stopping potential υ_0 for any frequency υ.

33. The observed characteristics of photoelectric effect could not be explained on the basis of wave theory of light.

(i) According to wave theory, the light propagates in the form of wavefronts and the energy is distributed uniformly over the wavefronts. With increase of intensity of light, the amplitude of waves and the energy stored by waves will increase. These waves will then, provide more energy to electrons of metal; consequently the energy of electrons will increase.

Thus, according to wave theory, the kinetic energy of photoelectrons must depend on the intensity of incident light; but according to experimental observations, the kinetic energy of photoelectrons does not depend on the intensity of incident light.

(ii) According to wave theory, the light of any frequency can emit electrons from metallic surface provided the intensity of light be sufficient to provide 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

(iii) According to wave theory, the energy transferred by light waves will not go to a particular electrons, but it will be distributed uniformly to all electrons present in the illuminated surface. Therefore, electrons will take some time to collect the necessary energy for their emission. The time for emission will be more for light of less intensity and vice versa. But experimental observations show that the emission of electrons take place instantaneously after the light is incident on the metal; whatever be the intensity of light.

OR

Failure of wave theory of light to explain photoelectric effect

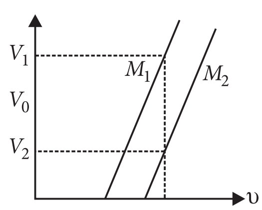
(i) According to wave theory, greater the intensity of radiation, greater the amplitudes of electric and magnetic fields and hence greater the energy density of the wave. So, the maximum kinetic energy of the photoelectron emitted must depend on intensity of incident light, however practically it does not happens. So independence of maximum kinetic energy of photoelectron emitted on intensity of incident light cannot be explained using wave theory of light.

(ii) Also, whatever the frequency of incident radiation may be, incident light of large intensity over a sufficient time must be able to impart enough energy to the electrons, so that they can get off the metal surface. So, a threshold frequency must not exist.

(iii) Further, number of electrons absorb energy continuously over the entire wavefront of the radiation. So, energy absorbed per unit time by an electron becomes very small. So, in that case electrons may take quite long time to come out of metallic surface on continuous exposure of light on the surface. However, practically we found that there is no time lag between incident of light and emission of photoelectron. So, we conclude that wave nature of light cannot be used to explain photoelectric effect.

34. (i) Slope of line $= \frac{\Delta V}{\Delta \upsilon}$ $[\because e\Delta V = h\Delta\upsilon]$

Slope of line $= \frac{h}{e}$



$\Rightarrow$ It is a constant quantity and does not depend on nature of metal surface.

(ii) Maximum kinetic energy of emitted photoelectron,

$KE = eV_0 = h\upsilon - h\upsilon_0$, ...(i)

For a given frequency $V_1 > V_2$ (from the graph)

So from equation (i),

$(KE)_1 > (KE)_2$

Since the metal M_1 has smaller threshold frequency *i.e.*, smaller work function. It emits electrons having a larger kinetic energy.

OR

Threshold Frequency : The minimum frequency of incident light which is just capable of ejecting electrons from a metal is called the threshold frequency. It is denoted by υ_0.

Stopping Potential : The minimum retarding potential applied to anode of a photoelectric tube which is just capable of stopping photoelectric current is called the stopping potential. It is denoted by V_0 (or V_S).

35. When a photon of wavelength λ is incident on a photocathode, the energy of the ejected electron is given by

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

$$\therefore \quad 3\times10^{-19} = \frac{hc}{3310\times10^{-10}} - \frac{hc}{\lambda_0} \quad ...(i)$$

and $$9.72\times10^{-20} = \frac{hc}{5000\times10^{-10}} - \frac{hc}{\lambda_0} \quad ...(ii)$$

Subtracting (ii) from (i), we get

$$(3-0.972)\times10^{-19} = \frac{hc}{10^{-10}}\left(\frac{1}{3310} - \frac{1}{5000}\right)$$

or $$2.028\times10^{-19} = \frac{h\times3\times10^8}{10^{-10}}\times\frac{1690}{3310\times5000}$$

$$\therefore \quad h = \frac{2.028\times10^{-19}\times10^{-10}\times3310\times5000}{3\times10^8\times1690}$$

$= 6.62 \times 10^{-34}$ J s.

Now $$W_0 = \frac{hc}{\lambda} - E$$

$$= \frac{6.62\times10^{-34}\times3\times10^8}{3310\times10^{-10}} - 3\times10^{-19}$$

$= (6-3)\times10^{-19} = 3\times10^{-19}$ J

Threshold wavelength,

$$\lambda_0 = \frac{hc}{W_0} = \frac{6.62\times10^{-34}\times3\times10^8}{3\times10^{-19}}$$

$= 6.62 \times 10^{-7}$ m $= 6620$ Å

OR

According to Einstein's photoelectric equation,

Energy of incident photon = Maximum K.E. of photoelectron + Work function of metal

or $$hv = K_{max} + W_0 = \frac{1}{2}mv_{max}^2 + h\upsilon_0$$

This equation explains the following important features :

(i) K_{max} depends linearly on frequency υ.

(ii) Existence of threshold frequency for any metal surface.

(iii) K_{max} does not depend on the intensity of incident light.

Derivation for λ_0 and W_0. According to Einstein's photoelectric equation,

$$h\upsilon = W_0 + K_{max} = h\upsilon_0 + K_{max}$$

or $$\frac{hc}{\lambda} = \frac{hc}{\lambda_0} + K_{max}$$

For wavelength λ_1,

$$\frac{hc}{\lambda_1} = \frac{hc}{\lambda_0} + K_{max}$$

For wavelength λ_2,

$$\frac{hc}{\lambda_2} = \frac{hc}{\lambda_0} + 2K_{max}$$

From (i) and (ii), we get

$$\frac{2hc}{\lambda_1} - \frac{hc}{\lambda_2} = \frac{hc}{\lambda_0} \quad \text{or} \quad \frac{2}{\lambda_1} - \frac{1}{\lambda_2} = \frac{1}{\lambda_0}$$

$$\therefore \quad \lambda_0 = \frac{\lambda_1\lambda_2}{2\lambda_2 - \lambda_1}$$

Work function,

$$W_0 = \frac{hc}{\lambda_0} = \frac{hc(2\lambda_2 - \lambda_1)}{\lambda_1\lambda_2}$$