87PHOTOELECTRIC EFFECT

The **photoelectric effect** or photo electricity is the emission of electrons or other free carriers when electromagnetic radiation light hits the surface of a metal. Electrons emitted in this manner are called **photoelectrons.** This phenomenon is commonly studied in electronic Physics and in fields of chemistry such as quantum chemistry and electrochemistry

Photoelectric Characteristics

1. The number of photoelectrons emited per second that is the photoelectric current is proportional to the intensity of the incident light, but is independent of its frequency.

2. The velocities (or kinetic energies) of the photoelectrons vary between zero and a definite **maximum value v_m.** The proportion of electrons having a particular velocity is independent of the intensity of incident light.

3. The maximum velocity, v_m of the photoelectrons is independent of the intensity of incident light, but is directly proportional to its frequency.

4. For a given metallic surface, the emission of photoelectrons occur only if the frequency of incident radiation is greater than a certain minimum frequency called the **threshold frequency.**

5. The process of emission is almost instantaneous the time lag (, 10^{-8}sec) between the illumination of the metal surface and electron emission being < 10^{-8} sec.

Failure of classical theory to explain photoelectricity.

According to classical electromagnetic theory, the photoelectric effect can be attributed to the transfer of energy from the light to an electron. From this perspective, an alteration in the intensity of light induces changes in the kinetic energy of the electrons emitted from the metal. According to this theory, even a sufficiently dim light is expected to show a time lag between the incidence of light on the metal surface and the subsequent emission of an electron.

But the experimental results did not correlate with either of the two predictions made by classical theory. Instead, experiments showed that electrons are dislodged only by the impingement of light when it reached or exceeded a threshold frequency. Below that threshold, no electrons are emitted from the material, regardless of the light intensity or the length of time of exposure to the light. Also the emission process is instantaneous.

Einsteins theory.

Because a low-frequency beam at a high intensity could not build up the energy required to produce photoelectrons like it would have if light's energy was continuous like a wave, Einstein proposed that a beam of light is not a wave propagating through space, but rather a collection of **discrete wave packets** (photons), each with energy $h\nu$ and frequency ν

Emission of conduction electrons from typical metals usually requires a few electron-volts, corresponding to short-wavelength visible or ultraviolet light. Emissions can be induced with photons with energies approaching zero (in the case of negative electron affinity) to over 1 MeV for core electrons in elements with a high atomic number. Study of the photoelectric effect led to important steps in understanding the quantum nature of light and electrons and influenced the formation of the concept of wave–particle duality. Other phenomena where light affects the movement of electric charges include the photoconductive effect (also known as photoconductivity or photoresistivity), the photovoltaic effect, and the photoelectrochemical effect.

Emission mechanism.

The photons of a light beam have a characteristic energy which is proportional to the frequency of the light. In the photoemission process, if an electron within some material absorbs the energy of one photon and acquires more energy than the work function (the electron binding energy) of the material, it is ejected. If the photon energy is too low, the electron is unable to escape the material. Since an increase in the intensity of low-frequency light will only increase the number of low-energy photons sent over a given interval of time, this change in intensity will not create any single photon with enough energy to dislodge an electron. Thus, the energy of the emitted electrons does not depend on the intensity of the incoming light, but only on the energy (equivalent frequency) of the individual photons. It is an interaction between the incident photon and the innermost electrons. The movement of an outer electron to occupy the vacancy then result in the emission of a photon.

Electrons can absorb energy from photons when irradiated, but they usually follow an "all or nothing" principle that is a photon cannot be partly absorbed by a metal surface. Either the whole energy of it is absorbed or it is not at all absorbed and the energy is re-emitted. If the photon energy is absorbed, some of the energy liberates the electron from the atom, and the rest contributes to the electron's kinetic energy as a free particle.

Photoemission can occur from any material, but it is most easily observable from metals or other conductors because the process produces a charge imbalance, and if this charge imbalance is not neutralized by current flow (enabled by conductivity), the potential barrier to emission increases until the emission current ceases. It is also usual to have the emitting surface in a vacuum, since gases impede the flow of photoelectrons and make them difficult to observe. Additionally, the energy barrier to photoemission is usually increased by thin oxide layers on metal surfaces if the metal has been exposed to oxygen, so most practical experiments and devices based on the photoelectric effect use clean metal surfaces in a vacuum.

Mathematical description

In 1905, Einstein proposed an explanation of the photoelectric effect using a concept first put forward by Max Planck that light waves consist of tiny bundles or packets of energy known as photons or quanta.

