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IDENTIFICATION OF PLANCK'S CONSTANT BY LIGHT EMITTING DIODES (LEDS)

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Abstract

In this paper, a simple analysis yet a straight forward method of determining the Planck's constant by evaluating the stopping potential of five different colors of light emitting diodes (LEDs) is presented. The study aimed to identify the Planck's constant based on the relationship between the potential difference of LEDs to their respective frequencies under room temperature with low illumination of ambient light by applying a simple theoretical analysis. The experiment was performed by connecting the circuit in series connection and the voltage reading of LEDs were recorded and then presented in a graph of frequency, f versus stopping voltage, V_o. To determine the Planck's constant, the best fit line was analyzed and the centroid was also identified in order to find the minimum and maximum errors due the gradient of the graph. From the analysis, results showed that the Planck constant value was $(5.997 \pm 1.520) \times 10^{-34}$ J.s with approximately 10% of deviation from the actual value. This demonstrates that a simple analysis can be utilized to determine the Planck's constant for the purpose of the laboratory teaching and learning at the undergraduate level and can be served as a starting point for the students to understand the concept of quantization of energy in Modern Physics more effectively. This is to further suggest that the Planck's constant can be identified via a low-cost and unsophisticated experimental setup.

Keywords: Planck's constant, LEDs, Modern Physics, Undergraduate's laboratory.

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Introduction

In Modern Physics, the Planck's constant is known as the fundamental physical constant that describes the behavior of particles at the atomic level based on the concept of quantum action and explains the quantization of energy to the spectral distribution of electromagnetic radiation (Indelicato et al. 2013; Checchetti & Fantini, 2015). The first numerical estimation of h was given by Planck, a German Physicist in 1990 as $h = 6.55 \times 10^{-34}$ J.s. In 1914, the American physicist Millikan measured experimentally its value for the first time using the photoelectric effect. The result was $h = 6.626\times10^{-34}$ J.s (Makowski, 2000).

Since then, many studies have been performed using multiple techniques and different approaches in order to determine this quantity and among them are based on the application of photoelectric effect, making use a watt balance and the other by using the light emitting diodes (LEDs) of various colors (Indelicato et al., 2013; Checchetti & Fantini, 2015; Keesing, 1981; Schlamminger et al., 2014; RayChaudhuri, 2011; Dryzek & Ruebenbauer, 1992; Zhou & Cloninger, 2008; Boys et al., 1978; Precker, 2007). From an educational point of view, the determination of Planck's constant is suitable to perform by using the LEDs due to its simplicity of circuit arrangement, the attractive and fascinating of color illumination, easy and simple steps to be carried out, no sophisticated equipment is needed and most considerably is it can be performed using low cost devices (Dryzek & Ruebenbauer, 1992; Zhou & Cloninger, 2008; Precker, 2007).

From the undergraduates Modern Physics laboratory perspective, the identification of the wavelength range of the emitted LEDs may be an interesting part for students in conducting the experiment due to the colorful spectrum. Even the spectrum of different LEDs can be measured with reasonable accuracy using a manual spectrometer and grating with good resolving power (Dryzek & Ruebenbauer, 1992), but the key parameter to be determined is the voltage required by an LED to begin emitting its spectrum with known frequency (Zhou & Cloninger, 2008) which can lead to the determination of Planck’s constant. On the other hand, the purpose of this measurement is to demonstrate to the students on the relationship between the energy of light with its frequency and wavelength. This seems to be interesting as a starting point for students to carry out their first experiment in Modern Physics in order to familiarize themselves with the concept of quantization of energy (Indelicato et al. 2013; Checchetti & Fantini, 2015) and, therefore, improve their ability to understand the meaning of quantization in the atomic world. However, the accurate measurement of the Planck’s constant is determined not only from the chosen method or whatever experimental setup itself, but also the way how easy the analysis of the collected data can be performed by the students in a simple yet a straightforward analysis. This may contribute to the great importance of improving the students’ understanding on the concept of quantization of energy based on the measurement of the Planck’s constant.

