Photons

Quantum theory of Radiation

The quantum theory of radiation was proposed by Max Plank in 1901 to explain the spectrum of black body radiation. According to this theory, the energy is emitted in the form of tiny packets (discrete forms) called quantum(quanta in plural). The quantum (or packet) of energy is called photon. The energy of photon is given by

$$E = hf\text{.........(i)}$$

Where, h is Planck's constant whose value is 6.626×10^{-34} Js and f is frequency of radiation. The energy of photon is the basic unit of energy and it depends on the frequency of radiation. The higher is the frequency, the larger will be the energy of photon and vice-versa.

The quantum theory of radiation successfully explains the various phenomena like photoelectric effect, Compton effect, x–rays spectraetc

If λ be the wavelength of radiation, then

$$\text{Velocity of light } (c) = \lambda f$$

$$\text{or, } f = \frac{c}{\lambda}$$

so equation I becomes,

$$\text{or, } E = \frac{hc}{\lambda}\text{...........(ii)}$$

Consider the photon to be a particle of mass m moving with velocity c. According to Einstein's mass energy relation, the equivalent energy of photon is

$$E = mc^2$$

$$hf = mc^2$$

$$m = \frac{hf}{c^2}\text{........iv}$$

This equation gives equivalent or effective mass of a photon.

The momentum of photon is given by

$$P = mc = \frac{hf}{c^2}c = \frac{hf}{c} = \frac{hf}{\lambda f} = \frac{h}{\lambda}.$$

Characteristics of Photons

i. Photons are electrically neutral. So they are not deflected by electric and magnetic fields.

ii. They travel in straight path with the speed of light in vacuum.

iii. The energy of photon is, $E = hf = \frac{hc}{\lambda}$. It depends on frequency or wavelength of electromagnetic radiation.

iv. The momentum of photon is, $P = \frac{hf}{c} = \frac{h}{\lambda}$.

v. The frequency of photon does not change as it moves from one medium to another.

vi. The wave length and the speed of the photon change as it moves form one medium to another.

Photoelectric Effect

The phenomenon of emission of electrons from metal surface when light of suitable frequency or wavelength incident on it is called photoelectric effect.

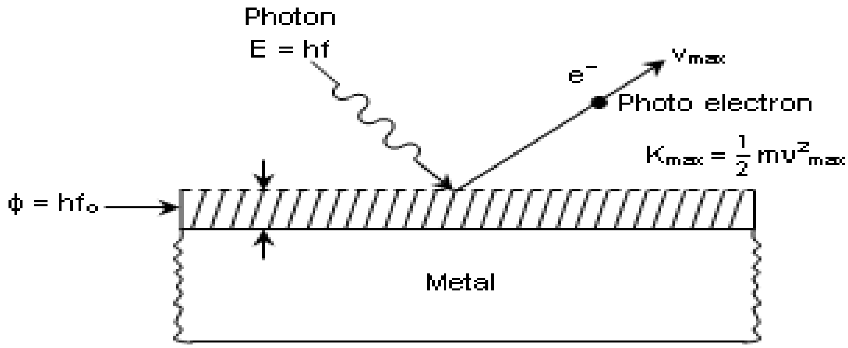


Fig **Emission of Photoelectron from metal surface**

1. **Photoelectrons**

The electrons which are emitted from the metal surface when light of certain frequency incident on it, are called *photoelectrons*. These electrons are highly energetic.

The maximum energy of a photoelectron is given by $K.E_{max} = \frac{1}{2} mv^2_{max}$

Where m is mass and v_{max} is maximum velocity of a photoelectron.

2. **Work function:**

The minimum energy of incident photon or radiation which is required to just emit an electron from the metal surface is known as *work function* of that metal. It is denoted by ϕ.

The work function of a metal is given by

$$\phi = hf_0$$

Where, h = 6.626×10^{-34} Js is Planck's constant and f_0 is threshold frequency.

