Analyzing the Photoelectric Effect by Mapping Stopping Potentials (V_s) and Frequencies (ν) of LEDs of Varying Wavelength(λ)

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The photoelectric effect is a fundamental quantum mechanical principle stating that the kinetic energy of emitted electrons is proportional to the frequency of light, not its intensity. This experiment explores these properties by manipulating four different LEDs of differing wavelengths: LED 1 $\big((420 \pm 10)$ nm$\big)$, LED 3 $\big((440 \pm 10)$ nm$\big)$, LED 5 $\big((485 \pm 40)$ nm$\big)$, and LED 7 $\big((505 \pm 20)$ nm$\big)$, as well as two neutral density filters of 0.2 and 0.5 applied to LED 7. The behavior was experimentally analyzed by measuring there different stopping potentials: $(7.56 \pm 0.01) \times 10^{-1}$ V for LED 1, $(5.49 \pm 0.01) \times 10^{-1}$ V for LED 3, $(3.60 \pm 0.01) \times 10^{-1}$ V for LED 5, $(2.17 \pm 0.01) \times 10^{-1}$ V for LED 7, $(2.20 \pm 0.01) \times 10^{-1}$ V for LED 7 with neutral density filter 0.2, and $(2.21 \pm 0.01) \times 10^{-1}$ V for LED 7 with neutral density filter 0.5. The corresponding frequencies were $(7.14 \pm 0.2) \times 10^{14}$ Hz for LED 1, $(6.82 \pm 0.5) \times 10^{14}$ Hz for LED 3, $(6.19 \pm 0.5) \times 10^{14}$ Hz for LED 5, and $(5.94 \pm 0.2) \times 10^{14}$ Hz for LED 7. The linear regression fit from this stopping potential versus frequency gave an experimental Planck's constant (h) value of $(6.7 \pm 0.2) \times 10^{-34}$ J s, a work function (ϕ) value of $(3.60 \pm 0.20) \times 10^{-19}$ J, and a threshold wavelength (λ_{thr}) of $(5.58 \pm 0.38) \times 10^{2}$ nm. The metal cathode utilized in the experiment was identified as Cesium (Cs), with a work function (ϕ) of (2.25 ± 0.13) eV.

Introduction

The discovery of the photoelectric effect was observed by Heinrich Hertz in 1887, marking a pivotal milestone in modern physics, revealing that light could induce the emission of electrons from the surface of a metal. The observed phenomenon challenged classical electromagnetic theory. Previous experiments had shown that the energy of emitted electrons depended on the frequency of light rather than its intensity. This remained a theory until 1905, when Albert Einstein proposed a quantum postulate, extending Planck's hypothesis of quantized energy packets, introducing the concept of photons, and formulating the now-famous Photoelectric Equation. In the 1920s, Robert Millikan experimentally confirmed this theory, solidifying the quantum nature of light. Fundamentally, the photoelectric effect is explained by the minimum frequency of incident light required to eject electrons from a material.

In this experiment, the photoelectric effect is observed qualitatively and quantitatively by measuring the stopping potential voltage for four different wavelengths of light. Ultimately, we analyze the photon frequency and electron energy to calculate our experimental Planck's constant (h), the work function (ϕ) to determine the material of the cathode, and the threshold wavelength (λ_{thr}), which is the wavelength at which the stopping potential becomes zero.

Theory

The photoelectric effect explains the emission of electrons from a material when it is exposed to electromagnetic radiation of sufficient energy. This effect exemplifies the quantized interaction between matter and light, with light transferring energy to electrons in discrete packets known as photons.

