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Determining Planck's Constant Using Raspberry Pi Microprocessor and Light-Emitting Diodes

Chittaranjan Ghosh[1], Koustav Dey[2]*
[1]Department of Physics, Sri Ramkrishna Sarada Vidyamahapitha,
Kamarpukur, Hooghly, West Bengal, 712612, India
[2]Electrical and Computer Engineering,
Missouri University of Science and Technology, Missouri 65401, USA

Abstract. This study introduces a methodology for estimating Planck's constant by employing light-emitting diodes (LEDs) through the mechanism of capacitor discharge. The innovation lies in the utilization of a cost-effective single-board microprocessor, the Raspberry Pi, which is seamlessly integrated with Python software to facilitate real-time data acquisition and visualization. Notably, the methodology diverges from traditional approaches by determining the threshold voltages of LEDs, thereby eliminating the need for direct current measurements and instead focusing on the voltage variations across the capacitor during the discharge phases. The precision of this technique is underscored by the measured value of Planck's constant, which is determined to be 6.05 $\times 10^{-34}$ J.s, aligning closely with accepted values within a margin of experimental error of 8.68%.

Keywords: Microcomputer, Raspberry Pi, RC circuit, Planck's constant, open-source software, experimental physics

Introduction

The integration of cost-effective single-board microcontrollers into physics laboratory exercises, both within classroom settings and in extended learning environments, is becoming increasingly prevalent. These devices are instrumental in exploring the behaviour of dynamical variables within physical systems that operate at scales comparable to Planck's constant, thereby necessitating a quantum physics framework for accurate description. Planck's constant itself is a cornerstone of quantum physics, foundational to the discipline's theoretical structure.

The employment of light-emitting diodes (LEDs) for the empirical determination of Planck's constant offers an accessible entry point for undergraduate students into the complexities of quantum physics (Pili & Violanda, 2019; Keesing, 1981; O'Connor & O'Connor, 1974; Ghosh & Dey, 2024; Holcomb, 1997; Nieves et al., 1997; Garver, 2006). By examining the band gap of LEDs, students can gain a rudimentary understanding of photon energy emission, fostering a more intuitive grasp of quantum mechanics principles.

Advancements in computer-based software, when interfaced with experimental circuitry, significantly enhance the accuracy of data collection and analysis in LED-related experiments. This technological synergy reduces potential errors, thereby improving the reliability of experimental outcomes (Zhou & Cloninger, 2008). The Raspberry Pi (RPi), a prominent single-board microprocessor, has garnered significant attention in educational circles for its versatility and ease of integration with General Purpose Input Output (GPIO) pins through Python programming. This setup offers a modern alternative to traditional laboratory equipment, encompassing DC power supplies, signal generators, and the conventional array of personal computers connected to oscilloscopes.

The enthusiasm within the physics community to leverage these technologies in pursuit of determining fundamental constants in physics is noteworthy. Such endeavours not only

* Corresponding Author

enrich the educational experience but also contribute to the ongoing quest to refine our understanding of the fundamental parameters that govern the universe.

In our study, we introduce an innovative experiment utilizing a capacitor-discharge method combined with RPi and LEDs to determine Planck's constant (h). This experimental setup is designed to be easily implemented in undergraduate laboratory sessions or classroom environments, offering a hands-on learning experience. This experiment not only aims to calculate Planck's constant with precision but also provides students with a valuable opportunity to deepen their understanding of fundamental physics concepts such as the charging and discharging processes of capacitors. Furthermore, it integrates the application of Python programming into the experimental procedure, enhancing students' computational skills and their ability to apply coding in scientific research. The inclusion of Python programming, in particular, emphasizes the importance of computational literacy in modern scientific inquiry, bridging the gap between theoretical physics and practical laboratory work. By engaging with this experiment, students not only grasp key principles of quantum mechanics but also develop a versatile skill set that encompasses both experimental physics and computational analysis.

Theoretical Background

The LED is an ordinary P-N junction diode which emits light when forward-biased. The 'electron' in the conduction band from N-side loses energy when recombined with the 'hole' in the valence band from the P-side. The energy difference of the conduction band to valence band is known as band gap E_g. The emission of light is possible only at the minimum applied voltage called threshold voltage or turn-on voltage of LED, V_{th}. The threshold potential V_{th} is related to band gap, E_g by

$$E_g = eV_{th} \tag{1}$$

$e = 1.602176634 \times 10^{-19}$ C is the electronic charge. If the light wave of frequency ν is emitted during the process, the photon energy is given by the Planck-Einstein relation

$$E_{th} = h\nu \tag{2}$$

h is the Planck's constant, c is the velocity of light in vacuum. Based on the wavelength frequency relation $\nu = c/\lambda$, from equations (1) and (2) we get

$$h = eV_{th} \cdot \frac{\lambda}{c} \tag{3}$$

Equation (3) provides the working formula of our experiment and the Planck's constant can be determined measuring V_{th}.