Since, velocity of light (c) = $\lambda_0 f_0$

or, $f_0 = \frac{c}{\lambda_0}$, where, λ_0 is threshold wavelength.

Thus, equation (i) becomes, $\phi = \frac{hc}{\lambda_0}$

The work function depends on nature of the metals.

3. Threshold frequency

The minimum frequency of incident radiation which can cause photo electric effect is called *threshold frequency*. It is denoted by f_o.

As we know,

Velocity of light (c) = $\lambda_o f_o$

or, Threshold frequency (f_o) = $\frac{c}{\lambda_o}$

Also, we have , Work function (ϕ) = hf_o

or, Threshold frequency (f_o) = $\frac{\phi}{h}$

Where, $h = 6.626 \times 10^{-34}$ Js is Planck's constant.

4. Threshold wavelength

The wavelength corresponding to threshold frequencyof is called *threshold wavelength.* It is denoted by λ_o. The incident radiation having threshold wavelength is just sufficient to eject electron from metal surface. The photoelectric effect takes place only if $\lambda \leq \lambda_o$.

Since,

Velocity of light (c) = $\lambda_o f_o$

or, Threshold wavelength(λ_o) = $\frac{c}{f_o}$

Where, f_o is threshold frequency of incident light.

Also, Work function (ϕ) = $hf_0 = \frac{hc}{\lambda_0}$

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

The threshold wavelength depends on the nature of the metal used.

Experimental study of Photoelectric Effect

It consists of an evacuated glass tube T with two electrodes, anode A and cathode C. The cathode is made up of photo sensitive alkali metal and emits the photoelectrons but the anode collects these electrons. The photoelectric current is measured by milliammeter (mA) and the potential difference across A and C is measured by voltmeter (V).

When light of suitable frequency is incident on the cathode through the window W, the energy of light is absorbed by the surface of the cathode and the photoelectrons are emitted from it. These electrons are accelerated towards the anode by applying positive potential on it with respect to the cathode. The emitted photoelectrons, produce photo electric current (I_p) and flows in the external circuit.

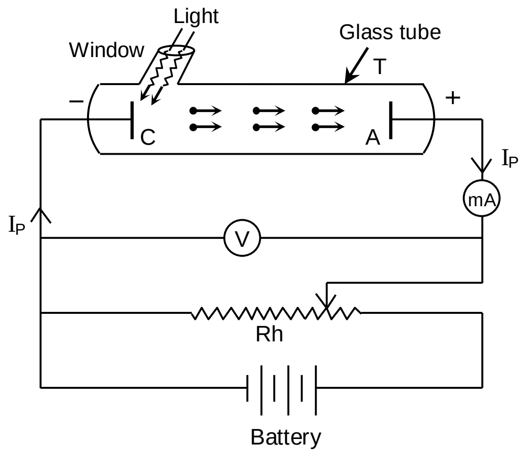


Fig- **Experimental set up for the study of Photoelectric effect.**

Characteristics of the photoelectric effect

1. **Variation of photoelectric current with intensity of incident light:**

   When the intensity of the incident light increases (keeping the frequency constant), there is increases in emission of photoelectrons from the metal surface. The photoelectric current (or photoelectrons emitted per second) is directly proportional to the intensity of incident light.

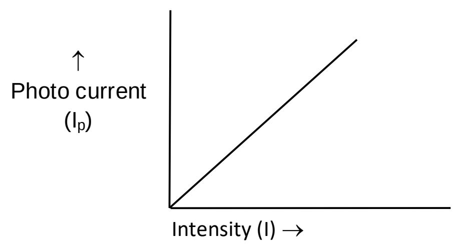


Fig: Effect of intensity of light on photo electric current

2. **Variation of photo electric current with anode potential**

When the suitable frequency of light falls on the surface of the cathode then the photoelectrons are emitted.These emitted photoelectrons are accelerated towards the anode which is positive potential with respect to cathode.The photoelectric current increases with increase in anode potential and becomes maximum at a certain potential.This current is called saturation current and remains constant with further increase in anode potential.

