MIDDLE EAST TECHNICAL UNIVERSITY

Photoelectric Effect

Author: Bartu Yaman
Lab Partner: Riza Serkan Kaskan
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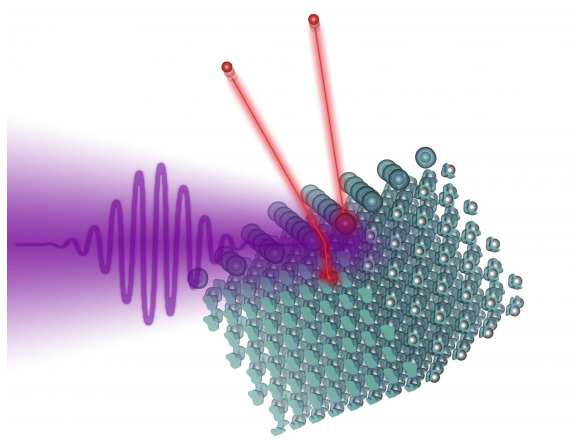

Contents

1 Introduction

1.1 Goal

The goal of this experiment is to investigate the relation between the frequency of incident photons and the photocurrent. This relation will allow us to investigate the particle nature of light, helping us to understand the progression of modern physics and quantum theory through the years.

1.2 Theory

The underlying physical mechanism of photoelectric effect can be investigated under two different approaches. Going through the classical wave theory approach first is beneficial to understand the importance of the quantum theory.

1.2.1 Classical Theory Interpretation

In 1886, Heinrich Hertz realized that ultraviolet light can be used to eject electrons from a metal surface.

From the classical wave theory of light, the energy per unit volume for an electromagnetic wave can be written as:

$$u(x,t) = u_E + u_B = \frac{1}{2}\epsilon_0 E^2 + \frac{1}{2\mu_0}B^2$$

This allows us to define the energy per unit area per unit time passing through a plane perpendicular to the wave, called the energy flux and denoted by S, which can be calculated by:

$$S = \frac{\text{Energy Passing Area A In Time t}}{\text{A * t}} = uc = \epsilon_0 c E^2 = \frac{1}{\mu_0}EB$$

More generally, the flux of energy through any surface depends on the orientation of the surface. To take the direction into account, we introduce a vector $\vec{S}$, called the Poynting vector as:

$$\vec{S} = \frac{1}{\mu_0}\vec{E}\vec{B}$$

The time average of the energy flux is the intensity I of the electromagnetic wave $S_avg = I$. Therefore it is clear that the energy is proportional to the intensity of light according to this interpretation.

The energy being proportional to the intensity (or the amplitude) according to the wave theory has some implications that conflict with the result of the photoelectric effect experiment. The problems with this intepretation are:

- The force applied to an electron is $F_E = eE$, which means that the force applied to an electron increases as the amplitude of the electric field, hence the amplitude, increases. This suggests that the kinetic energy of photoelectrons should increase as the intensity increases, which is not the case for the photoelectric effect. The maximum kinetic energy of photoelectrons are independent of are independent of light intensity.
- Wave theory suggests that the photoelectric effect should occur at any frequency, as long as the intensity if enough to excite the electrons on the surface of a metal. This contradicts with the existence of the cutoff frequency, ν_0.
- The wave theory requires a time delay between the emission of light and the ejection of photoelectrons, but no such delay has been measured.
- The wave theory implies that the ejection of photoelectrons should be continuous since an electromagnetic wave is continuous. Which is not correct as it will be explained in the quantum theory.

1.2.2 Quantum Theory Interpretation

The "light quanta" hypothesis, which was hypothesized by Einstein in 1905, provided a revolutionary explanation to the photoelectric effect. Einstein proposed that light behaves as a stream of independent, localized units ,or quanta, of energy.

Then he proposed that a photon could be absorbed by transferring all of its energy to a single electron and that radiation itself consisted of packets of energy, which can be shown as:

$$h\nu = \frac{1}{2}(mv^2)_{max} + W_0$$

where W_0 is the work function of the material. The work function is defined as the minimum thermodynamic work required to remove an electron from a solid and it can be shown as:

$$W = -e\varphi - E_F,$$

where $-e$ is the electron charge, φ is the electrostatic vacuum and E_F is the Fermi level inside the solid where The term $-e\varphi$ signifies the rest energy of an electron in vacuum. In quantum systems, if the process is allowed by quantum mechanics, either all of the energy from a photon is absorbed or none of the energy of the photon is absorbed. This means that if the energy is not enough, i.e. the frequency is insufficient, nothing will happen.

