THE PHOTOELECTRIC EFFECT

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ABSTRACT

We report the results of the Photoelectric Effect experiment which took place in the Robert H. McMickle Modern Physics Laboratory Dark Room at Bogazici University. Our main object is to verify the quantum nature of the light and to determine the Planck Constant by analyzing the experimental observations of the emission of electrons from an illuminated metal surface. The light produced by a high pressure mercury lamp is separated into its constituent colors and the light with different frequencies is fallen on a metal surface. Quantitative measurements are performed by applying an electric field that slows down the photoelectrons emitted from the metal surface. The stopping potential is determined by observing the current caused by the photoelectrons. By using the relation between the stopping potential over the specific frequency of the light and the ratio of the Planck constant over electron charge, we calculated the Planck constant as $h = 4.371 \pm 3.567 \times 10^{-34} Js$.

***K*eywords** Photoelectric Effect · Photon · Photoelectron · Planck Constant · Threshold Frequency · Work function

1 Introduction

Throughout history, natural philosophers and scientists have tried to answer one of the fundamental questions in the world: "What is the nature of light?" Newton defended the corpuscular theory of light contrary to Huygens who argued in favor of the wave nature of light. The corpuscular theory conserved its popularity until the beginning of 19th century. In 1803, Thomas Young studied the interference of light waves by shining light through a screen with two slits equally separated, the light emerging from the two slits, spread out according to Huygen's principle. The two slits experiment became one of the most strong evidence of the wave theory of light. In 1887, Heinrich Hertz and Wilhelm Hallwachs discovered that when a surface is exposed to electromagnetic radiation above a certain threshold frequency (typically visible light for alkali metals, near ultraviolet for other metals, and extreme ultraviolet for non-metals), the radiation is absorbed and electrons are emitted. They also found that electrodes illuminated with ultraviolet light create electric sparks more easily. This phenomena was called "Photoelectric Effect" and scientists tried to explain this phenomena from the viewpoint of classical electromagnetic theory. According to classical electromagnetic theory, this effect can be attributed to the transfer of energy from the light to an electron. From this perspective, an alteration in the intensity of light would induce changes in the kinetic energy of the electrons emitted from the metal. Furthermore, according to this theory, a sufficiently dim light would be expected to show a time lag between the initial shining of its light and the subsequent emission of an electron. However, the experimental results did not correlate with either of the two predictions made by classical theory. On the other and, in 1900, while studying black-body radiation, the German physicist Max Planck suggested that the energy carried by electromagnetic waves could only be released in "packets" of energy. In 1905, Albert Einstein published a paper advancing the hypothesis that light energy is carried in discrete quantized packets to explain experimental data from the photoelectric effect. Einstein's explanation for these observations was that light itself is quantized; that the energy of light is not transferred continuously as in a classical

*https://github.com/mtsngr/The-Photoelectric-Effect.git wave, but only in small "packets" or quanta. The size of these "packets" of energy, which would later be named photons, was to be the same as Planck's "energy element", giving the modern version of the Planck–Einstein relation:[2]

$$E = hf \tag{1}$$

According to Einstein, for a given metal surface, there exists a certain minimum frequency of incident radiation below which no photoelectrons are emitted. This frequency is called the "threshold frequency". Increasing the frequency of the incident light, keeping the number of incident photons fixed (this would result in a proportionate increase in energy) increases the maximum kinetic energy of the photoelectrons emitted. Thus the stopping voltage (V_s) increases. Above the threshold frequency, the maximum kinetic energy of the emitted photoelectron depends on the frequency of the incident light, but is independent of the intensity of the incident light. Besides that, the rate at which photoelectrons are ejected is directly proportional to the intensity of the incident light. An increase in the intensity of the incident beam (keeping the frequency fixed) increases the magnitude of the photoelectric current, although the stopping voltage remains the same. The maximum kinetic energy K_{max} of an ejected electron is given by

$$K_{max} = hf - \varphi \tag{2}$$

where h is the Planck constant and f is the frequency of the incident photon. The term φ is the work function (sometimes denoted W or ϕ) which gives the minimum energy required to remove an electron from the surface of the metal. The work function satisfies

$$\varphi = hf_0 \tag{3}$$

where f_0 is the threshold frequency for the metal. he maximum kinetic energy of an ejected electron is then

$$K_{max} = h(f - f_0) \tag{4}$$

Kinetic energy is positive, so if the inequality of $f > f_0$ is satisfied, then the photoelectric effect can occur.

