Modern Physics-Section2

Dr. Jayanta Das

Department of Physics, Maharaja College, Ara, Bihar-802301

1 Photoelectric Effect:Quantization of Light

Phtoelectric effect was discovered earlier in 1887, when German physicist Heinrich Hertz was performing experiment with spark gap generator. He observed that he could change the sparking voltage between two metal plate electrodes by irradiating the plates with ultraviolet lights. But, no proper scientific explanation of the phenomena was available at that time. In 1897, J J Thomson discovered electron (e^-), the elementary charged particle inside atom. Studies by Thomson revealed that the observed modification in sparking voltage is the effect of light pushing electrons out of the electrode metals. The electromagnetic theory of light, on the other hand, was already well established by James Clerk Maxwell in 1865. It was known that electromagnetic waves transport energy from one place to other. It was therefore easy to imagine that electromagnetic energy is absorbed by atoms and as a result, the electrons are pushed out. These electrons, as they originate due to light, were called 'photoelectrons'.

It was Philipp Lenard, an assistant of Hertz, who performed detailed studies on photoelectric effect later on. Putting the clean electrodes inside a vacuum tube, Lenard performed frequency and intensity dependent photoemission studies. These electrodes were connected to variable power supply and a micro-ammeter (μA) was used to measure electrical current through the circuit. In figure 1, a typical circuit diagram demonstrates the experimental arrangement for photoelectric effect. Ultraviolet light from external source falls on a photosensitive plate/cathode.

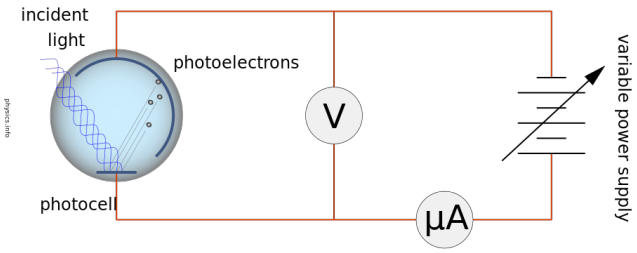

Figure 1: Photoelectric effect circuit

Photoelectrons emits out of one plate (emitter, cathode plate) and are collected on another plate (collector, anode plate). These electron flow through the closed loop while the photocurrent is measured by μ-Ammeter. This photocurrent (I) can be measured as a function of potential difference 'V' between the electrodes as well as function of frequency (ν) of the incident light. The voltage and frequency dependance of the current I will be discussed in different sections below.

1.0.1 Potential difference (V) *vs.* photocurrent (I_{ph}): Light intensity (I) dependence

A typical I_{ph}-V characteristic is shown schematically in figure 2 for a fixed frequency ν and three different intensities (I_1,I_2,I_3) of the incident light. The notable point is that, even at zero potential difference between the electrodes, a finite current could be measured by μ-Ammeter. This means that the emitted photoelectrons have their intrinsic

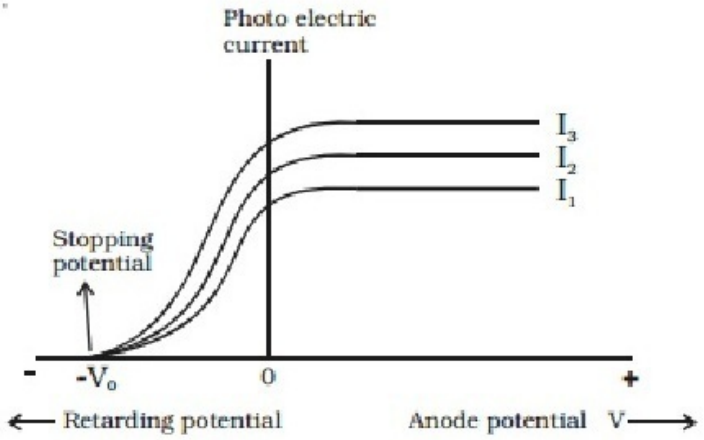

Figure 2: Variation of photocurrent I_{ph} with the potential difference V between the plates. The magnitude of photocurrent depends on incident light intensity, while the value of stopping potential V_S does not.

