Photoelectric Effect

In 1888, Hallwachs made the important observation that

(i) when ultra-violet light falls on a neutral zinc plate, the plate becomes positively charged.

(ii) when ultra-violet light falls on a negatively charged zinc plate, it loses its negative charge. and

(iii) when ultra-violet light falls on a positively charged zinc plate, it becomes more positively charged.

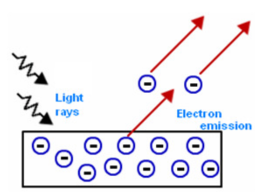
Therefore, Hallwach came to the conclusion that only negatively charged particles can be emitted by the zinc plate when it is irradiated with ultra-violet light. [Afterwards, it was discovered that alkali metals like lithium, sodium, potassium, rubidium and cesium eject electrons even when ordinary light i.e., visible light falls on them].

1

Photoelectric effect

The phenomenon of ejection of electrons from a metal surface when light of suitable frequency falls upon it is known as photoelectric effect.

The electrons so emitted are called photoelectrons. J J Thomson showed that these photoelectrons are not different from ordinary electrons.



Work Function

The minimum amount of energy required to eject an electron out of a metal surface is called work function of the metal. The work function of a metal depends on the nature of the metal.

Threshold Frequency

The emission of electrons from a particular material does not occur for light of all frequencies. Below a certain frequency photoelectric effect is not observed, no matter how intense the light may be. This frequency is known as threshold frequency. If ν_0 is the threshold frequency of radiation, then work function of the metal is related with the threshold frequency by the relation, $W = h\nu_0$.

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Stopping Potential

The retarding potential at which the collector is maintained at a negative potential with respect to the emitter, no electron will reach the collector and the current will become zero. This potential is called stopping potential. Work done by the stopping potential is equal to the maximum kinetic energy of the electrons.

If V_0 is the stopping potential applied between the anode and the cathode, then it is related with the maximum kinetic energy of the electron by the relation,

$$eV_0 = \frac{1}{2} m V_{max}^2$$

where e= electronic charge,
m= mass of electron and
V_{max}=maximum velocity of photoelectrons.

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LAWS OF PHOTOELECTRIC EFFECT

Following are the characteristics of photoelectric emission:

(i) The emission of photoelectrons takes place when the frequency of the incident radiation is above a certain critical value known as threshold frequency, which is an intrinsic characteristic of that metal.

(ii) The emission of photoelectrons is instantaneous. It has been found that the time lag between the incidence of photon and the emission of electron is less than 10^{-9} seconds.

(iii) The number of photoelectrons emitted from a metal surface depends only on the intensity of the incident light and is independent of its frequency.

(iv) The maximum kinetic energy with which photoelectrons are emitted from a metal surface depends only upon the frequency of the incident light and is independent of its intensity.

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Experimental study of photoelectric effect

The photoelectric effect was investigated by the German physicists Wilhelm Hallwachs and Philipp Lenard during the year 1886-1900. Hallwachs and Lenard constructed a photoelectric vacuum tube consisting of a cathode irradiated by ultraviolet light and an anode collecting electrons emitted by the cathode. A voltage, *V*, was applied between the anode and cathode to repel the electrons emitted by the cathode. The number of electrons arriving at the anode was measured by the current in an outside circuit connecting the anode and the cathode. Hallwachs and Lenard found that when monochromatic light fell on the cathode, no photoelectrons at all were emitted unless the frequency of the light was greater than some minimum value called the **threshold frequency.** This minimum frequency depends on the material of the cathode. For most metals the threshold frequency is in the ultraviolet (wavelength between 200 and 300 nm) but for potassium and cesium oxides it is in the visible spectrum (wavelength between 400 and 700 nm).

