The Photoelectric Effect

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The photoelectric effect refers to the process where solids emit electrons upon being illuminated by light with a frequency beyond a certain threshold. Understanding the photoelectric effect is essential as it serves as evidence for the quantum nature of light, or the description of light as discrete particles known as photons. To study the photoelectric effect, I obtain multiple IV curves for various frequencies of light by varying the applied voltage across the a photomultiplier tube. I then use linear fitting for points within the IV curve near the x-axis to identify stopping voltages. In doing so, I seek to verify the ratio of $\frac{h}{e}$, where h refers to Planck's constant and e to the elementary charge, and to identify the contact potential within the phototube. By calculating the slope of a stopping voltage versus frequency plot, I obtain an approximate ratio of $\frac{h}{e}$ of (4.982 ± 0.747)E-15 Vs which has around a 21% error compared to the theoretical value $\frac{h}{e} = 4.136$E-15 Vs. Observing the y-intercept of the stopping voltage versus frequency plot, I also report a contact potential of (1.961 ± 0.286) V.

I. INTRODUCTION

Physicist Heinrich Hertz discovered the photoelectric effect by shining ultraviolet light onto metal electrodes and observing sparking [1]. Although Hertz was the first to observe the phenomena, Albert Einstein provided explanation regarding the photoelectric effect in his paper on the quantum nature of light in 1905. In his paper, Einstein employs Max Planck's concept of the energy quanta of light: $E = h\nu$, where ν is the frequency of light, to explain the effect and describes the particle-like behavior of light [2]. Prior to Einstein's photoelectrons, classical physics could not explain the existence of a cutoff frequency, or a minimum frequency of light required to eject electrons, and the energy of the electron relying solely on the frequency of light instead of its intensity. Einstein provides an equation that describes the relationship between the maximum kinetic energy of an ejected electron and the energy stored in a photon [2]:

$$\frac{1}{2}mv^2 = h\nu - e\phi \tag{1}$$

where v is the maximum velocity of an ejected electron and ϕ represents the work function–the minimum energy required to remove an electron from the surface of a material. As such, the maximum kinetic energy of the ejected electrons can be measured by applying a reverse bias and measuring the minimum voltage necessary to stop the photocurrent. The minimum reverse bias required to halt the photocurrent is known as the stopping voltage.

By replacing the kinetic energy term with $E = eV_s$ and dividing by the elementary charge, we obtain the following equation [3]:

$$V_s = (\frac{h}{e})v - \phi \tag{2}$$

where V_s refers to the aforementioned stopping voltage. Through this equation, it is apparent that the stopping voltage varies linearly with the frequency of light and the slope of this linear relationship is expected to equal to $\frac{h}{e}$. Consequently, the y-intercept of this linear relationship should indicate the work function ϕ. However, given the design of the photomultiplier tube described in the following section, consideration is given to the fact that this method of approximating the work function will yield values different from that of most metals. By drawing on equation (2), I obtain the stopping voltages for various frequencies of light and use linear fitting between these two variables to determine the slope and the y-intercept.

II. EXPERIMENTAL SETUP

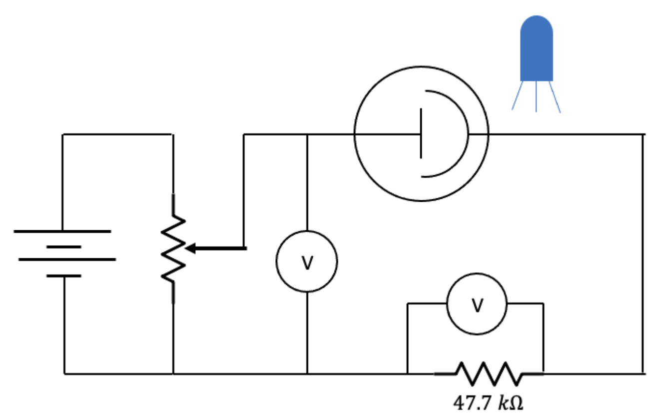

FIG. 1. A diagram of the apparatus is shown. A variable resistor is used to incrementally change the applied bias across the photomultiplier. LEDs of various frequencies are shined onto the cathode of the photomultiplier tube. Voltmeters are used to identify the applied voltage and to determine the photocurrent.