In our experiment, we collected 4 different dataset for each light color that are separated from the light of high energy mercury lamp. We recorded various current values corresponding to retarding potentials by slowly increasing the retarding potential from an initial value. Then, we made a graph of Current-Voltage for each dataset and fitted two different straight lines for both positive and negative current values. The lines had different slopes and they intersected on a point of negative current value. The x component of the intersection point gave us the value of stopping voltage (V_s). After that, we made another graph of stopping voltage versus frequency of the light ($V_s - f$). From the equation (6) the slope of $V_s - f$ graph gave us the ratio of $\frac{h}{q}$ as well as the Planck constant where q is the electron charge $q = 1.602 \times 10^{-19} C$.[3]

$$hf = qV_s + \varphi \tag{5}$$

$$V_s = \frac{h}{q} f - \frac{1}{q} W \tag{6}$$

[2]https://en.wikipedia.org/wiki/Photoelectric-effect access: March 26, 2019.
[3]https://en.wikipedia.org/wiki/Elementary-charge access: March 26, 2019.

2 Apparatus

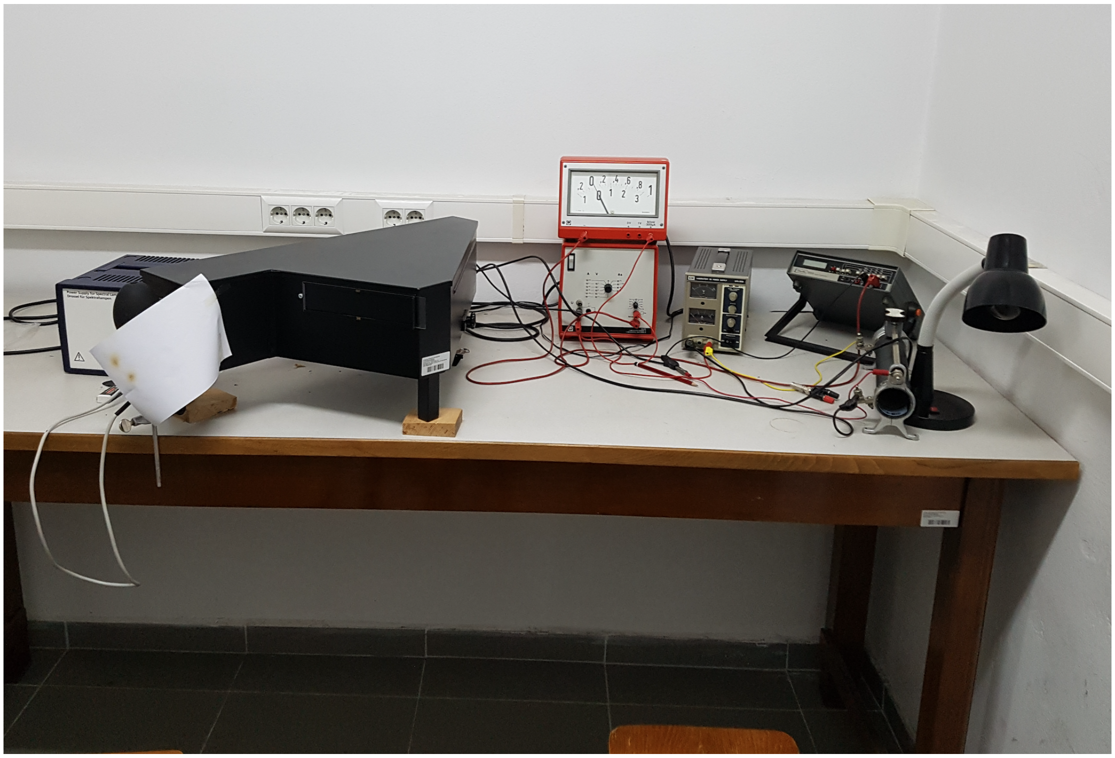

Figure 1: Experimental setup

Figure 2 shows the connection diagram for observing the photoelectric effect.

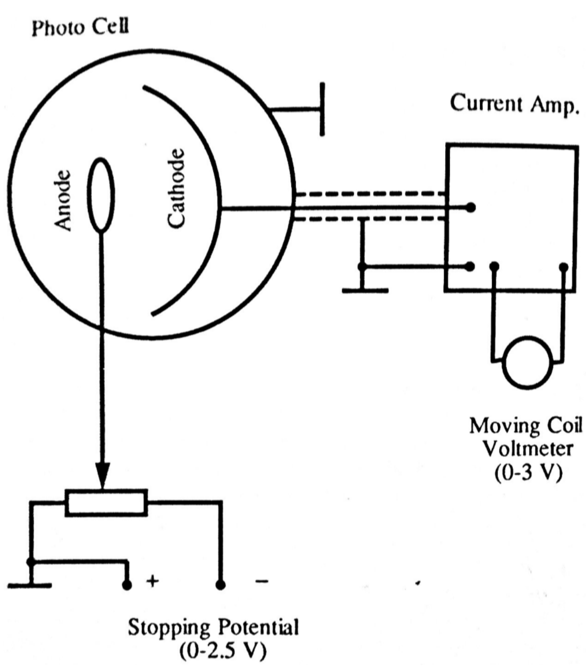

Figure 2: Connection diagram for observing the photoelectric effect.

