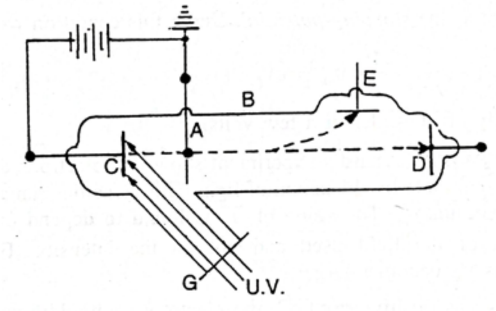
Photoelectric effect

Heinrich Hertz (1888) in Germany observed that when a plate of metal such as zinc is exposed to ultraviolet light, the plate becomes positively charged. Later P. Lenard (1899) in Germany showed that electrons are emitted from the metal surface. The phenomenon is known as photoelectric effect and the emitted electrons are known as photoelectrons.

Lenard's experiment:

Lenard's apparatus for measuring $\frac{e}{m}$ of the negatively charged particles emitted in photoelectric effect is shown below.



Lenard's experiment on photoelectricity.

B is a glass tube which is maintained at very low pressure with the help of pump. C is a plane metal plate which is kept at negative potential while A is another plane metal plate kept parallel to C at some distance from it. A is kept at zero potential. Thus A is positive with respect to C. There is a small hole at the centre of plate A through which beam of the emitted electrons from plate C can pass. Through a side window G a beam of ultraviolet light is made incident on plate C due to which photoelectrons are emitted from C. Emitted electrons are attracted towards plate A and a fraction of them passes through the hole in it to fall on the collector plate D. The resulting feeble electric current is detected with the help of an electrometer.

The enclosure B is placed between the poles of a magnet. If the magnetic field is perpendicular to the plane of the paper, then due to the magnetic field electrons coming out through the hole will describe circular arc and fall upon the collector E. The resulting current is recorded by another electrometer connected to it.

From the geometry it is possible to calculate the radius R of the circular arc. If V be the potential difference between C and A, then the kinetic energy gained by the electrons is given by

$$\frac{1}{2}mv^2 = \mathrm{e}V \text{ ....(1)}$$

As the electrons describe the circular arc, centripetal force is provided by the magnetic force and we have,

$$evB = \frac{mv^2}{R} \text{ ……………………………(2)}$$

From equations (1) and (2), we get

$$\frac{e}{m} = \frac{2V}{B^2 R^2}$$

From the measurement of $\frac{e}{m}$, Lenard concluded that emitted particles from the surface of metal plate upon irradiation is indeed electrons.

Lenard also observed that if a positive potential is applied to C instead of a negative potential, the electric current recorded at C decreased. This is due to the fact that the negatively charged electrons emitted from C then experience repulsive force in going towards A which is negative w.r.t. C. As the positive potential at C is increased, the current recorded at C ultimately becomes zero. If V_s be the potential difference between C and A when this happens, then electrons up to highest velocity v_m emitted from C are stopped from reaching A, V_s is known as the *stopping potential*. Under this condition,

$$\frac{1}{2} m{v_m}^2 = \mathrm{e}V_s$$

V_s is of the order of few volts.

Results of Lenard's experiment showed that electrons are emitted from the metal surface upon upon irradiation by light with velocities ranging from 0 up to a maximum velocity v_m. The value of v_m is found to depend on the wavelength (or frequency) of light and not on the intensity of light. For shorter wavelength v_m becomes larger.

From Lenard's experiment it is also concluded that the photoelectric current is independent of the wavelength of light and it depends on the intensity of light.

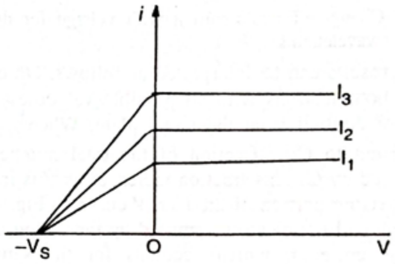
Einstein in 1905 proposed a theory of photoelectric effect based on the ideas underlying the newly discovered quantum theory of Max Planck. Einstein's theory was completely different from the electromagnetic theory of light.

Millikan in 1916 performed a series of experiments which conclusively supported the new theory of Einstein.

Millikan's experiment:

Millikan's experimental set up was almost similar to that of Lenard. Millikan used monochromatic light of different wavelengths and measured the photoelectric current emitted from different sources.

