The Photoelectric Effect

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Section 1
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I. PURPOSE

The purpose of this experiment is to investigate some aspects of the classical and quantum descriptions of the properties of light by studying the photoelectric effect and its properties, then using the h/e apparatus to make an accurate determination of Planck's constant.

II. ANALYSIS

A. Wave Model of light versus Quantum Model

As different amounts of the same coloured light were passed into the device, using the variable transmission filter to control the intensity, the stopping potential as measured by the digital multimeter fell slightly as the intensity of the light decreased, as seen in Table I and II below.

Intensity from maximum	Measured Stopping potentials $\overline{V}$ (V)	Charging Times $\overline{T}$ (ms)
100 %	0.61	2812
80 %	0.60	3881
60 %	0.58	4216
40 %	0.55	7156
20 %	0.50	7448

TABLE I: Averaged measurements from raw data in Appendix Table VI, showing the measurements for the stopping potential voltage and charge times for a given intensity of single Yellow coloured light at 578nm

Sample Calculations Averaging Stopping Voltage V in Table VI using row 1

$$\overline{V} = \frac{\sum_i^n V_i}{n}$$
$$\overline{V} = \frac{0.61+0.61+0.61}{3}$$
$$\overline{V} = 0.61$$

Sample Calculations Averaging Charging time T in Table VI using row 1

$$\overline{T} = \frac{\sum_i^n T_i}{n}$$
$$\overline{T} = \frac{2561+2960+3030+2698}{4}$$
$$\overline{T} = 2812.25$$

Intensity from maximum	Measured Stopping potentials $\overline{V}$ (V)	Charging Times $\overline{T}$ (ms)
100 %	0.66	3260
80 %	0.65	5272
60 %	0.63	5609
40 %	0.59	5292
20 %	0.53	5538

TABLE II: Averaged measurements from raw data in Appendix Table VII, showing the measurements for the stopping potential voltage and charge times for a given intensity of single Green coloured light at 546nm

Also, as the intensity decreased the charging time required for the apparatus to reach the maximum stopping potential increased. Similarly, as the wavelength of light decreased, the stopping potential and thus the maximum kinetic energy of the photoelectrons increased.

These results support the quantum model of light, where the stopping potential is dependent on frequency (where $\lambda \propto \frac{1}{f}$ as seen in Eq.1) and not intensity. The charging time also fits predictions as the number of electrons emitted would be proportional to the number of photons incident on the material, meaning it would take longer for the for enough electrons to be emitted for the material to reach its stopping potential. If the wave model was correct, we should would expect for the stopping potential to increase with intensity and time, as an increase in intensity would infer more energy in the wave which should then liberate more electrons, which is not observed experimentally.

$$E = \frac{hc}{\lambda} - \varphi = hf - \varphi \qquad (1)$$

The slight drop in measured stopping potential as the intensity of the source light is decreased can be attributed to apparatus acting as a discharging capacitor, due to its components for measuring the stopping potential, some of the capacitance is leaked away over time. Since the charging time is increased as the intensity decreases, the system finds an equilibrium dependent on the discharge rate of the apparatus and the charge rate by the photoelectric effect; when there is a lower charging rate a lower stopping voltage will be measured.

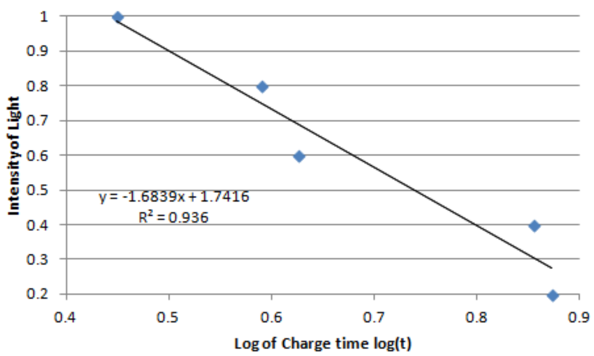

FIG. 1: Intensity of light versus the average charge time to reach the stopping potential ($\frac{I}{I_0} vs. Log(t)$)

As shown in Fig.1, the data suggests that intensity of the light negatively correlates with the charge time, so charge time increases as intensity decreases.

