CHAPTER 42

PHOTOELECTRIC EFFECT AND WAVE–PARTICLE DUALITY

42.1 PHOTON THEORY OF LIGHT

We have learnt that light has wave character as well as particle character. Depending on the situation, one of the two characters dominates. When light is passed through a double slit, it shows interference. This observation can only be understood in terms of wave theory which was discussed in detail in an earlier chapter. There are some phenomena which can only be understood in terms of the particle theory of light. When light of sufficiently low wavelength falls on a metal surface, electrons are ejected. This phenomenon is called the *photoelectric effect* and can be understood only in terms of the particle nature of light.

The particles of light have several properties in common with the material particles and several other properties which are different from the material particles. The particles of light are called *photons*. We list some of the important properties of photons.

(a) A photon always travels at a speed $c = 299,\, 792,\, 458 \text{ ms}^{-1} \approx 3{\cdot}0 \times 10^{8} \text{ m s}^{-1}$ in vacuum. This is true for any frame of reference used to observe the photon.

(b) The mass of a photon is not defined in the sense of Newtonian mechanics. We shall ignore this concept. We simply state that the *rest mass* of a photon is zero.

(c) Each photon has a definite energy and a definite linear momentum.

(d) Let E and p be the energy and linear momentum of a photon of light, and ν and λ be the frequency and wavelength of the same light when it behaves as a wave. Then,

$$E = h\nu = hc/\lambda \quad \text{and} \quad p = h/\lambda = E/c \qquad \dots (42.1)$$

where h is a universal constant known as the *Planck constant* and has a value $6{\cdot}626 \times 10^{-34}$ Js $= 4{\cdot}136 \times 10^{-15}$ eVs.

Thus, all photons of light of a particular wavelength λ have the same energy $E = hc/\lambda$ and the same momentum $p = h/\lambda$.

(e) A photon may collide with a material particle. The total energy and the total momentum remain conserved in such a collision. The photon may get absorbed and/or a new photon may be emitted. Thus, the number of photons may not be conserved.

(f) If the intensity of light of a given wavelength is increased, there is an increase in the number of photons crossing a given area in a given time. The energy of each photon remains the same.

Example 42.1

Consider a parallel beam of light of wavelengh 600 nm *and intensity* 100 W m^{-2}. *(a) Find the energy and linear momentum of each photon. (b) How many photons cross* 1 cm^2 *area perpendicular to the beam in one second?*

Solution :

(a) The energy of each photon $E = hc/\lambda$

$$= \frac{(4{\cdot}14 \times 10^{-15} \text{ eVs}) \times (3 \times 10^{8} \text{ m s}^{-1})}{600 \times 10^{-9} \text{ m}} = 2{\cdot}07 \text{ eV}.$$

The linear momentum is

$$p = \frac{E}{c} = \frac{2{\cdot}07 \text{ eV}}{3 \times 10^{8} \text{ m s}^{-1}} = 0{\cdot}69 \times 10^{-8} \text{ eVs m}^{-1}.$$

(b) The energy crossing 1 cm^2 in one second

$$= (100 \text{ W m}^{-2}) \times (1 \text{ cm}^2) \times (1 \text{ s}) = 1{\cdot}0 \times 10^{-2} \text{ J}.$$

The number of photons making up this amount of energy is

$$n = \frac{1{\cdot}0 \times 10^{-2} \text{ J}}{2{\cdot}07 \text{ eV}} = \frac{1{\cdot}0 \times 10^{-2}}{2{\cdot}07 \times 1{\cdot}6 \times 10^{-19}} = 3{\cdot}0 \times 10^{16}.$$

For a given wavelength λ, the energy of light is an integer times hc/λ. Thus, the energy of light can be varied only in quantums (steps) of $\frac{hc}{\lambda}$. The photon theory is, therefore, also called the quantum theory of light.

42.2 PHOTOELECTRIC EFFECT

When light of sufficiently small wavelength is incident on a metal surface, electrons are ejected from the metal. This phenomenon is called the *photoelectric effect.* The electrons ejected from the metal are called *photoelectrons.* Let us try to understand photoelectric effect on the basis of the photon theory of light.

We know that there are large number of free electrons in a metal which wander throughout the body of the metal. However, these electrons are not free to leave the surface of the metal. As they try to come out of the metal, the metal attracts them back. A minimum energy, equal to the work function φ, must be given to an electron so as to bring it out of the metal.

When light is incident on a metal surface, the photons collide with the free electrons. In a particular collision, the photon may give all of its energy to the free electron. If this energy is more than the work function φ, the electron may come out of the metal. It is not necessary that if the energy supplied to an electron is more than φ, it will come out. The electron after receiving the energy, may lose energy to the metal in course of collisions with the atoms of the metal. Only if an electron near the surface gets the extra energy and heads towards the outside, it is able to come out. If it is given an energy E which is greater than φ, and it makes the most economical use of it, it will have a kinetic energy $(E - \varphi)$ after coming out. If it makes some collisions before coming out, the kinetic energy will be less than $(E - \varphi)$. The actual kinetic energy of such an electron will depend on the total energy lost in collisions. It is also possible that the electron makes several collisions inside the metal and loses so much energy that it fails to come out. So, the kinetic energy of the photoelectron coming out may be anything between zero and $(E - \varphi)$ where E is the energy supplied to the individual electrons. We can, therefore, write

$$K_{max} = E - \varphi.$$

Table 42.1 : *Work functions of some photosensitive metals*

Metal	Work function (eV)	Metal	Work function (eV)
Cesium	1·9	Calcium	3·2
Potassium	2·2	Copper	4·5
Sodium	2·3	Silver	4·7
Lithium	2·5	Platinum	5·6

Let monochromatic light of wavelength λ be incident on the metal surface. In the particle picture, photons of energy hc/λ fall on the surface. Suppose, a particular photon collides with a free electron and supplies all its energy to the electron. The electron gets an extra energy $E = hc/\lambda$ and may come out of metal. The maximum kinetic energy of this electron is, therefore,

$$K_{max} = \frac{hc}{\lambda} - \varphi = h\nu - \varphi. \qquad \dots (42.2)$$

As all the photons have the same energy hc/λ, equation (42.2) gives the maximum kinetic energy of any of the ejected electrons.

Equation (42.2) is called *Einstein's photoelectric equation.* Einstein, after an average academic career, put forward this theory in 1905 while working as a grade III technical officer in a patent office. He was awarded the Nobel Prize in physics for 1921 for this work.

Threshold Wavelength

Equation (42.2) tells that if the wavelength λ is equal to

$$\lambda_0 = hc/\varphi,$$

the maximum kinetic energy is zero. An electron may just come out in this case. If $\lambda > \lambda_0$, the energy hc/λ supplied to the electron is smaller than the work function φ and no electron will come out. Thus, photoelectric effect takes place only if $\lambda \le \lambda_0$. This wavelength λ_0 is called the *threshold wavelength* for the metal. The corresponding frequency

$$\nu_0 = c/\lambda_0 = \varphi/h$$

is called the *threshold frequency* for the metal. Threshold wavelength and threshold frequency depend on the metal used.