The quantum theory is successful at explaining the existence of a cut off frequency as well. While observing the photoelectric effect, a positive external voltage is used to direct the photoemitted electrons onto the collector. If we use a negative voltage, it only allows the highest energy electrons to reach the collector. When there is no photocurrent, it means tat the negative voltage is enough to prevent the photoelectrons with the maximum kinetic energy K_{max}. This value of the voltage is called the cut off potential or the stopping potential V_0. When this value is reached, the work done by the cut off potential is enough to stop the electrons and this yields:

$$eV_0 = K_{max}.$$

It is clear that the approach chosen by Einstein negated all of the shortcomings of the classical wave theory to explain the photoelectric effect. Einstein was also able to calculate Planck's constant really close to the value Max Planck obtained using the data from photoelectric effect experiments.

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2 Experimental Details

2.1 Equipment

2.1.1 Mercury Lamp

A mercury arc lamp uses electric discharge through vaporized mercury to produce light. While being more energy efficient than incandescent and most fluorescent lights, mercury lamps are also be 10 to 100 times brighter than incandescent lamps (which could have been used for this experiment as well) and can provide intense illumination over a selected wavelength through the use of optical filters.

Mercury arc lamps produce very high luminance and radiance output levels compared to other continuously operating light sources used in optical microscopy.

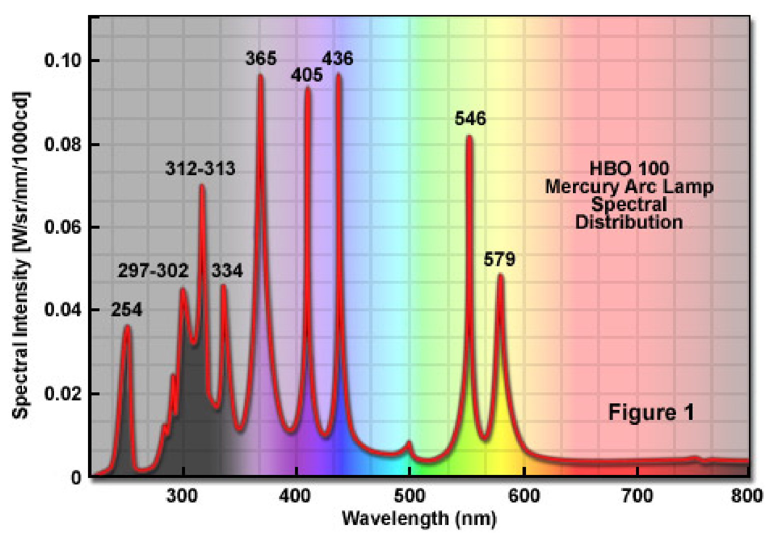

Figure 1: Optical spectra of a mercury arc lamp, similar to the one used in the experiment.

2.1.2 Optical Elements

2.1.2.1 Aperture

An aperture is a small opening that allows only a small portion of incident light to pass on through the other optical elements in the setup.

Figure 2: The optical elements used in this experiment. Apertures and optical filters.

An aperture with 4mm diameter was used throughout this experiment, which can be seen in Figure 2

2.1.2.2 Optical Filter

An optical filter is an optical device that only allows the selected wavelengths to pass on, while blocking all the other wavelengths.

Five different optical filters were used throughout the experiment to produce output light with different wavelengths, them being: 365nm, 405nm, 436, nm, 546nm and 577nm. These wavelengths of the optical filters are directly correlated with the peaks in the optical spectra of the mercury arc lamp as it is shown in Figure 1

2.1.3 Phototube

A phototube is a vacuum tube that is used to sense light that are mostly replaced by semiconductor photodetectors in recent years. The phototube contains a coated cathode and a circular anode inside which are crucial for the physics behind this experiment.

The photocathode surface needs to be coated with a substance that has a low work function. The work function being uniform is an advantage as well, but a nonuniform work function can be mitigated by using apertures before the phototube, reducing the illuminated area on the photocathode.

The anode is chosen to be in a ring shape to prevent any light from striking it directly. This still happens with a ring shaped anode but we can consider it as measurement error without worrying too much.

Figure 3: The phototube used in the experiment, photo is taken with the casing off.

2.2 Procedure

2.2.1 Calibration Procedure

After turning on the mercury arc lamp and letting the setup warm up, we disconnected the anode, cathode and ground cables of the phototube and turned on the calibration mode of the photoelectric effect apparatus. While in the calibration mode, we aadjusted the current calibration node until the current was zero on the screen, turned the calibration mode off and connected the cables of the phototube.

2.2.2 Experiment Procedure

After the calibration, we placed the 4mm aperture and the necessary color filter in front of the phototube and first found the stopping voltage value where the current was zero, then adjusted the voltage knob to measure current values from the apparatus. We repeated this procedure for all of the color filters.

