Note to 8.13 students:

Feel free to look at this paper for some suggestions about the lab, but please reference/acknowledge me as if you had read my report or spoken to me in person. Also note that this is only one way to do the lab and data analysis, and there are nearly an infinite number of other ways to do the lad that would be better.

I made some mistakes doing this lab. Here are a couple I found (and some more tips):

- This was my first time doing data analysis, and it shows. Look my chi square is over 100! Don't trust anything.

Photoelectric Effect

Rachel Bowens-Rubin*
MIT Department of Physics
(Dated: October 2, 2009)

The photoelectric effect was by studied by measuring the relationship of the current created when a photocell is hit with photons to an applied retarding potential. This relationship was measured for five different frequencies of incoming light. The cutoff voltage was then extracted from the data to determine Planck's constant using the photoelectric effect equation. Three different methods were used to determine the cutoff voltage, and they yielded values of Planck's constant equal to$h = 3.61 * 10^{-34} \pm 2.85 * 10^{-34}$, $h = 2.68 * 10^{-34} \pm 1.14 * 10^{-34}$, and $h = 3.86 * 10^{-34} \pm 2.65 * 10^{-34}$. These values correspond to the same range, but are lower than the expected value of Planck's constant.

I. INTRODUCTION

The observation of the photoelectric effect helped to lay the ground work for quantum mechanics. When the photon was first proposed, there was little supporting evidence that light carried quantized energy. In 1916, Millikan took the first measurements of the photoelectric effect and provided evidence in defense of quantized energy. A few examples of technology that work due to the photoelectric effect are photomultipliers, solar cells, early televisions, and night vision googles.

II. THEORY

A. The Photoelectric Effect

When a surface of metal is exposed to light, the energy from the photons causes electrons in the metal to become energized. The energized electrons will start moving through the metal, losing some of their energy. Once electrons are near the surface and have enough energy, they can leave the surface. This ejection of electrons due to the incident light is known as the "photoelectric effect." The kinetic energy of the ejected electron is related to the frequency of the incoming light by the relationship:

$$K = h\nu - \phi \tag{1}$$

where K is the maximum kinetic energy of the electron, h is Planck's constant, ν is the frequency, and ϕ is the work function of the cathode. The work function represents the amount of energy lost by the electron before being ejected. If the enery of the incoming photon is less than the work function, the electron will not be ejected.

*Electronic address: rbowru@mit.edu

B. Cutoff Voltage

When light shines onto a metal surface that is near another metal surface, a current begins to flow. If a retarding potential is applied in the direction to stop the electrons from moving to the other metal surface, the current begins to decrease. At some potential, the current will stop because the electrons will not have enough kinetic energy to cross the potential barrier. The potential at which the current equals zero is called the "cutoff voltage." In lab, it is easier to measure in the The Cutoff Voltage realtes to the maxium amount of

By knowing the cutoff voltage, the maximum kinetic energy of the electrons ejected can be determined by $V_{cut} = (e)K$, where e is the charge of an electron. Using equation 7, we can relate the frequency to the cutoff voltage by

$$V_{cut} = (h/e)\nu - \phi \tag{2}$$

where V is the applied potential. This allows Planck's constant and the work function to be measured in lab.

III. EXPERIMENTAL SETUP

The apparatus used to measure the photoelectric effect is shown in Figure 1. Light from the Oriel 65130 Mercury lamp passed through a filter in the filter wheel and entered the photocell. Inside the photocell, the light hit the metal cathode plate, which caused electrons to be ejected from the surface. Then the electrons traveled toward the anode ring, and if their kinetic energy was greater than the applied retarding potential, the electrons hit the anode which causes a current. The current was then read by a Keithly electrometer operating as an amperemeter. The voltage was controlled and supplied by a Agilent variable DC power supply. A large black cloth was used to cover the apparatus to prevent photons that were not from the mercury lamp from hitting the photocell.

