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An Illuminating Exploration of The Photoelectric Effect Using An Unknown Metal

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Abstract

The purpose of this experiment was to determine Planck's constant and the work function of the unknown metal comprising a photodiode. The photoelectric effect was analyzed by its output current and required canceling voltage under different apertures, wavelengths, and distances from light source. This experiment has determined Planck's Constant to be $(6.61 \pm 0.07) \times 10^{-34} Js$ which is in strong agreement with the accepted value of $6.62607015 \times 10^{-34} Js$. Additionally, the work function of the metal that comprises the diode was found to be $(2.61 \pm 0.05) \times 10^{-19} J$, this is equivalent to $3.15 \pm 0.06 eV$. Two metals are known to have work functions in strong agreement with this value: Nd $(3.2eV)$ and Y $(3.1eV)$. Because the energy of a photon is quantized, only high enough frequencies of light have enough energy to overcome a metal's work function and eject electrons. This is a key example of light behaving like a particle over a wave.

1 Introduction

At the beginning of the 20th century, Einstein first described the photoelectric effect, in which electromagnetic radiation of sufficient energy would produce an electrical current when projected onto metals. The purpose of this experiment was to explore the photoelectric effect through the relationship between the frequency of projected light and the resulting kinetic energy of the electrons released from the metal. The electrons released from the photodiode create the current, and their kinetic energy can be measured by observing the applied voltage (V) required to cancel this current. Certain frequencies (ν) of electromagnetic radiation will fail to produce any current. This is because they are below the threshold frequency of the metal, which is determined by the metal's innate work function (W_0). The equation that characterizes this relationship is:

$$V = \frac{h}{e}\nu - \frac{W_0}{e}, \tag{1}$$

where h is Planck's constant, and e is the charge of an electron. By analyzing voltage as a function of frequency, a value for both Planck's constant and the Work function of the metal may be determined.

This experiment will also briefly explore the effect that the aperture of the photodiode, and the wavelength of light used, have on the current-voltage relationship. It is expected that a larger aperture will increase the resulting current as more light is able to strike the photodiode. Light of greater frequencies (shorter wavelengths) will produce more current as the individual photons that make up high frequency radiation carry more energy that they pass along to the ejected electrons. It should be noted that the intensity of the light has no effect on the current if the photons are not energetic enough to overcome the metals work function. This behavior was an important clue to the fact that light may act as a particle in addition to acting like a wave, hinting at its quantum nature.

2 Materials

Mercury Lamp, Photodiode, Current Amplifier, DC Power Supply, PASCO, Computer, Analog Ruler, Red and Black Conductive Wire.

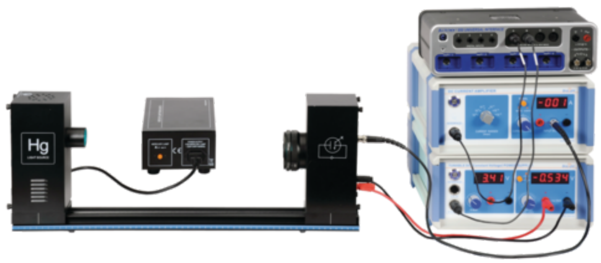


Figure 1: PASCO Lab Setup [1]

3 Methodology

3.1 Part 1: Planck's Constant

1. Lab setup was prepared as shown in Figure 1.
2. Mercury lamp was turned on and given 10 minutes to warm up.
3. Photodiode aperture was set to ∅2 mm.
4. Photodiode was positioned 40cm from mercury lamp.
5. Photodiode was set to filter out wavelengths excluding 365 nm.
6. Voltage was adjusted until until the current was measured to be zero. Then voltage measurement was recorded.
7. Steps 5 and 6 were repeated for filters of different wavelengths (405, 436, 546, 577nm).
8. Steps 4-7 were repeated for distances of 30 cm and 20 cm from mercury lamp.

3.2 Part 2: Variable Aperture

1. Photodiode was positioned 40cm from mercury lamp.
2. Photodiode filter was set to 436 nm.
3. Photodiode aperture was set to ∅2 mm.
4. Voltage was set to 30 V.
5. Voltage was decreased by 2 V increments as voltage and current were recorded until a voltage of 0 V was reached.
6. Voltage was next decreased by 0.1 V increments as voltage and current were recorded

until current of 0 A is reached.