Experimental Requirements

The basic design to perform the experiment consists of an RC circuit, Analog to Digital Converter (ADC) and Raspberry Pi 4 Model B running in the Raspbian operating system. The real-time analog voltage is read through channel CH0 of IC MCP3008 with eight channel 10-bit resolution. Circuit connections are built on a solderless breadboard. A 40-pin extension cable is connected between the GPIO of RPi and the T-shaped cobbler set on the breadboard as shown in Figure 1 to allow easier connections. The schematic circuit connection scheme using fritzing software is shown in Figure 2. The connections of MCP3008 are shown in Table 1. The voltage data is processed in RPi using Python software. The charging and discharging of the capacitor (Mandanici et al., 2021; Sanjaya et al., 2018) are used to implement our experiment. A special type of charging-discharging key is used to perform the charge and discharge process. The GPIO17 is selected for applying an input voltage of 3.3 V. The cathode of an electrolytic capacitor of 1000 µF in series with the resistor 4.7 kΩ is connected to the ground (GND) pin and the other end of the resistor is connected to the pin GPIO17. The data was collected and analyzed using Python scripts (Mandanici et al., 2021) and open-source libraries.

Experimental Procedures, Results and Discussion

The time constant of the RC circuit τ = RC = 4.7 s. The capacitor is charged through the resistor for 40 s with applying input voltage of 3.3 V via software for a time duration of 40s. Immediately after the first 40 seconds, the input voltage switched to 0 V via software and the capacitor discharges through the LED for another 40 s.

Table 1. Connection between MCP3008 pin and GPIO pin of RPi. NC means no connection

MCP3008 Pin details			MCP3008 pin details		Connected to GPIO
Pin. No.	Pin Name	Connected to capacitor	Pin. no.	Pin Name	Pin of RPi
1	CH0	Anode	9	DGND	GROUND
2	CH1	NC	10	CS/SHDN	GPIO8
3	CH2	NC	11	D-IN	GPIO10
4	CH3	NC	12	D-OUT	GPIO9
5	CH4	NC	13	CLK	GPIO11
6	CH5	NC	14	AGND	GROUND
7	CH6	NC	15	VREF	3.3 V
8	CH7	NC	16	VDD	3.3 V

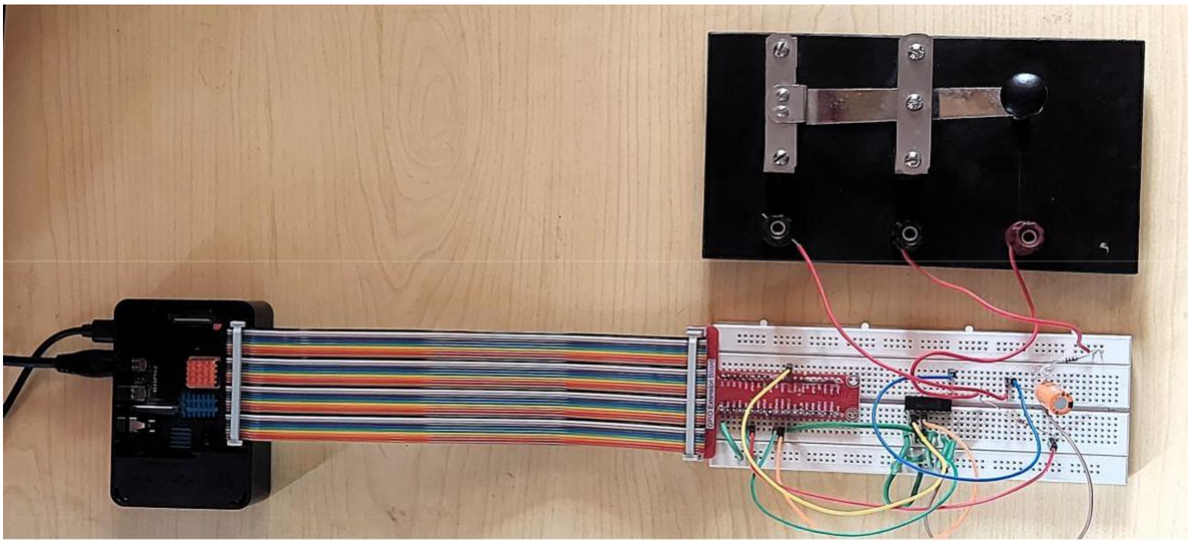

Figure 1. Experiment set-up. We used Raspberry Pi, 40-pin cable, extension board, solderless breadboard, jumpers, LEDs, MCP3008, special charging-discharging key,100 Ω, 4.7 kΩ resistor and 1000 µF capacitor