Writing $\varphi = h\nu_0$, equation (42.2) becomes

$$K_{max} = h(\nu - \nu_0). \qquad \dots (42.3)$$

Example 42.2

Find the maximum wavelength of light that can cause photoelectric effect in lithium.

Solution : From table (42.1), the work function of lithium is 2·5 eV. The threshold wavelength is

$$\lambda = hc/\varphi.$$

$$= \frac{(4{\cdot}14\times10^{-15}\ \text{eVs})\times(3\times10^{8}\ \text{m s}^{-1})}{2{\cdot}5\ \text{eV}}$$

$$= \frac{1242\ \text{eVnm}}{2{\cdot}5\ \text{eV}} = 497\ \text{nm}.$$

This is the required maximum wavelength.

Experimental Arrangement

A systematic study of photoelectric effect can be made in the laboratory with the apparatus shown in figure (42.1). Two metal plates C and A are sealed in a vacuum chamber. Light of reasonably short wavelength passes through a transparent window in the wall of the chamber and falls on the plate C which is called the *cathode* or the *emitter*. The electrons are emitted by C and collected by the plate A called the *anode* or the *collector*. The potential difference between the cathode and the anode can be changed with the help of the batteries, rheostat and the commutator. The anode potential can be made positive or negative with respect to the cathode. The electrons collected by the anode A flow through the ammeter, batteries, etc., and are back to the cathode C and hence an electric current is established in the circuit. Such a current is called a *photocurrent.*

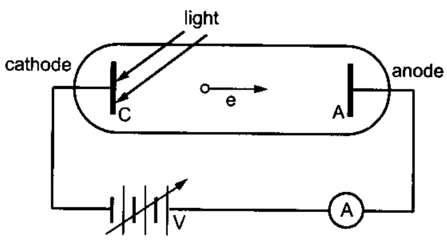

Figure 42.1

As photoelectrons are emitted from the cathode C, they move towards the anode A. At any time, the space between the cathode and the anode contains a number of electrons making up the *space charge*. This negative charge repels the fresh electrons coming from the cathode. However, some electrons are able to reach the anode and there is a photocurrent. When the anode is given a positive potential with respect to the cathode, electrons are attracted towards the anode and the photocurrent increases. The current thus depends on the potential applied to the anode. Figure (42.2) shows the variation in current with potential. If the potential of the anode is increased gradually, a situation arrives when the effect of the space charge becomes negligible and any electron that is emitted from the cathode is able to reach the anode. The current then becomes constant and is known as the *saturation current*. This is shown by the part bc in figure (42.2). Further increase in the anode potential does not change the magnitude of the photocurrent.

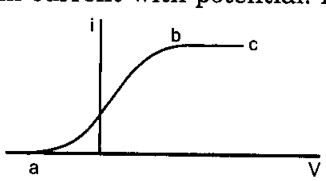

Figure 42.2

If the potential of the anode is made negative with respect to the cathode, the electrons are repelled by the anode. Some electrons go back to the cathode so that the current decreases. At a certain value of this negative potential, the current is completely stopped. The smallest magnitude of the anode potential which just stops the photocurrent, is called the *stopping potential.*

The stopping potential is related to the maximum kinetic energy of the ejected electrons. To stop the current, we must ensure that even the fastest electron fails to reach the anode. Suppose, the anode is kept at a negative potential of magnitude V_0 with respect to the cathode. As a photoelectron travels from the cathode to the anode, the potential energy increases by eV_0. This is equal to the decrease in the kinetic energy of the photoelectron. The kinetic energy of the fastest photoelectron, as it reaches the anode, is $K_{max} - eV_0$. If the fastest electron just fails to reach the anode, we should have

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

or, $$V_0 = \frac{hc}{e}\left(\frac{1}{\lambda}\right) - \frac{\varphi}{e}. \qquad \ldots (42.3)$$

We see that the stopping potential V_0 depends on the wavelength of the light and the work function of the metal. It does not depend on the intensity of light. Thus, if an anode potential of $-2{\cdot}0$ V stops the photocurrent from a metal when a 1 W source of light is used, the same potential of $-2{\cdot}0$ V will stop the photocurrent when a 100 W source of light of the same wavelength is used.

The saturation current increases as the intensity of light increases. This is because, a larger number of photons now fall on the metal surface and hence a larger number of electrons interact with photons. The number of electrons emitted increases and hence the current increases.

Figure (42.3a) shows plots of photocurrent versus anode potential for three different intensities of light.

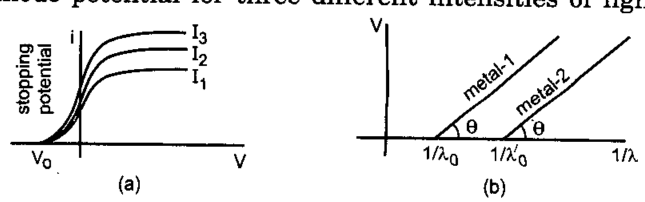

Figure 42.3

Note that the stopping potential V_0 is indepedent of the intensity of light.

The variation in stopping potential V_0 with $1/\lambda$ is shown in figure (42.3b) for cathodes of two different metals. From equation (42.3), the slope of each curve is

$$\tan\theta = \frac{hc}{e}$$

which is the same for all metals. Also, the curves intersect the $1/\lambda$ axis where V_0 is zero. Using equation (42.3), this corresponds to

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

or, $$\frac{1}{\lambda_0} = \frac{\varphi}{hc}$$

which is inverse of the threshold wavelength.

Let us summarise the results obtained from the experiments described above.

1. When light of sufficiently small wavelength falls on a metal surface, the metal emits electrons. The emission is almost instantaneous.

2. There is a threshold wavelength λ_0 for a given metal such that if the wavelength of light is more than λ_0, no photoelectric effect takes place.

3. The kinetic energies of the photoelectrons vary from zero to a maximum of K_{max} where

$$K_{max} = \frac{hc}{\lambda} - \varphi$$

with usual meanings of the symbols.

4. The photocurrent may be stopped by applying a negative potential to the anode with respect to the cathode. The minimum magnitude of the potential needed to stop the photocurrent is called the stopping potential. It is proportional to the maximum kinetic energy of the photoelectrons.

5. The stopping potential does not depend on the intensity of the incident light. This means that the kinetic energy of the photoelectrons is independent of intensity of light.

6. The stopping potential depends on the wavelength of the incident light.

7. The photocurrent increases if the intensity of the incident light is increased.

Photoelectric Effect and Wave Theory of Light

According to wave thoery, when light falls on a metal surface, energy is continuously distributed over the surface. All the free electrons at the surface receive light energy. An electron may be ejected only when it acquires energy more than the work function. If we use a low-intensity source, it may take hours before an electron acquires this much energy from the light. In this period, there will be many collisions and any extra energy accumulated so far will be shared with the remaining metal. This will result in no photoelectron. This is contrary to experimental observations. No matter how small is the intensity, photoelectrons are ejected and that too without any appreciable time delay. In the photon theory, low intensity means less number of photons and hence less number of electrons get a chance to absorb energy. But any fortunate electron on which a photon falls, gets the full energy of the photon and may come out immediately.