When a photon of frequency ν and energy $h\nu$ is absorbed by an electron a part of it is used up to overcome the surface potential barrier and the remaining energy imparts kinetic energy to the electron. Hence if $\mathbf{v_m}$ be the maximum velocity reached by the electron then:

Maximum kinetic energy = $\frac{1}{2}mv_m^2$ = hν - W ……(2.1)

where 'h' is the **Plancks constant**. W is the energy consumed to overcome the surface potential barrier. This is the minimum energy required to just eject an electron from the surface of the metal. It is called **work function.** The work function W is given by: W = $h\nu_0$ ……(2.2)

Where, ν_0 is the minimum frequency of incident light to **just eject an electron** from the metal surface. This frequency is called the **Threshold frequency.** From equation (2.1) and (2.2) we obtain:

$\frac{1}{2}mv_m^2$ = hν - $h\nu_0$ = h(ν - ν_0) ……..(2.3)

Equations 2.1 and 2.3 are two alternative expressions for the well known **Einstein's Photoelectric Equation.**

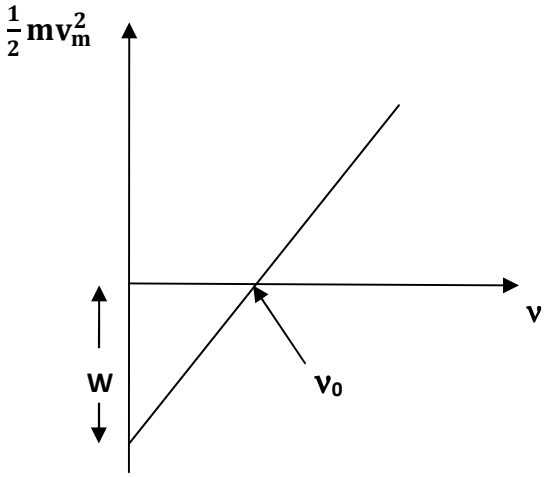

Fig. 2.1 Variation of maximum kinetic energy of photoelectrons as a function of frequency.

In the photon picture of Einstein each photon transmits a linear momentum p = $\frac{E}{c} = \frac{h\nu}{c}$, where E = hν is the energy of the photon and 'c' is the velocity of light.. The relativistic expression for energy E is given by:

$E^2 = p^2c^2 + m_0{}^2c^4$ ……(2.4)

m_0 being the rest mass of the concerned particle. The rest mass of photons is zero. So we have.

$E = pc \Rightarrow p = \frac{E}{c} = \frac{h\nu}{c} = \frac{h}{\lambda}$ ……(2.5)

Experimental verification of Einstein's equation.

Millikan experimentally verified Einstein's photoelectric equation and evaluated the work function and Planck's constant accurately and directly. The experimental arrangement is shown in the figure 2.2

