Lab #6: Light as a Particle - The Photoelectric Effect

Introduction

In the nineteenth century, it was observed that light falling on a piece of metal could cause electrons to be ejected from the surface of the metal. The classical theory of light as an electromagnetic wave, together with early models of atomic structure let physicists make some simple predictions of what should happen in experiments with this "photoelectric effect." Almost all these predictions failed miserably.

Explaining the photoelectric effect was one of the great early successes of quantum theory and won Einstein the Nobel Prize in 1921. Einstein's model suggested that light comes in discrete particles (called "photons"), and that the energy E of a photon of light is determined by the frequency (or wavelength) of the light, by equation 6.1,

$$E = hf = \frac{hc}{\lambda} \quad (6.1)$$

where, f is the frequency (in Hz) of the light, λ the wavelength of the light, c is the speed of light, and h is a constant called "Planck's Constant" (in honor of Max Planck, who first introduced the idea). The accepted value of h is $6.6261 \times 10^{-34}\,Js$, an extremely small number. Assuming light acts like a particle there should be a linear relationship between the kinetic energy of the electron and the frequency of the light of the photon. This relationship is given by equation 6.2,

$$K = hf - \phi \quad (6.2)$$

where ϕ is the work function of the metal, also called the binding energy of the valence electron of the metal atom. This relationship is shown in Figure 6.1. In addition, the intensity of the light is directly related to the number of photons that are incident on the metal. Since the intensity is related to the number of photons and since each photon has the same energy, a plot of the kinetic energy of the electron as a function of the intensity of the light shone on the metal surface should be a horizontal line, as seen in Figure 6.2.

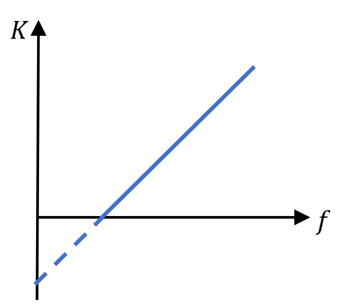

Figure 6.1: A plot of the kinetic energy of an ejected electron as a function of the frequency of light incident on a metal surface.

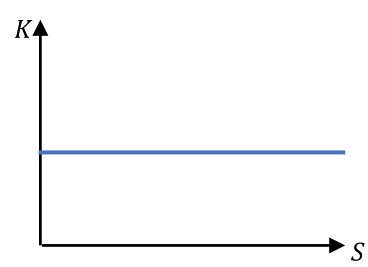

Figure 6.2: A plot of the kinetic energy of an ejected electron as a function of the intensity of light incident on a metal surface.

To determine the kinetic energy of the electron, we make the potential difference across the emitter/collector increasingly more negative to stop the fastest electrons from striking the collector. Work is done by the electric field created between the collector and emitter by this potential difference and the potential difference needed to stop the electrons from striking the collector we call V_{stop} and is determined by equation 6.3.

$$W = -eV_{stop} = K_f - K_i = -K_i \rightarrow eV_{stop} = K \quad (6.3)$$

In this lab, you will investigate the particle nature of light through the photoelectric effect and make a measurement of the value of Planck's constant.

The apparatus for this lab consists of a mercury lamp, which will serve as the light source for the experiment. A diffraction grating will be used to spread out the different frequencies of light from the mercury lamp, and a photoelectric effect box, consisting of a metal plate in an evacuated glass cell. The photoelectric cell is wired up in a box with some electronics (which are not important to performing the experiment), and the whole thing is connected to a voltmeter, which will allow you to measure the kinetic energy of electrons emitted from the metal plate.

Experiment #6: Light as a Particle – Photoelectric Effect Pre-Lab Exercises

Read laboratory experiment #6 on the Photoelectric effect, then answer the following questions in complete sentences. Be sure to print out and hand in any data and graphs you made along with the answers to these questions. The pre-laboratory exercise is due at the beginning of the laboratory period and late submissions will not be accepted.