- High pressure Mercury lamp with power supply.
- Spectrograph with a transmission grating.
- Photocell with housing.
- Current amplifier.
- Moving coil DC voltmeter with for the current amplifier (0-3 V).
- DC voltmeter (0-3 V).
- Power supply (0-3 V).
- Connecting leads.

3 Experimental Procedure

The experiment was done in the dark room because the light in the room could fell into the cathode metal and create current, which can make our data inaccurate. First of all, devices are carefully connected to each other. The moving coil DC voltmeter connected to the output of the current amplifier. Then, the scale of the current amplifier is adjusted and the voltmeter connected to the output of the amplifier to read the current. After that the retarding potential is increased slowly while recording the current. By the way, the current for zero retarding potential is also recorded and the retarding potential is kept below the 2.5 V. These steps are repeated for other colors in the mercury spectrum. Then we plotted our data as the current versus retarding potential and for each graph, we fitted 2 different straight lines representing the data of both negative and positive current values as well as corresponding voltages. Subsequently, we found the stopping voltage value by determining intersection point of these lines. The stopping voltage V_s value equals the x component of the intersection point. Finally, we made another graph of the V_s versus frequency of the light and fitted a straight line. By doing so, we calculated the value of the Planck's constant by using the relation in equation (6).[4]

4 Data

The data about the current (A) and voltage (V) values regarding the photoelectric effect with various light colors of yellow, green, cyan and blue is given in the following tables.

Table 1: Current and corresponding retarding voltage values of Yellow (left table) and Green (right table) lights.

Current $10^{-13}A$	Voltage (V)
2.8 ± 0.2	0.100 ± 0.001
2.0 ± 0.2	0.150 ± 0.001
1.6 ± 0.2	0.200 ± 0.001
1.0 ± 0.2	0.250 ± 0.001
0.8 ± 0.2	0.300 ± 0.001
0.4 ± 0.2	0.350 ± 0.001
0.22 ± 0.02	0.400 ± 0.001
0.06 ± 0.02	0.450 ± 0.001
0.00 ± 0.02	0.470 ± 0.001
-0.06 ± 0.02	0.500 ± 0.001
-0.08 ± 0.02	0.525 ± 0.001
-0.2 ± 0.2	0.700 ± 0.001

Current $10^{-13}A$	Voltage (V)
3.0 ± 0.2	0.050 ± 0.001
2.4 ± 0.2	0.100 ± 0.001
1.8 ± 0.2	0.150 ± 0.001
1.4 ± 0.2	0.200 ± 0.001
1.0 ± 0.2	0.250 ± 0.001
0.8 ± 0.2	0.300 ± 0.001
0.6 ± 0.2	0.350 ± 0.001
0.4 ± 0.2	0.400 ± 0.001
0.14 ± 0.02	0.450 ± 0.001
0.04 ± 0.02	0.500 ± 0.001
0.00 ± 0.02	0.525 ± 0.001
-0.04 ± 0.02	0.550 ± 0.001
-0.06 ± 0.02	0.580 ± 0.001
-0.08 ± 0.02	0.600 ± 0.001

[4] Gülmez, E. "*Advanced Physics Experiments*", Bogazici University Publications, 1999, pages 198-206.

Table 2: Current and corresponding retarding voltage values of Cyan (left table) and Blue (right table) lights.

Current $10^{-13}A$	Voltage (V)
0.22 ± 0.02	0.050 ± 0.001
0.18 ± 0.02	0.100 ± 0.001
0.12 ± 0.02	0.150 ± 0.001
1.00 ± 0.02	0.200 ± 0.001
0.06 ± 0.02	0.250 ± 0.001
0.04 ± 0.02	0.300 ± 0.001
0.00 ± 0.02	0.400 ± 0.001
-0.02 ± 0.02	0.500 ± 0.001
-0.04 ± 0.02	0.600 ± 0.001
-0.06 ± 0.02	0.750 ± 0.001
-0.08 ± 0.02	1.200 ± 0.001

Current $10^{-13}A$	Voltage (V)
1.8 ± 0.2	0.350 ± 0.001
1.4 ± 0.2	0.400 ± 0.001
1.2 ± 0.2	0.450 ± 0.001
1.0 ± 0.2	0.500 ± 0.001
0.6 ± 0.2	0.550 ± 0.001
0.4 ± 0.2	0.600 ± 0.001
0.0 ± 0.2	0.690 ± 0.001
0.01 ± 0.02	0.850 ± 0.001
0.04 ± 0.02	$0.1.000 \pm 0.001$
-0.2 ± 0.2	0.800 ± 0.001
-0.4 ± 0.2	0.900 ± 0.001

5 Analysis

Figure 3 shows the data of the current and the retarding voltage values in the table 1 for yellow light. Some error bars are not visible since the uncertainty of certain parameters are too small.