7. Steps 3-6 were repeated for apertures of ∅4 mm and ∅8 mm

3.3 Part 3: Specific Wavelengths

1. Photodiode was positioned 40 cm from mercury lamp and aperture was set to ∅2 mm.
2. Photodiode filter was set to 436 nm and voltage was set to 10 V.
3. Voltage was decreased by 2 V increments as voltage and current were recorded until a voltage of 0 V was reached.
4. Voltage was next decreased by 0.1 V increments as voltage and current were recorded until current of 0 A is reached.
5. Steps 2-4 were repeated for wavelengths of 365 nm and 405 nm.

4 Results

Different frequencies of light were projected onto a photodiode containing an unknown metal. A current near the photodiode was then observed and it was inferred that electrons were radiating away from the metal. The electric potential that was required to cancel this current measured at different frequencies of light while the light source to metal distance was also varied. These results can be found in Figure 2. A linear regression of equation 1 was applied to the data (Table 1) and from these results, Planck's Constant and the Work Function of the metal were calculated (Table 2). In parts 2 and 3, current was measured as a function of voltage while the aperture and wavelength were varied. These findings are presented in Figures 3 and 4. All figures contain error bars, however they are too small to be seen.

Table 1: Results From Fitting Equation x to Experimental Data of Stopping Potential Versus Frequency of Light With 3 DOF

	Fit Results					
Distance	$h/e\ (Vs \times 10^{-34})$	$\sigma_{h/e}\ (\pm Vs \times 10^{-34})$	$W_o/e\ (V)$	$\sigma_{W_o/e}\ (\pm Vs)$	χ^2	σ_{χ^2}
20 cm	3.94	0.08	1.51	0.05	6.4	0.8
30 cm	4.36	0.08	1.70	0.05	13.0	0.8
40 cm	4.30	0.08	1.67	0.05	6.5	0.8

Figure 2: Stopping Potential For Different Frequencies Observed at Various Distances

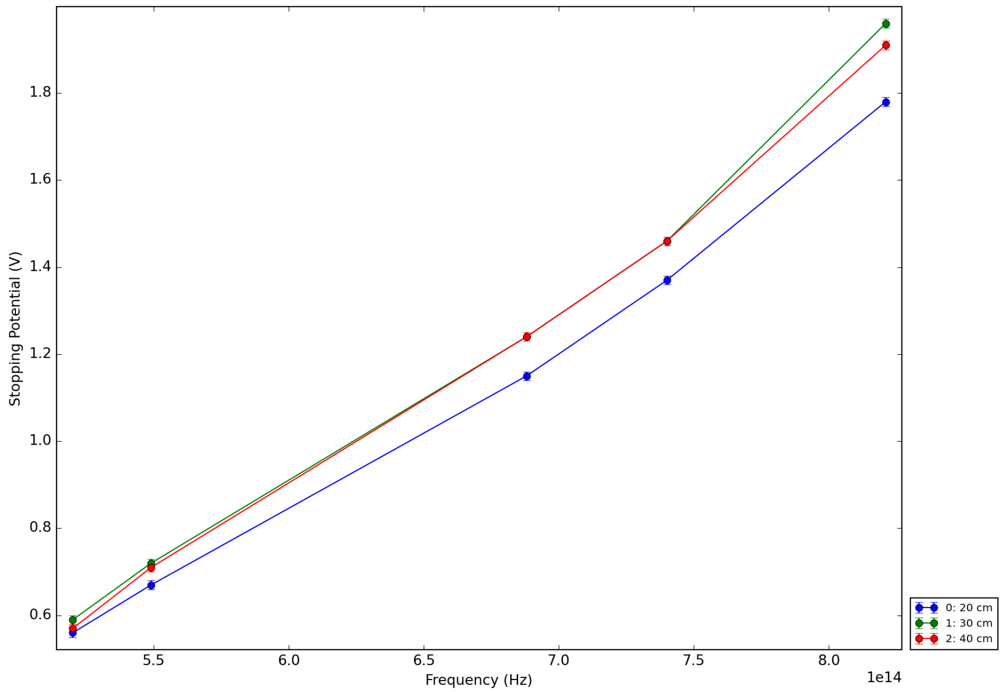


Table 2: Planck's Constant h And Work Function W_o of Material Used in Experiment

	h (Js)	W_o (J)
Experimental	$(6.61 \pm 0.07) \times 10^{-34}$	$(2.61 \pm 0.05) \times 10^{-19}$
Literature	$6.62607015 \times 10^{-34}$ [2]	Unknown