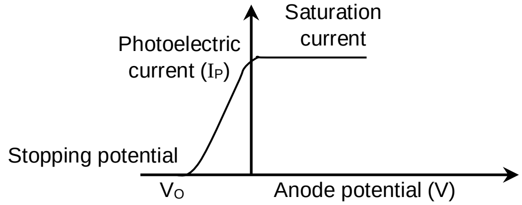


Fig Effect of anode potential on photo electric current

The negative potential is applied to the anode relative to the cathode by changing its polarity. As the negative potential increases gradually the photoelectric current decreases and finally becomes zero. The negative or retarding potential at which the photoelectric current becomes zero is called *stopping potential* or cut off potential (V_0). The variation of photoelectric current with anode potential is shown in Fig.

If the intensity of incident light is increased at constant frequency, it is found that there is increase in saturation current but no change in stopping potential as shown in Fig. Hence the stopping potential is independent of the intensity of light.

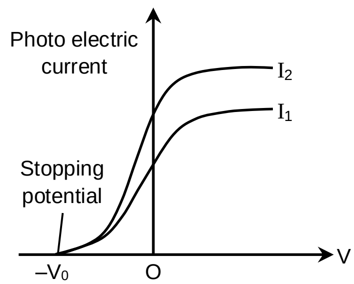


Fig- Variation of photo electric current with anode potential for different intensity of light

3. Variation of Photoelectric current with frequency of incident light:

The intensity of incident light is kept constant and the frequency is changed. It is found that the saturation current is same in all cases but stopping potential is different. The variation of photo current with anode potential for various frequencies is shown in Fig i. The stopping potential depends on the frequency of incident light. i.e. $V_0 \propto f$.

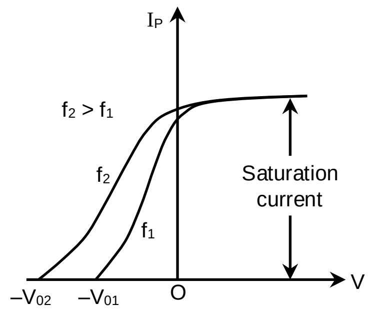


Fig i *Variation of photo electric current with anode potential for different frequency of light*

When a graph of stopping potential versus frequency of incident light is plotted, a straight line is obtained, as shown in Fig-ii. It shows that there is a minimum frequency of incident radiation which can cause photoelectric effect. Below this frequency, no photoelectrons are emitted. This frequency is called *threshold frequency* or *cut-off frequency f_0.* The value of threshold frequency depends on the nature of photosensitive metal.

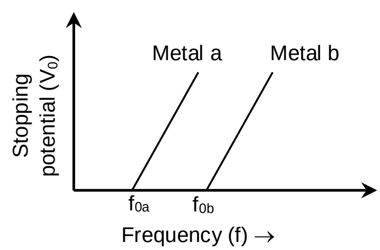


Figure ii Variation of stopping potential with frequency of incident light

Laws of photoelectric effect

1. The Photoelectric emission is an instantaneous phenomenon. There is no lagging of time between arrival incident radiation and emission of photoelectrons.
2. The electrons are emitted from the metal surface when the frequency of incident radiation is greater than threshold frequency.

3. The kinetic energy of photoelectron is independent of the intensity but directly proportional to the frequency of incident radiation.
4. The stopping potential is independent of the intensity but directly proportional to the frequency of incident radiation.
5. The rate of emission of electron i.e. photoelectric current is independent of the frequency but directly proportional to the intensity of incident radiation.

Einstein's Photoelectric Equation

According to Einstein, the energy of electromagnetic radiation i.e. light is discrete and is emitted in the form of small packets of energy called *quanta*. The quantum of radiation is called photon. The energy of a photon of frequency f is given by

$$E = hf$$

Where, h is a universal constant which is called Planck's constant. Its value is 6.626×10^{-34}Js. When a photon of certain frequency is incident on the metal surface, the energy of photon is used to eject the electron from the metal surface and the rest of the energy is used in imparting kinetic energy to the emitted electron as shown in Fig.