Some errors incurred in this part of the experiment are mostly equipment error and resolution. Mainly due to the leaking effect of the stopping voltage, it is hard to determine the actual stopping voltage of the system. If we knew accurately the discharge time of the capacitor system in the apparatus and with some further tests we could counteract this effect and get a more accurate measurement of V. We could also increase the resolution of the time measurement if we use a more automated timing system and voltage measurement system. There were times where the stopping voltage was between two values of the order 0.01 volts, if we had a DMM with a greater resolution we could better determine the stopping voltage without dealing with random fluctuations which definitely played a role in some of the measurement collected.

B. The relationship between energy and frequency

Using known wavelengths for the light emitted from the Hg lamp, we can calculate the frequencies using the known wave equation, Eq.2, and substituting c = 3.0 $\times 10^8$ m/s for v. A tabulated list of the wavelength and their corresponding frequencies can be found in Table III.

$$v = f\lambda \tag{2}$$

Sample Calculations for frequency using λ of 578nm (Yellow)

$$c = f\lambda$$
$$f = \frac{c}{\lambda}$$
$$f = \frac{3.0\times10^8 m/s}{5.78\times10^{-7} m}$$
$$f = 5.19 \times 10^1 4Hz$$

Wavelength (nm)	Frequency ($\times$ 10 ^{14} Hz)
578	5.19
546	5.49
436	6.88
405	7.41
365	8.22

TABLE III: Table listing wavelengths emitted by the Hg lamp and their corresponding frequencies.

Wavelength (nm)	Measured Stopping (V) potentials $\overline{V}$ (V)
578	0.62
546	0.70
436	1.19
405	1.24
365	1.26

TABLE IV: Average stopping potential voltage from raw data in Appendix Table VIII, for all the different wavelengths of light emitted from the Hg lamp for their first order spectrum

Wavelength (nm)	Measured Stopping (V) potentials $\overline{V}$ (V)
578	0.52
546	0.59
436	1.04
405	1.09
365	1.13

TABLE V: Average stopping potential voltage from raw data in Appendix Table IX, for all the different wavelengths of light emitted from the Hg lamp for their second order spectrum

The data from Tables III and IV were graphed, as seen in Fig. 2. Error estimates were made, using specification error estimates for digital multimeter to be 1% of the reading ± the least significant digit, and there difference between the first and second order averaging stopping voltages was about 0.1 volts for same wavelengths, so I factored in an error of 0.1 volts into the error as well. The linear regression did not fit the error bars of the last point, so I am assuming that is an outlying point for the data collected.

Sample Calculations for error estimates, using for 1 of Table IV

$$\Delta V = V \times DMM_{error} + 0.1v$$
$$\Delta V = 0.62 \times 0.01 + 0.01v + 0.1v$$
$$\Delta V = 0.1162$$

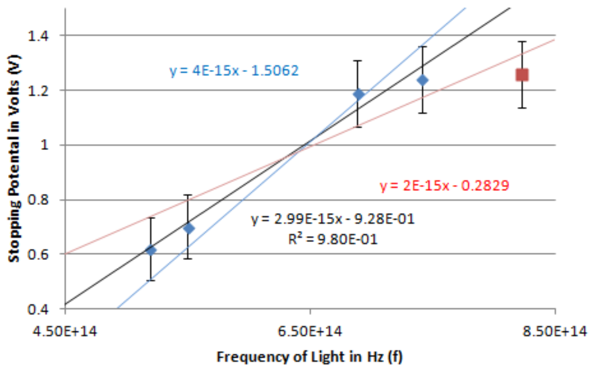

FIG. 2: Average stopping potential for frequencies of light emitted by the Hg lamp, $(\overline{V} vs. f)$, with the minimum and maximum uncertainty slopes also graphed in red and blue respectively.