1. Potassium has a work function of $\phi = 2.29 eV$. Light shone onto the surface of potassium can eject electrons from the surface of potassium. Light of various colors were shone onto a potassium emitter and electrons were ejected. The wavelengths of the incident light are given in Table PLE6.1 along with the measured speed of the ejected electrons. From the data on the speed of the ejected electrons, calculate and tabulate (in Table PLE6.1) the kinetic energy (in eV) of the ejected electrons. Show the calculation for one of the table entries.

$Color$	$\lambda\ (nm)$	$f\ (Hz)$	$^{v}/_{c}$	$K\ (eV)$	$V_{stop}\ (V)$
Green	546.074		0.000252		
Blue	435.835		0.00152		
Violet	404.656		0.00178		
Ultraviolet	365.483		0.00211		

Table PLE6.1: Colors of light that will eject electrons from a potassium surface. Also given are the speed (compared to the speed of light) of the ejected electrons from the potassium surface.

2. From the data on the kinetic energy of the ejected electrons (in eV), calculate and tabulate (in Table PLE6.1) the stopping potential difference (in V) that would be needed to stop the ejected electrons from striking the collector. Show the calculation for one of the table entries.

3. From the data on the wavelength of light that ejected electrons from the potassium emitter, calculate and tabulate (in Table PLE6.1) the frequency of the incident light. Show a calculation for one of the table entries.

4. Construct a plot of the stopping potential difference versus the frequency of the incident light that ejected electrons from the potassium surface. If the data are linear, fit the data with a straight line and determine the equation of the fit to the data and determine the work function of potassium. Show the calculations that you use below.

   Equation of the fit to the data: $V_{stop} =$

   Work function of potassium: $\phi_K =$

5. From the fit to the data, determine a value for Planck's constant, h. Show the calculation below.

   Planck's constant: $h =$

Experimental Procedure:

Activity 1: The photoelectric effect

The mercury lamps used as a light source in this experiment take a long time to warm up. If the lamp isn't already on, turn it on and allow it to warm up. **Warning:** When warmed up, the lamps and their housing are **very hot**. Do not touch the lamp when it's running.

The output of the mercury lamp contains light of five different colors of light, with wavelengths given in the table below. While the lamp warms up, calculate the frequency of the light associated with each wavelength, and record those values in the table.

When the lamp is warmed up, position the diffraction grating in front of the output slit of the light. Hold a white piece of paper in front of the diffraction grating, $10 - 20$ cm away. You should be able to identify at least two sets of colored lines, corresponding to the colors listed in Table 6.1 below. You may not be able to see the ultraviolet line clearly. Don't worry about that at this point. The diffraction grating is used to split the light form the mercury lamp into its component colors. The mask on the photoelectric cell has a special coating to make the ultraviolet line visible. Just make sure that you can see at least two sets of the visible lines, and adjust the grating as needed. Also, a large converging lens maybe positioned between the mercury lamp and the diffraction grating to focus the light onto the mask of the photoelectric cell and make the lines sharper.

Color	**Wavelength (nm)**	**Frequency (Hz)**
Yellow	578.035	
Green	546.074	
Blue	435.835	
Violet	404.656	
Ultraviolet	365.483	

Table 6.1: Wavelengths and frequencies of light.

Place the detector on the table, far enough back that the lines from the lamp are well separated from one another. Position the detector so that light from one of the blue lines passes through the slit and falls on the photoelectric cell. You can flip the small cylindrical light shield out of the way to make sure that the light hits the cell. Remember to put the light shield back in place before recording data.

With the light hitting the photoelectric cell, press the "PUSH TO ZERO" button on the side of the detector, and watch the voltmeter. After a short time (several seconds to perhaps minutes) the voltmeter reading should settle down to a steady value. This is the "stopping potential" for that color of light.

Record the stopping potential for each of the colors in one set of lines in Table 6.2 below. When you record the value for the yellow and green lines, you will need to place the appropriate colored filter in front of the detector (they stick to the front mask with magnets) to block light from the room lights. Take two measurements of the stopping potential for each color and calculate an average value of V_{stop}.