kinetic energy $\frac{1}{2}mv^2$ to reach the collecting plate even in absence of external electric field. At higher positive voltages, the plate current saturates. This happens when all the photoemitted electrons reach the collecting plate/anode, therefore the maximum current is reached. On the other hand, while the anode voltage is biased negatively with respect to the emitting plate, the current decreases gradually and eventually becomes zero. This occurs due to increasing repulsive force on the photoelectrons by the collecting plate. The corresponding negative voltage ($-V_S$) of the anode, for which the photocurrent just becomes zero, is called the *stopping potential*. $|-V_S|$ equals to the maximum kinetic energy of the emitted photoelectron $\frac{1}{2}mv^2_{max}$. It was observed later by Lenard (also we see in figure 2) that the intensity of the incident light has no effect on the magnitude of stopping potential. In figure 2, there are three characteristic curves corresponding to three incident light intensities I_1,I_2 and I_3. However, the stopping potential is same for all the cases. It is also interesting that the saturation photocurrent depends on the radiation intensity. As the radiation intensity increases, the saturation current also increases. Here, in the graph, $I_3 > I_2 > I_1$ and therefore the corresponding saturation current $I^{ph}_{s3} > I^{ph}_{s2} > I^{ph}_{s1}$.

1.0.2 Potential difference (V) *vs.* photocurrent (I_{ph}): Frequency (ν) dependence

In figure 3, photocurrent is plotted against the potential difference for different frequencies of the incident light while the intensity is fixed. Three characteristic curves are shown for three different frequencies *i.e.* ν_1, ν_2 and ν_3 respectively where $\nu_3 > \nu_2 > \nu_1$. At higher potential difference the current reach to its saturation value, which is same for these three cases since the intensity of the incident light is fixed. At lower voltage difference these three curves separate out and at for zero potential difference they intersect the y-axis at three points. At negative relative potential of the anode, the three characteristic curves corresponding to ν_1, ν_2 and ν_3 meet the x-axis at three different co-ordinates indicating the corresponding stopping potentials V^1_S, V^2_S and V^3_S respectively where $V^3_S > V^2_S > V^1_S$. It is interesting to note that the stopping potential depends on the incident light frequency. In the previous section, we have seen that the stopping potential does not depend on the incident light intensity. This is a very interesting phenomena regarding photoelectric effect.

1.0.3 Stopping potential (V_S) *vs.* frequency (ν): Material dependence

If we plot stopping potentials for various frequencies of the incident light, it shows linear behaviour, as shown in figure 4. In this figure, the behaviours of stopping potential as function of frequency are shown for two different metal A and B respectively. For each metal, there are respective frequencies at which the stopping potential reach down to zero value. This is called *threshold frequency* ν_{th} for that metal. Threshold frequency is significant because below this frequency no photoemission takes place whatever may be the intensity of the radiation. For metal A and B, value of ν_{th} are different. Evidently, threshold frequency is material specific. Notably, the slopes of the lines for the two metal are same, which indicates that the *rate* at which stopping potential changes with frequency is independent

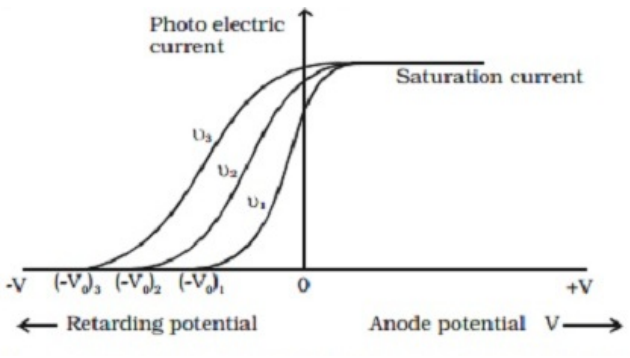

Figure 3: Stopping potential V_S depends on the frequency ν of the incident light.

of material properties.