The energy of a photon is equal to Planck's constant ($h = 6.626 \times 10^{-34}$ J $\cdot$ s) times the frequency (v) of the incident radiation:

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

Einstein's photoelectric equation describes the relationship between the kinetic energy of emitted electrons and the frequency of the incident light. In this equation, e is the elementary charge (1.602×10^{-19} C), V_s is the stopping potential (the voltage required to stop electron emission), and ϕ is the work function (the minimum energy required to release an electron from the material's surface). The equation implies that if the photon energy hv is smaller than the work function ϕ, no electrons will be emitted. This eliminates the intensity of light as a differentiating factor:

$$eV_s = hv - \phi \tag{2}$$

The threshold frequency (v_{thr}) is the minimum frequency required for electron emission. When the incident light has a frequency lower than v_{thr}, no photoelectrons are emitted. This confirms that the energy of emitted electrons depends on the frequency of light, not its intensity:

$$\phi = hv_{\text{thr}} \tag{3}$$

The kinetic energy of emitted electrons depends on frequency, with higher frequencies leading to more energetic electrons. Analytically, the slope of stopping potentials versus frequency results in a linear relation, with the slope theoretically corresponding to Planck's constant (h). The intensity of light can be modulated using neutral density (ND) filters, which reduce the intensity of light without altering its wavelength. The stopping potential of the light remains unchanged by the addition of this filter. I_0 is the initial incident light intensity, and I_T is the transmitted intensity after passing through the filter. The neutral density is defined as:

$$\mathrm{ND} = \log_{10}\left(\frac{I_0}{I_T}\right) \tag{4}$$

The linearized form of the PE equation allows for easy extraction of Planck's constant and the work function as a result of the embedded relationship.

$$V_s = \left(\frac{h}{e}\right)v - \left(\frac{\phi}{e}\right) \tag{5}$$

Other parameters of the PE effect can be derived from aspects of this linearized form of the PE effect. The work function is the minimum energy required to eject an electron from the surface of a material and is calculated from the intercept, equaling $-\phi/e$, utilizing standard uncertainty propagation.

$$\phi = -e \cdot (\text{intercept}) \tag{6}$$

$$\Delta\phi = e \cdot \Delta(\text{intercept}) \tag{7}$$

Threshold wavelength and frequency can additionally be derived from this linearization. The threshold frequency (f_{thr}) is the minimum frequency of incident light capable of ejecting electrons from the surface, while the threshold wavelength (λ_{thr}) is the longest wavelength of light that can still cause photoemission of electrons.

$$f_{\text{thr}} = -\frac{\text{intercept}}{\text{slope}} \tag{8}$$

$$\lambda_{\text{thr}} = \frac{c}{f_{\text{thr}}} \tag{9}$$

$$\frac{\Delta f_{\text{thr}}}{f_{\text{thr}}} = \left(\frac{\Delta\text{intercept}}{|\text{intercept}|}\right) + \left(\frac{\Delta\text{slope}}{|\text{slope}|}\right) \tag{10}$$

Experiment

The photoelectric effect (PE) is investigated by quantitatively measuring the relationship between the stopping potential voltage and the frequency of incident light for varying LEDs emitting different wavelengths. This information is utilized to extract Planck's constant and the work function of the metal cathode.

Firstly, a power supply system is set up to power the Mightex Multi-LED source, which holds a rotary of seven LED emission options. Voltage and current knobs on the power supply are initially set to zero while the power switch is on. To prepare for LED activation, the voltage knob is set anywhere in the range of 3 V to 5 V, which causes the multi-LED source to output the selected LED's emission depending on what numerical value is selected on the source. The wheel is set to number 1 and qualitatively measured for color output. Following this, utilizing a prism spectroscope, the outputted beam is aligned with a slit in the device to diffract the pattern to be viewed through the peephole, where a central wavelength and the symmetric spread of the light are collected. This process is repeated for every odd-numbered LED on the rotary (LED 1, 3, 5, 7).