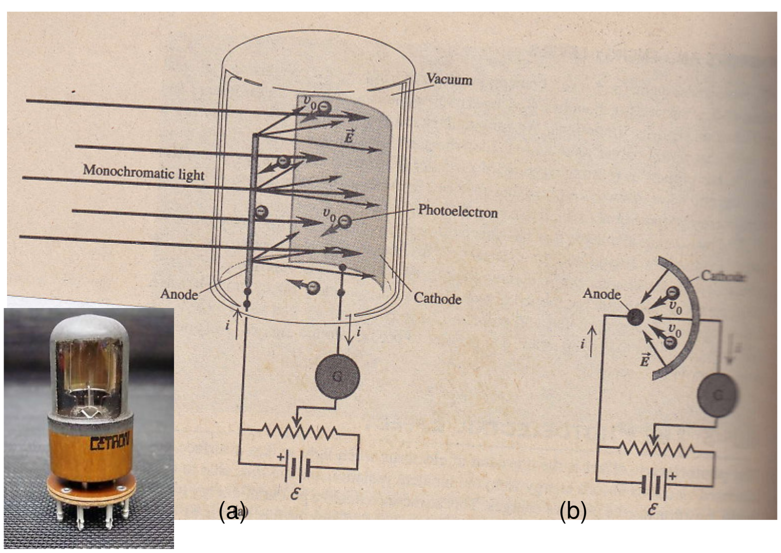

Fig 1. Schematic diagram of a phototube circuit (a) Electrons emitted from the cathode are pushed towards the anode by the electric field force. (b) Even when the direction of the field is reversed, some electrons still reach the anode.

When the frequency ν is greater than the threshold frequency, some electrons are emitted from the cathode with substantial initial speeds. This can be shown by reversing the polarity of the battery so that the electric field force on the electrons is back towards the cathode. If the magnitude of the field is not too large, the highest energy emitted electrons still reach the anode and there is still a current. We can determine the maximum kinetic energy of the emitted electrons by making the potential of the anode relative to the cathode, $V_{AC,}$ just negative enough so that the current stops. This occurs for $V_{AC} = -V_0$, where V_0 is called the **stopping potential**.

As an electron moves from the cathode to the anode, the potential decreases by V_0 and negative work $-eV_0$ is done on the electron, the most energetic electron leaves the cathode with kinetic energy $K_{max} = \frac{1}{2} m v_{max}^2$ and has zero kinetic energy at the anode. U sing the work energy theorem, we have

$$W_{tot} = -eV_0 = \Delta K$$
$$= 0 - K_{max}$$

Therefore, $K_{max} = \frac{1}{2} m\, v_{max}^2 = eV_0$

Hence by measuring the stopping potential V_0, we can determine the maximum kinetic energy with which electrons leave the cathode.

Some experimental results:

Figure 2 shows graphs of photocurrent as a function of potential difference V_{AC} for a light of constant frequency and two different intensities. When V_{AC} is sufficiently large and +ve, the curves levels off, showing that all the emitted electrons are being collected by the anode. The reverse potential $-V_0$ needed to reduce the current to zero is shown.

If the intensity of the light is increased while its frequency is kept the same, the current levels off at a higher value, showing that more electrons are being emitted per time. But the stopping potential V_0 is found to be the same.

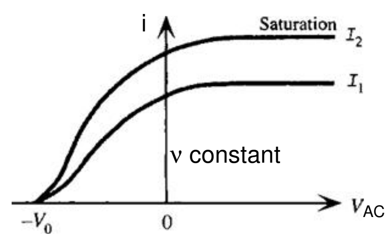

Fig 2. Photocurrent i as a function of the potential V_{AC} of the anode with respect to the cathode for a constant light frequency. The stopping potential V_0 is independent of the light intensity I, but the photocurrent for large positive V_{AC} is directly proportional to the intensity.

Figure 3 shows current as a function of potential difference for two different frequencies, with the same intensity in each case. We see that when the frequency of the incident monochromatic light is increased, the potential V_0 is increases. In fact V_0 turns out to be a linear function of the frequency ν.