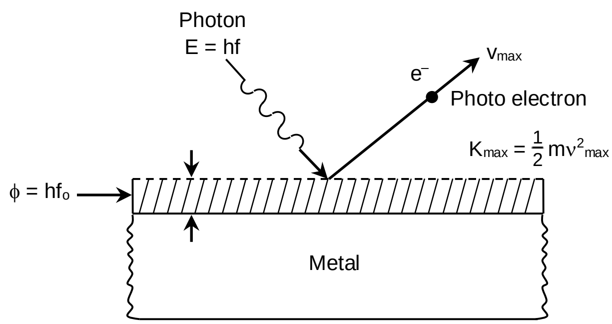


Fig-*Emission of Photoelectron from metal surface*

Let ϕ be the wok function and $K.E_{max}$ be the maximum Kinetic energy of an emitted electron.

From the principle of conservation of energy,

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

or, $E = \phi + K.E_{max}$

$\Rightarrow hf = \phi + K.E_{max}$

Since, $K.E_{max} = \frac{1}{2}mv^2_{max}$

$\therefore hf = \phi + \frac{1}{2}mv^2_{max}$ ……………………………….(i)

Where m is mass and v_{max} is maximum velocity of emitted electron.

If f_o be the threshold frequency, then, $\phi = hf_0$

$\therefore hf = hf_0 + \frac{1}{2}mv^2_{max}$ …………………………………………..(ii)

The maximum kinetic energy of photon is

$K.E_{max} = hf - \phi$

Or, $\frac{1}{2}mv^2_{max} = hf - hf_0$

or, $\frac{1}{2}mv^2_{max} = h(f - f_0)$ …………………….(iii)

The equations (i), (ii) and (iii) are known as Einstein's photo electric equations in different forms. Let λ be the wavelength of incident light (or photon) and λ_o be the threshold wavelength. We have,

$$f = \frac{c}{\lambda} \quad \text{and} \quad f_0 = \frac{c}{\lambda_0}$$, Where, c is velocity of light in vacuum.

For equation (iii), we get

$$\frac{1}{2} mv^2{}_{max} = hc\left(\frac{1}{\lambda} - \frac{1}{\lambda_0}\right)$$

This is another form of Einstein's Photo electric equation.

Conclusions:

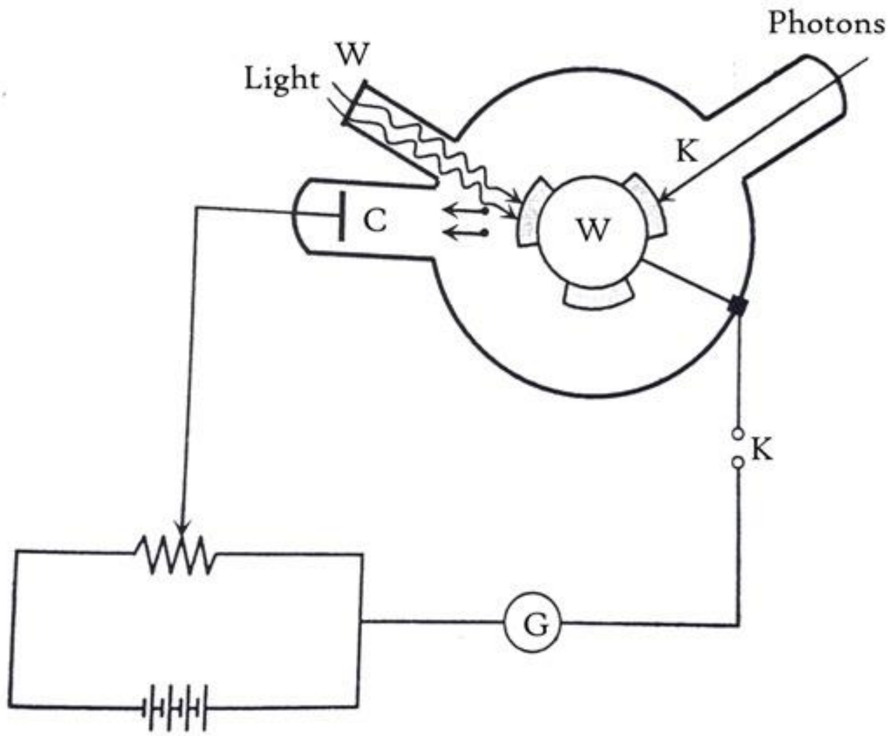
The following conclusions are drawn from the Einstein's photoelectric equation.