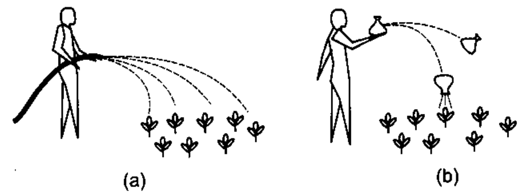

Figure 42.4

In figure (42.4), we illustrate an analogy to the wave and particle behaviour of light. In part (a), water is sprayed from a distance on an area containing several plants. Each plant receives water at nearly the same rate. It takes time for a particular plant to receive a certain amount of water. In part (b) of the figure, water is filled in identical, loosely-tied water bags and a particle physicist throws the bags randomly at the plants. When a bag collides with a plant, it sprays all its water on that plant in a very short time. In the same way, whole of the energy associated with a photon is absorbed by a free electron when the photon hits it.

The maximum kinetic energy of a photoelectron does not depend on the intensity of the incident light. This fact is also not understood by the wave theory. According to this theory, more intensity means more energy and the maximum kinetic energy must increase with the increase in intensity which is not true. The dependence of maximum kinetic energy on wavelength is also against the wave theory. There should not be any threshold wavelength according to the wave thoery. According to this theory, by using sufficiently intense light of any wavelength, an electron may be given the required amount of energy to come out. Experiments, however, show the existence of threshold wavelength.

Example 42.3

A point source of monochromatic light of 1·0 mW *is placed at a distance of* 5·0 m *from a metal surface. Light falls perpendicularly on the surface. Assume wave theory of light to hold and also that all the light falling on the circular area with radius* $= 1{\cdot}0 \times 10^{-9}$ m *(which is few times the diameter of an atom) is absorbed by a single electron on the surface. Calculate the time required by the electron to receive sufficient energy to come out of the metal if the work function of the metal is* 2·0 eV.

Solution : The energy radiated by the light source per second is 1·0 mJ. This energy is spread over the total solid angle 4π. The solid angle subtended at the source by the circular area mentioned is

$$d\Omega = \frac{dA}{r^2} = \frac{\pi \times (1{\cdot}0 \times 10^{-9}\ \mathrm{m})^2}{(5{\cdot}0\ \mathrm{m})^2} = \frac{\pi}{25} \times 10^{-18}\ \mathrm{sr}.$$

Hence the energy heading towards the circular area per second is

$$\frac{d\Omega}{4\pi}(1{\cdot}0\ \mathrm{mJ}) = 10^{-20}\ \mathrm{mJ}.$$

The time required for accumulation of 2·0 eV of energy on this circular area is

$$t = \frac{2{\cdot}0 \times 1{\cdot}6 \times 10^{-19}\ \mathrm{J}}{10^{-20}\ \mathrm{mJ\ s^{-1}}} = 3{\cdot}2 \times 10^4\ \mathrm{s} = 8{\cdot}8\ \text{hours}.$$

The assumption of continuous absorption of energy is based on the wave theory. The above calculation shows that if this theory were correct, the first electron would be ejected not before 8·8 hours of continuous irradiation. However, in actual case, photoelectrons come out almost without any time delay after light falls on the metal.

42.3 MATTER WAVES

We have seen that light behaves in certain situations as waves and in certain other situations as particles. We know that electrons behave as particles in many of the situations. Can electrons also show wave nature in some suitable situations ? The answer is *yes*. A large number of experiments are now available in which electrons interfere like waves and produce fringes. Electron microscope is built on the basis of the wave properties of electrons. Protons, neutrons or even bigger particles have intrinsic wave properties. It is only a question of putting them under proper experimental situations to bring out their wave character.

If an electron behaves as waves, what is its wavelength ? The relation was proposed by Prince Louis Victor de Broglie in his PhD thesis for which he was awarded the Nobel Prize in physics for 1929. The wavelength is given by

$$\lambda = \frac{h}{p} \qquad \dots (42.4)$$

where p is the momentum of the electron and h is the Planck constant. This wavelength is known as the *de Broglie wavelength* of the electron. Same is the case with other particles such as a neutron, a proton, a molecule, etc. In fact, the equation also applies to light. When light shows its photon character, each photon has a momentum $p = h/\lambda$ (equation 42.1).

Can we apply Newton's laws to find the motion of an electron if the electron has both particle and wave characters. Indeed we should not rely upon Newton's laws to discuss the behaviour of electrons in all situations. While discussing the "scope of classical physics" it was mentioned that the classical mechanics of Newton fails for particles of very small size. A rough estimate was given that the classical mechanics works well for particles of linear size greater than 10^{-4} cm. For smaller particles, we should use *quantum mechanics* which takes into account the dual nature (wave nature and particle nature) of electrons, protons and other subatomic particles.

Worked Out Examples

Use $h = 6{\cdot}63 \times 10^{-34}\ \mathrm{Js} = 4{\cdot}14 \times 10^{-15}\ \mathrm{eVs}$, $c = 3 \times 10^8\ \mathrm{m\ s^{-1}}$ and $m_e = 9{\cdot}1 \times 10^{-31}$ kg wherever required.

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1. *How many photons are emitted per second by a* 5 mW *laser source operating at* 632·8 nm ?

Solution : The energy of each photon is

$$E = \frac{hc}{\lambda} = \frac{(6{\cdot}63 \times 10^{-34}\ \mathrm{J\ s}) \times (3 \times 10^8\ \mathrm{m\ s^{-1}})}{(632{\cdot}8 \times 10^{-9}\ \mathrm{m})} = 3{\cdot}14 \times 10^{-19}\ \mathrm{J}.$$

The energy of the laser emitted per second is 5×10^{-3} J. Thus the number of photons emitted per second

$$= \frac{5 \times 10^{-3}\ \mathrm{J}}{3{\cdot}14 \times 10^{-19}\ \mathrm{J}} = 1{\cdot}6 \times 10^{16}.$$

2. *A monochromatic source of light operating at* 200 W *emits* 4×10^{20} *photons per second. Find the wavelength of the light.*

Solution : The energy of each photon $= \dfrac{200\ \mathrm{J\ s^{-1}}}{4 \times 10^{20}\ \mathrm{s^{-1}}} = 5 \times 10^{-19}\ \mathrm{J}.$

$$\text{Wavelength} = \lambda = \frac{hc}{E} = \frac{(6{\cdot}63 \times 10^{-34}\ \mathrm{J\ s}) \times (3 \times 10^8\ \mathrm{m\ s^{-1}})}{(5 \times 10^{-19}\ \mathrm{J})} = 4{\cdot}0 \times 10^{-7}\ \mathrm{m} = 400\ \mathrm{nm}.$$

3. *A hydrogen atom moving at a speed v absorbs a photon of wavelength* 122 nm *and stops. Find the value of v. Mass of a hydrogen atom* $= 1{\cdot}67 \times 10^{-27}$ kg.