In this paper, a simple analysis on the identification of Planck’s constant by using LEDs is systematically presented as follows: The first section provides an overview on a simple theoretical modelling showing the relationship between the energy of light to its frequency and voltage is systematically written for the students’ to understand clearly the fundamental ideas of the quantization of energy in relation to the use of LEDs as an emitting device. Then, a brief experimental setup used to collect preliminary data is properly designed. Next, the analysis on the measured data is systematically discussed as to show the students’ a few simple steps to analyze the results can be performed for estimating the value of the Planck’s constant. Finally, the paper is ended with a comprehensive conclusion which summarizes the entire work.

Theoretical Background

The light emitting diode or LED, is a semiconductor device which behaves as a light bulb and emits light when connected to a power supply (Checchetti & Fantini, 2015). The emission of light is in a form of discrete energy, called photon, where this energy is proportional to its frequency and can be given by:

$$E = hf \qquad (1)$$

This equation explains that the energy of each photon emitted by an LED is determined by the frequency of the radiation and the value of Planck’s constant (Zhou & Cloninger, 2008). The LED starts to emit light when the voltage has reached its minimum threshold and the current is allowed to flow through it. The relation between energy and the minimum threshold voltage can be written as:

$$E = eV_o \qquad (2)$$

where e is the charge of an electron with the value of 1.6022×10^{-19} C (Zhou & Cloninger, 2008). Equation (1) is comparable with equation (2) and this provides a linear correlation between the frequency and voltage as the LED is turned on. This correlation can be shown as:

$$hf = eV_o \qquad (3)$$

By rearranging equation (3), it gives equation (4) which demonstrates the linearity of y- and x- axes as defined by a straight line graph of y = mx + c. This can be shown from a plot of y- versus x-axis graph, where, the y-axis is represented the minimum threshold voltage, meanwhile the x-axis is the frequency of LED.

$$V_o = \frac{h}{e} f \tag{4}$$

From a plot of minimum threshold voltage versus frequency graph, the relation between these two axes provides a straight line slope where the magnitude of the Planck's constant can be identified from the multiplication of this slope to the charge of an electron.

Experimental Setup

LEDs Specification

In this experiment, five different colors of commercially available LEDs with different emission of wavelengths namely, red, orange, yellow, green and blue were studied. The nominal wavelength of each LED is presented in Table 1. The frequency of each LED was identified by applying the equation (5) where, c is speed of light = 3.0 × 10^8 m/s.

$$f = \frac{c}{\lambda} \tag{5}$$

Table 1. The wavelength and frequency of four different LEDs

Color of LED	Nominal Wavelength, λ (nm)	Frequency, f ($\times 10^{14}$ Hz)
Red	635	4.72
Orange	605	4.96
Yellow	590	5.09
Green	560	5.36
Blue	480	6.25

Circuit Arrangement

The experiment was conducted by connecting the LED in series with the power supply by using alligator clips. Then, the multimeter was connected across the LED in order to measure the value of the potential difference, V. Before starting, it is made sure that all lights in the room was turned off. This is to ensure that the emission of the LED light is traceable once the current flows through it. Once the power supply was applied, the light emitted from the LED and the voltage reading were observed and recorded simultaneously. After that, the experiment was repeated with another LED color. The reading was taken five times for each LED and its mean value was calculated. The frequency of each LED was calculated from the nominal LED's wavelength value. Finally, to find the Planck's constant, all measured data was tabulated in a graph of voltage, V against frequency, f.

Results and Discussion

The minimum voltage or the stopping voltage, V_o of each LED was obtained from a series connection and the results are shown in Table 2. Overall, among those five LEDs, the blue LED has the highest reading of stopping voltage at 1.376 V and the lowest reading is the red LED at 0.814 V. This shows that the stopping voltage increases with the increase in frequency which indicates the LED with color closely to the ultra violet region has the lower wavelength.

