# Photoelectric Effect

Lab Report # 03

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## Abstract

This experiment investigated the photoelectric effect to determine key quantum properties, including Planck's constant and the work function of a metal. By illuminating a photodiode with monochromatic light of varying frequencies, the stopping voltage required to suppress electron emission was measured. The relationship between stopping voltage and photon frequency was analyzed to validate the linearity predicted by Einstein's photoelectric equation. The experimentally derived Planck's constant, $(4.98 \pm 0.19) \times 10^{-34}\,Js$, exhibited a 14% deviation from the accepted value of $6.626 \times 10^{-34}\,Js$, and the calculated work function, $(0.947 \pm 0.079)\,eV$, closely matched the theoretical value of $0.948\,eV$. However, discrepancies in stopping voltage measurements, with percentage differences ranging from 20% to 28%, were attributed to systematic errors, apparatus limitations, and increased fractional uncertainties at lower photon frequencies. Despite these quantitative deviations, the experimental results qualitatively confirmed the principles of the photoelectric effect, affirming the dependence of electron kinetic energy on photon frequency and the independence of stopping voltage from light intensity. To improve quantitative accuracy, future work should address instrument calibration, noise reduction, and higher-resolution voltage measurements.

## Copyright Statement

# Contents

# 1 Introduction

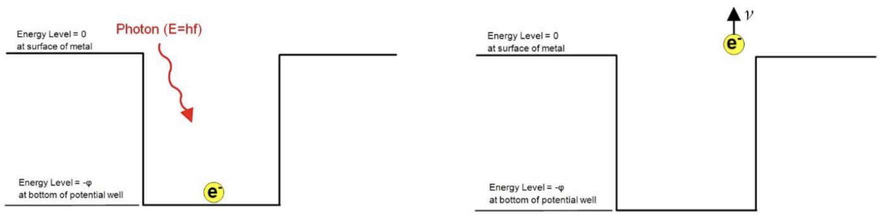
The photoelectric effect is a fundamental quantum phenomenon that demonstrates the particle-like behavior of light. When light, composed of photons, hits the surface of a metal, it can cause the ejection of electrons, provided that the photons have sufficient energy. The investigation of the photoelectric effect was motivated as a demonstration of the particle-like nature of light and its interaction with matter, challenging the classical wave theories of light. It was assumed that light comprises discrete energy packets known as photons, with energy quantized as $E_f = hf$, where $h$ is Planck's constant and $f$ is the frequency of the incident light. This assumption provided the foundation for understanding that the energy of the emitted electrons depends on the frequency of the light, rather than its intensity, as previously posited by classical physics. The monochrome filters used along with the photodiodes are extremely accurate, and we posit that their accuracy in filtering different frequencies of light is arbitrarily high. It was also assumed that no background light played a role in the experiment, and that an interaction between a photon and an electron leads to a direct and complete transfer of energy from the former to the latter.

The experiment relied on the principle that photons with energy exceeding the work function of the material ($\phi$) would eject electrons from the metal surface, transferring any excess energy into the kinetic energy ($E_K$) of the electrons. The relationship was expressed mathematically as $E_K = hf - \phi$. The stopping potential, the minimum voltage required to halt the photoelectric current, was measured and directly related to the maximum kinetic energy of the emitted electrons. This stopping potential allowed the determination of fundamental constants, such as the Planck constant and the work function of the metal. Measurements were taken under controlled conditions, assuming consistent photon flux, precise wavelength selection, and negligible energy losses during electron ejection. These values were compared to theoretical predictions, validating the quantum model of light and providing insights into the interaction between photons and electrons. Through these measurements and calculations, the experiment aimed to reaffirm the foundational principles of quantum mechanics.

## 2 Theory

The theory of the photoelectric effect is rooted in the quantum nature of light and describes the ejection of electrons from the surface of a metal when illuminated by light of sufficient energy. Electrons within a metal exist in potential energy wells, bound by an energy barrier known as the work function ($\phi$), which represents the minimum energy required for an electron to escape the surface. When light strikes the metal, its photons transfer energy to the electrons. If the energy of the photons exceeds the work function, the electrons are ejected with kinetic energy ($E_K$) equal to the difference between the photon energy $E_f$ and the work function. This relationship is expressed as $E_f = E_K + \phi$.