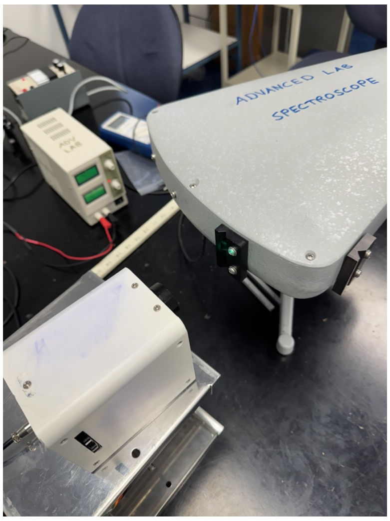

FIG. 1: Multi-LED source emitting light in the prism spectroscope

Following these recordings, a PE effect device is set up with a multimeter attached to monitor applied voltage. The PE device is activated and placed three inches away from the photocathode where the light contacts the aperture in the middle of a black cardboard inset. The voltage knob on the PE device is set so the multimeter reads 2 V, and the zero adjust knob is set to zero the current, sufficient to stop the PE effect. The voltage is slowly reduced until minimal current appears, adjusting the voltage forward and backward until the stopping potential is found; the minimum voltage at which photocurrent ceases. Five trials are taken following this process for statistical accuracy. This process is repeated for every odd-numbered LED on the rotary (LED 1, 3, 5, 7). For each LED, starting 0.3 V above the stopping potential, the voltage (V) versus current (nA) relationship is recorded in steps of 0.1 V down to 0.0 V. These measurements are repeated for each LED of differing wavelength to build a dataset correlating frequencies to stopping potentials.

The effect of light intensity on stopping potential is then tested utilizing LED 7. A neutral density filter (ND) is placed in front of the emitting LED, which uniformly reduces the light's intensity without affecting the emit-

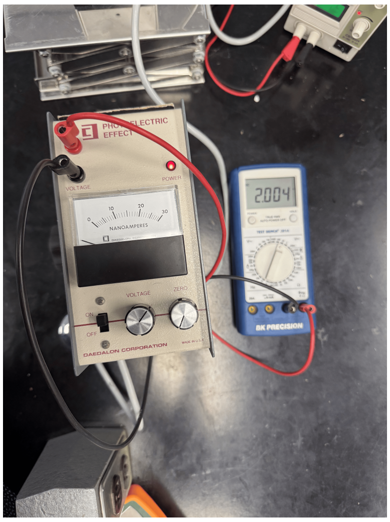

FIG. 2: Photoelectric Effect Device attached to the Multimeter.

ted wavelength. The same LED is tested under two ND filters; applied were 0.2 and 0.5. Subsequently, the relationship of applied voltage versus photocurrent detected on the PE device is recorded.

Analysis

This experiment utilized a DC power supply to deliver between [3,5]V to the Mighttex Multi-LED light source, which emits LED light of differing wavelengths (λ) onto the PE Effect device. The emitted light enters the PE Effect device, striking the metal cathode inside the vacuum tube. Each photon of incident light in the beam, according to Einstein's Photoelectric theory, carries energy ($E = hv$), where Planck's constant is h and v is the frequency of the light. If the photon's energy exceeds the metal cathode's work function (ϕ), electrons are released. The excess energy is converted into the kinetic energy of the emitted photoelectrons. The measured current through the anode is generated by these photoelectrons. This causes a photoelectric voltage tracked by the multimeter connected to the PE Effect device. Thus, Einstein's photoelectric equation, $hf = \phi + \frac{1}{2}mv^2$, explains the relationship between the kinetic energy of emitted electrons $\left(\frac{1}{2}mv^2\right)$, the work function ($\phi$), and photon energy ($hv$). The stopping potential voltage (V_s) halts the energetic electrons; this value can be found by calculating the maximum kinetic energy using the relationship $eV_s = \frac{1}{2}mv^2$. This relationship allows for direct variable correlation and calculation utilizing Einstein's Photoelectric theory and equations.

By applying the multi-LED source's directed light beam into the prism spectroscope, the observed colors, central wavelengths, and symmetric spreads were obtained for each of the odd-numbered LEDs on the rotary disc. Using the wave equation, the frequencies of