Solution : The linear momentum of the photon

$$= \frac{h}{\lambda} = \frac{6{\cdot}63 \times 10^{-34}\ \text{Js}}{122 \times 10^{-9}\ \text{m}} = 5{\cdot}43 \times 10^{-27}\ \text{kg m s}^{-1}.$$

As the photon is absorbed and the atom stops, the total final momentum is zero. From conservation of linear momentum, the initial momentum must be zero. The atom should move opposite to the direction of motion of the photon and they should have the same magnitudes of linear momentum. Thus,

$$(1{\cdot}67 \times 10^{-27}\ \text{kg})\, v = 5{\cdot}43 \times 10^{-27}\ \text{kg m s}^{-1}$$

or, $$v = \frac{5{\cdot}43 \times 10^{-27}}{1{\cdot}67 \times 10^{-27}}\ \text{m s}^{-1} = 3{\cdot}25\ \text{m s}^{-1}.$$

4. *A parallel beam of monochromatic light of wavelength* 500 nm *is incident normally on a perfectly absorbing surface. The power through any cross-section of the beam is* 10 W. *Find (a) the number of photons absorbed per second by the surface and (b) the force exerted by the light beam on the surface.*

Solution :

(a) The energy of each photon is

$$E = \frac{hc}{\lambda} = \frac{(4{\cdot}14 \times 10^{-15}\ \text{eVs}) \times (3 \times 10^{8}\ \text{m s}^{-1})}{500\ \text{nm}}$$

$$= \frac{1242\ \text{eVn m}}{500\ \text{nm}} = 2{\cdot}48\ \text{eV}.$$

In one second, 10 J of energy passes through any cross section of the beam. Thus, the number of photons crossing a cross section is

$$n = \frac{10\ \text{J}}{2{\cdot}48\ \text{eV}} = 2{\cdot}52 \times 10^{19}.$$

This is also the number of photons falling on the surface per second and being absorbed.

(b) The linear momentum of each photon is

$$p = \frac{h}{\lambda} = \frac{h\nu}{c}.$$

The total momentum of all the photons falling per second on the surface is

$$= \frac{nh\nu}{c} = \frac{10\ \text{J}}{c} = \frac{10\ \text{J}}{3 \times 10^{8}\ \text{m s}^{-1}} = 3{\cdot}33 \times 10^{-8}\ \text{Ns}.$$

As the photons are completely absorbed by the surface, this much momentum is transferred to the surface per second. The rate of change of the momentum of the surface, i.e., the force on it is

$$F = \frac{dp}{dt} = \frac{3{\cdot}33 \times 10^{-8}\ \text{Ns}}{1\ \text{s}} = 3{\cdot}33 \times 10^{-8}\ \text{N}.$$

5. *Figure (42-W1) shows a small, plane strip suspended from a fixed support through a string of length l. A continuous beam of monochromatic light is incident horizontally on the strip and is completely absorbed. The energy falling on the strip per unit time is W. (a) Find the deflection of the string from the vertical if the mirror stays in equilibrium. (b) If the strip is deflected slightly from its equilibrium position in the plane of the figure, what will be the time period of the resulting oscillations ?*

Solution :

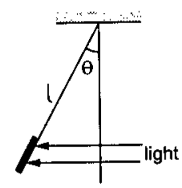

Figure 42-W1

(a) The linear momentum of the light falling per unit time on the strip is W/c. As the light is incident on the strip, its momentum is absorbed by the mirror. The change in momentum imparted to the strip per unit time is thus W/c. This is equal to the force on the strip by the light beam. In equilibrium, the force by the light beam, the weight of the strip and the force due to tension add to zero. If the string makes an angle θ with the vertical,

$$T\cos\theta = mg$$

and $$T\sin\theta = W/c.$$

Thus, $$\tan\theta = \frac{W}{mgc}.$$

(b) In equilibrium, the tension is

$$T = \left[(mg)^2 + \left(\frac{W}{c}\right)^2\right]^{1/2}$$

or, $$\frac{T}{m} = \left[g^2 + \left(\frac{W}{mc}\right)^2\right]^{1/2}.$$

This plays the role of effective g. The time period of small oscillations is

$$t = 2\pi\sqrt{\frac{l}{T/m}} = 2\pi \frac{\sqrt{l}}{\left[g^2 + \left(\frac{W}{mc}\right)^2\right]^{\frac{1}{4}}}.$$

6. *A point source of light is placed at the centre of curvature of a hemispherical surface. The radius of curvature is r and the inner surface is completely reflecting. Find the force on the hemisphere due to the light falling on it if the source emits a power W.*

Solution :

The energy emitted by the source per unit time, i.e., W falls on an area $4\pi r^2$ at a distance r in unit time. Thus, the energy falling per unit area per unit time is $W/(4\pi r^2)$. Consider a small area dA at the point P of the hemisphere (figure 42-W2). The energy falling per

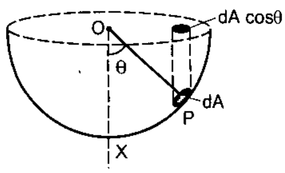

Figure 42-W2

unit time on it is $\frac{W\,dA}{4\pi r^2}$ · The corresponding momentum incident on this area per unit time is $\frac{W\,dA}{4\pi r^2 c}$ · As the light is reflected back, the change in momentum per unit time, i.e., the force on dA is

$$dF = \frac{2W\,dA}{4\pi r^2 c}.$$

Suppose the radius OP through the area dA makes an angle θ with the symmetry axis OX. The force on dA is along this radius. By symmetry, the resultant force on the hemisphere is along OX. The component of dF along OX is

$$dF\cos\theta = \frac{2W\,dA}{4\pi r^2 c}\cos\theta.$$

If we project the area dA on the plane containing the rim, the projection is $dA\cos\theta$. Thus, the component of dF along OX is,

$$dF\cos\theta = \frac{2\,W}{4\pi r^2 c}\,(\text{projection of } dA).$$

The net force along OX is

$$F = \frac{2\,W}{4\pi r^2 c}\left(\sum \text{projection of } dA\right).$$

When all the small areas dA are projected, we get the area enclosed by the rim which is πr^2. Thus,

$$F = \frac{2\,W}{4\pi r^2 c} \times \pi r^2 = \frac{W}{2c}.$$

7. *A perfectly reflecting solid sphere of radius r is kept in the path of a parallel beam of light of large aperture. If the beam carries an intensity I, find the force exerted by the beam on the sphere.*

Solution :