Table 2. The minimum voltage readings for five different color of LEDs

Color of LED	Frequency, f ($\times 10^{14}$ Hz)	Stopping Voltage, V_o (V)
Red	4.72	0.814
Orange	4.96	0.870
Yellow	5.09	0.918
Green	5.36	0.952
Blue	6.25	1.376

In order to identify the value of Planck's constant, a graph of potential difference, V against frequency, f was plotted as illustrated in Figure 1. In this graph, the x-axis represents the frequency and y-axis represents the stopping voltage. Overall, the graph shows that the stopping voltage of each LED increased linearly with the increase of the frequency. This can be seen from the best fit line that shows the linear relationship between the frequency and stopping potential with the slope of 0.3743×10^{-14}.

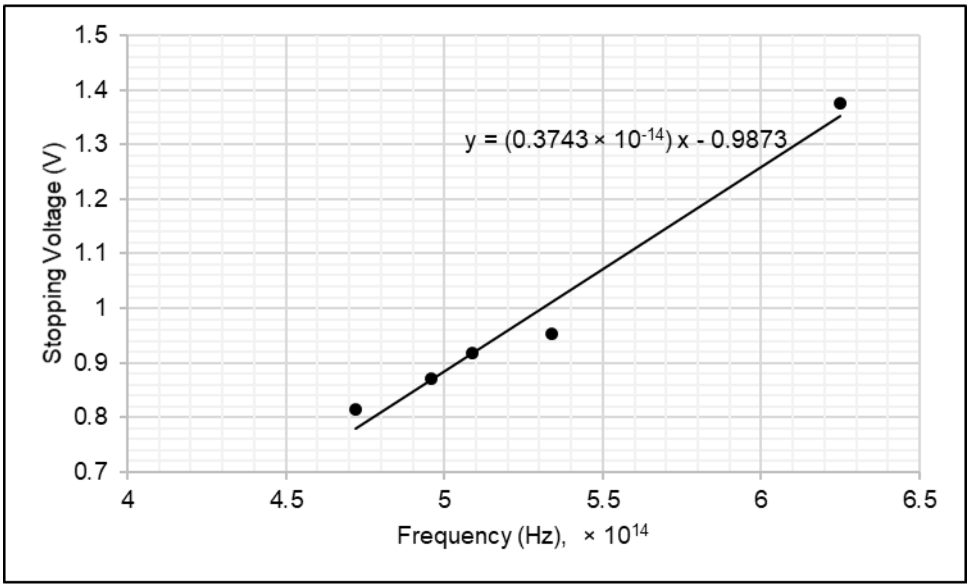

Figure 1. Graph of stopping voltage, V_o against frequency, f

Then, to further analyze the error due to the graph, the central point of data which is called centroid was determined using the following equation:

$$\left(\frac{\Sigma f}{n}, \frac{\Sigma V}{n}\right) \qquad (6)$$

where n is the number of reading. Table 3 shows the centroid due to the frequency and the potential difference was calculated from the sum of frequency and the sum of potential difference.

Table 3. The centroid due to the frequency and potential difference

Frequency, *f* **($\times 10^{14}$ Hz)**	**Stopping Voltage, V_o** **(V)**
4.72	0.814
4.96	0.870
5.09	0.918
5.34	0.952
6.25	1.376
$\Sigma f = 26.36$	$\Sigma V_o = 4.930$
$\frac{\Sigma f}{n} = 5.272$	$\frac{\Sigma V_o}{n} = 0.986$

Since the coordinate of the centroid is ($x = 5.272 \times 10^{14}$, $y = 0.986$). Therefore, the minimum and maximum slopes which lie to the centroid can be estimated from the error analysis due to a slope of the graph. Figure 2 shows the minimum and maximum slopes that indicates the error due to the slope of a graph. In this graph, the similar axis was chosen as to represent the frequency and the stopping voltage. The minimum and maximum slopes are represented in red and blue lines with the best fit line of each slope is 0.2876×10^{-14} and 0.4771×10^{-14} respectively. The dark line in this graph represents the actual slope of the original graph in Figure 1.