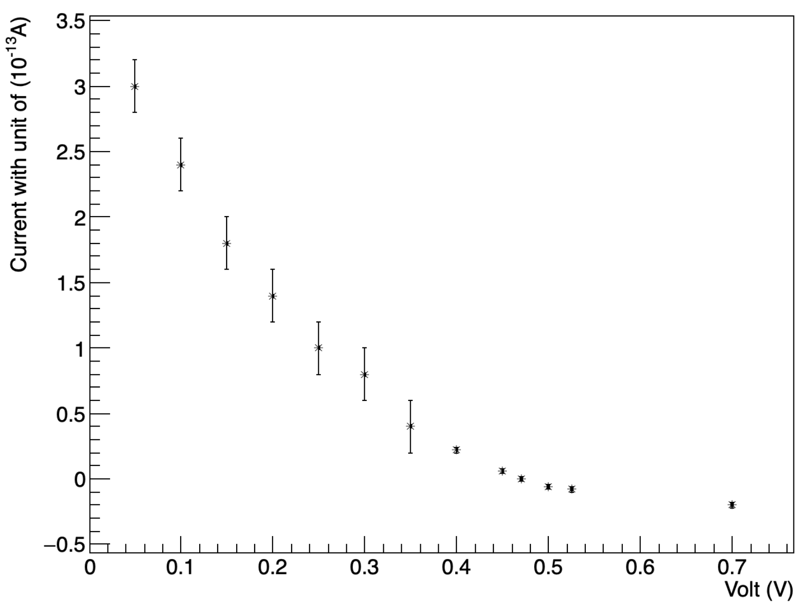

Figure 3: Graph of the current versus corresponding retarding voltage for positive current values of the yellow light.

We analyzed this data by fitting two different straight lines to the both positive and negative current values. We fitted straight lines by using some Root codes on computer.[5] The graphs of these fitted lines are showed separately in the following figures.

[5]The codes which are used in data analysis are available on GitHub. For the website link, see references.

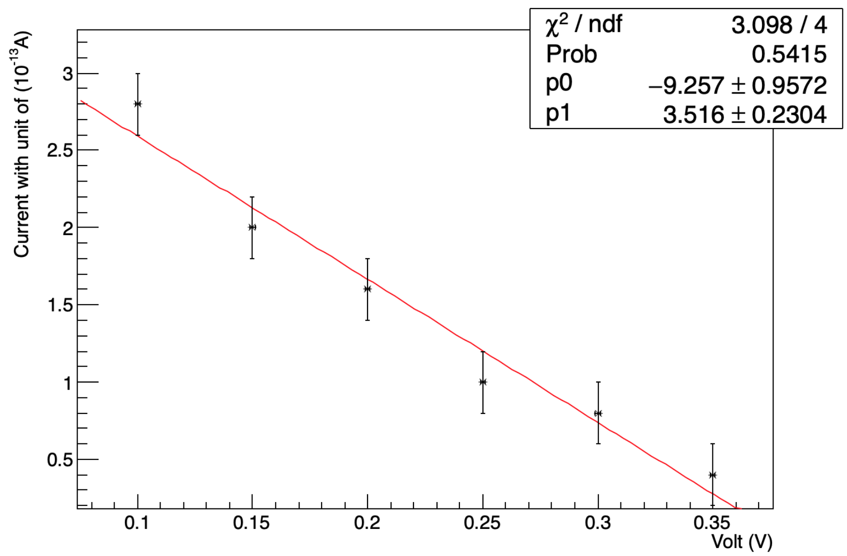

Figure 4: Graph of the current versus corresponding retarding voltage for the positive current values of the yellow light.

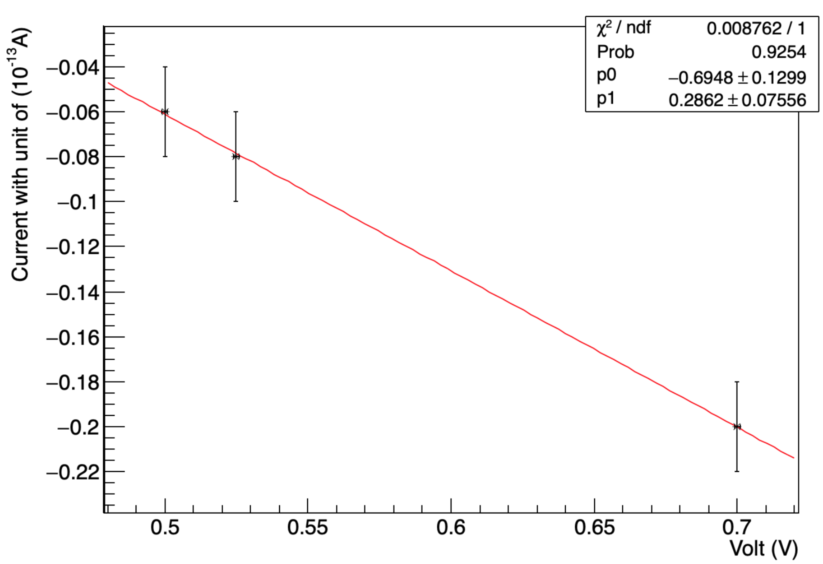

Figure 5: Graph of the current versus corresponding retarding voltage for the negative current values of the yellow light.