The slope of the average line in Fig.2, was found to be 2.99 $\times$ $10^{-15} V \cdot s$ with an intercept of -9.28 $\times$ 10^{-1} V. Using Eq.1 we can calculate Planck's constant to be 4.79 $\times$ 10 $^{-34}$ J $\cdot$ s and similarly calculate the work function to be 1.49 eV.

Sample Calculations for work function using an Intercept value of 9.28 $\times$ 10^{-1} V

$$\varphi = 9.28 \times 10^{-1} V \cdot e$$
$$\varphi = 9.28 \times 10^{-1} V \cdot 1.602 \times 10^{-19} colombs$$
$$\varphi = 1.49 eV$$

Sample Calculations for Planck's constant using a slope of 2.99 $\times$ 10^{-15} V $\cdot$ s from Fig.2

$$E = hf$$
$$\frac{E}{f} = h = (2.99 \times 10^{-15} V \cdot s) \times (11.602 \times 10^{-19} coloumbs)$$
$$h = 4.79 \times 10^{-34} J \cdot s$$

By this same process, using the minimum and maximum slopes from Fig.2 of 2.00 $\times$ $10^{-15} V \cdot s$ and 4.00 $\times$ $10^{-15} V \cdot s$ respectively, calculated using the error estimates for the data collected, we can calculate minimum and maximum uncertainties in our determination of the Planck's constant from this data. These values were calculated to be minimum, 3.20 $\times$ 10 $^{-34}$ J $\cdot$ s, and maximum, 6.41 $\times$ 10 $^{-34}$ J $\cdot$ s, and the work function is similarly bounded by 0.45 eV from the bottom, and 2.40 eV from the top.

Sample Calculation for Percent Difference of h, Plank's constant, with the accepted value of 6.63$\times$ 10^{-34} J $\cdot$ s

$$\%_{Difference} = \frac{|measured - accepted|}{accepted} \times 100$$
$$\%_{Difference} = \frac{|4.79 \times 10^{-34} - 6.63 \times 10^{-34}|}{6.63 \times 10^{-34}} \times 100$$
$$\%_{Difference} = 28\%$$

Comparing the measured value of Planck's constant with the accepted, of 6.63$\times$ 10^{-34} J $\cdot$ s, there was a 28% disparity. However, the accepted value is quite close to the upper bound of my uncertainty, only differing by 3%, so the accepted value is within, or close to my uncertainty estimate.

The same for errors can be said for this part of the experiment as the last, with knowing the discharge rate of the apparatus we could more accurately know the actual stopping voltages for each wavelength.

C. Critical Analysis

Some other properties of light which can show light have particle-like characteristics is momentum, more readily seen by observing the Compton Scattering of high energy photons explained by Eq.3. Momentum of the photon electron system is conserved in collision scenarios.

$$\lambda\prime - \lambda = \frac{h}{m_e c}(1 - \cos\theta) \tag{3}$$

Not all the photoelectrons ejected by the light have the same energy, but a distribution of energies with a maximum energy equal to h $\cdot$ f of the incident photon. Some explanations for this is that electrons may interfere and scatter off of other electrons in the metal, the only energies greater than the work function of the metal will escape. So when the incident photons have sufficiently higher energies, there are a distribution of energies of electrons that are emitted.

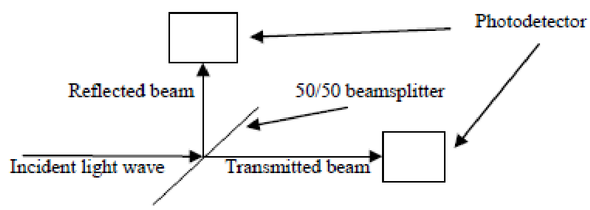

FIG. 3: An example of an intensity interferometer

If the experiment as illustrated above in Fig.3 were to be carried out, with the incident light wave had a very low intensity would one be able to distinguish between the wave and particle descriptions of the photoelectric effect? It has already been shown through the Hanbury Brown and Twiss (HBT) effect, that in cases like this photons will experience photon bunching, where detectors will experience a correlation between each other which is explained very well using the classical wave theory of light. So the wave-particle duality of the light wave is important for explaining the HBT effect.