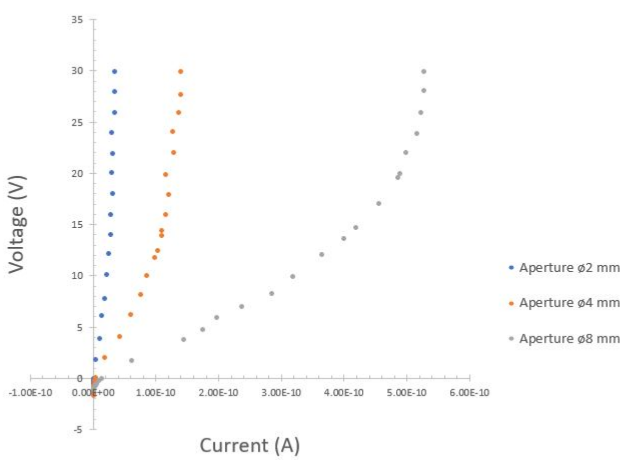


Figure 3: Part 2 – Current Measured At Varying Voltage at Three Different Apertures

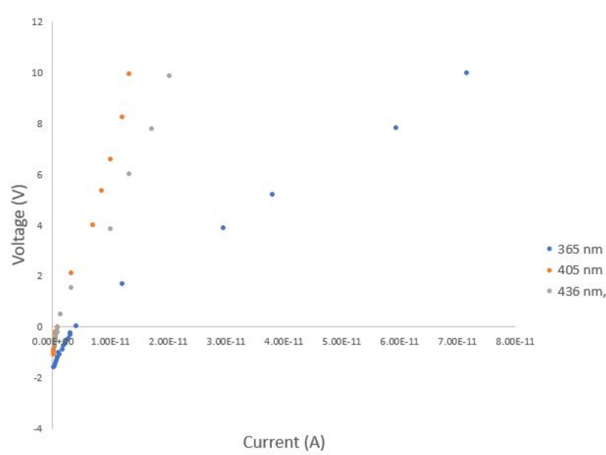


Figure 4: Part 3 – Current Measured At Varying Voltage at Three Different Wavelengths

5 Discussion

As seen in Table 2, Planck's Constant was determined to be $(6.61 \pm 0.07) \times 10^{-34} Js$ through analysis of the photoelectric effect. This calculated value is in strong agreement with the accepted value of h $(6.62607015 \times 10^{-34})$ [2]. Additionally, the work function of the metal that comprises the diode was found to be $(2.61 \pm 0.05) \times 10^{-19} J$ (equivalently $3.15 \pm 0.06 eV$). Two metals are known to have work functions in strong agreement with this value. The first is Neodymium with a work function of 3.2 eV and the second is Yttrium with a work function of 3.1 eV [3]. For reasons displayed in *Fourth Appendix*, the unknown metal is estimated to be Yttrium. Qualitative Analysis of Figure 3 confirms that a wider aperture generates more current by letting in more light. It also seems that at each aperture, there is a maximum current to which the data converges. Additionally, Figure 4 demonstrates that shorter wavelengths (higher frequencies) of light produce more current than that of longer wavelengths.

The linear regression used in part 1 had 3 degrees of freedom which should correspond to a χ^2 value of 3. However, all χ^2 values in Table 1 are far greater than 3 implying that the best-fit lines did not pass between enough error bars in the data. This suggests that the estimated uncertainties on Voltage must be too small. These uncertainties are described in *Fourth Appendix*.

6 Conclusions

Analysis of the photoelectric effect experimentally determined Planck's constant ($(6.61 \pm 0.07) \times 10^{-34} Js$) and the the work function of the metal comprising the photodiode ($(2.61 \pm 0.05) \times 10^{-19} J$). The calculated value of Planck's constant was in strong agreement with literature values and the calculated value of the work function suggests the photodide is either Neodymium or Yttrium [3]. It was observed that the photodiode's distance from the mercury lamp (and hence the intensity of light it received had no effect on work function). Selecting wider apertures on the photodiode produced more current as expected. Higher frequencies of light also produced greater currents as expected. The photoelectric effect is a prime example of a quantum phenomenon where the intuitions of classical physics begin to break down.