The rocker of the charge-discharge special key is kept at pressed state during charging process and released at the beginning of the discharge process to disconnect capacitor from 4.7kΩ charging resistor and connect to the LED. A 100Ω resister is connected before the LED as current limiter in the circuit to avoid exceeding diode current over 20 mA. The potential difference across capacitor is measured as a function of time. Two subsequent data is recorded with a time gap 100 ms via software. The charging and discharging time is large enough (~ 8.5

times of τ) to attains saturation region. The recorded potential is plotted in real time using Matplotlib library in Python. The non-zero constant voltage (V_{th}) obtained during capacitor discharge indicates the threshold voltage to turn-on LEDs. The charge and discharge voltage plots against time in our experiment for red LED and blue LED are shown in Figure 2 and 3 respectively. The same process repeated for all LEDs. We have used 5 mm red, orange, yellow, green and blue LEDs with wavelengths 660, 610, 585, 565 and 470 nm respectively purchased from local market.

Table 2. Turn on voltage (Threshold voltage) of five different LEDs and experimental calculated Planck's constant

Obs. No.	LEDs	Wavelength λ in [nm]	V_{th} in [Volt]	Planck's constant, h in [10^{-34} J.s]
1	Red	660	1.53	5.41
2	Orange	610	1.56	5.10
3	Yellow	585	1.62	5.07
4	Green	565	2.10	6.35
5	Blue	470	2.38	5.99

The Planck's constant is calculated using the threshold potentials of each LEDs assuming that the experiment is carried out in vacuum. Accordingly, the calculations used $e = 1.602176634 \times 10^{-19}$ C, $c = 2.99792458 \times 10^{8}$ m/s respectively.

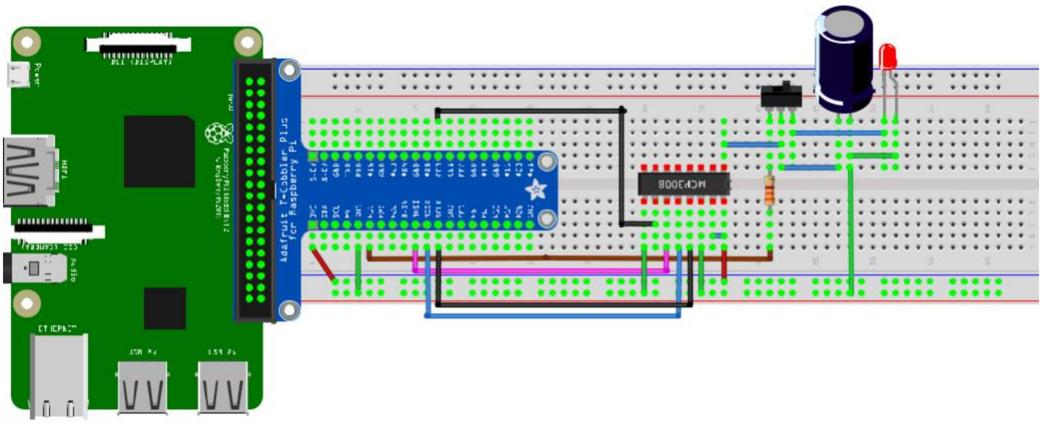

Figure 2. Schematic circuit connection scheme using Fritzing

In addition to this based on the threshold voltage from Table 2 for frequency of the emitted light of LEDs, the threshold voltage versus frequency is plotted in figure 3. The dash line shows the best-fitted line of frequency versus V_{th} and the calculated Planck's constant is 6.02896354 $\times 10^{-34}$ J.s.

