EXPERIMENT 12

THE PHOTOELECTRIC EFFECT AND PLANCK'S CONSTANT

White light that is passed through various filters illuminates the photoelectric surface of a phototube causing photoelectrons to be emitted with energies dependent upon the energy of the light hitting the surface. The electrons then flow through the phototube to the collector and constitute a current flow. A voltage called the stopping voltage or stopping potential is applied to halt the flow of photoelectrons. If the frequencies or wavelengths of the incoming light and the corresponding stopping voltages are known, then the value of Planck's Constant can be found.

THEORY

When light strikes a metallic surface, electrons are emitted from the surface. This effect is called the photoelectric effect. The emitted electrons, called photoelectrons, have varying kinetic energies that are primarily dependent upon the frequency of the light that strikes the surface. (See Figure 1.)
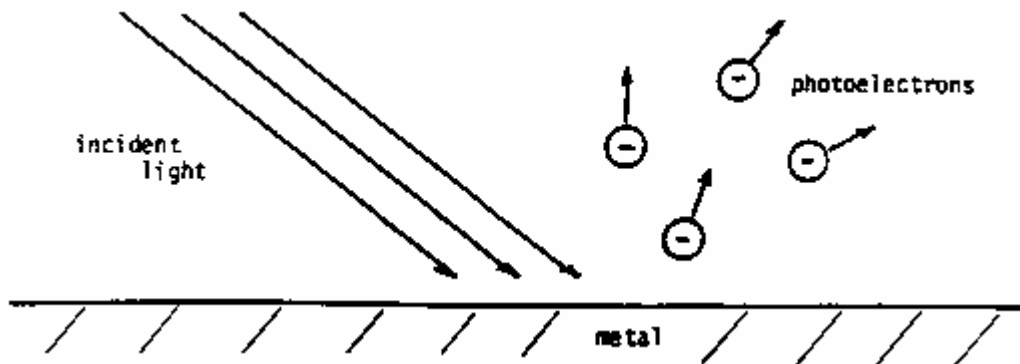

Figure 1. Light strikes a metallic surface and causes the emission of photoelectrons.

In 1905 Albert Einstein was able to provide an explanation of the photoelectric effect. He proposed that light acts like a particle having energy equal to *nf,* where *n* is Planck's constant and *f* is the frequency of the incident light. These particles of light, called photons or quanta collide with and transfer energy to the electrons in the metal. The emitted electrons then use part of this energy to migrate to the surface of the metal and part to free themselves from the electrostatic attraction of the metallic surface; the remainder goes into the kinetic energy of the electrons. For those electrons at the surface of the metal, no energy is used by the electrons to migrate to the surface, and thus, these electrons end up with the maximum possible kinetic energy, K_{max}. This can be expressed mathematically as

$$hf = W_f + K_{max},$$
(1)

where n is Planck's constant, f is the frequency of the incident light, and W, is the work function of the metallic surface, i.e., the energy needed to dislodge the electron from the surface.

Not all light will cause the electron emission. If the frequency of the light is less than a threshold frequency, f_o, then the photons do not provide enough energy to overcome the work function of the surface. At frequencies above the threshold frequency, electrons will be emitted. Therefore,

$$W_f = hf_o, \tag{2}$$

and (1) becomes

$$hf = hf_o + K_{max}. \tag{3}$$

A phototube consists of two electrodes in an evacuated glass tube. One electrode has a large photosensitive surface and is called the cathode or emitter. The other electrode is in the form of a wire and is the anode or the collector. In normal operation the anode is held at a positive potential with respect to the cathode. When the cathode is exposed to light, electrons are emitted from its photosensitive surface. These electrons are attracted to the positive anode and form a current that can be measured with an ammeter or galvanometer. (See Figure 2) The kinetic energy of the emitted electrons is dependent upon the frequency of light striking the phototube, and the quantity of emitted electrons is dependent on the intensity of the light.
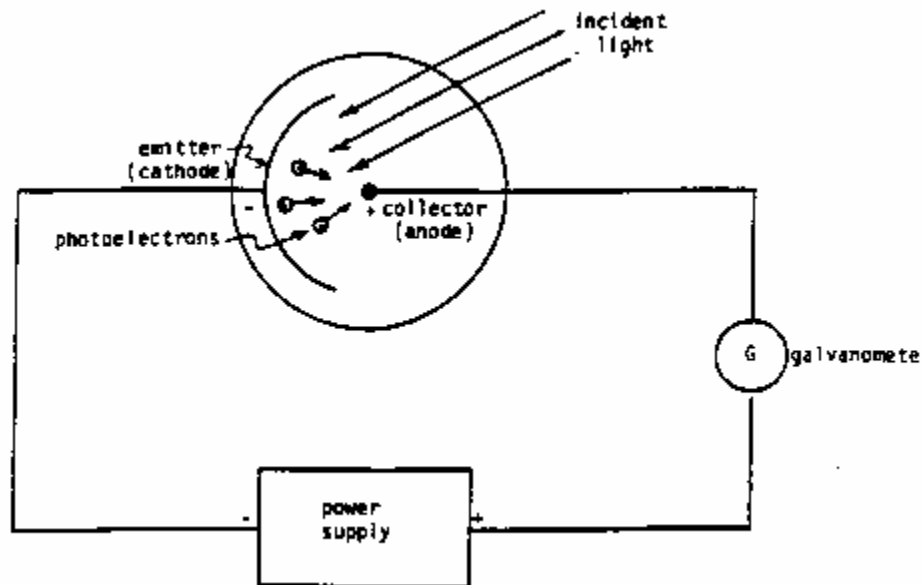