The optical frequency of a given spectral line is the same in all orders of the diffraction grating because the same properties of a double slit interference pattern. As wavelengths of light pass through the slits in the diffraction grating, they travel different distances and will either interfere constructively or deconstructively. The solution of this is dependent on the angle of the incident light, as seen in Eq.4, and the angle to a position somewhere on the other side of the diffraction grating.

$$d(\sin\theta_i + \sin\theta_m) = m\lambda \tag{4}$$

There are multiple solutions that are periodic due to the sin terms and the nature of angles, where the intensity falls off with greater orders, following some sort of normal distribution.

III. CONCLUSION

The experiment did investigate various aspects of the classical and quantum descriptions of the properties of light. It was found that the quantum nature of light more accurately describes the interactions causing the photoelectric effect because it was observed that the stopping potential, or maximum kinetic energy of liberated electrons, increases with frequency of the incident light, which doesn't fit the classical predictions of the stopping potential increasing with the intensity of the light. It was found that instead, the charge time, or the amount of liberated electrons per unit time decreased and as the intensity decreased, and increased as the intensity increased.

A value for Planck's constant was also found, to be 4.79 $\times$ 10 $^{-34}$ J $\cdot$ s which was 28% off of the accepted 6.63 $\times$ 10 $^{-34}$ J $\cdot$ s, and including uncertainty measurements, this value was bounding by 3.20 $\times$ 10 $^{-34}$ J $\cdot$ s from the bottom, 6.41 $\times$ 10 $^{-34}$ J $\cdot$ s from the top. The upper bound does fall quite close to the accept value, only differing by 3%. Similarly the work function was calculated to be 1.49 eV, bounded by 0.45 eV from the bottom, and 2.40 eV from the top.

Appendices

APPENDIX A: RAW DATA

1. Wave Model of light versus Quantum Model

Intensity from maximum	Measured Stopping potentials V (V)	Charging Times T (ms)
100 %	0.61, 0.61, 0.61	2561, 2960, 3030, 2698
80 %	0.60, 0.60, 0.60	3647, 3239, 3972, 4404, 3575
60 %	0.58, 0.58, 0.58	4885, 3797, 4092, 4162, 4143
40 %	0.54, 0.55, 0.55, 0.55	6037, 7810, 7115, 7558, 6248
20 %	0.50, 0.50, 0.50	7483, 7419, 7519, 7741, 7078

TABLE VI: Tabulation of raw data measuring the stopping potential voltage and charge times for a given intensity of single Yellow coloured light at 578nm.

Intensity from maximum	Measured Stopping potentials V (V)	Charging Times T (ms)
100 %	0.66, 0.66, 0.66, 0.66	3436, 2839, 2988, 3856, 3181
80 %	0.65, 0.65, 0.65	6712, 5224, 4765, 4446, 5212
60 %	0.63, 0.63, 0.63, 0.63	6047, 4327, 4678, 7695, 5299
40 %	0.59, 0.59, 0.59	4803, 5224, 5340, 4703, 5390
20 %	0.53, 0.53, 0.53	4935, 4808, 5593, 6048, 6307

TABLE VII: Tabulation of raw data measuring the stopping potential voltage and charge times for a given intensity of single Green coloured light at 546nm.

2. The relationship between energy and frequency

Wavelength (nm)	Measured Stopping potentials V (V)
578	0.62, 0.62, 0.62
546	0.70, 0.70, 0.70
436	1.19, 1.19, 1.19
405	1.24, 1.24, 1.24
365	1.26, 1.26, 1.26

TABLE VIII: Tabulation of raw data measuring the stopping potential voltage for all the different wavelengths of light emitted from the Hg lamp, for their first order spectrum

Wavelength (nm)	Measured Stopping potentials V (V)
578	0.52, 0.52, 0.52
546	0.59, 0.59, 0.59
436	1.04, 1.04, 1.04
405	1.09, 1.09, 1.09
365	1.13, 1.13, 1.13

TABLE IX: Tabulation of raw data measuring the stopping potential voltage for all the different wavelengths of light emitted from the Hg lamp, for their second order spectrum