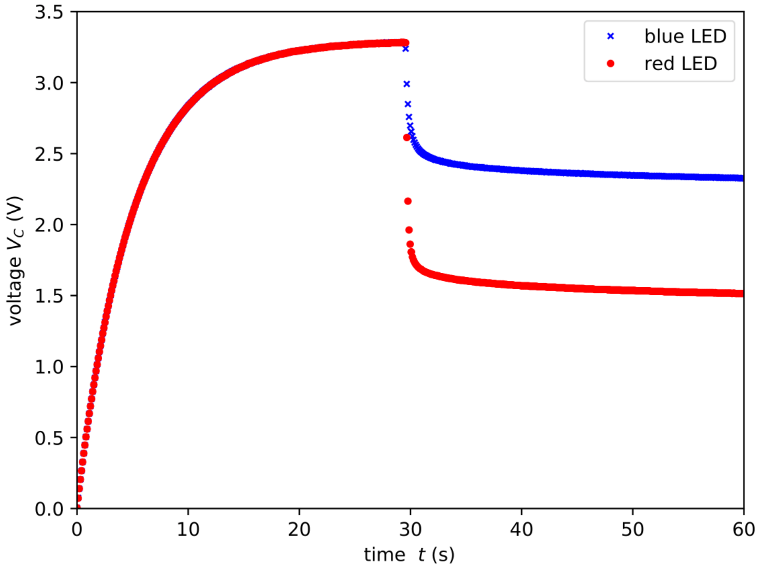

Figure 3. Plots of potential across capacitor during entire charging and discharging process for experimental data vs time. R = 4.7kΩ, C = 1000 µF. The experimental data for two extremities, blue LED and red LED are represented (x) and (•) respectively. The voltage is measured using RPi 4 B and ADC MCP3008.

Discussion and Conclusions

The threshold voltage to turn on LED during capacitor discharge is measured and using the proper equation on substituting the values of fundamental constants c, h the Planck's constant is calculated. A large number of data is collected and real-time plotted with the help of RPi. This method is reliable, repeatable and can be replicated in any Physics Laboratory. This method involves no eye estimation regarding 'turn-on' point of LEDs to emits light. Secondly, no lack of a well-defined 'turn-on' voltage case arises unlike I-V characteristics of LEDs. This study of determination of Planck's constant receiving of the energy needed to excite free electrons of LEDs from the charged capacitor greatly facilitate to achieve our goal. The conventional value of Planck's constant h= $6.62607015 \times 10^{-34}$ J.s.

The Planck's constant obtained from the graph is 6.05×10^{-34} with an experimental error of 9.01% to the conventional value as depicted in figure 4. The error may be due to the non-zero energy difference of band gap energy to the energy of the emitted light from LEDs (Zollman & Bearden, 2019). The result can be improved by determining the exact wavelength generated by the LEDs.

However, what may be the error, the experiment can help students to realize the confirmation of the Planck-Einstein relation which implies that the light is quantized. Moreover, they also become in contact with the RPi platform widely used in experimental measurements in the scientific research.

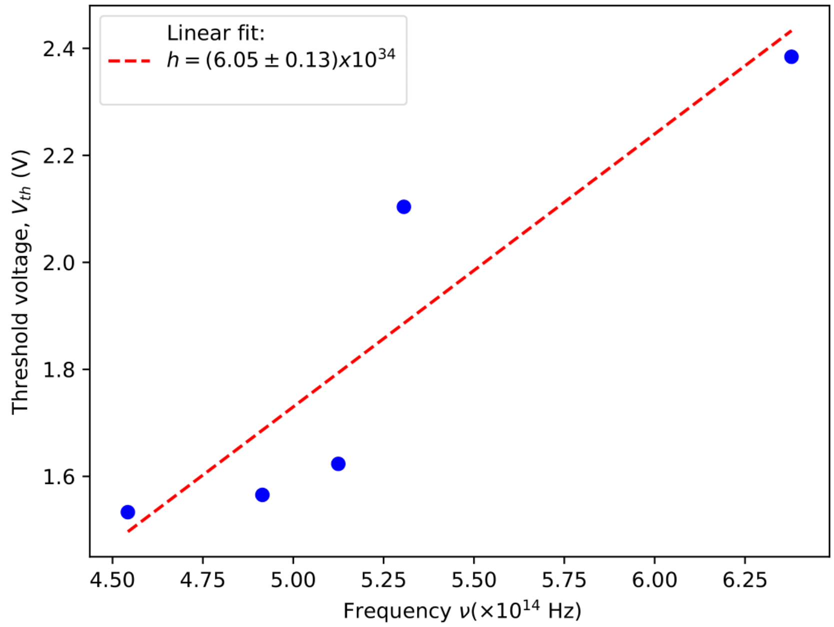

Figure 4. A graph of threshold potential versus frequency for five LEDs

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