The energy of a photon is described by Planck's equation, $E_f = hf$, where $h$ is Planck's constant and $f$ is the frequency of the incident light. If the photon energy equals the work function ($hf_0 = \phi$), the electrons will reach the surface of the metal but will not have sufficient energy to escape. For photons with energy less than the work function ($hf_0 < \phi$), no electrons will be emitted, regardless of the light's intensity. This principle highlights the threshold frequency ($f_c$), the minimum frequency of light required to cause photoemission, which corresponds to the cutoff wavelength below which photoemission occurs. Thus, not all colors of light will cause electrons to be emitted. Only colors corresponding to frequencies greater than $f_c$ (or equivalently, shorter wavelengths than the cutoff wavelength) have sufficient energy to eject electrons.




(a) Electron in potential well (b) Electron escaping potential well

Figure 1: Potential well model of the photoelectric effect

The intensity of the incident light does not affect the kinetic energy of the emitted electrons. Even if the light becomes brighter (i.e., its intensity increases), the energy of individual photons remains constant, and thus the kinetic energy of the ejected electrons remains unaffected. However, brighter light increases the number of photons striking the metal per unit time, which leads to an increase in the number of electrons being emitted per second (the photo-current). This confirms that the photo-current depends on light intensity, while the kinetic energy of the electrons depends solely on the frequency of the incident light. If the frequency of the light is increased while maintaining a constant intensity, the kinetic energy of the emitted electrons increases, as higher-frequency photons possess more energy. However, the number of electrons emitted per second may not necessarily increase, as it depends on the availability of electrons with sufficient energy to escape.

When light of the same frequency and intensity shines on two different metals with different work functions, electrons may be emitted from one metal but not from the other, depending on their respective work functions. For photoemission to occur, the photon energy must exceed the work function of the metal. If both metals emit electrons, the kinetic energy of the electrons will differ, as it depends on the difference between the photon energy and the work function of each metal. Furthermore, the photo-current may be larger for the metal with the smaller work function, as a greater proportion of incident photons may efficiently eject electrons. However, this also depends on the quantum efficiency [2] of the metal, which determines how effectively photons cause electron emission.

In the experiment, the kinetic energy of the emitted electrons was measured indirectly by applying a stopping potential ($V_s$) to the photodiode. This potential created an electric field that counteracted the motion of the electrons, and $V_s$ was adjusted until the photocurrent dropped to zero, indicating that all emitted electrons had been stopped. The relationship between the stopping potential and the kinetic energy of the electrons is given by $E_K = eV_s$, where $e$ is the elementary charge of the electron. Substituting this relationship and the relationship for the photonic energy into the photoelectric equation yields $eV_s = hf - \phi$. A plot of $V_s$ vs. $f$ was generated to study the relationship between stopping potential and frequency. The slope of the graph is proportional to $h/e$, allowing Planck's constant to be determined experimentally. The y-intercept corresponds to $-\phi/e$, which provides the work function of the metal. The x-intercept identifies the cutoff frequency, $f_c = \phi/h$ below which no photoemission occurs. This analysis also explored the dependence of the photo-current on light intensity, providing additional confirmation of the quantum theory of light.

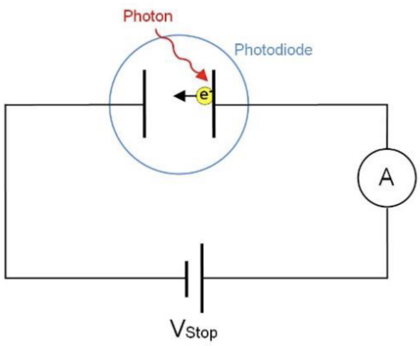



Figure 2: Photodiode circuit

# 3 Experimental Procedure

## 3.1 Experimental setup

The experimental setup to investigate the photoelectric effect was prepared by mounting the mercury lamp and the photodiode case on a track, ensuring proper alignment between the light source and the photodiode. The power cord from the Mercury Light Source enclosure was connected to the receptacle labeled 'POWER OUTPUT FOR MERCURY 220V' on the Mercury Lamp Power Supply, which was then connected to an electrical outlet. The mercury lamp was turned on and allowed to warm for at least 10 minutes to ensure stable light emission, while the lamp cover was kept in place to prevent direct exposure to the light.