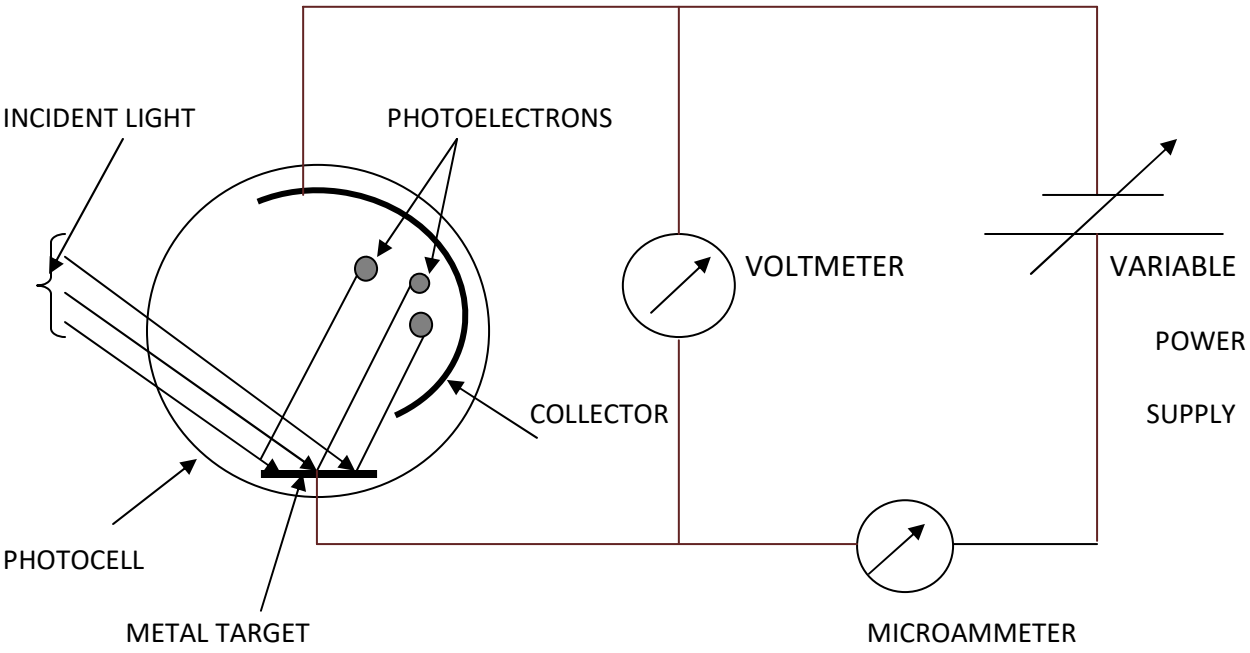

Fig. 2.2. Experimental set up to study photoelectric effect.

A photosensitive metal target is placed inside an evacuated photocell. Light is allowed to be incident on the target. The cell is connected with a variable power supply and a microammeter to measure the photoelectric current. A voltmeter is connected across the photocell.

Let i_p be the photocurrent and V be the potential drop across the photocell. The photoelectric behavior was studied by varying a number of parameters.

1. For a given monochromatic light, and fixed intensity I_1, the variation of i_p with V was noted and plotted on an indicator diagram. The same was repeated by varying the intensity to other values.

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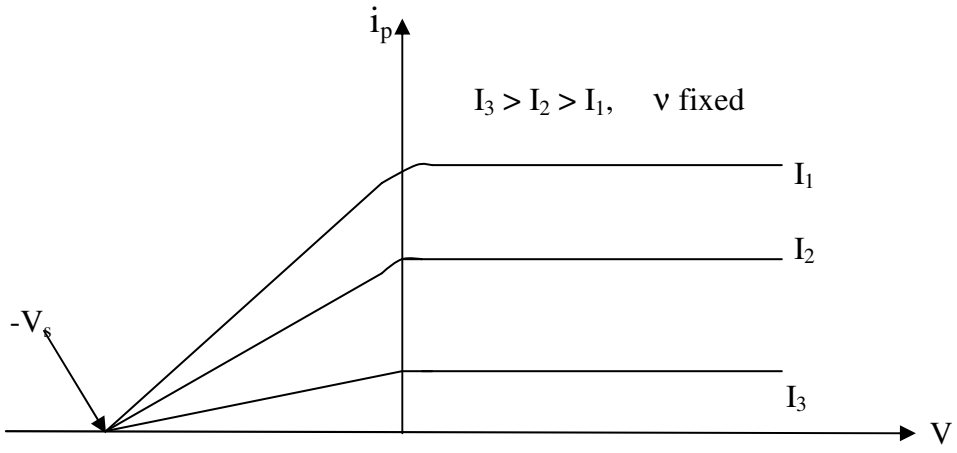

Fig. 2.3. Photocurrent vs. retarding potentials at fixed frequency and different intensities.

It was found that when the potential of the collector is negative, the current gradually increased with decrease in the magnitude of V. As soon as V becomes positive the photocurrent saturates. The saturation value of photoelectric current, increases with increase of intensity. The saturation current for a given intensity is attained when all the photoelectrons emitted at that intensity reaches the collector. Incidentally there is a non zero photocurrent even when V is zero, indicating that some of the electrons are emitted with a finite initial velocity. If the potential of the collector is made negative relative to the metal target, the current decreases and goes to zero at a particular value = $-V_s$, the value of V_s being same for all intensities. This negative potential is called **stopping potential** and is related to the maximum kinetic energy as:

$$eV_s = \frac{1}{2}mv_m^2 = h(\nu - \nu_0) \quad \text{.....(2.6)}$$

hence $$V_s = \frac{h(\nu - \nu_0)}{e} \quad \text{.....(2.7)}$$

where e is the charge of an electron.

Millikan thus measured the maximum kinetic energy of electrons emitted from a surface by a radiation of given frequency.

When the intensity of light is increased, there is an increase in saturation current (i.e. more electrons are ejected) but none of the electrons are more energetic, as the stopping potential remains unchanged.