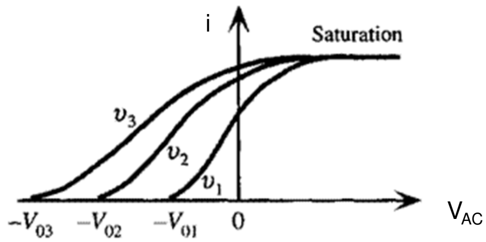

Fig 3. Photocurrent i as a function of the potential V_{AC} of an anode with respect to a cathode for two different light frequencies, ν_1 and ν_2 with the same intensity. The stopping potential V_0 increases linearly with frequency.

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Failure of Classical Physics in case of photoelectric effect

These results are hard to understand on the basis of the classical physics.

- When the intensity (average energy per unit area per unit time) increases, electrons should be able to gain more energy, increasing the stopping potential V_0. But V_0 was found independent of intensity.
- Also, classical physics offer no explanation for the threshold frequency. We know that the intensity of the electromagnetic wave such as light does not depend on frequency, so an electron should be able to acquire its needed escape energy from light of any frequency. Thus there should not be any threshold frequency, ν_0.
- Finally, we would expect it to take a while for an electron to collect enough energy from extremely faint light. But experiment shows that electrons are emitted as soon as any light with $\nu \geq \nu_0$ hits the surface.

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Einstein's photoelectric equation

The correct analysis of the photoelectric effect was developed by Albert Einstein in 1905. Based on assumptions made by Max Planck in 1900, Einstein postulated that a beam of light consist of small packages of energy called photons or quanta. The energy E of a photon is equal to $h\nu$, where h is Planck's constant.

A photon arriving at the surface is absorbed by an electron. This energy transfer is an all-or-nothing process, in contrast to the continuous transfer of energy in the classical theory; the electron gets all the photon's energy or none at all. If this energy is greater than the work function φ (minimum energy needed to remove an electron from the surface), the electron may escape from the surface.

Greater intensity as a particular frequency means a proportionally greater number of photons per second absorbed, thus a proportionally greater number of electrons emitted per second and the proportionally a greater current is seen.

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Thus Einstein applied conservation of energy to find that the maximum kinetic energy $K_{max}=½mv_{max}^2$ for an emitted electron is the energy hν gained from a photon minus the work function φ.

$$½mv_{max}^2=h\nu-\varphi$$

If ν_0 is the threshold frequency then $\varphi=h\nu_0$

$$\text{Then } ½mv_{max}^2=h\nu- h\nu_0\text{ ; or}$$

$$eV_0= h\nu- h\nu_0$$

We can measure the stopping potential V_0 for each of several values of frequency ν for a given cathode material. A graph of V_0 as a function of ν turns out to be a straight line and from such graph we can determine both the work function φ for the material and the value of the quantity *h/e*. After the electron charge –*e* was measured by Robert Millikan in 1909, Planck's constant h could also be determined from these measurements.

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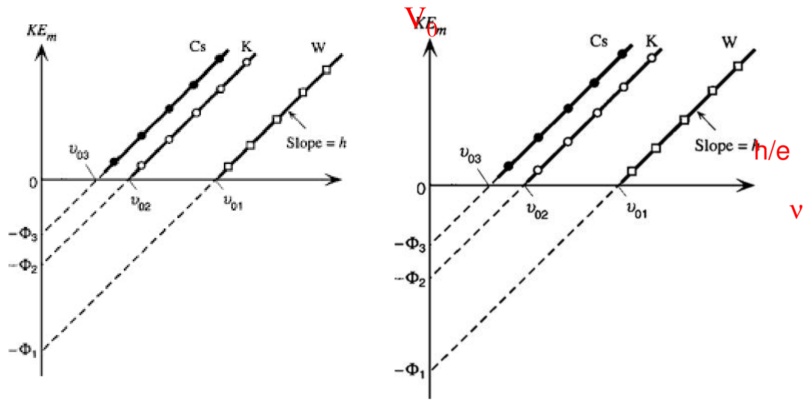

Figure 4. Determination of value of Planck’s constant, work function and threshold frequency

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Photoelectric Effect Applications

Below are the applications of Photoelectric effect:

1.The photoelectric effect is used in the photoelectric cell which converts a light energy into electrical energy.

2.In cinematography photoelectric effect has a application of reproducing the sound.