References

[1] Pasco. Photoelectric Effect Experiment. STEM SENSE Kits. Product EX-5549A. https://www.pasco.com/products/complete-experiments/quantum/ex-5549 2

[2] National Institute of Standards and Technology. Kilogram: Mass and Planck's Constant. Created May 14, 2018, Updated June 2, 2021. https://www.nist.gov/si-redefinition/kilogram-mass-and-plancks-constant 4, 5

[3] Washington State University. Electron Work Function of the Elements. https://public.wsu.edu/ pchemlab/documents/Work-functionvalues.pdf 5

A First Appendix: Author Contribution Statements

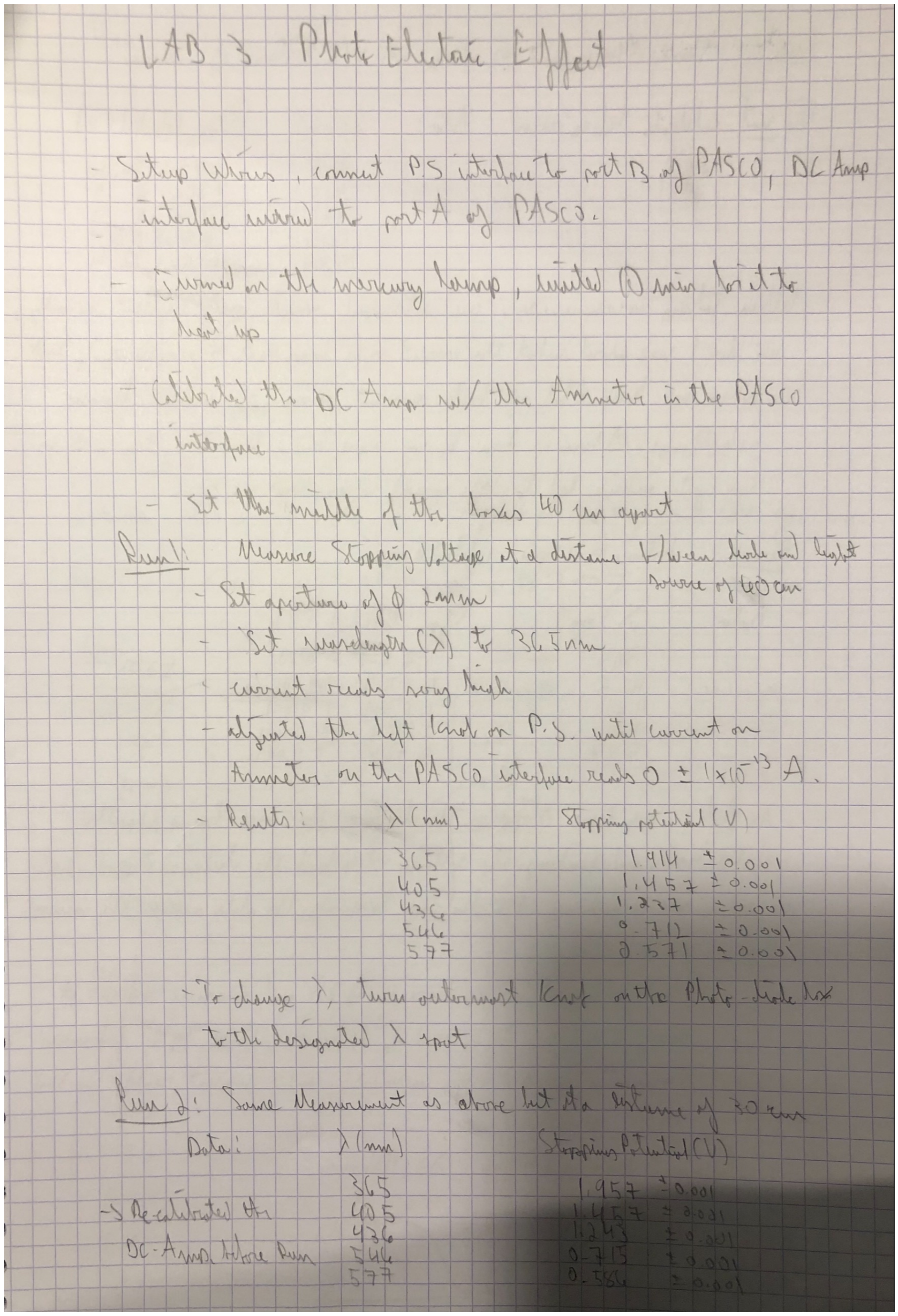
Monte Mahlum (ID 260968971)