1. The electrons are emitted from metal surface if the frequency of incident radiation is greater than the threshold frequency (i.e. $f > f_0$).
2. The kinetic energy of a photo electron is independent of the intensity but directly proportional to the frequency of incident radiation.
3. The rate of emission of photo electrons i.e. Photoelectric current is independent of the frequency but directly proportional to the intensity incident light.

Measurement of Planck's Constant by Millikan's Experiment

The experimental arrangement for the determination of planck's constant by millikan is shown in Fig-. It consists of evacuated glass tube . The alkali metals like sodium (Na), Potassium (K) and Lithium (Li) are mounted on the wheel 'W' which is placed at the center of the glass tube. The metal surfaces are kept fresh by using sharp knife edge 'K'.

When a beam of monochromatic light through the window falls on the target metal, the photo electrons are emitted from it. The photoelectrons are collected by the collector 'C' and the photoelectric current is produced. The negative potential is applied to the collector relative to the target metals with the help of variable d.c. source. The negative potential is increased gradually until the photoelectrons are just stopped to reach the collector and the photoelectric current becomes zero. The minimum potential which reduces the photoelectric current to zero is called *stopping potential V_0*.



The frequency of incident light can be varied by using different filters and the corresponding values of V_0 are obtained. The above observations are repeated for different metals.
At the stopping potential,
Work done on photoelectron = Maximum K.E. of photoelectron

$$\text{or, } eV_0 = \frac{1}{2} mv^2_{max}$$

Where m is mass, e is charge and v_{max} is maximum velocity of photoelectron.

Form Einstein's photoelectric equation, we have

$$\frac{1}{2}mv^2_{max} = hf - \phi$$

$$\text{or,} \quad \frac{1}{2}mv^2_{max} = hf - hf_0$$

Where, h is Planck constant, f is frequency of incident light and f_0 is threshold frequency.

From above equations, we have

$$eV_0 = hf - hf_0$$

$$\text{or,} \quad V_0 = \frac{h}{e}f - \frac{h}{e}f_0 \quad \text{..................i}$$

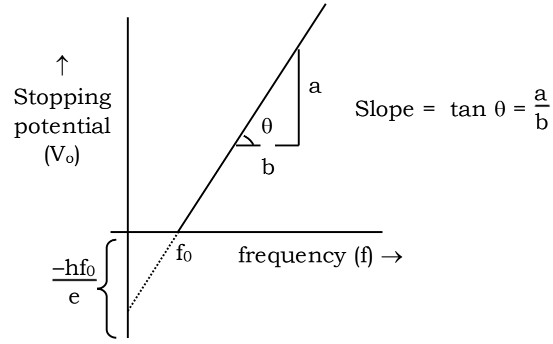


***Fig**-A graph between stopping potential and frequency*

This equation (i) represents the equation of straight line y = mx + C

Here, Slope (m) = $\frac{h}{e}$ and C = $\frac{-hf_0}{e}$

A graph of stopping potential (V_0) versus frequency of incident light (f) is plotted, which is a straight line as shown in Fig-

From graph,

$$\text{Slope (m)} = \tan\theta = \frac{a}{b}$$

$$\therefore \quad \frac{h}{e} = \tan\theta$$

$$\text{or,} \quad h = e\tan\theta$$

Knowing the values of charge on electron (e) and slope of the curve tan θ (i. e $\frac{a}{b}$), the value of Planck's constant (h) can be determined. The value of Planck's constant to the accuracy known at present is $h = 6.6260693 \times 10^{-34}$ Js.