3.Photoelectric effect also has an application in street lights for automatic switch on and off.

4.Traffic signals are using this effect for automatic controls and for count the machines.

5.Working of burglar alarm uses this photoelectric effect.

6.Television transmission is one of the applications of this photoelectric effect.

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The Photocell

The photoelectric effect has many practical applications which include the photocell, photoconductive devices and solar cells.

A photocell is usually a **vacuum tube** with two electrodes. One is a photosensitive **cathode** which emits electrons when exposed to light and the other is an **anode** which is maintained at a positive voltage with respect to the cathode. Thus when light shines on the cathode, electrons are attracted to the anode and an electron current flows in the tube from cathode to anode. The current can be used to operate a relay, which might turn a motor on to open a door or ring a bell in an alarm system. The system can be made to be responsive to light, as described above, or sensitive to the removal of light as when a beam of light incident on the cathode is interrupted, causing the current to stop. Photocells are also useful as exposure meters for cameras in which case the current in the tube would be measured directly on a sensitive meter.

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Closely related to the photoelectric effect is the photoconductive effect which is the increase in **electrical conductivity** of certain non metallic materials such as cadmium sulfide when exposed to light. This effect can be quite large so that a very small current in a device suddenly becomes quite large when exposed to light. Thus photoconductive devices have many of the same uses as photocells.

Solar cells, usually made from specially prepared silicon, act like a **battery** when exposed to light. Individual solar cells produce voltages of about 0.6 volts but higher voltages and large currents can be obtained by appropriately connecting many solar cells together. **Electricity** from solar cells is still quite expensive but they are very useful for providing small amounts of electricity in remote locations where other sources are not available. It is likely however that as the cost of producing solar cells is reduced they will begin to be used to produce large amounts of electricity for commercial use.

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Problems

P-1:Sodium has a work function of 2.36 eV. If a scientist illuminates a piece of sodium with a 450 nm wavelength light, what is the:

a.stopping potential;

b.maximum kinetic energy of the emitted electrons; and

c.emitted electrons maximum speed?

P-2: Gold has a work function of 5.10 eV. What is the minimum frequency of light to emit photoelectrons? What is the longest corresponding wavelength?

P-3: The work function of copper is 4.7 eV. What is the maximum velocity of photoelectrons produced by ultraviolet light of wavelength 100nm?

P-4: What should be the wavelength of monochromatic radiation to produce photoelectrons of maximum velocity 10^6m/s from iron? The work function for iron is 4.5 eV.

P-5: While conduction photoelectric effect experiment with light of a certain frequency, it was observed that reverse potential difference of 1.25 V is required to reduce the photocurrent to zero. Find (a) the maximum kinetic energy; (b) the maximum speed of the emitted photoelectrons.

6. Threshold frequency for copper is 1.2×10^{15}Hz. Find maximum energy of the photoelectron when light of 1.5×10^{15} Hz is directed on a copper photocathode.
7. Calculate the work function of sodium in eV when threshold wavelength is 680 nm. [Ans. 1.827 eV]
8. Photoelectric threshold wavelength for a metal is 300 nm. Find the kinetic energy of an electron ejected from it by radiation of wavelength 120 nm. [Ans. 6.2 eV]

9. A metal of work function of 4 electron volts is exposed to radiation of the wavelength 140 nm. What is the corresponding stopping potential?

$$\frac{hc}{\lambda} = \phi + K.E$$

$$K.E = \frac{hc}{\lambda} - \phi = \frac{6.625\times10^{-34}\times3\times10^{8}}{140\times10^{-9}} - 4\times1.6\times10^{-19}$$

$$= 7.796\times10^{-19}\ joule$$

$$= 4.87eV$$

$We know that$

$$K.E = eV_0$$

$Therefore,$

$$V_0 = 4.87\ V$$

When a radiation of certain wavelength is incident on a metallic surface, the stopping potentially is found to be 4.8 V. If the same surface is illuminated by the radiation of double the wavelength, the stopping potential is found to be 1.6 V. What is the threshold wavelength of the surface?