A DIN-plug-to-DIN-plug cable was connected between Channel A on the PASCO 850 interface and the DC Current Amplifier. Similarly, another DIN-plug-to-DIN-plug cable was connected between Channel B on the 850 Interface and the DC Power Supply port labeled "$-4.5V$ to $0V$." At this stage, no connections were made to the photodiode. On the DC Current Amplifier, the "CURRENT RANGES" switch was set to $10^{-13}A$. The "Calibration" button was pressed and adjusted to zero the meter, with the knob turned until the display read 000 A. Once calibrated, the "Calibration" button was returned to the "OUT" position for measurement purposes. The knobs on the DC Current Amplifier were not adjusted further throughout the experiment to maintain consistency.

The DC Power Supply was configured by ensuring that the button was in the "OUT" position to select the voltage range of $-4.5V$ to $0V$. The connections to the photodiode were then completed by attaching a special BNC-plug-to-BNC-plug cable between the port marked 'K' on the photodiode enclosure and the BNC-plug on the DC Current Amplifier. A red banana-plug patch cord was connected between the port marked 'A' on the photodiode enclosure and the red banana jack on the DC Power Supply, while a black banana-plug patch cord was connected between the black banana jacks on the photodiode enclosure and the DC Power Supply.

Adjustments to the aperture and filter were made during the experiment using the photodiode's Aperture Ring and Filter Ring. The Aperture Ring was adjusted by pulling it outward and rotating it until it clicked into position. The Filter Ring was rotated directly without pulling to change the filter setting. In the PASCO Capstone software, a data table was created to record the wavelengths of the filters as a user-entered set. A calculation column for the frequencies of the filters, with units of $10^{14}Hz$, was added and formatted to three decimal places. Additional columns were created for recording the voltage and for calculating the current readings using the formula:

$$\text{Current Reading} = [\text{Current, Ch(A)}] \times 10^{10}$$

The current readings were also formatted to three decimal places. A graph of voltage versus frequency was created, and the data collection mode was set to "Keep Mode" to ensure systematic data recording. This setup ensured accurate measurements and proper control over the variables during the experiment.

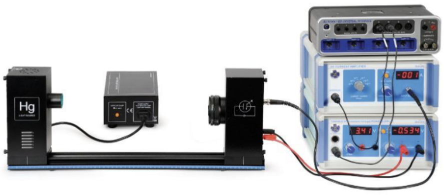


Figure 3: Experimental setup [1]

## 3.2 Data collection

### 3.2.1 Voltage vs frequency analysis

The procedure for measuring the stopping voltage as a function of light frequency was carried out using the photodiode and the mercury light source. The $8\,mm$ aperture and the $365\,nm$ filter on the photodiode were selected to begin the experiment. The cover of the Mercury Light Source was removed, and the "Preview" button on the control bar in the PASCO Capstone software was pressed to activate the system. The first row of the stopping voltage column in the data table was clicked to prepare for data entry. The voltage-adjustment knob on the DC Power Supply was carefully adjusted until the current displayed on the ammeter reached zero, ensuring that the emitted electrons were completely stopped. Once the current reading was zero, the "Keep Sample" button on the control bar was clicked to save the stopping voltage corresponding to the $365\,nm$ filter.

The filter ring on the photodiode was then rotated to the next filter with a longer wavelength, and the procedure was repeated. The stopping voltage was recorded by clicking the next row in the data table, adjusting the voltage knob to zero the ammeter reading, and clicking "Keep Sample." This process was repeated sequentially for all the available filters, with each corresponding stopping voltage being recorded in the table. Once measurements were completed for all filters, the system was stopped by clicking the "Stop" button on the control bar, and the cover was replaced onto the Mercury Light Source to ensure safety. This concluded the data collection phase of the experiment for voltage versus frequency. For the analysis, a linear fit was applied to the collected data to determine the slope of the voltage versus frequency graph. Planck's constant was calculated using the slope, and the percent difference between the experimental and accepted values was determined. Additionally, the y-intercept of the graph was used to calculate the work function of the metal used in the photodiode.