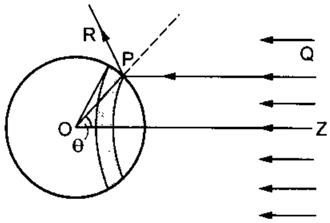

Figure 42-W3

Let O be the centre of the sphere and OZ be the line opposite to the incident beam (figure 42-W3). Consider a radius OP of the sphere making an angle θ with OZ. Rotate this radius about OZ to get a circle on the sphere. Change θ to $\theta + d\theta$ and rotate the radius about OZ to get another circle on the sphere. The part of the sphere between these circles is a ring of area $2\pi r^2 \sin\theta\, d\theta$. Consider a small part ΔA of this ring at P. Energy of the light falling on this part in time Δt is

$$\Delta U = I\Delta t(\Delta A\cos\theta).$$

The momentum of this light falling on ΔA is $\Delta U/c$ along QP. The light is reflected by the sphere along PR. The change in momentum is

$$\Delta p = 2\frac{\Delta U}{c}\cos\theta = \frac{2}{c}\,I\,\Delta t\,(\Delta A\cos^2\theta)$$

along the inward normal. The force on ΔA due to the light falling on it, is

$$\frac{\Delta p}{\Delta t} = \frac{2}{c}\,I\,\Delta A\cos^2\theta.$$

This force is along PO. The resultant force on the ring as well as on the sphere is along ZO by symmetry. The component of the force on ΔA, along ZO is

$$\frac{\Delta p}{\Delta t}\cos\theta = \frac{2}{c}\,I\,\Delta A\cos^3\theta.$$

The force acting on the ring is

$$dF = \frac{2}{c}\,I\,(2\pi r^2\sin\theta\,d\theta)\cos^3\theta.$$

The force on the entire sphere is

$$F = \int_0^{\pi/2} \frac{4\pi r^2 I}{c}\cos^3\theta\sin\theta\,d\theta$$

$$= -\int_{\theta=0}^{\pi/2} \frac{4\pi r^2 I}{c}\cos^3\theta\,d(\cos\theta)$$

$$= -\frac{4\pi r^2 I}{c}\left[\frac{\cos^4\theta}{4}\right]_0^{\pi/2} = \frac{\pi r^2 I}{c}.$$

Note that integration is done only for the hemisphere that faces the incident beam.

8. *Find the threshold wavelengths for photoelectric effect from a copper surface, a sodium surface and a cesium surface. The work functions of these metals are* 4·5 eV, 2·3 eV *and* 1·9 eV *respectively.*

Solution : If λ_0 be the threshold wavelength and φ be the work function,

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

$$= \frac{1242\text{ eV nm}}{\varphi}.$$

For copper, $\lambda_0 = \frac{1242\text{ eV nm}}{4{\cdot}5\text{ eV}} = 276\text{ nm}.$

For sodium, $\lambda_0 = \frac{1242\text{ eV nm}}{2{\cdot}3\text{ eV}} = 540\text{ nm}.$

For cesium, $\lambda_0 = \dfrac{1242 \text{ eV nm}}{1{\cdot}9 \text{ eV}} = 654 \text{ nm}.$

9. *Ultraviolet light of wavelength* 280 nm *is used in an experiment on photoelectric effect with lithium* ($\varphi = 2{\cdot}5$ eV) *cathode. Find (a) the maximum kinetic energy of the photoelectrons and (b) the stopping potential.*

Solution :

(a) The maximum kinetic energy is

$$K_{\text{max}} = \frac{hc}{\lambda} - \varphi$$

$$= \frac{1242 \text{ eV nm}}{280 \text{ nm}} - 2{\cdot}5 \text{ eV}$$

$$= 4{\cdot}4 \text{ eV} - 2{\cdot}5 \text{ eV} = 1{\cdot}9 \text{ eV}.$$

(b) Stopping potential V is given by

$$eV = K_{\text{max}}$$

or, $$V = \frac{K_{\text{max}}}{e} = \frac{1{\cdot}9 \text{ eV}}{e} = 1{\cdot}9 \text{ V}.$$

10. *In a photoelectric experiment, it was found that the stopping potential decreases from* 1·85 V *to* 0·82 V *as the wavelength of the incident light is varied from* 300 nm *to* 400 nm. *Calculate the value of the Planck constant from these data.*

Solution :

The maximum kinetic energy of a photoelectron is

$$K_{\text{max}} = \frac{hc}{\lambda} - \varphi$$

and the stopping potential is

$$V = \frac{K_{\text{max}}}{e} = \frac{hc}{\lambda e} - \frac{\varphi}{e}.$$

If V_1, V_2 are the stopping potentials at wavelengths λ_1 and λ_2 respectively,

$$V_1 = \frac{hc}{\lambda_1 e} - \frac{\varphi}{e}$$

and $$V_2 = \frac{hc}{\lambda_2 e} - \frac{\varphi}{e}.$$

This gives, $$V_1 - V_2 = \frac{hc}{e}\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right)$$

or, $$h = \frac{e(V_1 - V_2)}{c\left(\dfrac{1}{\lambda_1} - \dfrac{1}{\lambda_2}\right)}$$

$$= \frac{e(1{\cdot}85 \text{ V} - 0{\cdot}82 \text{ V})}{c\left(\dfrac{1}{300 \times 10^{-9} \text{ m}} - \dfrac{1}{400 \times 10^{-9} \text{ m}}\right)}$$

$$= \frac{1{\cdot}03 \text{ eV}}{(3 \times 10^{8} \text{ m s}^{-1})\left(\dfrac{1}{12} \times 10^{7} \text{ m}^{-1}\right)}$$

$$= 4{\cdot}12 \times 10^{-15} \text{ eVs}.$$

11. *A beam of* 450 nm *light is incident on a metal having work function* 2·0 eV *and placed in a magnetic field B. The most energetic electrons emitted perpendicular to the field are bent in circular arcs of radius* 20 cm. *Find the value of B.*

Solution : The kinetic energy of the most energetic electrons is

$$K = \frac{hc}{\lambda} - \varphi$$

$$= \frac{1242 \text{ eV nm}}{450 \text{ nm}} - 2{\cdot}0 \text{ eV}$$

$$= 0{\cdot}76 \text{ eV} = 1{\cdot}2 \times 10^{-19} \text{ J}.$$

The linear momentum $= mv = \sqrt{2mK}$

$$= \sqrt{2 \times (9{\cdot}1 \times 10^{-31} \text{ kg}) \times (1{\cdot}2 \times 10^{-19} \text{ J})}$$

$$= 4{\cdot}67 \times 10^{-25} \text{ kgms}^{-1}.$$

When a charged particle is sent perpendicular to a magnetic field, it goes along a circle of radius

$$r = \frac{mv}{qB}.$$

Thus, $$0{\cdot}20 \text{ m} = \frac{4{\cdot}67 \times 10^{-25} \text{ kg m s}^{-1}}{(1{\cdot}6 \times 10^{-19} \text{ C}) \times B}$$

or, $$B = \frac{4{\cdot}67 \times 10^{-25} \text{ kg m s}^{-1}}{(1{\cdot}6 \times 10^{-19} \text{ C}) \times (0{\cdot}20 \text{ m})} = 1{\cdot}46 \times 10^{-5} \text{ T}.$$

12. *A monochromatic light of wavelength* λ *is incident on an isolated metallic sphere of radius a. The threshold wavelength is* λ_0 *which is larger than* λ. *Find the number of photoelectrons emitted before the emission of photoelectrons will stop.*