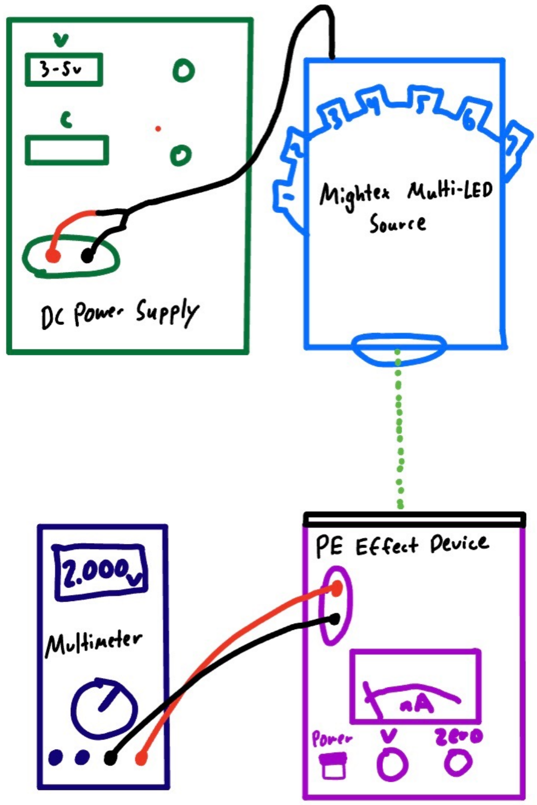

FIG. 3: Experimental Setup Observing the Photoelectric Effect

these LEDs were calculated based on the proportionality constant $c = 3.0 \times 10^8$ m/s, applied to the relationship $\nu = \frac{c}{\lambda}$.

LED	Central Wavelength (nm)	Frequency (Hz)
1	420 ± 10	$(7.14 \pm 0.17) \times 10^{14}$
3	440 ± 10	$(6.82 \pm 0.15) \times 10^{14}$
5	485 ± 40	$(6.19 \pm 0.51) \times 10^{14}$
7	505 ± 20	$(5.94 \pm 0.24) \times 10^{14}$

TABLE I: Central wavelength and corresponding frequency values for observed LEDs

To experimentally map the stopping potential voltages of the individual odd-numbered LEDs, a photoelectric effect (PE) device was used to measure the photocurrent and applied voltage. A multimeter was utilized to track the changes when voltage was applied to the system, allowing the relationship to be mapped. Five trials were conducted per LED, varying the applied voltage to the PE device to determine when the current just rose above 0 nA. This voltage reading on the multimeter is the stopping potential voltage for the LED; the lowest voltage that yields zero current for that wavelength of light.

The plot measures the photocurrent (nA) as a function of applied stopping voltage (V_s) for the four odd-

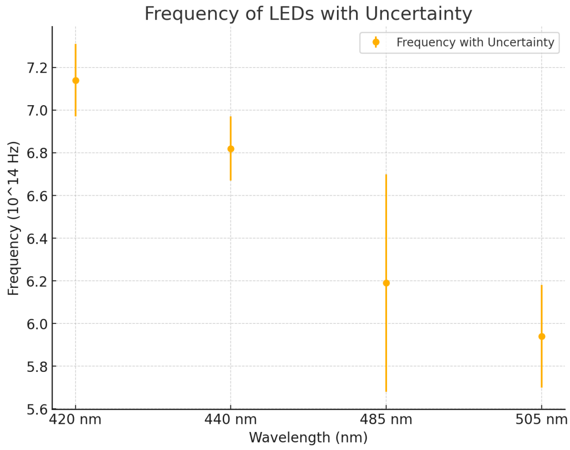

FIG. 4: Frequency versus Wavelength Relation for different LEDs

LED (Wavelength)	Stopping Potential (Vs)
LED 1 (420 nm)	0.756 ± 0.001
LED 3 (440 nm)	0.549 ± 0.001
LED 5 (485 nm)	0.360 ± 0.001
LED 7 (505 nm)	0.217 ± 0.001

TABLE II: Stopping potential voltages for different LEDs

numbered LEDs, each corresponding to a different wavelength of incident light. The trend shows that the photocurrent decreases as the stopping voltage increases. When the stopping potential (V_s) threshold is reached for each of the different wavelengths, the photocurrent becomes zero. The stopping potential represents the minimum voltage required to prevent photoelectrons from reaching the anode, the maximum kinetic energy of the emitted photoelectrons. Since frequency (ν) is inversely proportional to wavelength (λ), shorter wavelengths correspond to higher stopping potentials. Thus, LED 1 has the shortest wavelength and highest V_s, while LED 7 has the longest wavelength and lowest V_s.