### 3.2.2 Stopping voltage vs light intensity analysis

The procedure for investigating the effect of light intensity on the stopping voltage was conducted by varying the aperture size while keeping the wavelength constant. The stopping voltage for the $436\,nm$ filter and the $8\,mm$ aperture, as recorded in the previous procedure, was entered into the appropriate table for reference. With the mercury light source covered, the aperture on the photodiode tube was adjusted from 8 mm to 4 mm. After uncovering the mercury light source, the "Preview" button was pressed in the PASCO Capstone software to begin monitoring. The voltage adjust knob on the DC Power Supply was carefully turned until the current on the ammeter reached zero, ensuring that the emitted electrons were completely stopped. The stopping voltage corresponding to the 4 mm aperture was then recorded in the table.

Next, the aperture was reduced further to $2\,mm$. The mercury light source was uncovered again, and the same procedure was repeated. The voltage adjust knob was manipulated to bring the ammeter current to zero, and the stopping voltage for the $2\,mm$ aperture was recorded in the table. Once all stopping voltages were recorded for the three aperture sizes, the average and standard deviation of the stopping voltages were calculated. The changes in stopping voltage with variations in light intensity, as controlled by the aperture size, were analyzed. This analysis was used to determine whether the kinetic energy of the emitted electrons was influenced by changes in light intensity, providing insight into the relationship between these two variables.

#### 3.2.3 Current vs light intensity in the phototube

The procedure for investigating the relationship between current and light intensity in the phototube was conducted by varying the aperture size while measuring the current at different voltages. Initially, a graph of Current Reading versus Voltage was prepared in the PASCO Capstone software to facilitate data analysis. With the mercury light source covered, the aperture on the photodiode tube was adjusted to $2\,mm$, and the $436\,nm$ filter was installed. The Current Range switch on the DC Current Amplifier was set to $10^{-12}$, and the amplifier was recalibrated to ensure accurate measurements. The mercury light source was then uncovered to allow light to strike the photodiode.

On the DC Power Supply, the range button was pressed in to set the voltage range from $-4.5V$ to $30\,V$. The initial voltage was set to $-4.5\,V$. Using the "Preview" feature in PASCO Capstone, the system was monitored until the current readings stabilized. The "Keep Sample" option was used to record data at this voltage. The voltage was then incrementally adjusted from $-4.5V$ to $30\,V$ in small steps of $0.5\,V$ to ensure a smooth curve on the graph. At each step, the system was allowed to stabilize before recording the current reading using the "Keep Sample" option. The process continued until the voltage reached $30\,V$, at which point data collection was stopped. Next, the aperture was changed to $4\,mm$ to increase the light intensity. The procedure was repeated with the wider aperture, starting from a voltage of $-4.5\,V$ and incrementing in steps of $0.5\,V$ up to $30\,V$. Current readings were recorded at each step as described previously. This allowed for a comparison of the current-voltage behavior of the phototube at different light intensities.

# 4 Data and Analysis

## 4.1 Stopping voltage vs frequency

| | **Wavelength** $(nm)$ | **Frequency** $10^{14}\,Hz$ | **Stopping voltage Ch B** $(V)$ | **Current Reading** $10^{-10}\,A$ |
|---|---|---|---|---|
| 1 | 365.0 | 8.214 | -1.63 | 0.000 |
| 2 | 404.7 | 7.408 | -1.34 | 0.000 |
| 3 | 435.8 | 6.879 | -1.16 | 0.000 |
| 4 | 546.1 | 5.490 | -0.775 | 0.000 |
| 5 | 577.0 | 5.196 | -0.671 | 0.000 |