M.M contributed by taking raw data, analyzing this data via Data Analysis prompts, answering lab questions, writing the Lab Report, and completing the assignment.

Evan Henderson (ID 260970960)

E.H contributed by taking raw data, analyzing this data via Data Analysis prompts, answering lab questions, writing the Lab Report, and completing the assignment.

B Second Appendix: Lab Book



LAB 3 Photo Electric Effect

- Setup wires, connect PS interface to port B of PASCO, DC Amp interface wire to port A of PASCO.
- Turned on the mercury lamp, waited 10 min for it to heat up
- Calibrated the DC Amp w/ the Ammeter in the PASCO interface
- Set the middle of the boxes 40 cm apart

Run 1: Measure Stopping Voltage at a distance b/ween diode and light source of 40 cm
- Set aperture of ϕ 2mm
- Set wavelength (λ) to 365nm
- current reads very high
- adjusted the left knob on P.S. until current on Ammeter on the PASCO interface reads $0 \pm 1\times10^{-13}$ A.
- Results:

λ (nm)	Stopping potential (V)
365	1.914 ± 0.001
405	1.457 ± 0.001
436	1.237 ± 0.001
546	0.712 ± 0.001
577	0.571 ± 0.001

- To change λ, turn outermost knob on the Photo-diode box to the designated λ spot

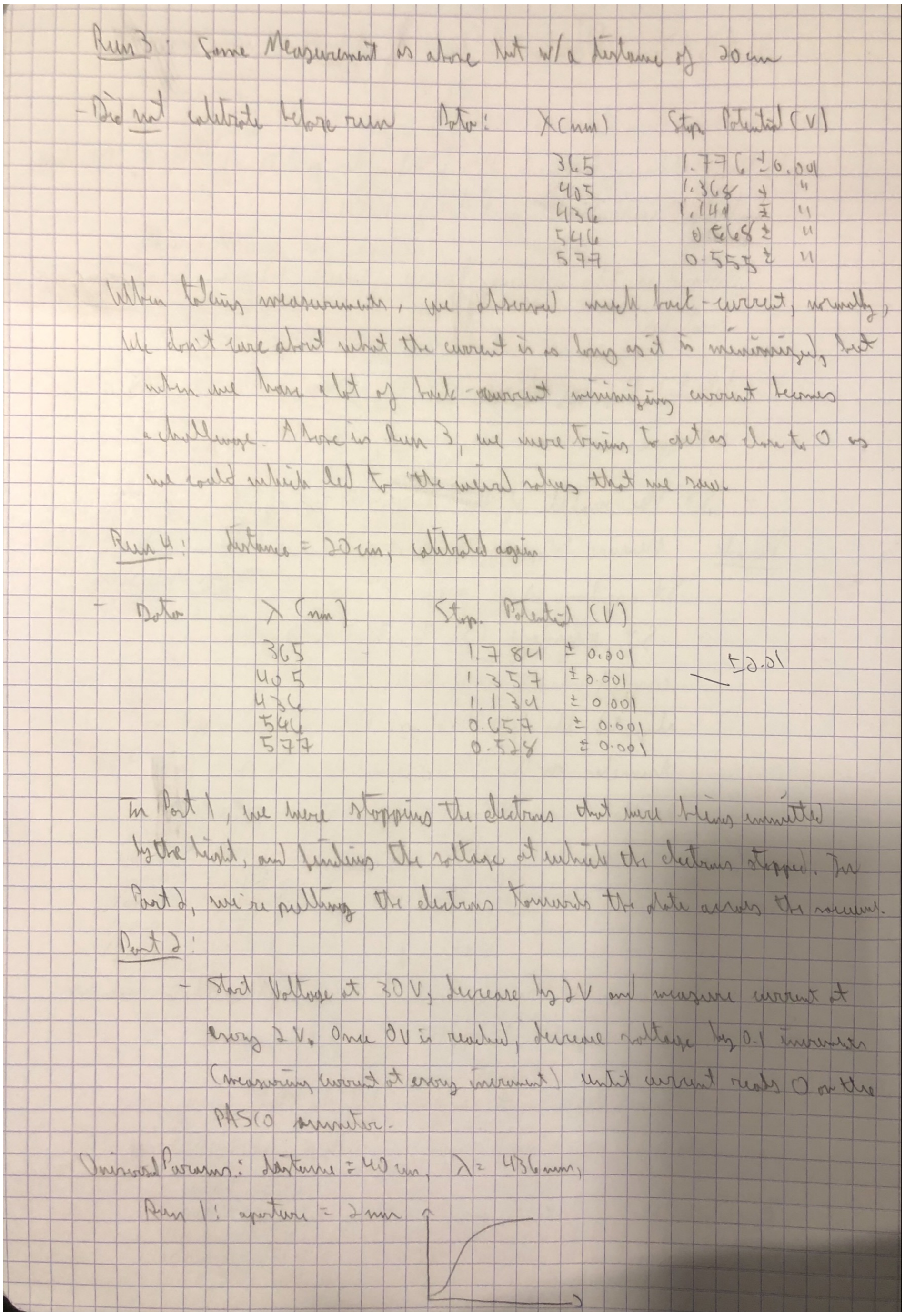
Run 2: Same Measurement as above but at a distance of 30 cm