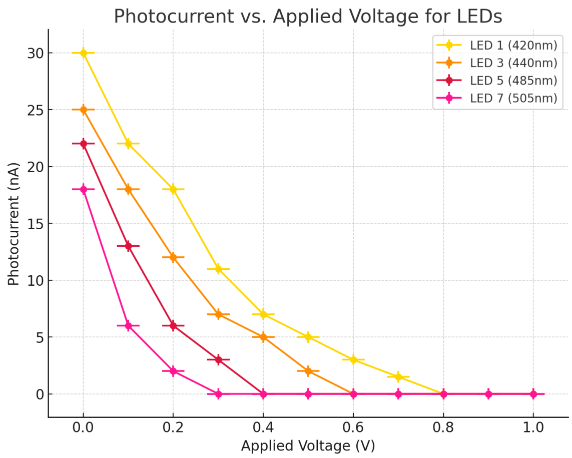

FIG. 5: Photocurrent versus Applied Voltage for LEDs

To redundantly prove the main theory of the photoelectric effect, that the energy of light depends on the wavelength, not the intensity. LED 7 was tested at three different intensity ranges: unfiltered, ND 0.2, and ND 0.5. As observed in the plot, the photocurrent decreases as the light intensity decreases. This occurs because with fewer photons reaching the photocathode, fewer electrons are emitted. Normalizing the data collapses the three curves into the same shape with identical stopping potentials (V_s) of 0.220 ± 0.001 V. Changing the intensity only affects the magnitude of the photocurrent, not the stopping potential of LED 7. Normalization showed that all datasets reach a peak value of 1, illustrating that electron kinetic energy depends solely on photon energy.

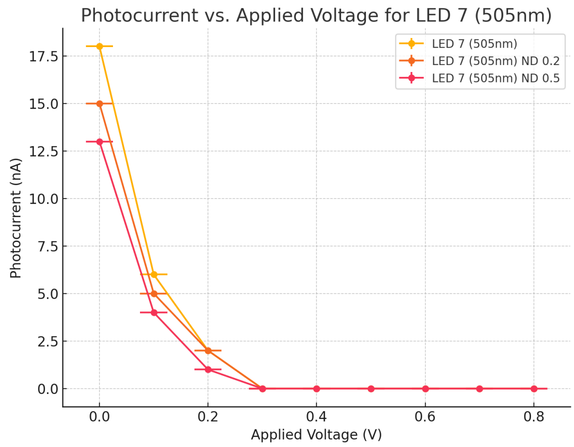

FIG. 6: Photocurrent versus Applied Voltage for LED 7 at varying Intensities

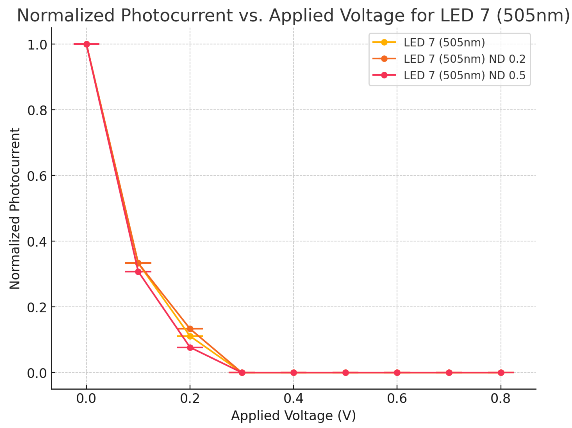

FIG. 7: Normalized Photocurrent Showing Constant Stopping Potential

In order to analyze the photoelectric effect quantitatively, a linear fit was applied to the plotted values of frequency (ν) and stopping potential (V_s). By linearizing the photoelectric equation, direct comparisons can be made between the different data points by running a linear regression, with the experimental slope corresponding to h/e and the intercept corresponding to $-\phi/e$. This relationship allows for the straightforward numerical extraction of the experimental Planck's constant (h), the work function (ϕ), and the threshold wavelength (λ_{thr}).