Table 1: Experimental data for 4.1

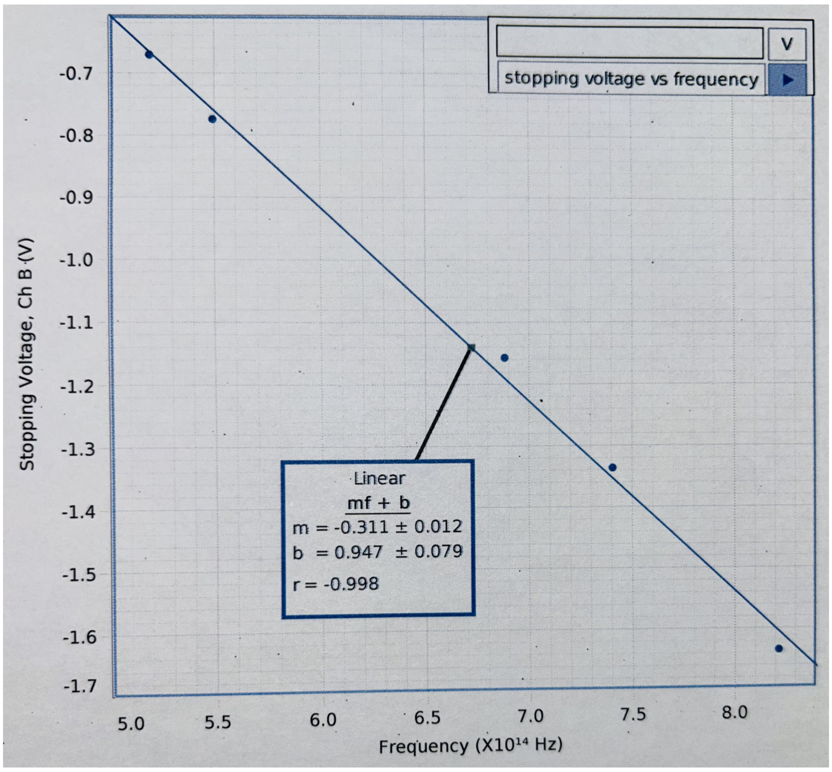



Figure 4: Stopping voltage vs frequency plot

$$\text{We know:} \quad eV_s = hf - \phi \implies V_s = \frac{h}{e}f - \frac{\phi}{e} \tag{1}$$

Evaluating Planck's constant from the slope, we get the following:

$$m = \frac{h_{ex}}{e} \implies h_{ex} = me = \frac{0.311 \times 1.602 \times 10^{-19}}{10^{14}}$$

$$\therefore h_{ex} = 4.98 \times 10^{-34}\,Js$$

Evaluating the work function from the y-intercept:

$$\therefore \phi = eb = 0.947\,eV$$

Since $E_K \propto f$, the greatest kinetic energy of the electrons corresponds to the highest frequency of incident light used, i.e. $8.214 \times 10^{14}$ Hz. This frequency falls in the ultraviolet spectrum, with a bluish-white leakage of visible light. The corresponding kinetic energy is obtained as follows:

$$E_K = hf - \phi = eV_s = 1.602 \times 10^{-19} \times 1.63 = 1.63\,eV$$

Calculating cut-off frequency and wavelength:

$$f_c = \frac{\phi}{h} = \frac{b}{m} = \frac{0.947 \times 10^{14}}{0.311} = 3.05 \times 10^{14}\,\text{Hz}$$

$$\lambda_c = \frac{c}{f_c} = \frac{3.00 \times 10^{8}}{3.05 \times 10^{14}} = 985\,nm$$

This photonic frequency/wavelength corresponds to infrared light with close to zero leakage of visible light.

## 4.2 Stopping voltage vs light intensity

| | **Aperture** ($mm$) | **Stopping Voltage** ($V$) |
|---|---|---|
| 1 | 2 | -1.33 |
| 2 | 4 | -1.33 |
| 3 | 8 | -1.32 |
| Mean | 5 | -1.33 |
| Std. Dev. | 3 | 0.01 |

Table 2: Experimental data for 4.2

The mean stopping voltage value, calculated as 1.33 V, remained consistent across the different light intensities (apertures). The standard deviation of 0.01 V indicates negligible variation in the stopping voltage despite the change in aperture diameter. The lack of change in stopping voltage with increased light intensity suggests that the kinetic energy of the emitted electrons is independent of the light intensity. This result aligns with the predictions of the photoelectric effect, which state that the kinetic energy of the emitted electrons depends only on the frequency of the incident light and not on its intensity. Light intensity affects only the number of photons incident on the metal, and therefore the number of electrons emitted (photo-current), but not the energy of each individual electron.