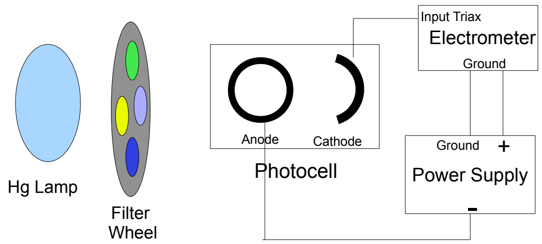

FIG. 1: Photoelectric Effect Apparatus: Light from a Mercury lamp was filtered and then hit the Cathode within the photocell. The power supply's negative terminal is connected to the anode. The power supply's positive and ground terminals are connected to the ground of the electrometer. The input triax on the electrometer is connected to the cathode to read the current.

IV. RESULTS AND DISCUSSION

A. Data Collection

Five bandpass filters were used with the wavelengths (in nanometers) of 365.0 ± 2, 404.7 ± 2, 435.8 ± 2, 546.1 ± 2, and 577.0 ± 2.

The voltage was increased from zero using steps of 0.1 Volts until the current became constant. Five measurements were performed at each voltage value for each filter. The data collected using the 546.1nm filter are shown in Figure 2.

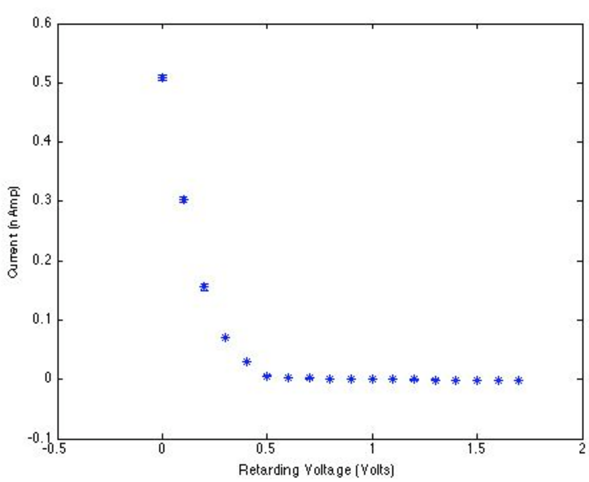

FIG. 2: Example Data Set (Average Current Measurement Versus Applied Retarding Voltage at 546.1nm): The error bars represent the standard deviation of the measurements taken at the same voltage level.

Currents were measured using the nanoamp setting on the electrometer until a current of 0.02 nanoamps was measured. At this value, the electrometer setting was changed to measure in picoamps and for most filters an additional measurement was taken using the same voltage. The average offsets found are listed in Table 1.

Table 1: NanoAmp to PicoAmp Offset

Filter Center Wavelength (nm)	Average Offset (nAmp)
404.7	0.0074 ± 0.0078
435.8	0.0109 ± 0.0004
546.1	0.0143 ± 0.0010
577.0	0.0111 ± 0.0004

B. Method 1: Interpolate Cutoff Voltage

The first method used to determine the cutoff voltage was to interpolate using the points closest to zero. To find the value with zero current, a line was created between the nearest point with positive current and the nearest point with negative current. The slope of the line, y-intercept, and interpolated cutoff voltage were found using the following:

$$m = \frac{I_{-} - I_{+}}{V_{-} + V_{+}}, \sigma_m = \sqrt{\sigma_{I-}^2 + \sigma_{I+}^2)} \tag{3}$$

$$b = I_{+} - mV_{+}, \sigma_b = \sigma_{I+} \tag{4}$$

$$Vcut = -b/m \tag{5}$$

$$\sigma_{Vcut} = \sqrt{V_{cut}^2(\frac{\sigma_m^2}{m^2} + \frac{\sigma_b^2}{b^2})} \tag{6}$$

where I_{-} is the current of the point with a negative current, I_{+} is the current of the point with a positive current, V_{-} is the voltage applied for the point with a negative current, V_{+} is the voltage applied for the point with a positive current, m is the slope, and b is the y-intercept.

