## 1. Introduction

According to Einstein, light is emitted in the form of photons and the energy distribution of photons is not continuous (not governedby the Maxwell's electromagnetic theory). Rather, a photon has unit energy of "*hv*",where *v*is the frequency of light and *h* is a constant. By illuminating a metal surface with light, the free electrons of the metal will absorb the photon's energy. If the photon's energy is higher than the barrier energy of the metal, electrons could escape from the metal surface. This effect is called the photoelectric effect. The kinetic energy of the escaped electron (i.e. photoelectron) will be:

$$E = h\nu - W_s \text{ or } \frac{1}{2}m{v_m}^2 = h\nu - W_s \tag{1}$$

where $h$ is Planck's constant ($6.626\times10^{-34}$J·s), $v$ is the frequency of the illuminating light, $m$ is the mass of an electron, $v_m$is theinitial speed of the photoelectron at the metal surface, and $W_s$is the escape energy or the work function of the metal.

Equation (1) gives the maximum kinetic energy of the photoelectron without any obstruction in space. Thehigher frequency of the illuminating light is, the greater of the maximum kinetic energy of the photoelectron will be resulted, as seen in Fig. 1 (a). Considering the certain initial kinetic energy of the photoelectron, there may be some photoelectrons escaped from the metal surface (cathode) to form a photo-current even when no positive voltage is applied between the anode and the cathode. When such voltage is reversed at a certain value, photoelectronscan no longer reach the anode and hence the photo-current is zero at this time, as shownin Fig. 1 (b). This negative potential $U_S$is calledas the cutoff voltage of the photoelectric effect, described by:

$$eU_s - \frac{1}{2}m{v_m}^2 = 0 \tag{2}$$

Substitute (2) into (1), we get

$$eU_s = h\nu - W_s \qquad \text{or } h\nu = \frac{1}{2}mv_m^2 + W_s \tag{3}$$

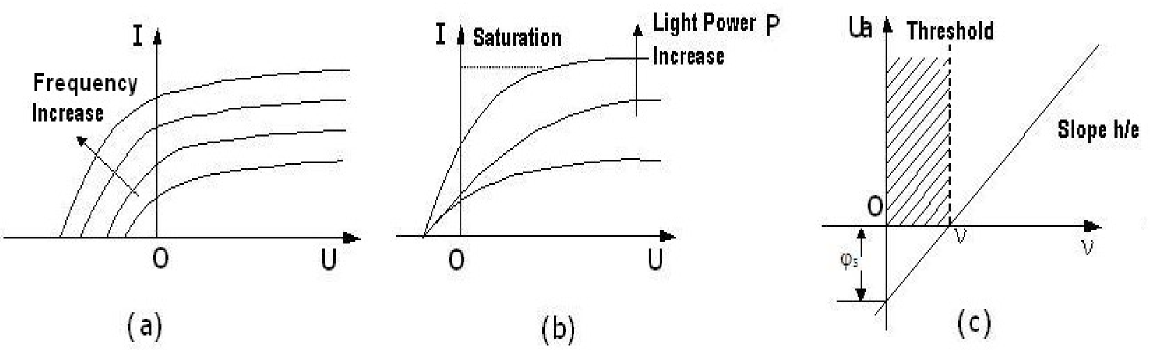

Figure 1Dynamic energy of photoelectrons *versus* light frequency (a), photocurrent *versus* light power (b), and cutoff frequency of photoelectric effect (c)

