Photoelectric Effect

Objective

Using "*Borderless Lab365*" platform to (i) study the effects of frequency and intensity of light on the stopping potential in photoelectric effect, and (ii) determine an experimental value of Planck's constant.

Theory

- The photoelectric effect is the emission of electrons from the surface of a metal when light is shined on the metal. Under classical wave model for light, it is predicted that the *energy of the emitted electrons would increase with increasing light intensity*. However, it was discovered that the energy of the emitted electrons was proportional to the **frequency of the incident light** instead of its intensity. Indeed, no electrons would be emitted if the light frequency was below a certain threshold, no matter how strong was the intensity of the light.
- There are four aspects of photoelectron emission which conflict with the prediction from the classical view that the instantaneous intensity of electromagnetic radiation is related to the product of the electric and magnetic fields of the radiation. Specifically:

  1. No photoelectrons are emitted from the metal when the incident light is below a minimum frequency, regardless of its intensity. (The value of the minimum frequency is unique to each metal.)
  2. Photoelectrons are emitted from the metal when the incident light is above a threshold frequency. The *kinetic energy* of the emitted photoelectrons increases with the *frequency* of the light, not to the intensity of light.
  3. The *number* of emitted photoelectrons increases with the *intensity* of the incident light. However, the kinetic energy of these electrons is independent of the light intensity.
  4. Photoemission is effectively instantaneous.

- In 1905, Albert Einstein gave a simple explanation of these discoveries using a concept of 'photon' (i.e. quantum particle of light) based on Planck's theory on quantum of radiant energy, i.e.

$$E = hf \qquad (1)$$

where E is the energy of the photon (radiation), f is the light frequency and h is a fundamental constant of nature called Planck's constant.

- A schematic diagram of the photoelectric effect apparatus is shown in Figure 1.

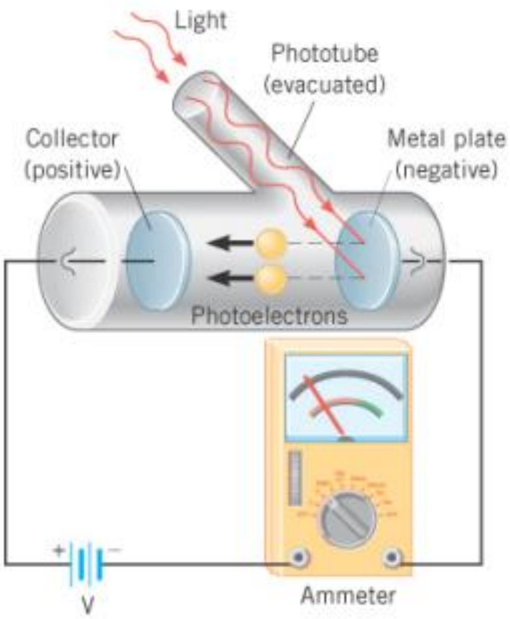


Figure 1: A schematic diagram of the photoelectric effect apparatus.

When light strikes the metal plate, electrons will be emitted from it and collected by a nearby electrode (collector). The metal plate in this case is known as a photocathode. If the photocathode and the collector are placed inside of a container evacuated of air, then an electron current will flow from the photocathode to the anode. The air, if not removed, would scatter the electrons and prevent them from flowing to the anode. The electrons emitted from the photocathode have kinetic energy. This energy can be measured by applying an electric field (by means of a voltage between the photocathode and the anode). If the electrode has a negative voltage relative to the photocathode, then the electron current will be reduced. As the applied voltage is made larger and larger, eventually the electron current vanishes because no electrons can overcome the applied voltage. This stopping voltage (V_S) is then a measure of the maximum kinetic energy of the emitted electrons.

- Applying conservation of energy and assuming light is quantized in units of energy hf, we obtain the famous Einstein equation.

$$KE_{max} = hf - \phi \qquad (2)$$

where KE_{max} is the maximum kinetic energy of the emitted electron, ϕ is the work function of the metal (i.e. energy required to release an electron from the metal surface and will be different for different metal).

- In this experiment, in order to verify the Einstein equation above, the photocathode is illuminated with several different color LEDs. Each LED produces a narrow spectrum of wavelengths λ and hence a narrow range of light frequencies $f = c/\lambda$. The wavelengths (λ) are in meters, the frequencies (f) are in Hertz (Hz) and c is the speed of light (2.998×10^8 m/s).
- If the collector plate is charged negatively to the 'stopping' potential (V_s) such that the emitted electrons cannot reach the collector, resulting in zero measured photocurrent. Then, the maximum kinetic energy of the emitted electron will have energy eV_s where e ($= 1.60 \times 10^{-19}$ C) is the charge of an electron. Then, equation (2) becomes

  $$eV_s = hf - \phi \,. \qquad (3)$$

  By plotting a graph of V_s against f as $V_s = (h/e)f - \phi/e$, the Planck's constant can be determined from the slope of the graph.
- Note that the stopping voltage in the Einstein equation V_o is only dependent on the frequency of the light f and not on its intensity. By using only one color LED and measuring V_o for several different light intensities, it can be shown that while the number of electrons emitted per second i.e. the photocurrent does change with the LED intensity, the stopping voltage V_o does not. The conclusion is that electrons must absorb the light in packets of energy hf and these packets are called photon.