Figure 3 shows a plot of the cutoff voltage versus the frequency of light for method one. The value of Planck's constant was determined to be $h = 3.61 * 10^{-34} \pm 2.85 * 10^{-34}$, and the reduced chi squared was $\chi_\nu = 61.1$. A major contributing factor to the large value of the reduced chi squared is the small size of the error bar for the 435.8nm filter. Because of the large variation in the size of the error bars, the reduced chi squared would also decrease if a weighted fitting process had been used.

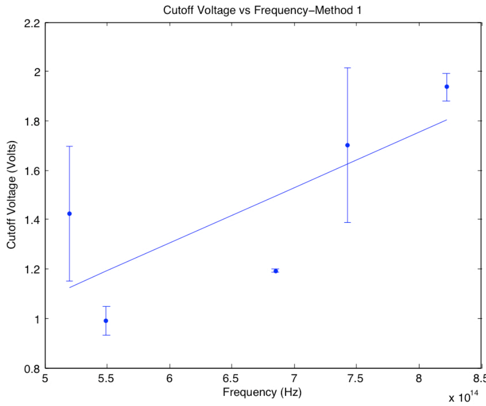

FIG. 3: Method One Results (Cutoff Voltage Versus Frequency): The line shown represents the unweighed line of best fit, and the points represent the data found in the experiment. The slope of the line was used to determine a value for Planck's constant of $h = 3.61 * 10^{-34} \pm 2.85 * 10^{-34}$.

C. Method 2: Tangent Intersections

The second method used to determine the cutoff voltage was to find the intersection of the tangent lines from the beginning and end of the curve. If there was no back-current due to the photoelectric effect seen on the Anode, the current would decrease linearly until the current was zero. Once the voltage was high enough to cause the current to be zero, increasing the voltage would still yield a current of zero. The cutoff voltage is defined to be the intersection of the decreasing line and the zero line.

The first and last three points were used to create the two tangent lines. Figure 4 shows an example of the data with their tangent lines. The following equations were used to calculate the cutoff voltage and its error once the tangent lines were found:

$$Vcut = \frac{m_2 b_1 - m_1 b_2}{m_2 - m_1} \tag{7}$$

$$\sigma_{Vcut} = V_{cut}[\sigma_{m1}^2(\frac{(b_1 - b_2)m_2}{(m_1 - m_2)^2})^2 + \sigma_{m2}^2(\frac{-(b_1 - b_2)m_1}{(m_2 - m_1)^2})^2 + \sigma_{b1}^2(\frac{-m_2}{(m_1 - m_2)})^2 + \sigma_{b2}^2(\frac{m_1}{(m_1 - m_2)})^2]^{1/2} \tag{8}$$

where m_1 is the slope of the tangent line using the first three points, m_2 is the slope of the tangent line using the last three points, b_1 is the y-intercept of the tangent line using the first three points, b_2 is the y-intercept of the tangent line using the last three points, and σ is the error.

Figure 5 shows a plot of the cutoff voltage versus the

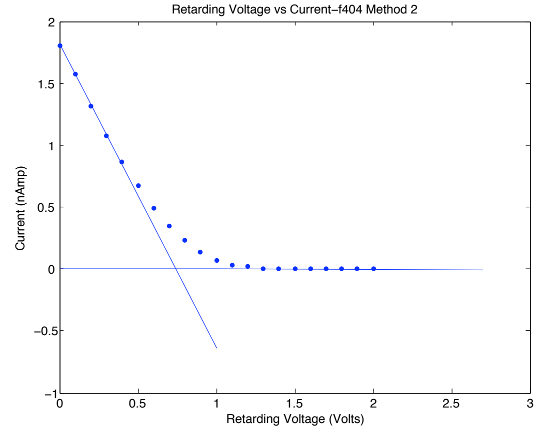

FIG. 4: Example of Tangent Intersections (Cutoff Voltage vs Frequency of 404.7nm): The intersection of the tangent lines from the start and end of the curve were used to determine the cutoff voltage.