Data:

→ Re-calibrated the DC-Amp before Run

λ (nm)	Stopping Potential (V)
365	1.957 ± 0.001
405	1.457 ± 0.001
436	1.243 ± 0.001
546	0.715 ± 0.001
577	0.586 ± 0.001

Figure 5: Lab Book page one



Run 3: Same Measurement as above but w/ a distance of 20 cm

- Did not calibrate before run Data:

λ (nm)	Stop. Potential (V)
365	1.776 ± 0.001
405	1.368 ± "
436	1.140 ± "
546	0.668 ± "
577	0.553 ± "

When taking measurements, we observed much back-current, normally, we don't care about what the current is as long as it is minimized, but when we have a lot of back-current minimizing current becomes a challenge. Above in Run 3, we were trying to get as close to 0 as we could which led to the weird values that we saw.

Run 4: distance = 20 cm, calibrated again

- Data

λ (nm)	Stop. Potential (V)
365	1.784 ± 0.001
405	1.357 ± 0.001
436	1.139 ± 0.001
546	0.657 ± 0.001
577	0.528 ± 0.001

±0.01

In Part 1, we were stopping the electrons that were being emitted by the light, and finding the voltage at which the electrons stopped. In Part 2, we're pulling the electrons towards the plate across the vacuum.

Part 2:

- Start Voltage at 30 V, decrease by 2 V and measure current at every 2 V. Once 0 V is reached, decrease voltage by 0.1 increments (measuring current at every increment) until current reads 0 on the PASCO ammeter.

Universal Params: distance = 40 cm, λ = 436 nm,

Run 1: aperture = 2 mm

Figure 6: Lab Book page two

C Third Appendix: Further Discussion of Unknown Metal

While the calculated value of Planck's Constant is in strong agreement with the accepted value, it is slightly lower than expected. One explanation for this discrepancy is that the data in part 1, taken from a 20 cm distance seems to be systematically shifted to a lower slope, and a less negative y-intercept. This is claimed because only one data point from the 20 cm distance is in agreement with those from a 30 and 40 cm distance. This shift decreased the calculated value for both h and W_o. Based on this shift it is estimated that the metal used in the photodiode is more likely to be Yttrium. The reason the 20 cm distance is said to be shifted over the other distances is that this interpretation is backed by the literature value for h. However, with only three data sets, further experimentation is required to reach any strong conclusions.

D Fourth Appendix: Uncertainties

The value for the stopping potential was recorded only once the current reached 0 so the uncertainty that was used for voltage was 0.02 V, half of this value coming from the voltage itself and the other half coming from current. No value for repeatability was found for the instruments so the resolution was taken to be their error. The χ^2 values suggest that the resolution is not an adequate estimate, but more information on the repeatability of these instruments could lead to better results.