Equation (3) is called the Einstein's equation, which statesthat no photocurrent is given when the photoelectron energy *hv* is less than the work function $W_s$, as electrons cannot escape from the metal surface under such condition. For a given metal material, the minimum frequency of the illuminating light to create a photoelectric effect is $\nu_0 = Ws/h$, which is called as the cutoff frequency of the photoelectric effect (also known as the Red limit). Work function $Ws$ is the inherent property of a metal material, which is independent of the frequency of the incident light. Equation (3) can be rewritten as:

$$U_s = \frac{h}{e}\nu - \frac{W_s}{e} = \frac{h}{e}(\nu - \nu_o) \tag{4}$$

Equation (4) shows that the cutoff voltage $U_s$is a linear function of the frequency of incident light, $\nu$. Obviously, $U_s = 0$ when $\nu = \nu_0$, under such condition, there is no photocurrent.The slope of the straight line as described by Equation (4) is a constant $k (= h/e)$, as shown in Fig. 1 (c), thus

$$h = ek \tag{5}$$

where$e$ is the electron charge ($1.602 \times 10^{-19}$Coulombs).

Therefore, Planck's constant can be calculated by measuring the cutoff voltage $U_s$ versus the frequency of illumination light, plotting the $U_s$- $\nu$ curve, and acquiring the slope $k$. **Note**: the illumination light does not need to have a single wavelength as only the cut-off wavelength (the maximum frequency) matters for the determination of the cut-off voltage ($U_s$). This is because the photoelectrons, released by light illumination at the cut-off wavelength, have the maximum kinetic energy. If the photoelectrons with the maximum kinetic energy can be stopped by the reverse potential, other photoelectrons with less kinetic energy can be stopped as well. Thus, a broadband light source such as Tungsten lamp with long-pass filters such as color filters can be used to measure Planck's constant based on Equation (4).

Figure 2 showsthe experimental schematic of the photoelectric effect for determining Planck's constant using a photoelectric tube. When a light beam of frequency $v$ and power $P$ illuminates the cathode of a phototube, photoelectrons escape from the cathode. If a positive potential is applied to the anode relative to the cathode, the photoelectrons will be accelerated; if a reverse potential is applied to the anode, the photoelectrons will be decelerated. The photocurrent will decrease with an increase in the reverse potential, $U_{KA}$. Finally, the photocurrent will be zero when $U_{KA} = U_{s.}$ Figure 3 shows the typical$I$-$V$ characteristic curve of a photoelectric tube.

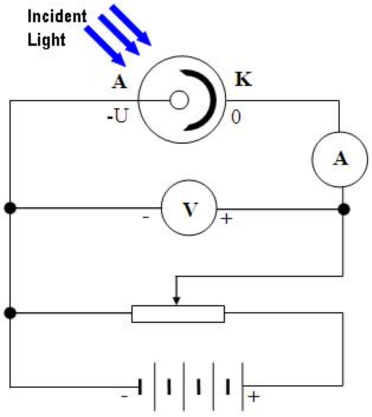

Figure 2 Experimental schematic

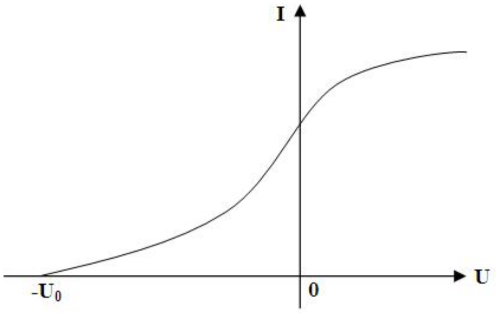

Figure 3$I$-$V$ characteristic curve

By illuminating a phototube with different light frequencies $v$, corresponding *I*-*V* curves of the phototube can be acquired, so that the corresponding cutoff voltages $U_s$ of the phototube can be obtained. By plotting $U_s \sim v$ curve, an approximately straight line should be seen, as predicted by Einstein's photoelectric equation. Hence, Planck's constant $h$ can be calculated from the slope $k$ of the line using Eq. (5). In addition, the cutoff voltage $U_0$ of the cathode material can be found from the intersection of the *I*-*V* curve with the horizontal axis of the plot. Thus, the cutoff frequency $v_0$ can be achieved from $U_0$,which equals the electron escape potential $\Phi_S$, as seen in Fig. 1 (c).