4. Principle of Experiments

In quantum physics, light is emitted in the form of photons and the energy distribution of photons is not continuous, which cannot be explained by the Maxwell's electromagnetic theory. A photon has unit energy of "$h\nu$", where ν 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:

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

where h is the Planck's constant (6.626×10^{-34} J·s), ν is the frequency of the illuminating light, m is the mass of an electron, v_m is the initial 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. The higher the frequency of the illuminating light is, the larger the maximum kinetic energy of the photoelectron as shown in Fig. 2 (a). Considering the certain initial kinetic energy of the photoelectron, there may be photoelectrons that escape from the metal surface (cathode) to form a photo-current in the absence of positive voltage applied between the anode and the cathode. In the presence of sufficient negative voltage between the anode and the cathode, photoelectrons can no longer reach the anode leading to zero photo-current as seen in Fig. 2 (b). This negative potential U_S is known as the cutoff voltage of the photoelectric effect, as described by:

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

Substitute (2) into (1), we get

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

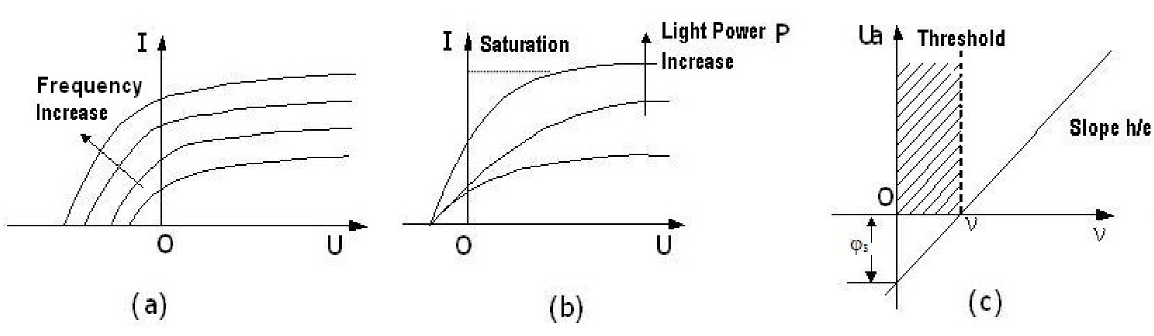

Figure 2 Dynamic energy of photoelectrons *vs* light frequency (a), photocurrent *vs* light power (b), and cutoff frequency of photoelectric effect (c)

Equation (3) is called the Einstein's equation, which states that no photocurrent is given when the photoelectron energy $h\nu$ 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 $\nu_0 = W_s/h$, called the cutoff frequency of the photoelectric effect (also known as the Red limit). It should be noted that work function W_s 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, ν. 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. 2 (c), thus

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

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

Therefore, the Planck's constant can be calculated by measuring the cutoff voltage U_s versus the frequency of illumination light, plotting the $U_s \sim \nu$ curve, and acquiring the slope k.

Figure 3 shows the experimental schematic of the photoelectric effect for determining Planck's constant using a photoelectric tube. When a light beam of frequency ν 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, photoelectrons will be accelerated; if a reverse potential is applied to the anode, 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 4 shows the $I \sim V$ characteristic curve of a photoelectric tube.

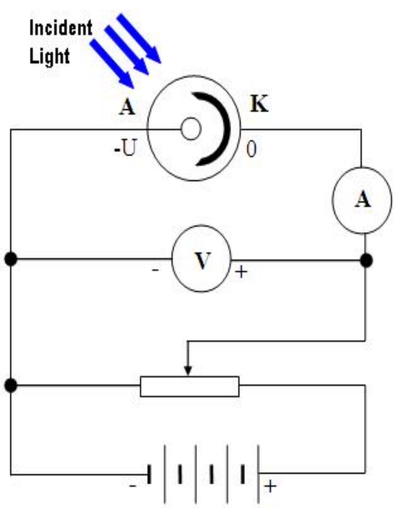

Figure 3 Experimental schematic

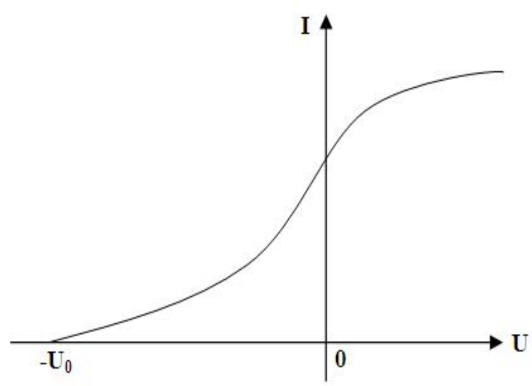

Figure 4 *I~V* characteristic of phototube

By illuminating a phototube with different light frequencies ν, corresponding $I \sim V$ curves of the phototube can be acquired, so that the corresponding cutoff voltages U_s of the phototube can be obtained. By plotting $U_s \sim \nu$ curve, an approximately linear line should be obtained as predicted by Einstein's photoelectric equation. Hence, the 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 $I \sim V$ 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 Φ_S, as seen in Fig. 2 (c).

It should be noted that Einstein's equation was derived using the same metal material for both emitter (cathode) and receiver (anode). Under such case, there is no influence of the so-called "contact potential difference." However, the phototube used in this experiment is made of different metals for the cathode and the anode. Thus, there exists a contact potential difference that is related to their work functions. Usually, a cathode has a smaller work function than that of an anode. The relationship between the applied voltage and the work functions is therefore modified as:

$$U_{KA} = U'_{KA} + \varphi_A - \varphi_K \tag{6}$$

For cutoff voltage, $U_S = U'_S + \varphi_A - \varphi_K$. Substitute it into (3), we get:

$$eU'_S + e\varphi_A - e\varphi_K = h\nu - e\varphi_K \text{, or } U'_S = \frac{h}{e}\nu - \varphi_A \tag{7}$$

If there is a contact potential difference, the $I \sim V$ characteristic curve shifts along the horizontal axis by an amount of $\varphi_{KA}=\varphi_A-\varphi_K$, which should be taken into consideration when processing the experimental data. However, the anode of the photoelectric tube used in this experiment is coated with the cathode material and therefore there is no contact potential difference between the anode and the cathode of the phototube ($\varphi_{KA}=0$). As a result, there is no need to modify the equations.