Apparatus

- Light source of different light frequencies
  (Red – 625nm, Yellow – 590 nm, Green – 520nm, Blue – 455nm)
- Phototube with ammeter and voltmeter to measure the I-V characteristics
- Photodiode for light intensity measurement

Procedures

A. Measuring the current-voltage (I-V) characteristics using different light intensities with constant light frequency

1. Log in the experiment module "Photoelectric Effect" in the "*Borderless Lab365*" platform. https://stem-ap.polyu.edu.hk/remotelab/
2. In the Control Panel, click 'Blue' button to choose the blue light for the measurement.
3. Slide the 'Light Power' bar to turn on the light and adjust the light intensity.
4. Click 'Measure' to obtain the I-V graph (In this experiment, the V will be increased while I will be measured automatically).

5. Repeat steps 3-4 at least five more times (at least six different intensity values obtained in the measurement) to obtain the corresponding I-V data with different light intensities.

B. Measuring current-voltage (I-V) characteristics using different light frequencies with approximately same light intensity

6. In the Control Panel, click 'Green', 'Yellow', or 'Red' button to choose light of different colour for the measurement.
7. Move the 'Light Power' bar to turn on the light and adjust the light intensity.
8. Click 'Measure' to obtain the I-V data.
9. Repeat steps 7-9 using different colors (*the intensity should be set approximately the same level for all color set*) to obtain I-V data for different light frequencies.
10. Turn off the light and press "LOGOUT" on the left when you complete the experiment.

Analysis and Discussion

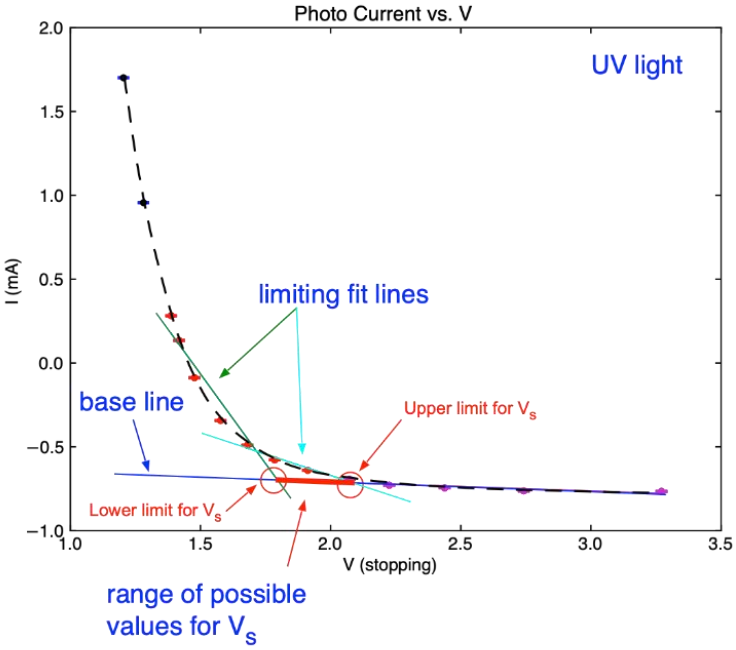
A. Measuring current-voltage (I-V) characteristics – different light intensities with constant light frequency

i) Plot the *I-V* data for different light intensities on the same graph.
ii) Plot a graph of stopping potential against intensity. (indicate which value of V_s will you use in the plot?)

Questions:

1. How is the stopping potential (V_s) related to the frequency?
2. How is the photocurrent related to the light intensity?
3. Did your data show the fact that the *number* of emitted photoelectrons increases with the *intensity* of the incident light while the kinetic energy of these electrons is independent of the light intensity?

Analysis method recommended: In plotting the current-voltage graph, it is important to determine the minimal retarding voltage from which one can determine kinetic energy of the ejected photo-electrons. This is the recommended method to find stopping potential using *I-V* graphs.



Typical I-V curve for the UV line are shown as an example. Note the base line and the two limiting lines fitted to determine the range of values for the stopping voltage.
Note that the I increases smoothly and it is not obvious to determine the exact value of the minimal value of Vs. In order to get a reasonable value, the following procedure will be suggested:

Draw a Base line: Fit a line to the data where V_s is very large and *I* basically *constant*.

Draw the first limiting fit lines: *the first limiting fit line* - Fit a line to the data (2 to 3 points are enough) where V_s is close to the base line and *I* changes slightly (as shown in the blue line in the figure).

The value for V_s at the intersection of the first limiting line and the base line will be the upper limit of the stopping potential to prevent electrons from reaching the anode.

(for reference: to estimate the lower limit for Vs. We draw the second limiting fit line - In the area where the current starts to rise (typically a current increase of 100 – 300 µA as shown in the figure), fit a second line to these data points (as shown in the green line). The intersection of the base line and the second limiting line will be the lower limit of the V_s value).

We will use the value of V_s at the intersection of the first limiting line and the base line (the upper limit) as the experimental values.

B. *Measuring current-voltage (I-V) characteristics – different light frequencies with approximately same light intensity*

i. Plot the I-V graphs for four different light frequencies.
ii. Obtain the range of stopping potentials for the four different frequencies of light with approximately same light intensity.
iii. Plot a graph of stopping potential against frequency with approximately same light intensity.
iv. The slope of the graph gives *h/e*. Determine the Planck's constant, *h*.

Questions:

1. How is the stopping potential (V_s) related to the light intensity?
2. Did your measured Planck's constant close to the theoretical value? What is the percentage error?
3. What are the possible errors of the experiment?