Solution : As the metallic sphere is isolated, it becomes positively charged when electrons are ejected from it. There is an extra attractive force on the photoelectrons. If the potential of the sphere is raised to V, the electron should have a minimum energy $\varphi + eV$ to be able to come out. Thus, emission of photoelectrons will stop when

$$\frac{hc}{\lambda} = \varphi + eV$$

$$= \frac{hc}{\lambda_0} + eV$$

or, $$V = \frac{hc}{e}\left(\frac{1}{\lambda} - \frac{1}{\lambda_0}\right).$$

The charge on the sphere needed to take its potential to V is

$$Q = (4\pi\varepsilon_0 a)V.$$

The number of electrons emitted is, therefore,

$$n = \frac{Q}{e} = \frac{4\pi\varepsilon_0 a V}{e}$$

$$= \frac{4\pi\varepsilon_0 a hc}{e^2}\left(\frac{1}{\lambda} - \frac{1}{\lambda_0}\right).$$

13. *Light described at a place by the equation*

$E = (100\ \text{V m}^{-1})\,[\sin(5 \times 10^{15}\ \text{s}^{-1})\,t + \sin(8 \times 10^{15}\ \text{s}^{-1})t]$

falls on a metal surface having work function 2·0 eV. *Calculate the maximum kinetic energy of the photoelectrons.*

Solution : The light contains two different frequencies. The one with larger frequency will cause photoelectrons with largest kinetic energy. This larger frequency is

$$\nu = \frac{\omega}{2\pi} = \frac{8 \times 10^{15}\ \text{s}^{-1}}{2\pi}.$$

The maximum kinetic energy of the photoelectrons is

$$K_{max} = h\nu - \varphi$$

$$= (4{\cdot}14 \times 10^{-15}\ \text{eVs}) \times \left(\frac{8 \times 10^{15}}{2\pi}\ \text{s}^{-1}\right) - 2{\cdot}0\ \text{eV}$$

$$= 5{\cdot}27\ \text{eV} - 2{\cdot}0\ \text{eV} = 3{\cdot}27\ \text{eV}.$$

□

QUESTIONS FOR SHORT ANSWER

1. Can we find the mass of a photon by the definition $p = mv$?
2. Is it always true that for two sources of equal intensity, the number of photons emitted in a given time are equal ?
3. What is the speed of a photon with respect to another photon if (a) the two photons are going in the same direction and (b) they are going in opposite directions ?
4. Can a photon be deflected by an electric field ? By a magnetic field ?
5. A hot body is placed in a closed room maintained at a lower temperature. Is the number of photons in the room increasing ?
6. Should the energy of a photon be called its kinetic energy or its internal energy ?
7. In an experiment on photoelectric effect, a photon is incident on an electron from one direction and the photoelectron is emitted almost in the opposite direction. Does this violate conservation of momentum ?
8. It is found that yellow light does not eject photoelectrons from a metal. Is it advisable to try with orange light ? With green light ?
9. It is found that photosynthesis starts in certain plants when exposed to the sunlight but it does not start if the plant is exposed only to infrared light. Explain.
10. The threshold wavelength of a metal is λ_0. Light of wavelength slightly less than λ_0 is incident on an insulated plate made of this metal. It is found that photoelectrons are emitted for sometime and after that the emission stops. Explain.
11. Is $p = E/c$ valid for electrons ?
12. Consider the de Broglie wavelength of an electron and a proton. Which wavelength is smaller if the two particles have (a) the same speed (b) the same momentum (c) the same energy ?
13. If an electron has a wavelength, does it also have a colour ?

OBJECTIVE I

1. Planck constant has the same dimensions as
   (a) force × time (b) force × distance
   (c) force × speed (d) force × distance × time.
2. Two photons having
   (a) equal wavelengths have equal linear momenta
   (b) equal energies have equal linear momenta
   (c) equal frequencies have equal linear momenta
   (d) equal linear momenta have equal wavelengths.
3. Let p and E denote the linear momentum and energy of a photon. If the wavelength is decreased,
   (a) both p and E increase
   (b) p increases and E decreases
   (c) p decreases and E increases
   (d) both p and E decrease.
4. Let n_r and n_b be respectively the number of photons emitted by a red bulb and a blue bulb of equal power in a given time.
   (a) $n_r = n_b$ (b) $n_r < n_b$ (c) $n_r > n_b$
   (d) The information is insufficient to get a relation between n_r and n_b.
5. The equation $E = pc$ is valid
   (a) for an electron as well as for a photon
   (b) for an electron but not for a photon
   (c) for a photon but not for an electron
   (d) neither for an electron nor for a photon.
6. The work function of a metal is $h\nu_0$. Light of frequency ν falls on this metal. The photoelectric effect will take place only if
   (a) $\nu \geq \nu_0$ (b) $\nu > 2\nu_0$ (c) $\nu < \nu_0$ (d) $\nu < \nu_0/2$.
7. Light of wavelength λ falls on a metal having work function hc/λ_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) $\lambda < \lambda_0/2$.

8. When stopping potential is applied in an experiment on photoelectric effect, no photocurrent is observed. This means that
   (a) the emission of photoelectrons is stopped
   (b) the photoelectrons are emitted but are re-absorbed by the emitter metal
   (c) the photoelectrons are accumulated near the collector plate
   (d) the photoelectrons are dispersed from the sides of the apparatus.
9. If the frequency of light in a photoelectric experiment is doubled, the stopping potential will
   (a) be doubled (b) be halved
   (c) become more than double
   (d) become less than double.
10. The frequency and intensity of a light source are both doubled. Consider the following statements.
    (A) The saturation photocurrent remains almost the same.
    (B) The maximum kinetic energy of the photoelectrons is doubled.
    (a) Both A and B are true. (b) A is true but B is false.
    (c) A is false but B is true. (d) Both A and B are false.
11. A point source of light is used in a photoelectric effect. If the source is removed farther from the emitting metal, the stopping potential
    (a) will increase (b) will decrease
    (c) will remain constant
    (d) will either increase or decrease.
12. A point source causes photoelectric effect from a small metal plate. Which of the following curves may represent the saturation photocurrent as a function of the distance between the source and the metal?

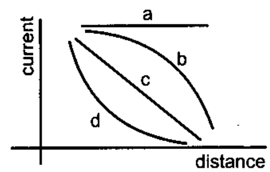

Figure 42-Q1

13. A nonmonochromatic light is used in an experiment on photoelectric effect. The stopping potential
    (a) is related to the mean wavelength
    (b) is related to the longest wavelength
    (c) is related to the shortest wavelength
    (d) is not related to the wavelength.
14. A proton and an electron are accelerated by the same potential difference. Let λ_e and λ_p denote the de Broglie wavelengths of the electron and the proton respectively.
    (a) $\lambda_e = \lambda_p$ (b) $\lambda_e < \lambda_p$ (c) $\lambda_e > \lambda_p$
    (d) The relation between λ_e and λ_p depends on the accelerating potential difference.