Verification of Einstein's photoelectric Equation:

The experimental graph between stopping potential and frequency of incident light is in agreement with Einstein's photoelectric equation. The value of Planck's constant (h) determined form Millikan's experiment agrees to the value of h obtained from experiments on black body radiation. This also confirms the validity of Einstein Photoelectric equation, which is the supporter of quantum theory of radiation.

1. What is threshold frequency?
2. Explain why photoelectric effect cannot be observed with all wavelengths of light.
3. What is meant by stopping potential?

4. What is the threshold frequency for photoelectric emission? Does it depend on the intensity of light?
5. What happens to the kinetic energy of photoelectrons when the intensity of incident light is doubled? Justify your answer.

6. If we go on increasing the wavelength of light incident on a metal surface, what charges take place in the number of electrons and energy of the electrons?
7. Human skin is relatively insensitive to visible light, but ultra violet radiation can cause service burns. Does this have anything to do with photon energies? Explain.

LONG QUESTION

1. What is photoelectric effect? Discuss Einstein's photoelectric equation. Write some apllications of photoelectric effect.
2. Describe Millikans' experiment to determine the value of Plank's constant. Explain how Einstein's photoelectric equation is varified from this experiment.
3. What is photoelectric effect? Explain the effect of increase of (i) frequency (ii) intensity of the incident radiation on photoelectrons emitted by a phototube.
4. Discuss photoelectric effect and derive Einstein's photoelectric equation. What is stopping potential?
5. Explain photoelectric effect to write Einstein's photoelectric equation. Describe Millikan's laboratory method to determine Planck's constant.
6. What is work function of a metal? Does it depend on the intensity of incident light? Discuss Einstein's photoelectric equation.
7. Explain photoelectric effect and present the necessary theory to determine the value of Planck's constant.
8. What is photoelectric effect? Derive Einstien's photoelectric equation. Define various terms used in it.
9. What is photoelectric effect? Discuss Einstein's Photoelectric equation. Does the work function of a metal depend on intensity of light?

10. Write down Einstein's photoelectric equation and describe an experiment to verify it.

NUMERICAL DISCUSSION

1. A clean nickel surface of work function 5.1 eV is exposed to light of wavelength 235 nm. What is the maximum speed of the photoelectrons emitted from its surface?

Ans: 2.91×10^{-20}J, 2.52×10^{5} m/sec

2. Sodium has a work function of 2eV. Calculate the maximum energy and speed of the emitted electrons when sodium is illuminated by a radiation of 150nm. What is the threshold frequency of radiation for which electrons are emitted from sodium surface?

Ans: 10^{-18}J, 1.5×10^{6} m/s, 4.8×10^{14} Hz)

3. Radiations of wavelength 5400A^{o} fall on a metal whose work function is 1.9 eV. Find the energy of the photoelectrons emitted and their stopping potential. Planck's constant = 6.62×10^{-34} Js.

6.38×10^{-20} J = 0.4ev

4. Light of frequency 5 x 10^{14}Hz librates electrons with energy 2.3x10^{-19}J from a certain metallic surface. What is the wavelength of ultraviolet light which librates electrons of energy 8.93×10^{-19}J from the same surface? (Given h = 6.62 x 10^{-34}JS, C = 3×10^{8} m/s)

Ans: 2×10^{-7}m

5. 400 nm wavelength of light falls on a photo sensitive material of work function 2.3 eV. Compute the maximum energy of photoelectrons.