2. . For a light of, and fixed intensity I_1, and fixed V, the frequency was varied with a given range and the variation of i_p with V was plotted on an indicator diagram. The same was repeated by varying the frequency of incident light to other values.

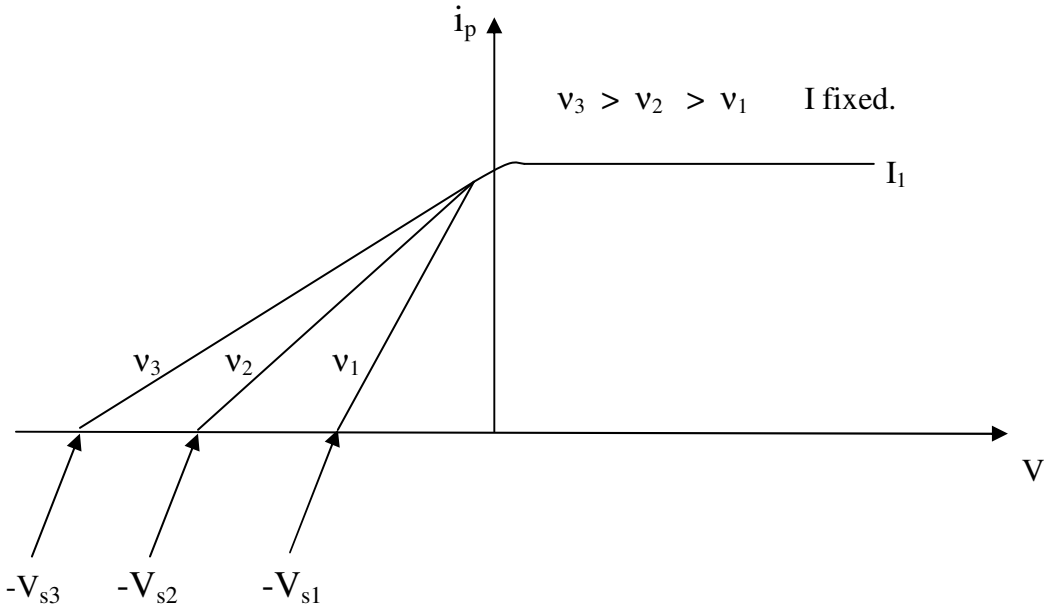

Fig. 2.4. Photocurrent vs. retarding potentials at fixed intensitiesynd different frequenc

It was found that saturation current remains same for all frequencies at fixed intensity showing that the number of electrons emitted in each case is same for all frequencies. But the stopping potential has a larger negative value for higher frequencies.

3. For a light of fixed intensity I_1, the stopping potentials was measured at different frequencies and the variation of maximum kinetic energy (eV_s) with ν was calculated and plotted on an indicator diagram.

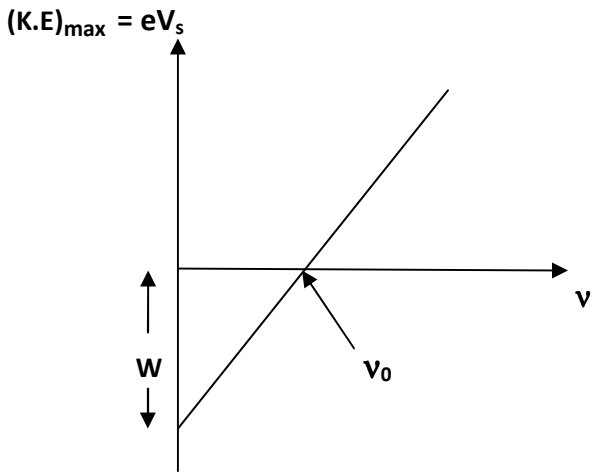

Fig. 2.5. Variation of maximum kinetic energy of photoelectrons as a function of frequency.

The graph was a straight line with Y – intercept at –W. and X-intercept at ν_0, the threshold frequency, the equation of the line being :

$$eV_s = h(\nu - \nu_0) \quad \text{.....(2.7)}$$

Equation (2.7) shows that whatever be the metal, the slope of the line was always the same (equal to Planck's constant 'h') although the value of W and ν_0 varied from metal to metal. The Planck'c costant was thus calculated by Millikan by noting V_s , ν and ν_0. Once 'h' became known he also calculated the work function of the concerned metal by using the relation $W = h\nu_0$. Also the work function could be obtained from the intercept of the graph (2.5)