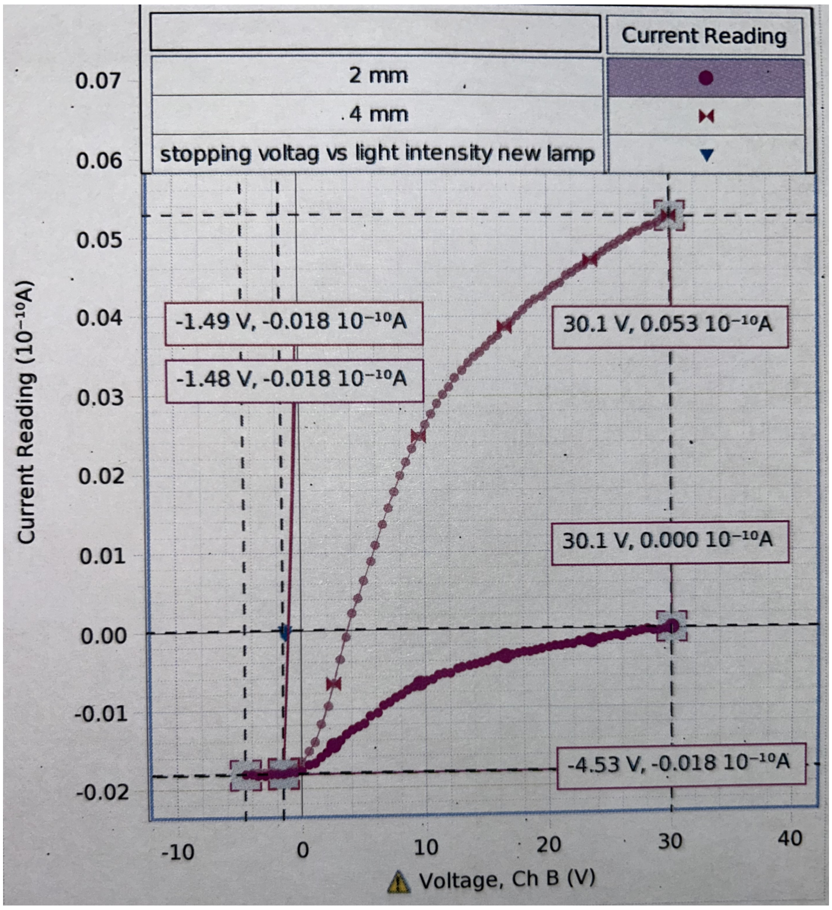



Figure 5: Voltage vs current reading plot

### 4.3 Current vs light intensity in the phototube

The data reveals a clear relationship between light intensity and the photoelectric current, as increasing the light intensity (by changing the aperture from 2 mm to 4 mm) resulted in a significant increase in the measured current. This indicates that a higher light intensity, corresponding to a greater number of incident photons, leads to more electrons being emitted per second, thus increasing the photo-current. However, the stopping voltage remained unchanged at approximately -1.49 V regardless of the light intensity. Since the stopping voltage is directly proportional to the maximum kinetic energy of the emitted electrons, this result confirms that the kinetic energy of the electrons is independent of light intensity and is instead solely determined by the frequency of the incident light. This observation aligns with the predictions of the photoelectric effect, where the energy of the ejected electrons depends on the photon energy (frequency) and not the number of photons (intensity).

# 5 Calculations and Results

## 5.1 Calculations of Results

Theoretical values of the stopping voltage $V_s$ at different frequencies ($f$), assuming $\phi = 9.48\,eV$:

| | **Wavelength** ($nm$) | **Frequency** $10^{14}\,Hz$ | **Stopping voltage** ($V$) |
|---|---|---|---|
| 1 | 365.0 | 8.214 | -2.45 |
| 2 | 404.7 | 7.408 | -2.12 |
| 3 | 435.8 | 6.879 | -1.90 |
| 4 | 546.1 | 5.490 | -1.32 |
| 5 | 577.0 | 5.196 | -1.20 |

Table 3: Theoretical data to compare against 4.1

## 5.2 Description of results

The relationship expressed in equation (1) was utilized to calculate the theoretical values of the stopping voltage ($V_s$) at different frequencies ($f$), based on the assumption that the work function ($\phi$) equals $0.948\,eV$. The experimental value of Planck's constant ($h_{ex}$) was determined to be $(4.98 \pm 0.19) \times 10^{-34}\,Js$ in section 4.1 using the slope of the stopping voltage vs. frequency plot. This result differs from the accepted theoretical value of $6.626 \times 10^{-34\,Js}$, with a percentage difference of 14%. The fractional uncertainty in the experimental value was calculated to be approximately 4%. The work function was also obtained from the y-intercept of the experimental plot as $(0.947 \pm 0.079)\,eV$.