3 Measurement And Data Analysis

3.1 Presentation Of Data

		Aperture: 4mm				
		$\lambda = 365nm$	$\lambda = 405nm$	$\lambda = 435nm$	$\lambda = 546nm$	$\lambda = 577nm$
Data	-2V	$-3.4A$	$-12A$	$-11.1A$	$-9.3A$	$-3.7A$
	-1.5V	$209A$	$3.2A$	$-6.5A$	$-9A$	$-3.6A$
	-1.0V	$637A$	$101A$	$104.7A$	$-8.3A$	$-3.5A$
	-0.5V	$1084A$	$236A$	$316A$	$98.3A$	$22A$
	0V	$1600A$	$385A$	$540A$	$350A$	$125.2A$
	5V	$8570A$	$2160A$	$3060A$	$2040A$	$721A$
	10V	$14600A$	$3660A$	$5180A$	$3170A$	$1141A$
	15V	$19670A$	$4860A$	$6800A$	$4000A$	$1401A$
	20V	$23700A$	$5900A$	$8250A$	$4610A$	$1577A$
	25V	$27300A$	$5900A$	$8250A$	$4610A$	$1577A$
	30V	$30200A$	$7480A$	$10400A$	$5290A$	$1790A$

Table 1: Experimental Data

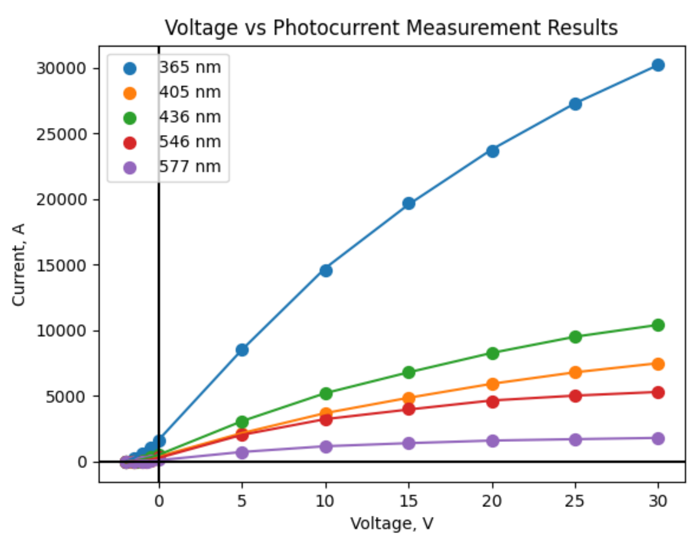

Figure 4: Voltage versus current plot of the data in Table 1.

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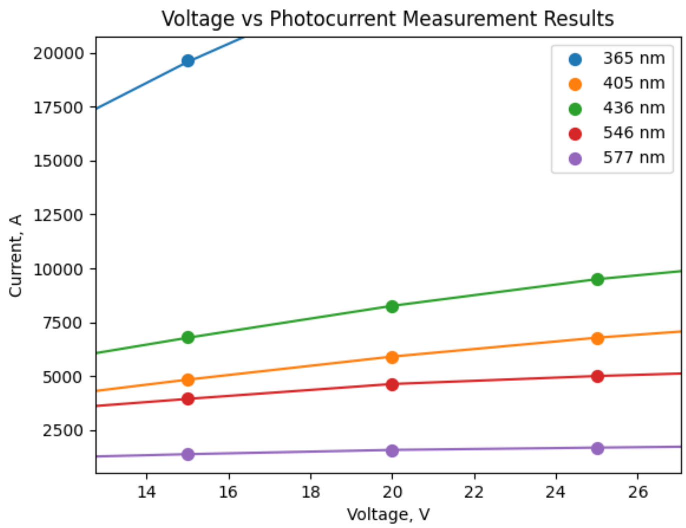

Figure 5: Voltage versus current plot of the data in Table 1, enlarged to highlight the difference in current.

Stopping Voltages, V: Current = 0A	
365 nm	-1.944 V
405 nm	-1.55 V
436 nm	-1.331 V
546 nm	-0.784 V
577 nm	-0.683 V

Table 2: Stopping Voltage Data

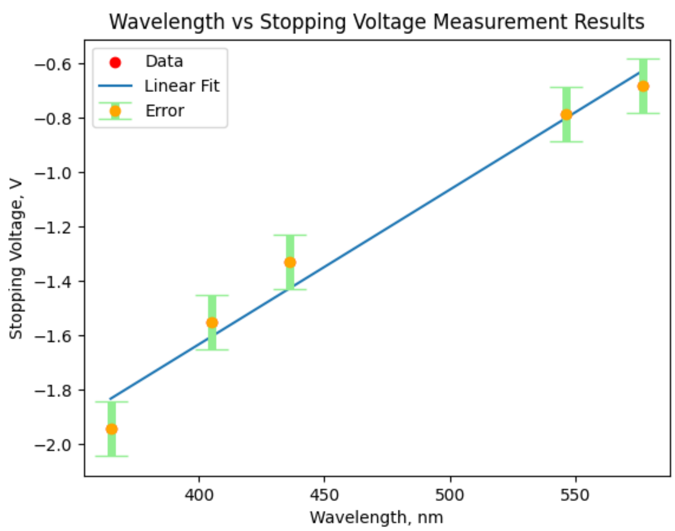

Figure 6: Voltage versus current plot of the data in Table 2.