OBJECTIVE II

1. When the intensity of a light source is increased,
   (a) the number of photons emitted by the source in unit time increases
   (b) the total energy of the photons emitted per unit time increases
   (c) more energetic photons are emitted
   (d) faster photons are emitted.
2. Photoelectric effect supports quantum nature of light because
   (a) there is a minimum frequency below which no photoelectrons are emitted
   (b) the maximum kinetic energy of photoelectrons depends only on the frequency of light and not on its intensity
   (c) even when the metal surface is faintly illuminated the photoelectrons leave the surface immediately
   (d) electric charge of the photoelectrons is quantized.
3. A photon of energy $h\nu$ is absorbed by a free electron of a metal having work function $\varphi < h\nu$.
   (a) The electron is sure to come out.
   (b) The electron is sure to come out with a kinetic energy $h\nu - \varphi$.
   (c) Either the electron does not come out or it comes out with a kinetic energy $h\nu - \varphi$.
   (d) It may come out with a kinetic energy less than $h\nu - \varphi$.
4. If the wavelength of light in an experiment on photoelectric effect is doubled,
   (a) the photoelectric emission will not take place
   (b) the photoelectric emission may or may not take place
   (c) the stopping potential will increase
   (d) the stopping potential will decrease.
5. The photocurrent in an experiment on photoelectric effect increases if
   (a) the intensity of the source is increased
   (b) the exposure time is increased
   (c) the intensity of the source is decreased
   (d) the exposure time is decreased.
6. The collector plate in an experiment on photoelectric effect is kept vertically above the emitter plate. Light source is put on and a saturation photocurrent is recorded. An electric field is switched on which has a vertically downward direction.
   (a) The photocurrent will increase.
   (b) The kinetic energy of the electrons will increase.
   (c) The stopping potential will decrease.
   (d) The threshold wavelength will increase.
7. In which of the following situations the heavier of the two particles has smaller de Broglie wavelength? The two particles
   (a) move with the same speed
   (b) move with the same linear momentum
   (c) move with the same kinetic energy
   (d) have fallen through the same height.

EXERCISES

Use $h = 6{\cdot}63 \times 10^{-34}$ J s $= 4{\cdot}14 \times 10^{-15}$ eVs, $c = 3 \times 10^{8}$ m s^{-1} and $m_e = 9{\cdot}1 \times 10^{-31}$ kg wherever needed.

1. Visible light has wavelengths in the range of 400 nm to 780 nm. Calculate the range of energy of the photons of visible light.
2. Calculate the momentum of a photon of light of wavelength 500 nm.
3. An atom absorbs a photon of wavelength 500 nm and emits another photon of wavelength 700 nm. Find the net energy absorbed by the atom in the process.
4. Calculate the number of photons emitted per second by a 10 W sodium vapour lamp. Assume that 60% of the consumed energy is converted into light. Wavelength of sodium light = 590 nm.
5. When the sun is directly overhead, the surface of the earth receives $1{\cdot}4 \times 10^{3}$ W m^{-2} of sunlight. Assume that the light is monochromatic with average wavelength 500 nm and that no light is absorbed in between the sun and the earth's surface. The distance between the sun and the earth is $1{\cdot}5 \times 10^{11}$ m. (a) Calculate the number of photons falling per second on each square metre of earth's surface directly below the sun. (b) How many photons are there in each cubic metre near the earth's surface at any instant? (c) How many photons does the sun emit per second?
6. A parallel beam of monochromatic light of wavelength 663 nm is incident on a totally reflecting plane mirror. The angle of incidence is 60° and the number of photons striking the mirror per second is $1{\cdot}0 \times 10^{19}$. Calculate the force exerted by the light beam on the mirror.
7. A beam of white light is incident normally on a plane surface absorbing 70% of the light and reflecting the rest. If the incident beam carries 10 W of power, find the force exerted by it on the surface.
8. A totally reflecting, small plane mirror placed horizontally faces a parallel beam of light as shown in figure (42-E1). The mass of the mirror is 20 g. Assume that there is no absorption in the lens and that 30% of the light emitted by the source goes through the lens. Find the power of the source needed to support the weight of the mirror. Take $g = 10$ m s^{-2}.

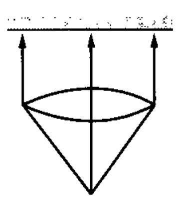

Figure 42-E1

9. A 100 W light bulb is placed at the centre of a spherical chamber of radius 20 cm. Assume that 60% of the energy supplied to the bulb is converted into light and that the surface of the chamber is perfectly absorbing. Find the pressure exerted by the light on the surface of the chamber.
10. A sphere of radius 1·00 cm is placed in the path of a parallel beam of light of large aperture. The intensity of the light is 0·50 W cm^{-2}. If the sphere completely absorbs the radiation falling on it, find the force exerted by the light beam on the sphere.
11. Consider the situation described in the previous problem. Show that the force on the sphere due to the light falling on it is the same even if the sphere is not perfectly absorbing.
12. Show that it is not possible for a photon to be completely absorbed by a free electron.
13. Two neutral particles are kept 1 m apart. Suppose by some mechanism some charge is transferred from one particle to the other and the electric potential energy lost is completely converted into a photon. Calculate the longest and the next smaller wavelength of the photon possible.
14. Find the maximum kinetic energy of the photoelectrons ejected when light of wavelength 350 nm is incident on a cesium surface. Work function of cesium = 1·9 eV.
15. The work function of a metal is $2{\cdot}5 \times 10^{-19}$ J. (a) Find the threshold frequency for photoelectric emission. (b) If the metal is exposed to a light beam of frequency $6{\cdot}0 \times 10^{14}$ Hz, what will be the stopping potential?
16. The work function of a photoelectric material is 4·0 eV. (a) What is the threshold wavelength? (b) Find the wavelength of light for which the stopping potential is 2·5 V.
17. Find the maximum magnitude of the linear momentum of a photoelectron emitted when light of wavelength 400 nm falls on a metal having work function 2·5 eV.
18. When a metal plate is exposed to a monochromatic beam of light of wavelength 400 nm, a negative potential of 1·1 V is needed to stop the photocurrent. Find the threshold wavelength for the metal.
19. In an experiment on photoelectric effect, the stopping potential is measured for monochromatic light beams corresponding to different wavelengths. The data collected are as follows:

wavelength (nm):	350	400	450	500	550
stopping potential(V):	1·45	1·00	0·66	0·38	0·16

Plot the stopping potential against inverse of wavelength ($1/\lambda$) on a graph paper and find (a) the Planck constant, (b) the work function of the emitter and (c) the threshold wavelength.

20. The electric field associated with a monochromatic beam becomes zero $1{\cdot}2 \times 10^{15}$ times per second. Find the maximum kinetic energy of the photoelectrons when this light falls on a metal surface whose work function is 2·0 eV.
21. The electric field associated with a light wave is given by

$$E = E_0 \sin [(1{\cdot}57 \times 10^{7}\ \text{m}^{-1})(x - ct)].$$

Find the stopping potential when this light is used in an experiment on photoelectric effect with the emitter having work function 1·9 eV.