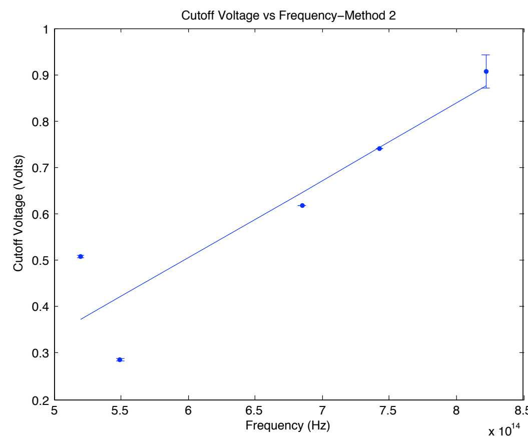

FIG. 5: Method Two Results (Cutoff Voltage Versus Frequency): The line shown represents the unweighed line of best fit, and the points represent the data found in the experiment. The slope of the line was used to determine a value for Planck's constant of $h = 2.68 * 10^{-34} \pm 1.14 * 10^{-34}$.

frequency of light for method two. The value of Planck's constant was determined to be $h = 2.68 * 10^{-34} \pm 1.14 * 10^{-34}$, and the reduced chi squared was $\chi_\nu = 120$.

D. Method 3: Estimate Voltage Curve Rise

The third method to determine the voltage cutoff points was to estimate where the voltage curve begins to rise. To estimate this rise, the points were compared to the second tangent line from method two. The distance between the data and the line were determined, and the point at which the distance was closest to 0.02nAmp was defined as the cutoff voltage. The distance of 0.02nAmp

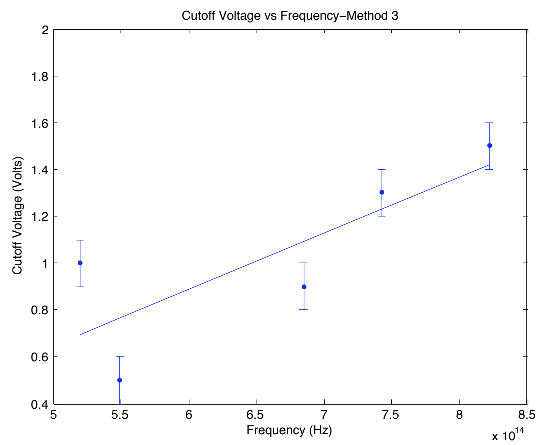

FIG. 6: Method Three Results (Cutoff Voltage Versus Frequency): The line shown represents the unweighed line of best fit, and the points represent the data found in the experiment. The slope of the line was used to determine a value for Planck's constant of $h = 3.86 * 10^{-34} \pm 2.65 * 10^{-34}$.

was chosen because it is the smallest distance that can be seen visually. The error of each cutoff voltage was $\pm$ 0.1 Volts.

Figure 6 shows a plot of the cutoff voltage versus the frequency of light for method three. The value of Planck's constant was determined to be $h = 3.86 * 10^{-34} \pm 2.65 * 10^{-34}$, and the reduced chi squared was $\chi_\nu = 0.505$.

V. SUMMARY

Three different methods were used to determine Planck's constant from the measurement of the current at different voltage levels of a photocell being hit by photons. The values for Planck's constant for methods one, two, and three were respectively: $h = 3.61 * 10^{-34} \pm 2.85 * 10^{-34}, h = 2.68 * 10^{-34} \pm 1.14 * 10^{-34}, andh = 3.86*10^{-34} \pm 2.65*10^{-34}$. The three methods were within the error of each other, and were lower than the expected value for Planck's constant, $h = 6.62606896 * 10^{-34}$.

Acknowledgments

I would like to acknowledge Kathryn Decker French for taking data with me, Josh Horowitz for spending his time to teach me more about physics and error analysis, and Sid Creutz for proof reading my paper.

1. Mohr, Peter J.; Taylor, Barry N.; Newell, David B. (2008). *CODATA Recommended Values of the Fundamental Physical Constants: 2006.* Rev. Mod. Phys. 80: 633730
2. Melissionos, *Experiments in Modern Physics* (Academic Press, 1966).
3. French and Taylor. *An Introduction to Quantum Physics* (Norton, 1978).
3. MIT Physics Department, *Junior lab written report notes* (2007).