Theoretical and experimental values of the stopping voltage were compared, and discrepancies were analyzed. For instance, at a frequency of $8.21410^{14}\,Hz$, the theoretical stopping voltage was calculated as $-2.45\,V$, whereas the experimental value was measured as $-1.63\,V$, yielding a percentage difference of 20%. Similar trends were observed across all measured frequencies, with the percentage differences ranging from 20% to 28%. The data and calculations have been systematically evaluated and presented in Tables 3 and 4. Additionally, the data from sections 4.2 and 4.3 were analyzed to evaluate the relationship between light intensity and stopping voltage, confirming that the kinetic energy of electrons are not affected by light intensity.

# 6 Error Analysis

## 6.1 Derivations

Starting with equation (1), we assume that the frequency is selected to an arbitrarily high precision because of the nature of monochrome filters.

$$eV_s = hf - \phi \implies V_s = \frac{hf}{e} - \frac{\phi}{e}$$

The stated assumption, along with the constant charge of electrons, leaves two variables that can cause errors:

$$dV_s = \frac{f}{e}dh - \frac{1}{e}d\phi \implies \|\Delta V_s\| = \sqrt{\left(\frac{f}{e}\Delta h\right)^2 + \left(\frac{1}{e}\Delta\phi\right)^2}$$

$$\therefore \Delta V_s = \frac{1}{e}\sqrt{(f\Delta h)^2 + (\Delta\phi)^2} \tag{2}$$

Furthermore, error in Planck's constant and the work function can be analyzed from the error in the graph:

$$h_{ex} = me \implies dh_{ex} = e\,dm \implies \Delta h_{ex} = e\Delta m \tag{3}$$

$$\phi = b \implies d\phi = db \implies \Delta\phi = \Delta b \tag{4}$$

## 6.2 Calculation of Error

Percentage difference in the theoretical and experimental values for Planck's constant:

$$\%\text{ diff} = \frac{h_t - h_{ex}}{h_t + h_{ex}} \cdot 100\% = \frac{6.626 - 4.98}{6.626 + 4.98} \cdot 100\% = 14\%$$

Error in Planck's constant: $\Delta h = 1.602{\times}10^{-19}{\times}0.012{\times}10^{-14} = \pm 1.92{\times}10^{-35}\,Js$

Error of the work function, obtained from Figure 4: $\Delta\phi = \pm 0.079\,eV$.

Fractional uncertainty and percentage differences in stopping voltage:

| | **Frequency** $\times 10^{-14}$ **Hz** | **Th. voltage** $(V)$ | **Ex. voltage** $(V)$ | $\Delta V/V$ % | % **diff** % |
|---|---|---|---|---|---|
| 1 | 8.214 | -2.45 | -1.63 | 7.7 | 20 |
| 2 | 7.408 | -2.12 | -1.34 | 8.9 | 23 |
| 3 | 6.879 | -1.90 | -1.16 | 9.8 | 24 |
| 4 | 5.490 | -1.32 | -0.775 | 10 | 26 |
| 5 | 5.196 | -1.20 | -0.671 | 12 | 28 |

Table 4: Error data for 4.1

### 6.3 Description of error

The calculated results indicated that the fractional uncertainty in stopping voltage increased significantly more rapidly than the percentage difference between theoretical and experimental values. Fractional uncertainties ranged from approximately 7.7% at the highest frequency to 12% at the lowest, while percentage differences rose from 20% to 28% across the same range. These results suggested that errors associated with measurements of stopping voltage were disproportionately amplified at lower voltages, likely due to limitations in the experimental apparatus and measurement resolution. Additionally, the derived uncertainty in Planck's constant was calculated as $\pm 1.92 \times 10^{-35}\, Js$, while the uncertainty in the work function was found to be $\pm 0.079\, eV$. The large percentage difference of 14% between the theoretical and experimental values of Planck's constant reinforced the presence of systematic discrepancies.