To obtain a fit for the linear relationship shown in equation (2), multiple IV curves for each corresponding frequency of light need to be obtained. The IV curves are taken using the setup shown in Fig. 1. where the LED shown in blue is cycled through multiple colors: red (624 ± 6.7)nm, orange (605 ± 7.0)nm, yellow (590 ± 7.0)nm, green (525 ± 12.5)nm, aqua (505 ± 12.5)nm, blue (467 ± 12.73)nm [4]. It should be noted that the uncertainties for the LEDs for the red, yellow, green, and blue are obtained in [4] using the half width half max of the spectral distributions. For orange and aqua, this information is not provided, but the uncertainties for yellow and green are used correspondingly. The LEDs are positioned such that the exposed surface area is maximized on the cathode plate (shown as a semicircle in Fig. 1.) is and minimized on the anode. These adjustments for the positioning are essential to minimize the negative anode current.

To minimize anode exposure to the LED light as well as prevent ambient light from interfering, a cover with a slit is placed over the phototube, and the apparatus is enclosed in a cardboard box. A variable resistor is used to adjust the applied voltage to the circuit and measured with a voltmeter. Since the photocurrent tend be on the scale of 10^{-8} milliamps, a voltmeter in combination with $47.7K\Omega$ resistor is used to detect the current. Obtaining an IV curve, the applied voltage is swept between -22.5V and 22.5V starting with a large negative bias to measure the residual back current from the anode. In addition, the phototube is grounded between switching LEDs to prevent charge buildup on the electrode plates.

III. RESULTS AND DISCUSSION

A. IV Curves

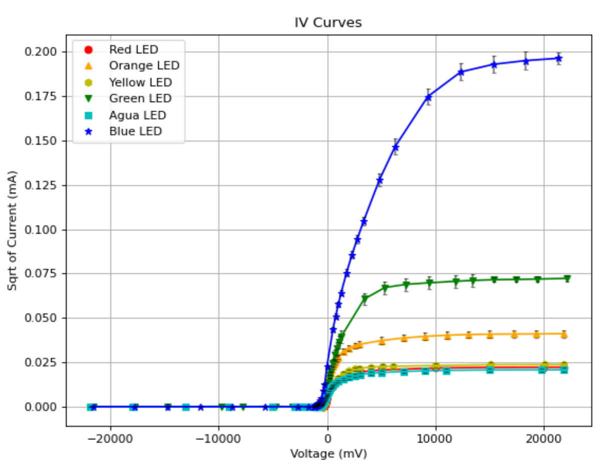

FIG. 2. IV curves for the various LEDs are shown above. The uncertainty for the data points ranged from 10^{-3} to 10^{-5} milliamps. The square root of current is plotted with respect to voltage for curve fitting purposes as discussed in section III.B.

Within the phototube, photons emitted by the LED are absorbed by the electrons within the cathode. Photoelectrons are then ejected and may flow to the anode. Thus, only by shining light above the cutoff frequency will the circuit be completed, and current be allowed to flow. By applying a reverse bias, the voltage difference will work against the photocurrent, diminishing the magnitude of current as shown in Fig. 2. Applying a forward bias eventually results in saturation of the photocurrent, demonstrated by the plateauing of the curves at higher voltages in Fig. 2. The magnitude of saturated photocurrent is proportional to the intensity of light reaching the surface of the cathode plate. It should be noted that, upon using an infrared LED, there is no photocurrent response as the frequency is below the cutoff.

Regarding the uncertainty of each data point, fluctuations of around ± 0.003 mV would occur–specifically within the voltmeter readings across the $47.7K\Omega$ resistor. Using this fluctuation value and assuming the resistor had an uncertainty around $\pm 5\%$, I convert the 0.003 mV uncertainty into a percentage for each data point and sum with the uncertainty from the resistor to provide a percentage error for the current readings. Since I plot the square root of current in Fig. 2, I also halve the uncertainties.