22. The electric field at a point associated with a light wave is $E = (100\ \text{Vm}^{-1}) \sin [(3{\cdot}0 \times 10^{15}\ \text{s}^{-1})t] \sin [(6{\cdot}0 \times 10^{15}\ \text{s}^{-1})t]$. If this light falls on a metal surface having a work function of 2·0 eV, what will be the maximum kinetic energy of the photoelectrons ?

23. A monochromatic light source of intensity 5 mW emits 8×10^{15} photons per second. This light ejects photoelectrons from a metal surface. The stopping potential for this setup is 2·0 V. Calculate the work function of the metal.

24. Figure (42-E2) is the plot of the stopping potential versus the frequency of the light used in an experiment on photoelectric effect. Find (a) the ratio h/e and (b) the work function.

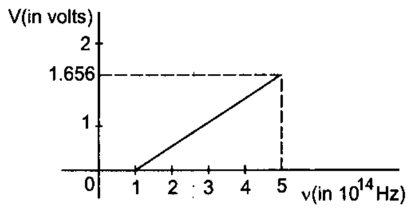

Figure 42-E2

25. A photographic film is coated with a silver bromide layer. When light falls on this film, silver bromide molecules dissociate and the film records the light there. A minimum of 0·6 eV is needed to dissociate a silver bromide molecule. Find the maximum wavelength of light that can be recorded by the film.

26. In an experiment on photoelectric effect, light of wavelength 400 nm is incident on a cesium plate at the rate of 5·0 W. The potential of the collector plate is made sufficiently positive with respect to the emitter so that the current reaches its saturation value. Assuming that on the average one out of every 10^6 photons is able to eject a photoelectron, find the photocurrent in the circuit.

27. A silver ball of radius 4·8 cm is suspended by a thread in a vacuum chamber. Ultraviolet light of wavelength 200 nm is incident on the ball for some time during which a total light energy of $1{\cdot}0 \times 10^{-7}$ J falls on the surface. Assuming that on the average one photon out of every ten thousand is able to eject a photoelectron, find the electric potential at the surface of the ball assuming zero potential at infinity. What is the potential at the centre of the ball ?

28. In an experiment on photoelectric effect, the emitter and the collector plates are placed at a separation of 10 cm and are connected through an ammeter without any cell (figure 42-E3). A magnetic field B exists parallel to the plates. The work function of the emitter is 2·39 eV and the light incident on it has wavelengths between 400 nm and 600 nm. Find the minimum value of B for which the current registered by the ammeter is zero. Neglect any effect of space charge.

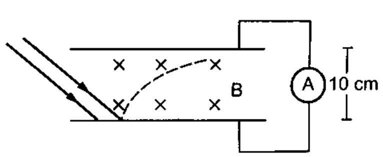

Figure 42-E3

29. In the arrangement shown in figure (42-E4), $y = 1{\cdot}0$ mm, $d = 0{\cdot}24$ mm and $D = 1{\cdot}2$ m. The work function of the material of the emitter is 2·2 eV. Find the stopping potential V needed to stop the photocurrent.

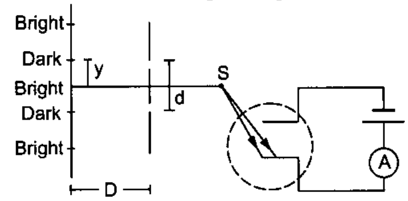

Figure 42-E4

30. In a photoelectric experiment, the collector plate is at 2·0 V with respect to the emitter plate made of copper ($\varphi = 4{\cdot}5$ eV). The emitter is illuminated by a source of monochromatic light of wavelength 200 nm. Find the minimum and maximum kinetic energy of the photoelectrons reaching the collector.

31. A small piece of cesium metal ($\varphi = 1{\cdot}9$ eV) is kept at a distance of 20 cm from a large metal plate having a charge density of $1{\cdot}0 \times 10^{-9}\ \text{C m}^{-2}$ on the surface facing the cesium piece. A monochromatic light of wavelength 400 nm is incident on the cesium piece. Find the minimum and the maximum kinetic energy of the photoelectrons reaching the large metal plate. Neglect any change in electric field due to the small piece of cesium present.

32. Consider the situation of the previous problem. Consider the fastest electron emitted parallel to the large metal plate. Find the displacement of this electron parallel to its initial velocity before it strikes the large metal plate.

33. A horizontal cesium plate ($\varphi = 1{\cdot}9$ eV) is moved vertically downward at a constant speed v in a room full of radiation of wavelength 250 nm and above. What should be the minimum value of v so that the vertically upward component of velocity is nonpositive for each photoelectron ?

34. A small metal plate (work function φ) is kept at a distance d from a singly ionized, fixed ion. A monochromatic light beam is incident on the metal plate and photoelectrons are emitted. Find the maximum wavelength of the light beam so that some of the photoelectrons may go round the ion along a circle.

35. A light beam of wavelength 400 nm is incident on a metal plate of work function 2·2 eV. (a) A particular electron absorbs a photon and makes two collisions before coming out of the metal. Assuming that 10% of the extra energy is lost to the metal in each collision, find the kinetic energy of this electron as it comes out of the metal. (b) Under the same assumptions, find the maximum number of collisions the electron can suffer before it becomes unable to come out of the metal.

□

ANSWERS

OBJECTIVE I

1. (d)	2. (d)	3. (a)	4. (c)	5. (c)	6. (a)
7. (c)	8. (b)	9. (c)	10. (b)	11. (c)	12. (d)
13. (c)	14. (c)				

OBJECTIVE II

1. (a), (b)	2. (a), (b), (c)	3. (d)
4. (b), (d)	5. (a)	6. (b)
7. (a), (c), (d)		

EXERCISES

1. 2.56×10^{-19} J to 5.00×10^{-19} J
2. 1.33×10^{-27} kg m s^{-1}
3. 1.1×10^{-19} J
4. 1.77×10^{19}
5. (a) 3.5×10^{21} (b) 1.2×10^{13} (c) 9.9×10^{44}
6. 1.0×10^{-8} N
7. 4.3×10^{-8} N
8. 100 MW
9. 4.0×10^{-7} Pa
10. 5.2×10^{-9} N
13. 860 m, 215 m
14. 1.6 eV
15. (a) 3.8×10^{14} Hz (b) 0.91 V
16. (a) 310 nm (b) 190 nm
17. 4.2×10^{-25} kg m s^{-1}
18. 620 nm
19. (a) 4.2×10^{-15} eVs (b) 2.15 eV (c) 585 nm
20. 0.48 eV
21. 1.2 V
22. 3.93 eV
23. 1.9 eV
24. (a) 4.14×10^{-15} eVs (b) 0.414 eV
25. 2070 nm
26. 1.6 μA
27. 0.3 V in each case
28. 2.85×10^{-5} T
29. 0.9 V
30. 2.0 eV, 3.7 eV
31. 22.6 eV, 23.8 eV
32. 9.2 cm
33. 1.04×10^{6} m s^{-1}
34. $\dfrac{8\pi\varepsilon_0 dhc}{e^2 + 8\pi\varepsilon_0 \varphi d}$
35. (a) 0.31 eV (b) 4