Figure 2.   The phototube connected for normal operation.

Because the work function W_t (or hf_o) is constant, the maximum kinetic energy depends directly on the frequency of the incident light. If the potential applied to the anode is gradually decreased to zero and then made negative, then a certain voltage will be reached where the electrons

emitted from the cathode will not have enough energy to reach the anode and will be repelled back to the cathode. At this voltage called the "stopping potential," V_S, the electron current from the cathode to the anode will cease to flow. At this voltage the maximum kinetic energy of the electrons is

$$K_{max} = eV_s,\qquad(4)$$

and therefore,

$$eV_s = hf - W_f,\qquad(5)$$

where e = the electronic charge 1.602 x 10^{-19} C and V_S is the stopping potential. By experimentally determining the stopping potential for several values of the frequency of the incident light and using (5) above, Planck's constant can be determined.

APPARATUS

  o Welch photoelectric tube apparatus
  o filters with known cut-off frequencies
  o voltmeter
  o incandescent light source   o galvanometer
  o power supply   o 6 leads

PROCEDURE

a) Connect the voltmeter, galvanometer, and power supply to the phototube connections.

b) Plug in the galvanometer and adjust the index on the galvanometer to some convenient reading on the scale with one lead to the galvanometer disconnected. This reading on the galvanometer corresponds to the situation where no current flows through the galvanometer. Now reconnect the lead to the galvanometer.

c) Plug in and turn on the light source. Place the light source directly in front of the opening to the phototube.

d) Note the wavelength of the filter and insert it in the slot above the phototube.

e) Adjust the potentiometer on the phototube apparatus until the voltmeter reads as close to zero as possible. Record the galvanometer reading.

f)   Adjust the potentiometer until the voltmeter read 0.05 volts. Record the galvanometer reading. Continue in the above fashion at 0.05 volt intervals until a voltage of 1.00 volts is -reached.

g)   Change the filter and repeat steps (d) through (g). Repeat for the remaining filters.

ANALYSIS

Equation (5) can be rearranged to allow a simple analysis. Dividing each side of the equation by the electronic charge, a. (5) becomes

$$V_s = \left(\frac{h}{e}\right)f - \frac{W_f}{e}. \tag{6}$$

The form of (6) is the same as that of a straight line, y = mx + b, where the ordinate is the stopping potential V,, the abscissa is frequency f , the slope is (h/e), and the intercept is W_f/e. Note that W_f/e is the value of the work function in electron volts.

On one graph, plot the voltage versus galvanometer readings for each filter and draw the best smooth curve that fits the data for each of the filters. Identify those voltages where the curves cross the galvanometer reading corresponding to no current flow. (See step (b) of the Procedure.) These voltages represent the stopping voltages for each of the filters (i.e., the voltage that stops the most energetic electrons from reaching the anode).

On a separate graph, plot the stopping voltage versus the frequency for each filter with voltage graphed on the ordinate and the frequency on the abscissa. The resulting graph should be a straight line. Find the slope of the line that best fits the data, and use the slope to calculate Planck's constant, h. Use (6) to calculate the work function, W_f/e, of the phototube in electron volts. The accepted values for Planck's constant and the work function are $h = 6.62 \times 10^{-34} J$ and $W_f = 2.06 eV$. Report the experimental and accepted values of Planck's constant and the work function in a table. Include the percentage errors.