Determination of Planck's constant and work function of metal using photoelectric effect

Objective

I. To determine Planck's constant 'h' from the stopping voltages measured at different frequencies (wavelengths) of light.
II. To determine the work function 'ϕ' of a metal.

Introduction

One of the most important experiments from the early 20th century was the photoelectric effect experiment. In this experiment, shining light upon a metal surface may cause electrons to be emitted from the metal. In 1905, Albert Einstein working in a Swiss patent office published a paper in which he explained the photoelectric effect. He argued that light travels in little energy bundles (or packets) called *photons.* The energy of one of these photons is hv, where h is the fundamental constant of nature as proposed by Max Planck to explain blackbody radiation, and v is the frequency of the photon. This novel interpretation of light turned out to be very significant and secured a Nobel Prize for Albert Einstein. Robert Millikan, co-founder of the California Institute of Technology and fellow Nobel Prize Winner, performed the careful experimental verification of Einstein's predictions.

Theory:

An electron in a metal can be modelled as a particle in an average potential well due to the net attraction and repulsion of protons and electrons. The minimum depth that an electron is located inside the potential well is called the work function of the metal, Φ (see Fig. 1). In other words, it is a measure of the amount of work that must be done on the electron (located in the well) to make it free from the metal. Since different metal atoms have different number of protons, it is reasonable to assume that the work function (Φ) depends on the metal. This is also supported by the fact that different metals have different values for electrical properties that should depend on the electron binding, including conductivity. The electron in the potential well of a metal is shown below in Fig. 1. It is analogous to a marble trapped in a water-well. The shallower the well (i.e. the lower the work function "Φ"), less is the energy required to cause the emission of the electron. If we shine a light with sufficient energy, then an electron is emitted.
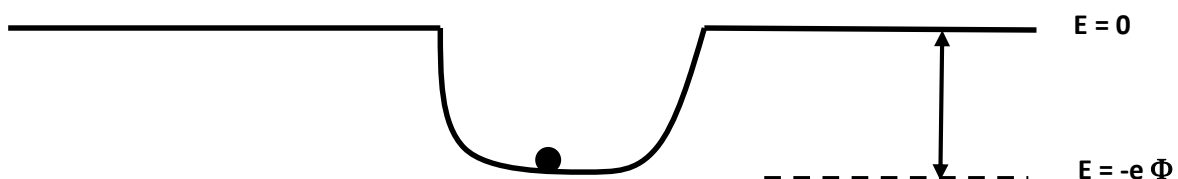

Figure 1: Electron in a potential well at a depth "Φ"

When a photon with frequency "v" strikes the surface of a metal, it imparts all of its energy to a conduction electron near the surface of the metal. If the energy of the photon (hv) is greater than the work function (Φ), the electron may be ejected from the metal. If the energy is less than the work function, the electron will simply acquire some kinetic energy that will dissipate almost immediately in subsequent collisions with other particles in the metal. By conservation of energy, the maximum kinetic energy with which the electron could be emitted from the metal surface T_{max}, is related to the energy of the absorbed photon hv, and the work function Φ, by the relation,

$$T_{max} = \frac{1}{2}mv^2_{max} = hv - e\Phi$$
$$\ldots (1)$$

Figure 1

Now consider the case of electrons being emitted by a photocathode in a vacuum tube, as illustrated Fig.2. In this case, all emitted electrons are slowed down as they approach the anode, and some of their kinetic energy is converted into potential energy. There are three possibilities that could happen.

i)   First, if the potential is small then the potential energy at the anode is less than the kinetic energy of the electrons and there is a current through the tube.

ii) The second is if the potential is large enough the potential energy at the anode is larger than the kinetic energy and the electrons are driven back to the cathode. In this case, there is no current.
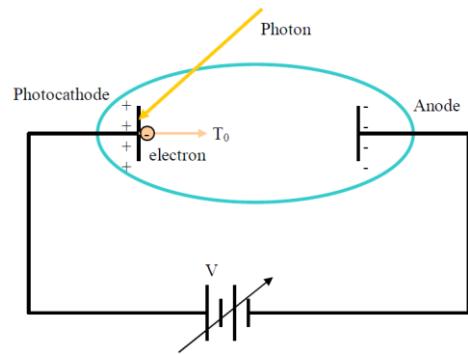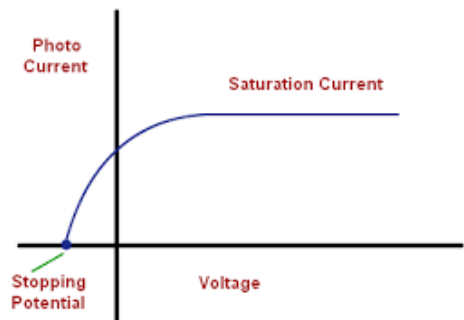