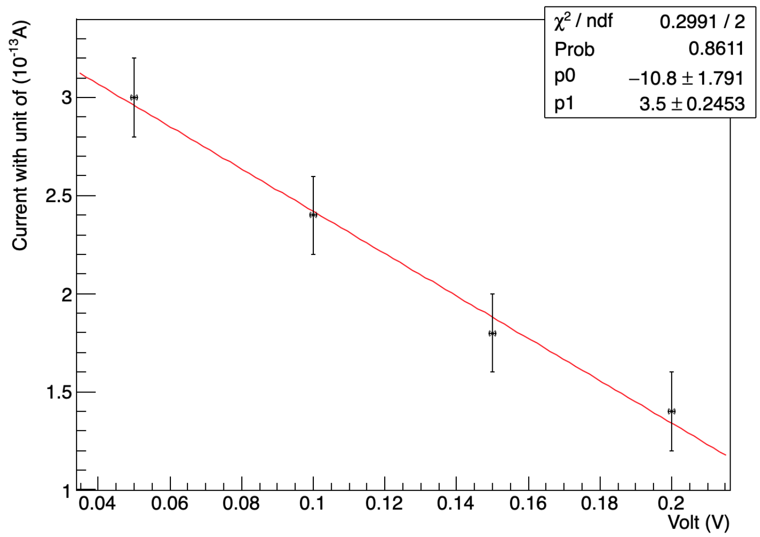

Figure 6: Graph of the current versus corresponding retarding voltage for the positive current values of the green light.

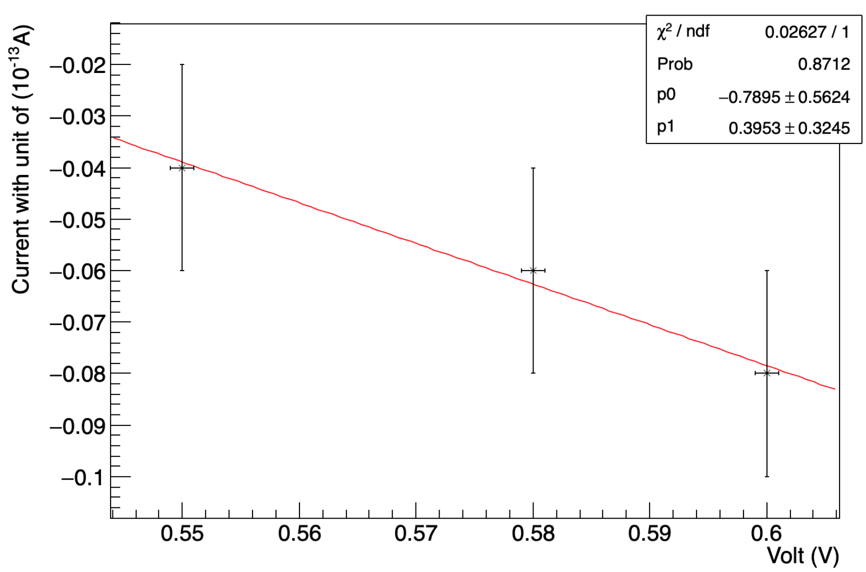

Figure 7: Graph of the current versus corresponding retarding voltage for the negative current values of the green light.

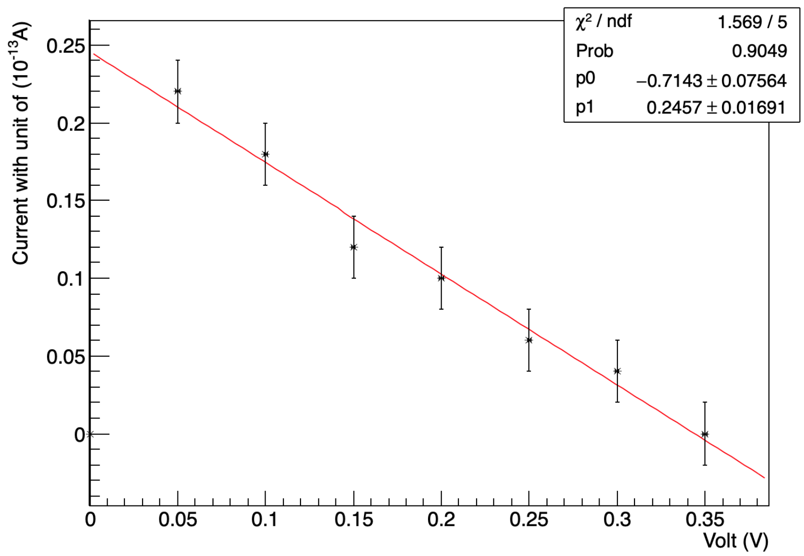

Figure 8: Graph of the current versus corresponding retarding voltage for the positive current values of the cyan light.