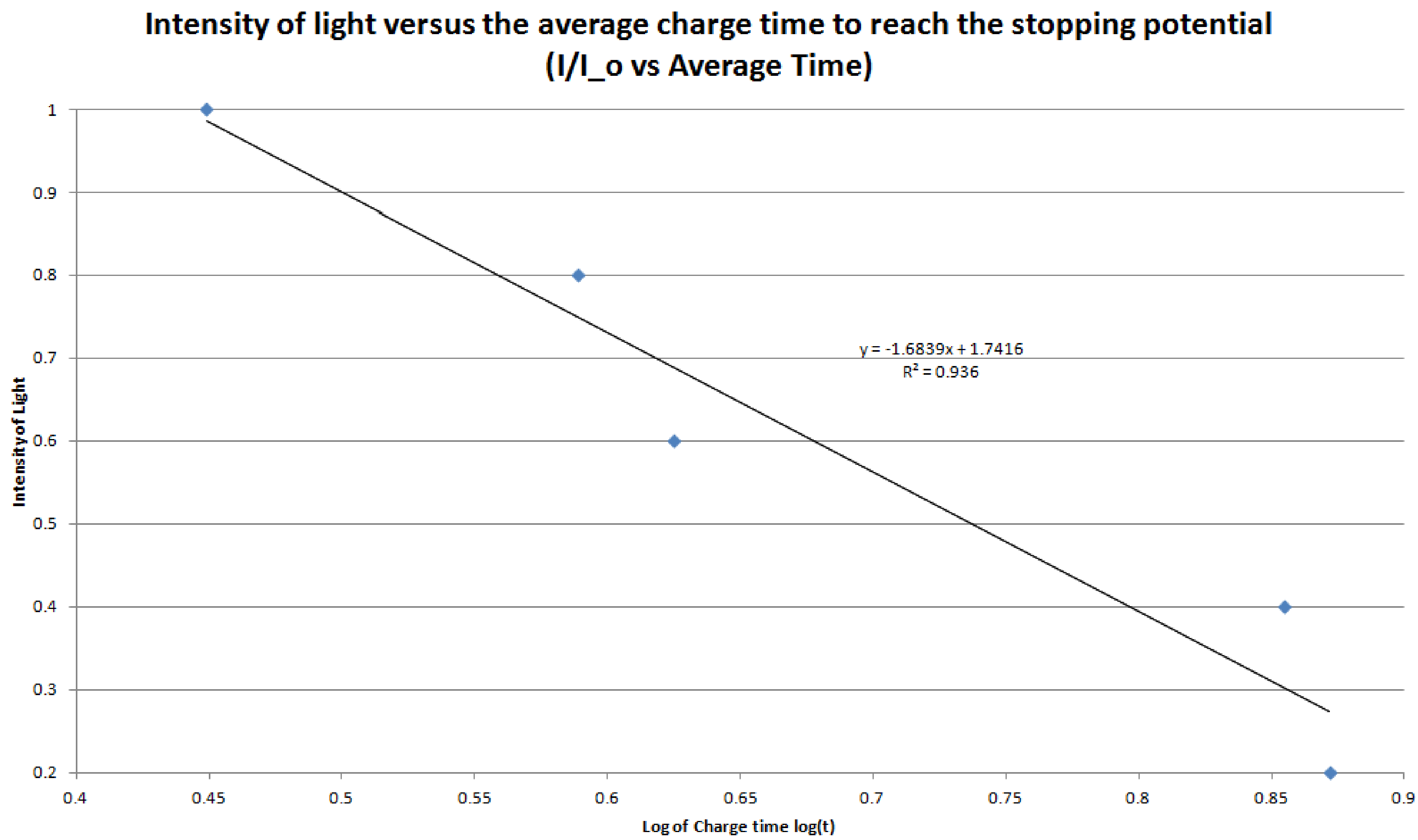

FIG. 1: Intensity of light versus the average charge time to reach the stopping potential ($\frac{I}{I_0} vs. Log(t)$)