$$\frac{hc}{\lambda} = \phi + 4.8 \times e$$

Or, $\frac{hc}{\lambda} - \frac{hc}{\lambda 0} = 4.8 \times e$ (i)

$$\frac{hc}{2\lambda} = \phi + 1.6 \times e$$

0r, $\frac{hc}{2\lambda} - \frac{hc}{\lambda 0} = 1.6 \times e$ (ii)

Therefor, dividing (i) by (ii) , we obtain, $\frac{\frac{hc}{\lambda} - \frac{hc}{\lambda 0}}{\frac{hc}{2\lambda} - \frac{hc}{\lambda 0}}=3$

Or, $\frac{hc}{\lambda} - \frac{hc}{\lambda 0}=3[\frac{hc}{2\lambda} - \frac{hc}{\lambda 0}]$

Or, $-\frac{hc}{2\lambda} + \frac{2hc}{\lambda 0}=0$

Or, $\frac{hc}{2\lambda} = \frac{2hc}{\lambda 0}$; Or , $\lambda_0=4\ \lambda$

11. If the wavelength of the incident radiation changes from one value to other value, the corresponding kinetic energy emitted by the photo electrons also changes from one value to other value. What is the work function of the metal surface?

$$\frac{hc}{\lambda_1} = \phi + E_1 \quad \Rightarrow hc = \varphi\lambda_1 + E_1\lambda_1$$

$$Again\ for\ another\ wavelength,$$

$$\frac{hc}{\lambda_2} = \phi + E_2 \quad \Rightarrow hc = \varphi\lambda_2 + E_2\lambda_2$$

$$Therefore,\ \varphi\lambda_1 + E_1\lambda_1 = \varphi\lambda_2 + E_2\lambda_2$$

$$or, \varphi(\lambda_1 - \lambda_2) = E_2\lambda_2 - E_1\lambda_1$$

$$Therefore,\ \varphi = \frac{E_2\lambda_2 - E_1\lambda_1}{\lambda_1 - \lambda_2}$$

12. For a certain metal threshold frequency is given. When the incident frequency is doubled the threshold frequency, electrons comes out with a velocity 4×10^6 m/s. If the incident frequency is five times threshold frequency, what is the velocity with which the electrons come out?

$$\frac{1}{2}mv^2 = h(\upsilon - \upsilon_0)\ becomes,\ \frac{1}{2}mv_1^{\ 2} = h(2\upsilon_0 - \upsilon_0) = h\upsilon_0$$

$$This\ gives, v_1 = \sqrt{\frac{2h\upsilon_0}{m}} = 4\times10^6\ m/s$$

$$and\ \ \frac{1}{2}mv_2^{\ 2} = h(5\upsilon_0 - \upsilon_0) = 4h\upsilon_0$$

$$\frac{v_2^{\ 2}}{v_1^{\ 2}} = 4,\ or, v_2 = 2v_1 = 8\times10^6\ m/s$$

13. Photoelectric effect from a metallic surface is observed from two different frequencies where first frequency is greater than that of the second frequency. If the ratio of the maximum kinetic energy emitted by the photo electrons in both the cases is given, find the expression of threshold frequency of the metal surface?

$$h\upsilon_1 = h\upsilon_0 + 1E, \quad and\ for\ second\ case \quad h\upsilon_2 = h\upsilon_0 + pE$$

$$This\ gives,\ \ E = \frac{h\upsilon_2 - h\upsilon_0}{p}$$

$$Substituting\ this\ value, we\ get, h\upsilon_1 = h\upsilon_0 + 1(\frac{h\upsilon_2 - h\upsilon_0}{p})$$

$$or,\ h\upsilon_1 = h\upsilon_0 + \frac{h\upsilon_2}{p} - \frac{h\upsilon_0}{p},\ or,\ h\upsilon_1 - \frac{h\upsilon_2}{p} = h\upsilon_0(1 - \frac{1}{p})$$

$$or, \frac{ph\upsilon_1 - h\upsilon_2}{p} = h\upsilon_0(\frac{p-1}{p}),\ or, ph\upsilon_1 - h\upsilon_2 = h\upsilon_0(p-1)$$

$$or,\ \upsilon_0 = \frac{p\upsilon_1 - \upsilon_2}{p-1}$$

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14. when ultraviolet light with a wavelength of 240 nm shines on a particular metal plate, electrons are emitted from plate 1, crossing the gap to plate 2 and causing a current to flow through the wire connecting the two plates. The battery voltage is gradually increased until the current in the ammeter drops to zero, at which point the battery voltage is 1.40 V.