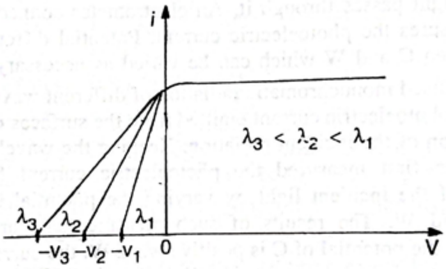
Keeping the wavelength of light fixed, he first measured the photoelectric current for different intensities I of the incident light by varying the potential difference between the irradiated metal plate and the collector. The results are shown below.



Change of photo-current with voltage for different light intensities.

When the potential of the collector is positive w.r.t.to the metal plate, the current is almost constant (saturated) for a given intensity of the light. If the potential of the collector is negative w.r.t. the metal plate, the current decreases and becomes zero at a particular potential $-V_s$ which is the same for the different intensities. The negative potential V_s is known as the stopping potential.

He next studied the variation of photoelectric current with the potential difference between the metal plate and the collector by using light of different wavelengths λ. The result is shown below.



Change of photo-current with voltage for different wavelengths.

The current attains saturation when the collector is at positive potential and it decreases with increasing negative potential. For a particular wavelength λ_1, the current goes to zero for a stopping potential $-V_1$. When the wavelength is λ_2, the stopping potential is $-V_2$ and so on. For the different wavelengths $\lambda_1, \lambda_2, \lambda_3, \ldots.$, the intensities were adjusted to have the same saturation current. The stopping potential has larger negative value for shorter wavelength, i.e., for higher frequency.

Upon irradiation, photoelectrons with all possible velocities from 0 up to a maximum velocity v_m are emitted from the metal plate. When a positive potential is applied to the collector, a fraction of the total number of electron is collected by the collector. This fraction increases as V increases, which are shown by the rising portion of the curve. For higher positive potentials, all emitted electrons are collected by the collector which is indicated by the saturation of photoelectric current. When negative retarding potential is applied at the collector, the electrons having lower energy are unable to reach the collector and the photocurrent i gradually decreases with increasing negative potential. Finally for a potential $-V_s$, photoelectrons of all velocities up to the maximum velocity v_m are prevented from reaching the collector. At this point, we can equate the maximum kinetic energy of the electrons to the energy required to overcome the effect of the retarding potential. Therefore,

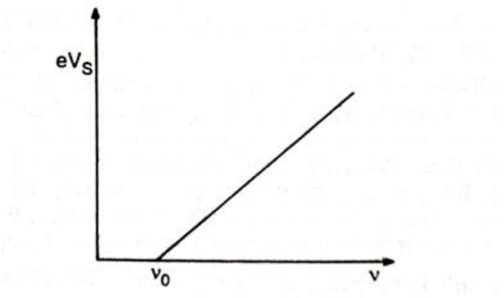
$$\frac{1}{2}mv_m{}^2 = \mathrm{e}V_s$$

Here m and e are the mass and charge of electron.

The important conclusions which can be drawn from Millikan's experiment are:

(i)The photoelectric current depends on the intensity of the light used and is independent of the wavelength (or frequency) of light.

(ii)The photoelectrons are emitted with all possible velocities from 0 up to a maximum velocity v_m which is independent of the intensity of light but depends on the wavelength (or frequency) of light. The maximum kinetic energy of the emitted photoelectrons increases linearly with the frequency ν .



Variation of the velocity of the photoelectrons with the frequency of the incident light.

(iii)Photoelectrons are emitted instantaneously, i.e., there is no time gap between the incidence of light and the emission of the photoelectrons.

(iv)The straight line graph showing the variation of the maximum kinetic energy of the emitted photoelectrons and the frequency ν of the light intersects the frequency-axis at some point ν_0 . No photoelectron emission takes place below this frequency. This minimum frequency ν_0 is known as the threshold frequency. Its value depends on the nature of the emitting material.

Failure of the electromagnetic theory of light:

The above mentioned experimental facts cannot be explained on the basis of classical electromagnetic theory. According to it light wave consists of mutually perpendicular electric and magnetic fields propagating as transverse wave with finite velocity which is the characteristic of the medium. The intensity of light is determined by the amplitudes of these electromagnetic oscillations. When light falls on the metal, the electrons in it is acted on by the oscillating electric field and gains energy from the field. Hence larger the amplitude of the electric field vector, larger the amount of energy gained by the electrons. So according to this theory, energy of the emitted photoelectrons should depend on the intensity of the incident light which is contrary to the observed fact.