Figure 2: A schematic of a vacuum Phototube and a typical I-V characteristics

iii)   The third case is if the voltage just stops the electrons (with maximum kinetic energy T_{max}) from reaching the anode. The voltage required to do this is called the "stopping potential" (V_0). Typical I-V characteristics for a given frequency of light are depicted in Fig. 2. Thus Eq. 1 can be rewritten as,

$$eV_0 = hv - e\Phi \qquad\qquad \ldots (2)$$

$$V_0 = \frac{h}{e}v - \Phi \qquad\qquad \ldots (3)$$

It is worth noting here that, since the anode and cathode surfaces are different, an additional contact potential "A" comes into the picture which simply gets added to the work function "Φ". Eq. (3) can be written in terms of wavelength as

$$V_0 = (\frac{hc}{e})(\frac{1}{\lambda}) - (\Phi + A) \qquad \qquad ... (4)$$

Standard value of **h** is known[1] to be 6.626×10^{-34} J-s.

Experimental Set up:

The present experimental set-up (see Fig. 3) comprises of a tungsten-halogen light source with five different colour filters, a Cesium-type vacuum phototube, a built-in power supply and a current multiplier. The base of the phototube is built into a dark room and in front of it a receptor (pipe) is installed to mount filters.

Figure 3: Experimental set up

Procedure:

1. Plug in and switch on the apparatus using the red button at the bottom right corner of the set up.
2. Before the lamp is switched on, put the toggle switch in current mode and check that the dark current is zero. If it is not zero, note down the dark current value.
3. Turn on the lamp source (it may take 5-10 mins. to warm up). Intensity of lamp is pre-setup. You should not change intensity while taking data.
4. Insert one of the five specified filters into the drawtube of the receptor.
5. Set the voltage direction switch to "+ve" polarity. Adjust the voltage knob at minimum and current knob is at "X 0.01" position. Vary the voltage in steps of 0.5 Volt and record

the current till the value of current becomes relatively constant. Use the display mode switch to record the values of voltage and the corresponding current each time.

6. Now, set the voltage direction switch to "-ve" polarity. Make sure the voltage knob at minimum and change the current knob to "X 0.001". Vary the voltage very slowly and record the current till the value of current reaches the value of dark current. Use the display mode switch to record the values of voltage and the corresponding current each time.

7. The above steps 5 and 6 provides data to plot the I-V characteristics of the phototube for the wavelength (or frequency) selected by the filter.

8. Repeat the steps 5-7 for all the filters provided.

9. Fill up the observation tables and draw necessary plots. Determine the values of Planck's constant and work function of the metal used in the phototube.

Observations:

Specification of Filters:

Colour	Blue	Green	Yellow	Orange	Red
Wavelength (nm)	460	500	540	570	635

Table for I-V (+ve polarity) characteristics (for each filter separately tabulate the reading)

Voltage (+ ve polarity)	Current (µA)

Table for I-V(-ve polarity) characteristics (for each filter separately tabulate the reading)

Voltage (- ve polarity)	Current (µA)

Table for stopping potential versus wavelength

Stopping potential (V)					
Wavelength (nm)					

Graph:

1. Plot I~ V characteristics for different wavelengths.
2. Plot Stopping potential ~ (1/wavelength) and calculate slope and intercept by least square fit. A sample graph is shown in Fig.4.
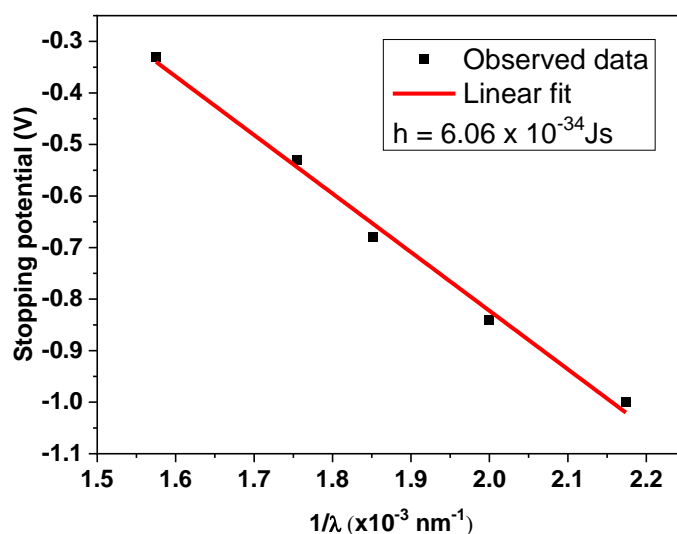

Fig. 4: Sample graph

Calculation and estimation of error: Determine '*h*' and '*φ*' and from the slope and intercept and estimate error in both the quantities.

Precautions:

1. Rotate all the knobs very slowly.
2. Handle the filters with utmost care and avoid touching their surfaces.

References:

1. https://javalab.org/en/photoelectric_effect_2_en/ (simulation with varying intensity and voltage)
2. https://phet.colorado.edu/en/simulations/photoelectric/about (simulation of photoelectric effect for different metals: https://phet.colorado.edu/sims/cheerpj/photoelectric/latest/photoelectric.html?simulation=photoelectric