B. Stopping Voltages

To calculate the stopping voltages for each IV curve, a linear fit is applied to a window of data points near where the graph appears to cross the x-axis. Before selecting a window and performing the linear fit, I first plot the $\sqrt{I}$ versus Voltage. The shape of the curve near the stopping voltage can be approximated as such [2]:

$$I = I_o + \alpha(V - V_o)^2 \tag{3}$$

where I_o is the anode current. An example of this quadratic relationship between current and voltage, near the stopping voltage, is shown in Fig.4. Thus, to achieve an approximately linear relationship between current and voltage near the stopping voltage, I first subtract the negative anode current from the current readings before taking the square root. Since the anode current remains constant across high negative biases within my IV curves, I subtract the constant I_o values from every data point. After subtracting the anode current and taking the square root, I perform linear fitting is shown in Fig. 5. Using this method, I summarize my stopping voltages from this linear fitting procedure in Table 1.

LED Color	Stopping Voltage (mV)]
Red	-419.26 ± 56.86
Orange	-522.01 ± 20.30
Yellow	-570.11 ± 40.08
Green	-880.15 ± 45.68
Aqua	-1031.79 ± 111.16
Blue	-1217.21 ± 139.60

Table 1. A table displays the stopping voltages with uncertainties for each corresponding LED light. Before plotting these stopping voltages in Fig. 5, the absolute value is taken.

It should be noted that the window selection for the linear fitting is arbitrary and the stopping voltage can vary depending on the selection of points. To obtain the uncertainties for the stopping voltages, I performed a linear fit using five different windows for each IV curve. With these range of values, I halve the difference between the maximum and minimum stopping voltages and use this as a metric for error. Since adjusting the window would dramatically alter the linear fit, and thus alter the stopping voltage, I do not consider the error associated with the uncertainty in the individual data points.

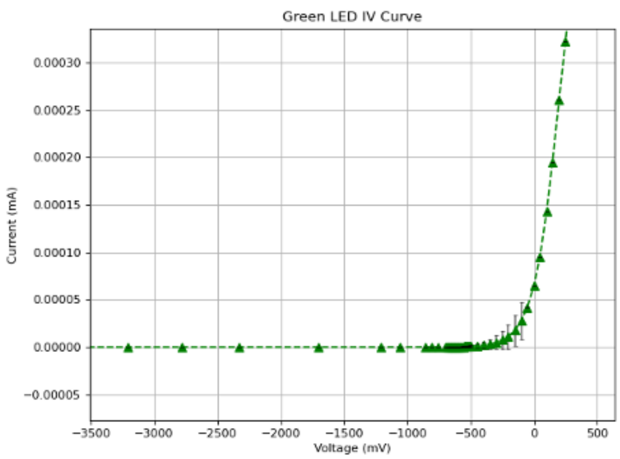

FIG. 3. An example of the quadratic relationship between current and voltage at points near the stopping voltage. The sample shown above is taken directly from measurements using the green LED.

C. Stopping Voltages v. Frequency

A plot of the final results is shown in Fig. 5. with the dashed line indicating the line best fit. Here, the slope of the plot is (4.982 ± 0.747)E-15 Vs. The uncertainty for the slope is calculated in a similar fashion to the stopping voltages. In particular, I constructed five plots for the stopping voltage versus frequency by using various combinations of the stopping voltages found at different windows for each LED. Upon doing so, I halve the difference between the minimum and maximum slope to find the uncertainty. When compared to the expected value for $\frac{h}{e}$ = 4.136E-15 Vs, there is a 20.46 % error. The uncertainty of calculated slope is ±14.94% which is comparable to the percent error. Since the percent error does not fall within the uncertainty of the slope, this indicates that there are other sources of error beyond the uncertainty associated with linear fitting. For