(a) What is the energy of the photons in the beam of light, in eV?

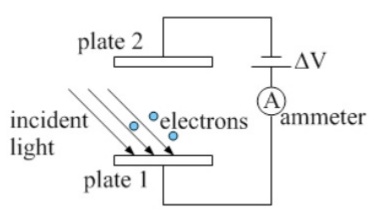
(b) What is the maximum kinetic energy of the emitted electrons, in eV?

(c) What is the work function of the metal, in eV?

(d) What is the longest wavelength that would cause electrons to be emitted, for this particular metal?

(e) Is this wavelength in the visible spectrum? If not, in what part of the spectrum is this light found?

Solution:



(a)

$$E = \frac{hc}{\lambda} = \frac{6.625\times10^{-34}\times3\times10^{8}}{240\times10^{-9}} = 8.28\times10^{-19}\,Joue = 5.17eV$$

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(b) Maximum kinetic energy

$$(K.E)_{\max} = eV_0 = e \times 1.40V = 1.40eV$$

(c)
$$\phi = \frac{hc}{\lambda} - (K.E)_{\max} = 5.17eV - 1.40eV = 3.77eV$$

(d)
$$\phi = \frac{hc}{\lambda_0},\ or, \lambda_0 = \frac{hc}{\phi} = \frac{6.625 \times 10^{-34} \times 3 \times 10^{8}}{3.77 \times 1.6 \times 10^{-19}} = 3.29 \times 10^{-7} m$$

(e) This wavelength lies in UV region of the electromagnetic spectrum.

15. With a particular metal plate, shining a beam of red light on the metal causes electrons to be emitted. (a) If we replace the red light by blue light, do we know that electrons will be emitted? (b) If the two beams have the same intensity and are incident on equal areas of the plate, do we get the same number of electrons emitted per second in the two cases?

The work function for tungsten (W) is $\phi_W = 4.52$ eV.

(a) What is the longest light wavelength (sometimes referred to as the cutoff wavelength, λ_c) that can result in production of a photocurrent?

To eject an electron, a photon must have at least as much energy as ϕ_W. Using $E_\gamma = hc/\lambda_c = \phi_W$ gives $\lambda_c = hc/\phi_W = 1240/4.52$ eV-nm/eV $= 274.3$ nm.

(b) What is the maximum kinetic energy, K_{max}, of emitted electrons when light of wavelength $\lambda = 200$ nm is used to irradiate a piece of W?

If the enegy of the photon is greater than the work function, $hc/\lambda > \phi$, then the extra energy goes into kinetic energy of the photoelectrons. In this case, we have $K_{max} = hc/\lambda - \phi_W = 1240/200 - 4.52 = 1.68$ eV.

(c) What is the stopping potential (voltage) for this case ($\lambda = 200$ nm)?

The potential energy of an electron in an electric potential is $q{\cdot}V = e{\cdot}V$, where $q = e$ is the charge of an electron, and V is the applied voltage. The stopping potential is given by the voltage needed to stop the electrons with kinetic energy K_{max} when that voltage is applied across two electrodes, one of which is the photocathode - the metal plate from which the electrons are emitted in the photoelectric process. As the electrons travel from the photocathode to the other electrode, they increase their electric potential energy, and thus their kinetic energy decreases - they slow down. If the voltage is adjusted so that the potential energy increases by exactly K_{max} just before the electrons reach the second electrode, they will stop and thus no current will be recorded. Thus we have $K_{max} = 1.68$ eV $= e \cdot V$, so the stopping potential is exactly 1.68 V.