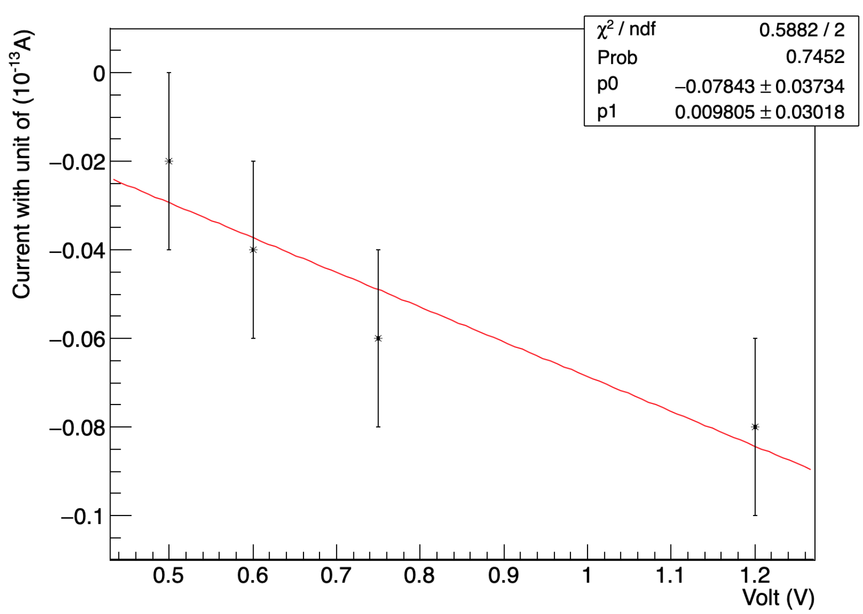

Figure 9: Graph of the current versus corresponding retarding voltage for the negative current values of the cyan light.

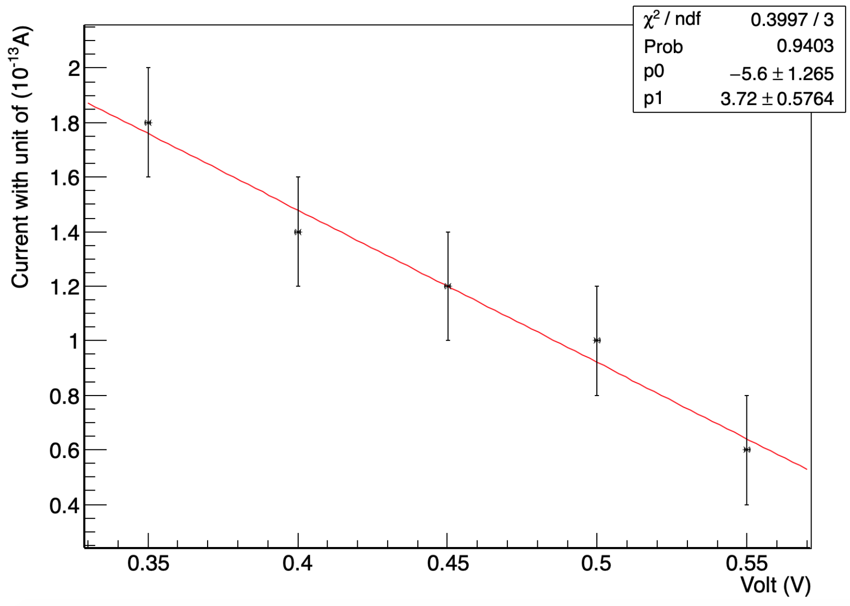

Figure 10: Graph of the current versus corresponding retarding voltage for the positive current values of the blue light.