(ii)Further, according to the e.m. theory, the velocity of the emitted photoelectrons should not depend on the frequency (or wavelength) of light which is contrary to the observed fact. Whatever be the frequency of the incident light, the electron will be emitted if it gets sufficient time to collect the required energy for emission. As the wave passes by the electron, the electron receives small amount of energy from each passing wave. Finally, when it collects the sufficient energy from the successive passing waves to break away from the metal, it is emitted. The time required for this purpose may be of the order of few seconds. But the emission of photoelectrons is instantaneous.

(iii)The incident e.m. wave acts equally on all the electrons on the metal surface. There is no reason why only some electrons will be able collect the required energy for emission from the passing waves. Given sufficient time, all electrons should be able to collect the required energy for emission. So there is no reason why the photoelectric current should depend on the intensity of the incident light. This is again contrary to the observed fact.

Einstein's light quantum hypothesis and photoelectric equation:

Maximum kinetic energy of the emitted photoelectrons increases linearly with the frequency of the incident light. This can be expressed by an equation of the form

$$\frac{1}{2}mv_m^{\ 2} = \mathrm{e}V_s = a\nu - \in \text{.......................(1)}$$

where a and $\in$ are two constants. Value of constant a was accurately determined by Millikan and also by other workers and was found to be equal to the Planck's constant h .

Hence, the above equation becomes

$$\frac{1}{2}mv_m^{\ 2} = \mathrm{e}V_s = h\nu - \in \text{........................(2)}$$

If we put $\nu = \nu_0 = \frac{\in}{h}$, then from eq. (2) we see that the energy of the emitted photoelectrons becomes zero. So there will be no emission of photoelectrons if the frequency of light $\nu < \nu_0$, ν_0 is the threshold frequency. Eq. (2) is known as the Einstein's photoelectric equation.

Einstein used the quantum hypothesis of Planck to explain all the observed characteristics of photoelectric effect (1905) and was able to deduce the photoelectric equation theoretically. According to Planck the atomic oscillators in the black body can only have discrete energy values $\in_n = nh\nu$ (n is an integer) and emission or absorption of energy by them takes place in discrete amount by $h\nu$. Einstein went one step further and postulated that light is emitted from a source in the form of bundles of energy of the amount $h\nu$, known as *light quanta or photon.* Here h is the Planck's constant. This is known as Einstein's light quantum hypothesis.

Explanation of observed characteristics of photoelectric phenomenon:

When a photon of energy $h\nu$ falls on a metal surface, the electron absorbs the energy $h\nu$ and is emitted from the metal provided $h\nu$ is greater than the energy $\in$ required to remove the electron from the metal. $\in$ is known as the *work function* of the metal. The extra amount of energy $(h\nu - \in)$ is taken away by the electron as its kinetic energy. Thus, the photoelectric equation is easily explained. If $h\nu < \in$, i.e., $\nu < \nu_0$, no photoelectron emission takes place. This explains the existence of the threshold frequency.

Further, according to this theory, larger the intensity, i.e., larger the number of photons falling on the metal, greater is the probability of their encounter with the atomic electrons and hence greater is the photoelectric current. Therefore, increase of photoelectric current with the increase in intensity of the incident light is easily explained by this theory.

Finally, as soon as a photon of energy $h\nu > \in$ fall on metal, electron absorbs and is emitted instantaneously. Thus instantaneous emission of photoelectrons upon irradiation of light finds an easy explanation.

Note:

Einstein's light quantum hypothesis postulates corpuscular nature of light in contrast to the wave nature of light postulated in the electromagnetic theory. Phenomena like interference, diffraction and polarization supports the wave nature of light where photoelectric effect provides a direct evidence for the corpuscular nature of light.

Eq. (2) can be written in the following form,

$$V_s = \left(\frac{h}{e}\right)\nu - \frac{\in}{e} \quad \text{..............(3)}$$

From slope and the intercept of stopping potential (V_s) vs frequency of light (ν) we can evaluate the values of Planck's constant and the work function of the metal.

Photoelectric effect not only takes place for metals, other materials in solid, liquid and gaseous form exhibit this phenomena when electromagnetic radiation of appropriate frequency (or wavelength) falls on them. For isolated atoms, as in gas, for emission of photoelectrons, the minimum energy required is the binding energy of the outermost electrons to the atom which is of the order of few electron volts. So these can be emitted by the action of visible or ultraviolet light. Electrons in the inner orbits of heavier atoms are bound much more strongly and for the their emission X-rays or γ-rays is required.