Color	**Stopping Potential for Trial 1 (V)**	**Stopping Potential for Trial 2 (V)**	**Stopping Potential Average (V)**
Yellow			
Green			
Blue			
Violet			
Ultraviolet			

Table 6.2: Stopping potential for different colors of light.

Construct a plot of the stopping potential V_{stop} (on the y-axis) versus the frequency f of the light (on the x-axis). If light acts as a particle, there should be a linear relationship between the stopping potential and the frequency. If the data are linear, then using equations 6.2 and 6.3, fit the data with a straight line and determine the equation of the fit and record it below.

$V_{stop} =$

Activity 2: The kinetic energy of the electron versus the intensity of the light

A third filter is included with the apparatus and consists of different patterns of dots and lines which allow you to vary the intensity of the light, while leaving the frequency unchanged. Different zones of the filter allow 100%, 80%, 60%, 40% and 20% of the intensity of the incident light to pass through.

Choose one of the colored lines to start and record the stopping potential for each of the different zones of the transmission filter. Also make a note of approximately how long it takes the voltmeter reading to reach a steady value. Record these values in Table 6.3 below. Repeat for each of the other colors that you have making the Table 6.3 and make sure to use the yellow and green filters for the yellow and green lines respectively.

Transmission (%)	Stopping Potential (V) for Yellow	Stopping Potential (V) for Green	Stopping Potential (V) for Blue	Stopping Potential (V) for Violet	Stopping Potential (V) for UV
100					
80					
60					
40					
20					

Table 6.3: Stopping potential for different transmission intensities of light.

Construct a plot of the stopping potential V_{stop} (on the y-axis) versus the intensity S of the light (on the x-axis) for each color of light on the same plot. There should be 5 lines total on this plot. If light acts as a particle, the kinetic energy of the ejected electron should be a constant independent of the intensity of the light. Fit the data with straight lines and determine the equation of the fits.

$V_{stop,yellow} =$

$V_{stop,green} =$

$V_{stop,blue} =$

$V_{stop,violet} =$

$V_{stop,UV} =$

Data Analysis & Post-Laboratory Exercises

Based on your data collected, graphs generated, and equations of fits to the data, answer the following questions. Be sure to print out and hand in your data and graphs along with the answers to these questions.

1. From your plot of V_{stop} versus the f for the five different colors of light you measured, what is the equation of the fit to the data?

   $V_{stop} =$

2. From your plot of V_{stop} versus the f for the five different colors of light you measured, are your data consistent with the model for the photoelectric effect? Explain.

3. From your plot of V_{stop} versus the f, what is the slope of the line? From the slope of the line, what is the experimental value of Planck's constant h? Calculate the percent difference between this and the accepted value.

   $h_{expt} =$

4. From your plot of V_{stop} versus the f, what does the x-intercept of the line represent? What does the y-intercept represent?

5. From your plot of V_{stop} versus the f, what is the minimum frequency of light that will produce photoelectrons?

   $f_{min} =$

6. Calculate the kinetic energy K of the ejected electron for each color of light. At what speed v would an electron need to be moving to have that kinetic energy?

   $K_{orange} =$ $v_{orange} =$
   $K_{green} =$ $v_{green} =$
   $K_{blue} =$ $v_{blue} =$
   $K_{violet} =$ $v_{violet} =$
   $K_{UV} =$ $v_{UV} =$

7. From your plot of the stopping potential V_{stop} versus intensity S of light transmitted for each color of light, what are the equations of the fits to the data?

   $V_{stop,yellow} =$

   $V_{stop,green} =$

   $V_{stop,blue} =$

   $V_{stop,violet} =$

   $V_{stop,UV} =$

8. From your plots of the stopping potential V_{stop} versus the frequency of the light f and the stopping potential V_{stop} versus intensity S of light transmitted for each color of light, do your results support the fact that light behaves as a wave or a particle. Be sure to fully explain your answer and show how your plots supports your choice for light acting as a wave or a particle.