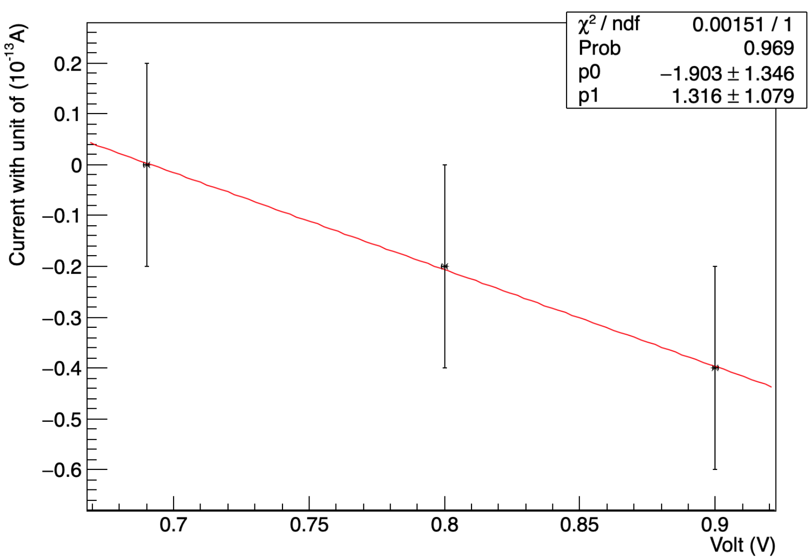

Figure 11: Graph of the current versus corresponding retarding voltage for the negative current values of the blue light.

In the graphs, p_0 denotes the slope of the fitted line and p_1 denotes the y-intercept of the line. Thus, by using the equation of a straight line, we can find the intersection point of two lines as below:

$$y = mx + n \tag{7}$$

$$\begin{aligned} m_1 x + n_1 &= m_2 + n_2 \\ m_1 x - m_2 x &= n_2 - n_1 \\ x &= \frac{n_2 - n_1}{m_1 - m_2} \end{aligned}$$

The x component of the intersection point of the fitted lines in figure 4 and figure 5 on the same coordinate system gives us the stopping potential value V_s. We determined 4 different intersection points as well as stopping potentials. Each stopping potential corresponds to one of the specific light frequency in the mercury spectrum is showed in Table 3.

Table 3: Stopping Voltage V_s and Frequency of lights with different colors.

	Stopping Voltage (V_s, Volt)	Frequency of light (Hz)
Yellow	0.377 ± 4.45	$5.19 \times 10^{14} Hz$
Green	0.323 ± 7.33	$5.49 \times 10^{14} Hz$
Cyan	$-3,37 \pm 0.109$	$6.08 \times 10^{14} Hz$
Blue	0.650 ± 2.03	$6.88 \times 10^{14} Hz$

The uncertainty of stopping voltage values are calculated by using the equation (8).

$$\sigma_x = \sqrt{\left(\frac{n_1}{m_1 - m_2}\right)^2 \sigma_{n_2}^2 + \left(\frac{n_2}{m_1 - m_2}\right)^2 \sigma_{n_1}^2 + \left(\frac{n_2 - n_1}{m_2}\right)^2 \sigma_{m_1}^2 + \left(\frac{n_2 - n_1}{m_1}\right)^2 \sigma_{m_2}^2} \tag{8}$$

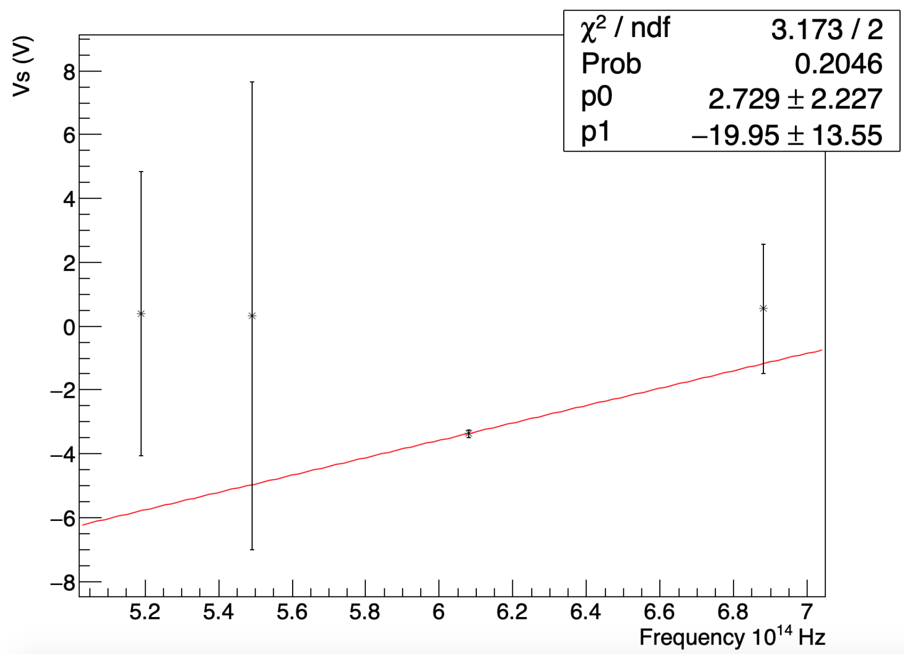

Figure 12: Graph of the Stopping Voltage V_s versus Frequency of light.