Ans: 0.803 eV

6. Sodium has a work function of 2 ev. Calculate the maximum energy and speed of the emitted electrons when sodium is illuminated by radiation of wave length 150 nm. (Given mass of electron = 9.1 x 10^{-31} Kg)

Ans: 1.48 x 10^{6} m/sec. and 9.96×10^{-19} J

7. The work function for the surface of aluminium is 4.2 eV. How much potential difference will be required to stop the emission of maximum energy electrons emitted by light of wavelength 2000 A? (Plank's constant, h = 6.6×10^{-34} JS)

Ans: 2 V

8. Light of wavelength 5 x 10^{-7} m falls on a sensitive metal-plate with photo electric work function 1.90 eV. Find kinetic energy of the photoelectrons emitted and

stopping potential. (given h = 6.62 x 10^{-34} JS)

Ans: E_k = 0.58 eV; Vs = 0.58 V

9. Ultraviolet light of wavelength 3.6 x 10^{-7} m is made to fall on a smooth surface of potassium. The work function of potassium is 2eV. Determine maximum energy of emitted photo electrons and stopping potential.

1.5eV, 1.5V

10. Electrons with maximum kinetic energy of 3 eV are ejected from a metal surface by ultra-violet radiation of wavelength 1.5 × 10^{-7} m. Determine work function, threshold wavelength and the stopping potential for the metal (Planck's constant, h = 6.62x10^{-34}JS)

Ans: 5.275 eV., 2.35 × 10^{-7} m, 3V

11. The photoelectric threshold wavelength of a tungsten surface is 272 nm. Calculate the maximum velocity of the electrons ejected from this tungsten surface by ultraviolet radiation of frequency 1.45 × 10^{15} Hz. (h = 6.62 x 10^{-34} JS, c = 3×10^{8} m/s, m_e = 9.1x10^{-31}kg)

Ans: 7.1 x 10^{5}m/sec

12. When ultraviolet light with a wavelength of 400 nm falls on a certain metal surface, the maximum kinetic energy of the emitted electrons is 1.10 eV. What is the maximum kinetic energy of the photoelectrons when light of wavelength 300 nm falls on the same surface?

Ans: 2.137eV

13. What will be the change in the stopping potential for photoelectrons emitted from a source if the wavelength of incident light is reduced from 400 nm to 360 nm?

Ans: 0.34V

14. The maximum energy of photoelectrons emitted from a metal plate is 1.2 ev. If the threshold wavelength is 2.48x10^{-9}m, calculate the wavelength of incident light. (Given Planck's constant is 6.62x10^{-34}JS.)

Ans: 2.47 × 10^{-9} m

15. Light of wavelength 6000 Å falls on a photosensitive plate of work function 1.9 eV. Find the speed of the photoelectrons emitted, (h = 6.62x10^{-34} JS and m_e = 9.1x10^{-31}kg)

Ans:2.44x105 m/sec

16. When a light of frequency 5.4 x 10^{14} Hz is incident on a metal surface, the maximum energy of the electrons emitted is 1.2x10^{-19} J. If the same surface is illuminated with light of frequency 6.6 × 10^{14} Hz, the maximum energy of the

electrons is 2×10^{-19} J. Find the value of Planck's constant.

Ans: 6.67 x 10^{-34} JS

17. A UV light of 400 nm strikes a cesium surface of work function 1.9 eV. Find the velocity of electron emitted from the cesium surface (m_e= 9.1 x 10^{-31}kg. c = 3 x 10^8 m/s h = 6.62 x 10^{-34} J.S.)

Ans: 6.5 x 10^5 m/s

18. The photoelectric work function of potassium is 2eV and the surface is illuminated with radiation of wavelength 350 nm. What potential difference have to be applied between a potassium surface and the collecting electrode in order just to prevent collection of electrons? What would be the kinetic energy of the electrons?

Ans: 1.5V, 2.4x10^{-19}J

19. The maximum kinetic energy of the electrons emitted from a metallic surface is 1.6 x 10^{-19}J when the frequency of the radiation is 7.5 x 10^{14} Hz. Calculate the minimum frequency of the radiation for which electrons will be emitted. Assume that h = 6.6 x 10^{-34} Js.

Ans: 5.1 x 10^{14} Hz