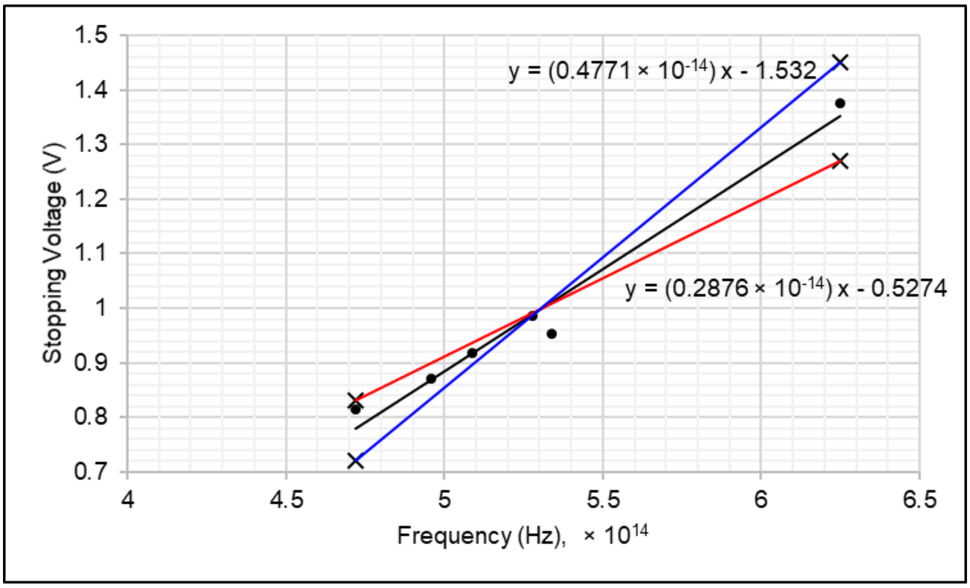

Figure 2. The maximum and minimum lines for error analysis due to slope of the graph

Next, the extrapolated slopes shown in Figure 1 and Figure 2 were then multiplied with the charge of an electron as to determine the value of the Planck's constant with the minimum and maximum error due to the actual graph. This can be shown in Table 4, the summary of the calculated Planck's constant with minimum and maximum error. Overall, the calculated Planck's constant from the actual slope is 5.997 × 10^{-34} J.s, while the minimum and maximum errors are 4.608 × 10^{-34} J.s and 7.644 × 10^{-34} J.s respectively.

Table 4. The summary of Planck's constant with minimum and maximum values

Slope	**Planck's constant (× 10^{-34} J.s) = slope × *e***
Actual slope (Dark)	5.997
Minimum slope (Red)	4.608
Maximum slope (Blue)	7.644

From the above data (Table 4), the uncertainty of the experiment can be identified by finding the multiplication of charge of an electron to the average of the difference between the maximum and minimum slopes, which gives 1.520 × 10^{-14}. Hence, the value of the Planck's constant determined by using LEDs is (5.997 ± 1.520) × 10^{-34} J.s with approximately 10% of deviation from the actual value. Although the value obtained from the LEDs-based identification is not showing a good precision of the Planck's constant, but this technique seems to be very effective to demonstrate to the entry-level of undergraduate students on the fundamental concept of quantization energy in Modern Physics. In fact, this value is in good agreement with the other researchers which reported that the Planck's constant values vary from 5.77 × 10^{-34} to 7.67 × 10^{-34} by applying the computer-based experiment to verify the Planck's constant value using LEDs (Zhou & Cloninger, 2008).

Conclusion

In summary, the study shows that the Planck's constant was successfully identified by only applying a simple analysis and unsophisticated experimental setup. This appears to be fascinating for the undergraduate students as a starting point to carry out their experiment on the fundamental explanation of the quantization of energy in Modern Physics by investigating the relationship between energy and frequency of LEDs. In addition, this suggests that their ability to understand the concept of quantization is more effective through a hands-on experience, interesting demonstration using various attractive colors of LEDs and simple analysis on the data. Furthermore, the unsophisticated equipment used in this work indicates that the identification of Planck's constant can be done by only using commercially available LEDs which are considerably inexpensive in the market. In fact, this reflects to the cost efficiency in terms of short-term budgeting compared to some fundamental Physics experiments which require highly advanced equipments and regular maintenance.

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