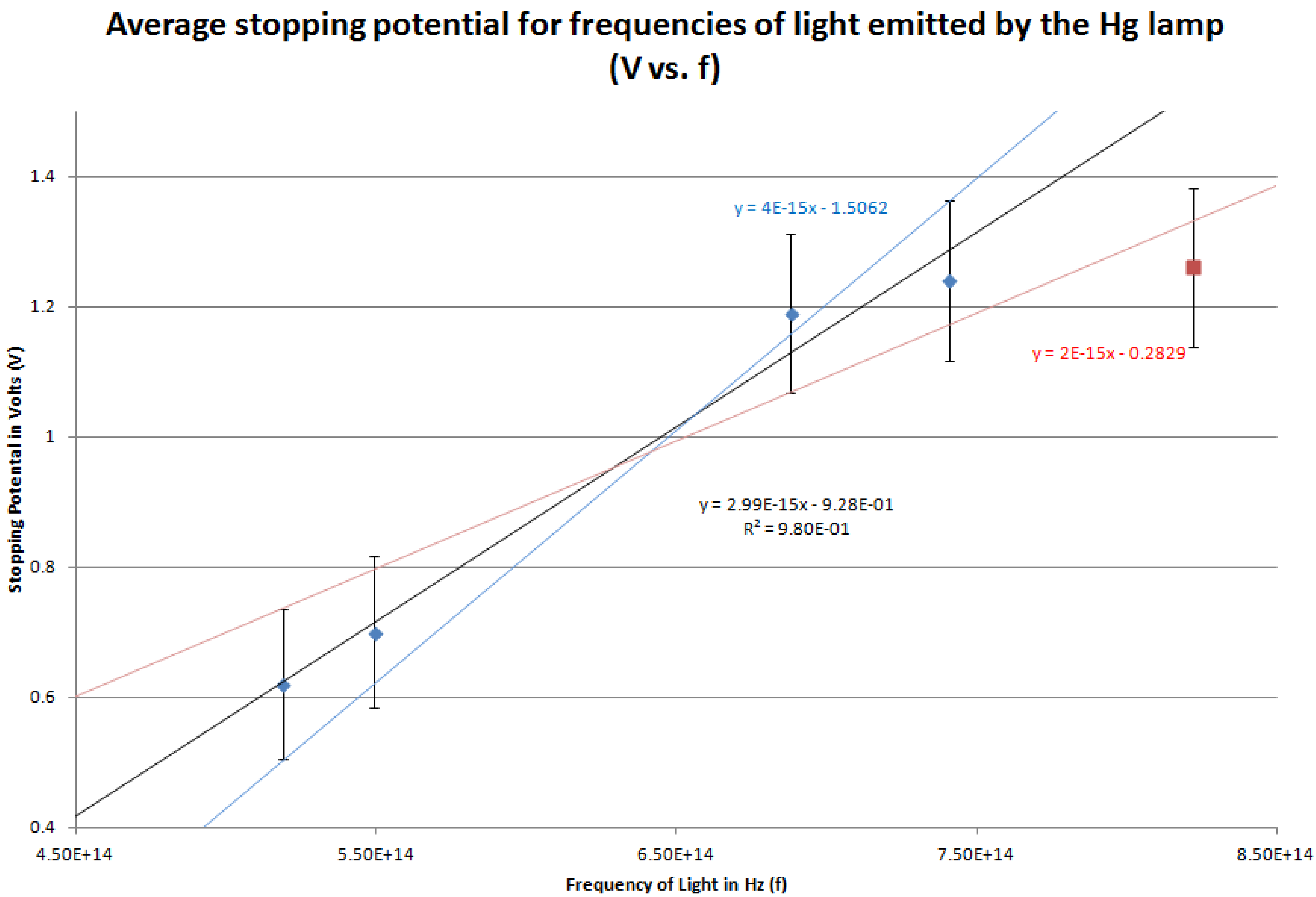

FIG. 2: Average stopping potential for frequencies of light emitted by the Hg lamp, $(\overline{V} vs. f)$, with the minimum and maximum uncertainty slopes also graphed in red and blue respectively.