The rapid growth of fractional uncertainty relative to the percentage difference underscored a critical sensitivity of the experiment to systematic and random measurement errors, particularly at lower stopping voltages. This trend implied that the precision of voltage measurements diminished significantly for lower-energy photons, potentially due to a combination of instrument calibration errors, and increasing relative significance of electrical noise. The validity of the experiment could, therefore, be questioned based on the observed discrepancies and the magnitudes of associated uncertainties. Conversely, the experiment's validity could be argued as reasonable by citing the consistency of the experimental data with the theoretical linear relationship between stopping voltage and frequency. This agreement demonstrated that the core principles of the photoelectric effect were upheld, even if the derived constants showed deviations.

However, the large percentage differences in stopping voltage and the increasing fractional uncertainty at lower voltages highlighted significant shortcomings in the experimental setup. Improvements in instrument calibration, reduction of noise, and higher-precision apparatus could address these issues and minimize discrepancies. Ultimately, the experiment's validity depended on the interpretation of the observed results. While it provided qualitative confirmation of the photoelectric equation, the quantitative accuracy of the derived constants was limited by systematic and random errors. Future iterations of the experiment should focus on enhancing control over sources of error to improve the reliability and robustness of the results.

# 7 Conclusion

The experiment successfully validated the qualitative principles of the photoelectric effect, demonstrating the linear relationship between stopping voltage and light frequency, as predicted by quantum theory. The experimental determination of Planck's constant, $(4.98 \pm 0.19) \times 10^{-34}\, Js$, was found to differ from the accepted value of $6.626 \times 10^{-34}\, Js$ by 14%. This percentage difference, while significant, was accompanied by a relatively small fractional uncertainty of 4%, suggesting that the experimental methods were consistent but influenced by systematic errors. Similarly, the work function of the metal, calculated as $(0.947 \pm 0.079)\, eV$, aligned closely with the theoretical assumption of $0.948\, eV$, supporting the validity of the experiment in capturing the physical properties of the material.

The stopping voltage was observed to depend solely on the frequency of incident light, with no variation across different light intensities, consistent with theoretical predictions. This confirmed that the kinetic energy of ejected electrons depends only on photon energy and not on photon flux. The measured photo-current increased with light intensity, corroborating the hypothesis that the number of emitted electrons is proportional to the number of incident photons. Discrepancies between theoretical and experimental stopping voltages, such as a 20% difference at $8.214 \times 10^{14}\, Hz$, were attributed to limitations in instrumentation, calibration errors, and electrical noise. The trend of increasing fractional uncertainty at lower stopping voltages highlighted the experiment's sensitivity to measurement precision for low-energy photons, which may have amplified errors.

Despite these discrepancies, the experimental data supported the core principles of the photoelectric equation, affirming the quantum nature of light and the linear dependence of electron kinetic energy on light frequency. While the derived constants exhibited deviations, the experimental outcomes remained physically consistent with theoretical expectations. Improvements in equipment calibration and measurement precision would likely reduce systematic errors, enhancing the quantitative accuracy of future results. Consequently, the experiment was deemed successful in providing qualitative confirmation of the photoelectric effect, though quantitative measurements exhibited limitations due to inherent experimental uncertainties.

# Appendix A List of equipment

- Mercury lamp and power supply (included in SE-6609)
- Photodiode (included in SE-6609)
- Track (included in SE-6609)
- DC amplifier (BEM-5004)
- DC power supply I (BEM-5001)
- 850 universal interface (UI-5000)

## References


[1] Hanks, A. (n.d.). *Photoelectric effect.* American Association of Physics Teachers (AAPT) Advanced Labs. https://advlabs.aapt.org/bfyiii/files/PhotoelectricEffect.pdf

[2] Shaheen, S. E., Brabec, C. J., Sariciftci, N. S., Padinger, F., Fromherz, T., & Hummelen, J. C. (2001). 2.5% efficient organic plastic solar cells. *Applied Physics Letters*, 78(6), 841–843. https://doi.org/10.1063/1.1345834