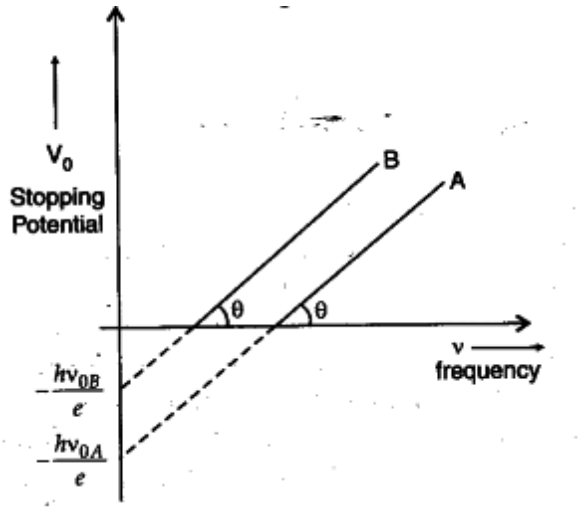

Figure 4: Frequency dependence of the stopping potential.

1.0.4 Failure of classical explanation

The well-established classical electrodynamics (based upon Maxwell's equations) has given the idea that electromagnetic wave is composed of sinusoidal electric filed $\overrightarrow{E}$ and magnetic field $\overrightarrow{B}$ where both are mutually perpendicular and also perpendicular to the direction of propagation $\overrightarrow{k}$. The energy density u associated to the electromagnetic wave is :

$$u = \frac{1}{2}\epsilon_0 E^2 + \frac{1}{2}\frac{B^2}{\mu_0}$$

. In other words, the energy of an electromagnetic wave depends on its intensity (I), at least classical mechanics tell us that. So, why the stopping potential V_S (i.e. the maximum kinetic energy of the photoelectron $\frac{1}{2}mv^2_{max}$) depends on frequency ν of the incident light, and not on its intensity? Also, the classical wave model of light does not explain why no photoelectrons are ejected below the threshold frequency ν_{th}, as it predicts that photoelectron must emit if the intensity of the incident light is sufficient enough. In contradiction to this classical theory, it was experimentally observed that even a faint beam (low intensity) of light with frequency higher than ν_{th} can eject photoelectrons, while a high intensity beam with frequency lower than ν_{th} can not.

1.0.5 Einstein's explanation

This failure of the classical mechanics was resolved by the quantum theory of light invented by Albert Einstein in 1905. Einstein proposed that light is composed of 'energy packets' or 'quanta'. The quanta of light is called 'Photon'. A light of frequency ν is made up of such energy packets or photons where each photon has energy $h\nu$. In brief, quantum theory provides the discrete or particle nature of light. Let's discuss how Einstein explained the crucial observations related to photoemission. In simple language, photoemission is photon in, electron out phenomena as

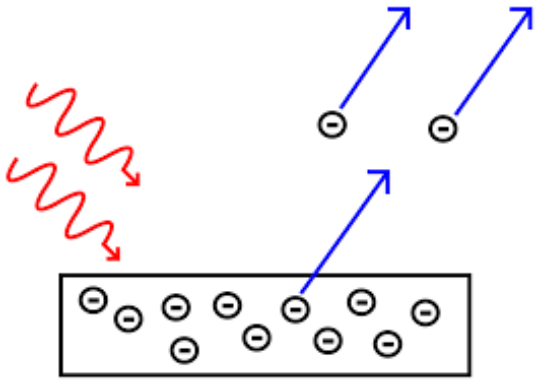

Figure 5: Photoemission: photon in, electron out

shown in figure (5). Within the atom, the electrons are bound to the nucleus while they revolve around. Let's say. the binding energy is E_B. When a photon of energy hν is absorbed, a part of that energy is expended to remove the electron from atomic bond and a larger portion of the rest energy becomes the kinetic energy of the emitting electron $\frac{1}{2}mv^2$. Therefore, it is obvious that, if the binding energy of the electron is less then its kinetic energy will be higher. In case, if the electron binding energy is zero, then its kinetic energy is maximum. Inside a metallic crystal, there are many free electrons (electrons with zero binding energy) at finite temperature. But, these free electrons are bound to the crystal and therefore can not come out of the crystal spontaneously. This binding of the electron to the crystal is expressed in terms of *work function* ϕ of the material. Therefore, the photon energy $h\nu$ may be expressed as:

$$h\nu = E_B + \frac{1}{2}mv^2 + \phi$$

For free electrons inside metal E_B=0, therefore, the kinetic energy becomes maximum, and we may write:

$$h\nu = \frac{1}{2}mv_{max}^2 + \phi$$

this correlation of the photon energy to the maximum kinetic energy of the photoelectrons was drawn by Einstein, where ϕ is the work function of the plate/cathode material. The above equation may also be written as,

$$h\nu - \phi = \frac{1}{2}mv_{max}^2$$

. If $\phi = h\nu_{th}$, then

$$h(\nu - \nu_{th}) = \frac{1}{2}mv_{max}^2$$

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(A) The stopping potential V_S *i.e.* the maximum kinetic energy of the electrons $\frac{1}{2}mv_{max}^2$ depends on frequency of the incident photon ν. Therefore, we measure different stopping potentials V_S^1, V_S^2 and V_S^3 while incident light frequencies are ν_1, ν_2 and ν_3 respectively. This explains the graph we observe in figure (3).

(B) Einstein's equation of photoelectric effect clearly shows that, for photoemission to occur (i.e. $\frac{1}{2}mv_{max}^2 > 0$) the condition is $h\nu > h\nu_{th}$, i.e. the incident photon frequency has to be greater than the threshold frequency. This equation also explains, how the stopping potential V_S (or, $\frac{1}{2}mv_{max}^2$) depends linearly on the incident photon frequency. The maximum kinetic energy of the photoelectrons decreases as the incident photon frequency ν decreases.

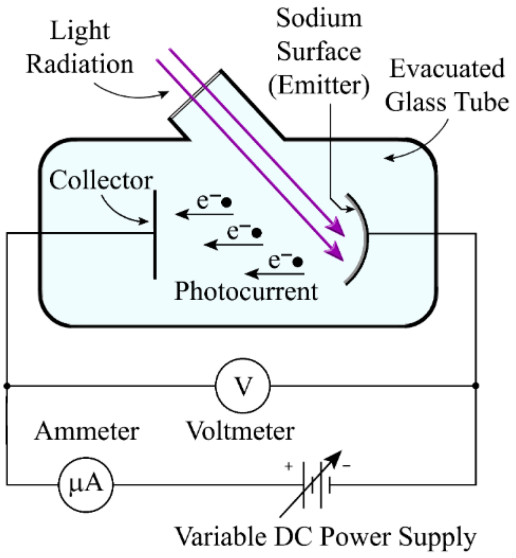

Figure 6: A circuit diagram for Photoelectric effect experiment

When ν decreases down to ν_{th} then ϕ=hν_{th}, therefore $\frac{1}{2}mv_{max}^2$=0. So the stopping potential also becomes zero. As a result, no photoelectrons can come out of the metal surface. This explains figure (4).

(C) If the incident radiation frequency is just higher than the threshold frequency ν_{th} photoemission process starts. Under this condition, if the intensity of irradiation increases then the incident photon density becomes higher. As a result, the number of emitted photoelectrons increases which results in higher circuit current. This explains the plot shown in figure (2).

(D) In figure (4), we observe that the slope of the linear variation of stopping potential with frequency is same for all metal. From Einstein's photoelectric equation we may easily derive that $\frac{\partial V_S}{\partial \nu}$ is constant. Therefore, as per expectation, the slope should not depend on material properties.

Einstein's quantum model of light was successful to explain all the aspects of photoelectric effect. In fact, this model opened up a whole new branch of physics later, called *Quantum Optics*. Notably, in the definition that says- light is made up of small energy *packets*, Einstein cautiously avoided the term 'particles' - just to distinguish it from our well-known classical particles. These energy packets are the quanta of light, called *photon*. They have no rest mass.

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[1] Figures are collected from online resources.