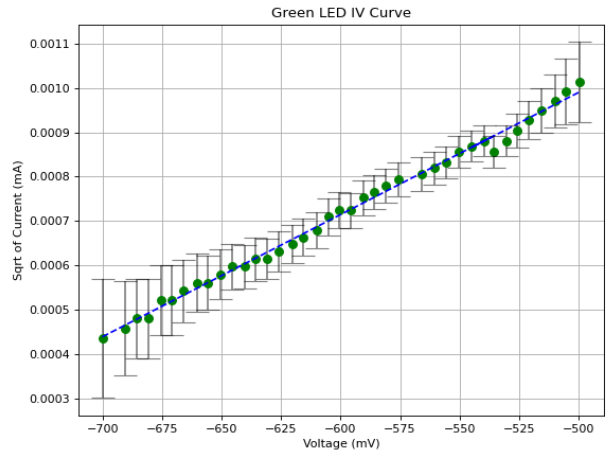

FIG. 4. An example of a linear fit using data taken from the green LED. The dashed line displays the line best fit. The root of the linear equation (the stopping voltage), obtained via linear fitting, is (-859.27±45.68) mV.

example, several sources of error to consider are: (1) the ±0.003 mV fluctuations within voltage readings across the resistor, (2) high anode current present for several IV plots, (3) electrostatic charge buildup on the electrodes, and (4) the distribution of wavelengths produced by the LED. The work function, based off of the linear

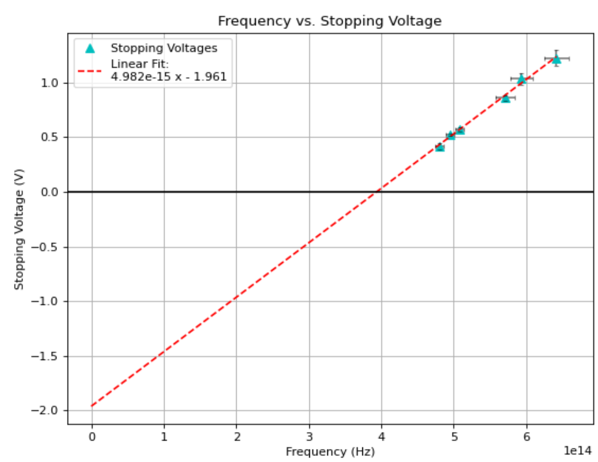

FIG. 5. A plot of the stopping voltages versus frequency of light is shown above. The line of best fit yielded: $y = 4.982 * 10^{-15}x - 1.961$ and is plotted in red.

fit, is equal to (1.961±0.286)V. However, it is important to consider the fact that the anode and cathode are constructed from different materials. Since the metals in the electrodes differ, the resolved work function here is actually the contact potential [5], which is the difference in work functions between the two materials. In other words, equation (2) is actually:

$$V_s = (\frac{h}{e})v - (\phi_A - \phi_B) \quad (2)$$

where $\phi_A - \phi_B$ represents the difference in work functions between the anode and the cathode. For this reason, the work function of (1.961±0.286)V differs from that of many metals ($\approx 4.0V$) [6].

To reduce the error between the slope and the expected $\frac{h}{e}$, the sources of error should be reduced. In particular, rather than using LEDs as the primary light source, perhaps a more precise light source could be used. For example, lasers with narrow linewidths could be used to illuminate the cathode surface. Doing so would result in less surface area exposure and thus result in lower photocurrents, but perhaps using multiple lasers could be an option. By using focused light sources with narrow spectral bandwidths, we can more precisely position the setup such that the anode would not be exposed to the light and prevent additional error associated with the distribution of wavelengths.

IV. CONCLUSION

Overall, the results yielded from this experiment indicated a 20.46 % error between the calculated slope and the expected ratio of $\frac{h}{e}$. These results could be improved by using a more focused light source with narrow spectral bandwidths. Of course, a more straightforward method to reduce the error is to ensure that the ambient light levels are very low and positioning the LED such that anode current is minimized. Through performing this experiment, I calculate an approximate value for the ratio of $\frac{h}{e}$ of (4.982 ± 0.747)E-15 $Vs$and identify a value for the contact potential of (1.961±0.286)V for the photomultiplier tube.

Understanding the photoelectric effect and the experimental evidence supporting Einstein's theory on the quantum nature of light is essential for learning modern physics. Beyond educational purposes, the photoelectric effect has direct applications in technology. In particular, the photomultiplier utilizes the photoelectric effect to trigger a chain reaction of excited photoelectrons, amplifying the initial light signal and becoming a sensitive optical detector [7].

V. ACKNOWLEDGMENTS

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