$$V = (4.18 \times 10^{-15})v - 2.25 \tag{11}$$

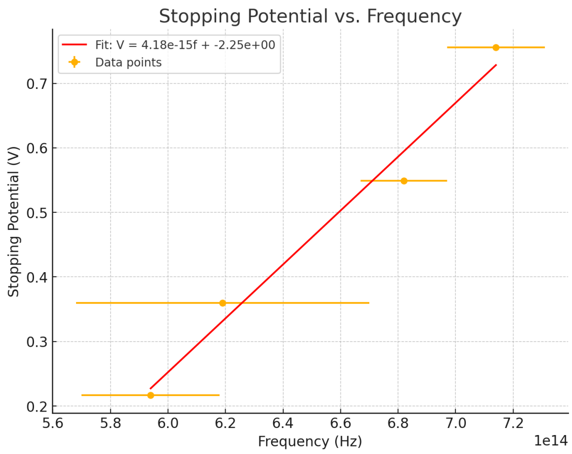

FIG. 8: Linear fit of stopping potential (V_s) versus frequency (v) with error bars.

Quantity	Experimentally Calculated	Analytically Proven
Planck's Constant	$(6.7 \pm 0.2) \times 10^{-34}$ $J{\cdot}s$	$(6.626) \times 10^{-34}$ $J{\cdot}s$
Work Function	$(3.60 \pm 0.2) \times 10^{-19}$ J	$(3.60) \times 10^{-19}$ J
Threshold Wavelength	558 ± 38 nm	580 nm

Table 1: Comparison of experimentally calculated values and analytically proven constants for the photoelectric effect using a cesium photocathode

Comparing the experimentally calculated value of Planck's constant, $h = (6.7 \pm 0.2) \times 10^{-34}$ J·s, to the known analytical value, $h = (6.626 \pm 0.2) \times 10^{-34}$ J·s, it is clear that our experimental measurement—obtained through the correlated relationship between stopping potentials (V_s) and frequencies (ν), agrees within a two-sigma uncertainty range of $[6.3, 7.1] \times 10^{-34}$ J·s. Experimentally, the work function (ϕ) of the unknown material cathode was found to be $(3.6 \pm 0.2) \times 10^{-19}$ J. To identify the material, this value was converted to electron volts (eV) using the conversion factor $1\,\text{eV} = 1.602 \times 10^{-19}$ J, a unit more commonly used to identify photoelectric properties. This equals 2.25 ± 0.13 eV. Comparing this value with known work functions, Cesium (Cs) aligns most closely with this experimental value, with a range of [2.14, 2.3] eV. Cesium has one of the lowest work functions, making it ideal for photoelectric applications, as it requires relatively minimal energy to eject electrons. Additionally, the experimentally measured threshold wavelength (λ_{thr}) of 558 ± 38 nm further confirms this, as back-solving by plugging this value into the equation $\phi = \frac{hc}{\lambda_{\text{thr}}}$ yields a ϕ of approximately 2.22 eV, which falls within Cesium's known range. We can confidently conclude that the metal cathode used in this experiment was, in fact, Cesium.

Conclusion

The experimental results demonstrated the quantum nature of light through the photoelectric effect by clearly establishing the dependent relationship between stopping potential (V_s) and the frequency of incident light. The finalized experimental Planck's constant $(6.7 \pm 0.2) \times 10^{-34}$ J s, work function $(3.6 \pm 0.2) \times 10^{-19}$ J, and the threshold wavelength (558 ± 38) nm, when compared to expected values, almost nearly aligned when taking into account uncertainty ranges. The metal of the photocathode was identified to be Cesium (Cs), with a value of (2.25 ± 0.13) eV, known for its suitability for photoemission. Overall, the consistency of trends in stopping potentials across the varying four wavelengths of light $(7.56 \pm 0.01) \times 10^{-1}$ V for LED 1, $(5.49 \pm 0.01) \times 10^{-1}$ V for LED 3, $(3.60 \pm 0.01) \times 10^{-1}$ V for LED 5, and $(2.17 \pm 0.01) \times 10^{-1}$ V for LED 7. Confirming that the kinetic energy of emitted electrons depends on the frequency of light and not its intensity, as predicted by Einstein's photoelectric equation. This trend could be further experimentally explored and proven by experimenting with a broader range of wavelength LEDs to show more discrete energy transfer between photons and electrons.

References

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