By using equation (6), the slope of the fitted line on the graph of the Stopping Voltage V_s versus Frequency of light gives us the relation in below:

$$m_{slope} = 2.729 \pm 2.227 = \frac{h}{q} \tag{9}$$

$$h = q \times m_{slope} = 2.729 \pm 2.227 \times 10^{-14} \times 1.602 \times 10^{-19} = 4.371 \pm 3.567 \times 10^{-34} Js \tag{10}$$

6 Conclusion

In our experiment, we calculated the Planck constant as $h = 4.371 \pm 3.567 \times 10^{-34} Js$ and this value is far away from the accepted value $h = 6.626 \times 10^{-34} Js$. One of the most important reason of this result is imperfectness of the our data. We studied on the very small scale so that we measured the current in units of picoamperes and our instruments could not eliminate even the effect of a tiny change in the conditions of the environment. For example, when we walk around the setup the needle of ammeter is rapidly moves towards the maximum value. Therefore, although we did our best to avoid such kinds of errors, our data was influenced in a negative way by the malfunction of the instruments and unpreventable changes in the conditions of the environment. However, we can eradicate all these systematical errors to some extend and we may find more satisfaying results by using modern and high quality equipments.

On the other hand we, also, tried to validate the effect of the light frequency on the kinetic energy of the photoelectrons. Although our data is partially failed to show the proportional relationship between the magnitude of the stopping potential energy and the kinetic energy of the photoelectrons, we know that the magnitude of the stopping potential should be higher for the cases of higher frequencies. The Equations (4) and (5) show this relationship. Even though it is a little bit hard to see this relationship in our data, we can see that the magnitude of the stopping potential is higher for the blue light than the yellow light.

Moreover, in the data analysis part we took the x component of the intersection point of the two fitted lines on the current-retarding voltage graphs, as the stopping voltage value not the zero point of the current on the x-axis. The direction of the photoelectron flow is from cathode to anode. However, the light can, also, cause anode metal to emit electrons, which create reverse current in the circuit. We can eliminate this effect by taking the V_s value below the level of 0 point of the current (x-axis).

7 Appendix

7.1 Least Square Method

Fitting a straight line is an approximation of solution for a bunch of value. The main idea of this approximation was published by Adrien-Marie Legendre in 1805. "Least squares" means that the overall solution minimizes the sum of the squares of the residuals made in the results of every single equation. Data fitting is one of the most important application of this method. The best fit in the least-squares sense minimizes the sum of squared residuals (a residual being: the difference between an observed value, and the fitted value provided by a model).[6] We may wish to test whether a certain hypothesis is supported by the data, in which case the goodness of the fit may establish the level of confidence with which the hypothesis should be accepted. The method of least squares follows directly from the assumption that each individual measurement is a member of a Gaussian population with a mean given by the true value of y_i, $\bar{y}(x_i; a_\lambda)$ for the standard deviation of this Gaussian we used the experimental error σ_i of each measurement.[7]

7.2 Error Propagation

The error propagation for a function f of variables x_i' with respect to errors of these variables σ_{x_i}'s is

$$\sigma_f = \sqrt{\sum_i \left(\frac{\partial f}{\partial x_i}\right)^2 \sigma_{x_i}^2 + \cdots} \tag{11}$$

By using the equation (5), error propagation of a function $f(x+y) = x+y$ of variables x and y with respect to errors of these variables σ_x and σ_y is derived as below:[8]

$$f(x+y) = x+y \tag{12}$$

$$(\sigma_f)^2 = (\frac{\partial f}{\partial x})^2\sigma_x^2 + (\frac{\partial f}{\partial y})^2\sigma_y^2 \tag{13}$$

$$\frac{\partial f}{\partial x} = 1 \frac{\partial f}{\partial y} = 1 \tag{14}$$

$$\sigma_f^2 = \sigma_x^2 + \sigma_y^2 \tag{15}$$

[6]https://en.wikipedia.org/wiki/Least-squares. access: March 28, 2019.
[7]Melissinos, A.C. and Napolitano, J. "Experiments in Modern Physics"., Academic Press., pages: 447-464, 2003.
[8]Gülmez, E. "*Advanced Physics Experiments*", Bogazici University Publications, 1999, pages 198-206.

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[1] Melissinos, A.C. and Napolitano, J."Experiments in Modern Physics". Academic Press. pages: 447-464, 2003.

[2] Erhan Gülmez. *"Advanced Physics Experiments"*. Bogazici University Publications. pages: 22-27, 1999.

[3] "https://en.wikipedia.org/wiki/Photoelectric-effect access: March 26, 2019."

[4] "https://en.wikipedia.org/wiki/Elementary-charge access: March 26, 2019."

[5] "https://en.wikipedia.org/wiki/Least-squares. access: March 28, 2019."

[6] "https://github.com/mtsngr/The-Photoelectric-Effect.git"