4 Results And Discussion

4.1 Results

Equation of the line in Figure 6 is $f(x) = 0.005695x - 3.911$, which in physical context means that we have $V_s(\nu) = 0.005695\nu - 3.911$. Multiplying this equation with electron charge e, we know that the resulting term needs to be equal to $KE_{max} = h\nu - \Phi$.

$$V_s(\nu)e = KE_{max} \rightarrow 0.005695\nu e - 3.911e = h\nu - \Phi \tag{1}$$

Then we obtain Planck's constant and the work function as:

$$h = 0.005695e = 4.354e^{-15}(5 \text{ percent error}) \quad \text{and} \quad \Phi = 3.911e = 1.617e^{-18} \tag{2}$$

In terms of errors, the phototube was isolated quite well from external light sources but it was quite apparent that there was some charge buildup inside the photoelectric effect experiment apparatus which forced us to re-calibrate it several times during the experiment to get consistent measurements.

4.2 Discussion

The validity of Einstein's theory was easily recognizable even without carrying out any calculations. Just looking at raw data was enough to say that photon energy depended on the wavelength of the incident photons but plotting the data and carrying out the calculations to validate the results with already established constants solidified this claim.

It should be noted that our photocurrent measurements didn't reach the saturation current and it is obvious from Figure 4 that even if they did, the saturation current values wouldn't be the same for all wavelengths. This can be explained by looking at Figure 1 and realizing that the intensities for each wavelength is different since saturation current is related to the intensity.

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References

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[2] David J. Griffiths. *Introduction To Electrodynamics*. Cambridge University Press, 2017.

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[4] Kenneth Krane. *Modern Physics*. Wiley, 2012.

[5] Zeiss Michael W. Davidson. Fundamentals of mercury arc lamps.

5 Appendix

5.1 Python Code

```
import pandas as pd
import matplotlib.pyplot as plt
import numpy as np


# Plotter function for convenience.
def Plot1():
    # Read the CSV file that contains the data and import it to Python as a Pandas Dataframe.
    df = pd.read_csv("PE_data.csv")

    #print(df.to_string())

    # Pass the head strings for easier plotting.
    x_data_head = ["Voltage, 365 nm", "Voltage, 405 nm", "Voltage, 436 nm", "Voltage, 546 nm", "Voltage, 577 nm"]
    y_data_head = ["Current, 365 nm", "Current, 405 nm", "Current, 436 nm", "Current, 546 nm", "Current, 577 nm"]
    # Pass the wavelength strings for easier plotting.
    wavelength = ["365 nm", "405 nm", "436 nm", "546 nm", "577 nm"]
    # Loop over all data series.
    for i in range(len(x_data_head)):
        # Plot the data on top of each other.
        x = df[x_data_head[i]]
        y =  df[y_data_head[i]]
        plt.scatter(x, y,s=50, label=wavelength[i])
        fit = np.poly1d(np.polyfit(x, y, 6))
        plt.plot(x, fit(x))
    # Initialize the legends.
    plt.legend()
    # Initialize the labels.
    plt.xlabel("Voltage, V")
    plt.ylabel("Current, A")
    # Initialize the title.
    plt.title("Voltage vs Photocurrent Measurement Results")
    plt.axhline(0, color = "black")
    plt.axvline(0, color = "black")
    plt.show()


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```python
def Plot2():
    x_arr = [365, 405, 436, 546, 577]
    y_arr = [-1.944, -1.55, -1.331, -0.784, -0.683]

    plt.scatter(x_arr, y_arr, c="Red", label="Data")
    fit = np.polyfit(x_arr, y_arr, 1)
    poly = np.poly1d(fit)
    print(poly)
    plt.plot(x_arr, poly(x_arr), label="Linear Fit")
    plt.errorbar(x_arr, y_arr, 0.1, fmt = 'o',color = 'orange',
            ecolor = 'lightgreen', elinewidth = 5, capsize=10, label="Error")
    plt.xlabel("Wavelength, nm")
    plt.ylabel("Stopping Voltage, V")
    plt.title("Wavelength vs Stopping Voltage Measurement Results")
    plt.legend()
    plt.show()

# Run the plotters.
Plot1()
Plot2()
```


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