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A Simple Photovoltaic Experiment for Measuring Planck's Constant Using Colour Lasers

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ABSTRACT

The photovoltaic experiment provided a simple, affordable method to determine Planck's constant through empirical learning. This experiment allowed students to present concrete data using easily available, low-cost materials. The experiment utilised a photovoltaic method, employing a simple, self-designed setup that used three laser pointers with wavelengths of 650nm (red), 535nm (green), and 405nm (blue) as independent variables. A 6V, 1W mini solar cell was used as the target, while the speed of light and electron charge were treated as control variables. The laser pointers were powered by a 3V battery. The data were analysed by plotting the relationship between 1/λ (inverse wavelength) and the measured voltage as the dependent variable. A linear regression analysis was performed to obtain the gradient, which was used to calculate Planck's constant. The experiment yielded a calculated Planck's constant of 7.09×10^{-35}*Js, with a deviation of* 5.69×10^{-34}*Js, resulting in a relative error of 8.89%. This relative error could be attributed to several factors, including refraction effects caused by the glass layer and adhesive used to protect the semiconductor plate of the solar cell, as well as discrepancies between the actual wavelengths of the laser beams and the labelled wavelengths on the laser pointers.*

INTRODUCTION

Scientific research is a systematic investigation of natural phenomena using scientific methods through both inductive and deductive approaches. The inductive method involves observation, hypothesis formulation, testing, data analysis, and evaluation. Meanwhile, the deductive method focuses on developing theories and mathematical models, computer simulations, and deductive reasoning. Experimental science generally relies on the inductive method through experimentation and observation (Hadi, 2023).

This statement is reinforced by Suja (2019), who explained that inductive reasoning begins with specific observations and moves toward general conclusions, while deductive reasoning starts from general principles and leads to specific conclusions. Inductive reasoning is empirical in nature and concludes the whole, whereas deductive reasoning provides a rational character to scientific knowledge and remains consistent with previously accumulated knowledge.

This study adopts an inductive approach to test the constant proposed in Planck's quantum theory, as conducted by previous researchers. The Photoelectric Effect Experiment was first introduced by Albert Einstein in 1905 as one of the facts supporting the validity of Planck's Quantum Theory, which states that Planck's Constant is a fundamental constant of nature closely related to quantum concepts in modern physics (Beiser, 1990; Adhiguna & Taqwa, 2020).

Expressions of truth in science are inherently tentative; they may change when examined through different tools or perspectives, or evolve. Science teaches us to continue the process—either discovering new knowledge or confirming existing truths. Dasmo et al. (2019) noted that in 1887, Heinrich Hertz experimented by illuminating a cathode plate with various types of light, demonstrating that electrons were emitted from the plate. This experiment later became known as the photoelectric effect. In classical physics, this phenomenon was puzzling because many aspects could not be explained using classical theory. Max Planck later proposed that vibrating atoms can absorb or emit energy only in discrete bundles called quanta (Krane, 2008).

Physics, as a branch of science, contains numerous mathematical equations, empirical observations supported by experiments, and theories constructed through logical reasoning by scientists. Among the prominent theories in the scientific world is quantum theory, which discusses the dual nature of light. Light behaves as a particle because it can collide with other particles, and as a wave because it exhibits wave properties (Setiawan & Samsudin, 2023).

As particles, light strikes a metal surface containing atoms composed of electrons, protons, and neutrons. Electron energy levels allow for the possibility of exchanging energy with incoming photons. Each electron has a threshold (work function) that must be exceeded to remain in its orbit. When the energy supplied by a photon exceeds this threshold, the electron becomes excited and is ejected, producing moving charges that generate an electric current. This phenomenon is known as the photoelectric effect.

A key condition for electron emission is that the photon energy must be greater than the electron's threshold energy. This phenomenon needs to be explained to students and the general public so that they can understand and observe it directly. Several physical quantities are involved in this study, including photon energy—determined by the colour or wavelength (λ) of light—electron charge ($e = 1.6 \times 10^{-19}$C), the speed of light ($c = 3 \times 10^{8}$m/s), and Planck's constant ($h \approx 6.63 \times 10^{-34}$Js). These quantities are fundamentally related through the photoelectric effect, which explains the emission of electrons due to incident electromagnetic radiation (Einstein, 1905; Tipler & Llewellyn, 2012). Through experimental activities, students can gain direct empirical experience in understanding the photoelectric and photovoltaic phenomena, as widely implemented in physics education laboratories (Anwar et al., 2018; Mogi et al., 2021). The key distinction between the Photoelectric Effect and the Photovoltaic Effect is that in the Photoelectric Effect, electrons are emitted into open space, whereas in the Photovoltaic Effect, the electrons enter a different material (Tedi, 2023). The relationship between light wavelength and energy has long been established, beginning with Thomas Young's pioneering work on light interference, which enabled the measurement of light wavelengths and the characterization of the visible spectrum ranging from red (700–650nm), yellow (600–550nm), green (550–500nm), to blue (500–450nm) (Young, 1802; Singh, 2008).

Understanding modern physics concepts requires real experimentation. Courses in modern physics must therefore be supported by laboratory work or hands-on experiments. Many physical phenomena are difficult to observe directly because they are abstract, such as the photoelectric effect. Furthermore, experimental equipment is often expensive. As a result, many educators use virtual laboratories with computer-based simulations, such as PhET (Physics Education Technology) (Anwar et al., 2018; Dasmo et al., 2019; Hamdani, 2022). PhET, developed by the University of Colorado, provides various simulations through the Simulation-Based Laboratory (SBL) method.

With technological developments, these devices can now be computerised. This motivated researchers to develop data acquisition systems using Arduino and LabVIEW for photoelectric effect experiments (Umma, 2017; Putri, 2019). For these reasons, the authors consider it necessary to conduct a photoelectric experiment using simple, accessible tools that can be performed by anyone, anywhere. Through a photovoltaic approach using solar cells, this study aims to facilitate students' empirical construction of scientific understanding through the acquisition of concrete data using affordable, everyday tools.

RESEARCH METHOD

Acting as the photon energy is a monochromatic beam from a laser pointer (hf) that is alternately directed at the solar cell, producing a flow of charge with kinetic energy (Ek), indicated by the electron-volt (eV) voltage displayed on a digital multimeter in volts. To determine the value of Planck's constant, a regression analysis method was employed (Firdaus, 2017).

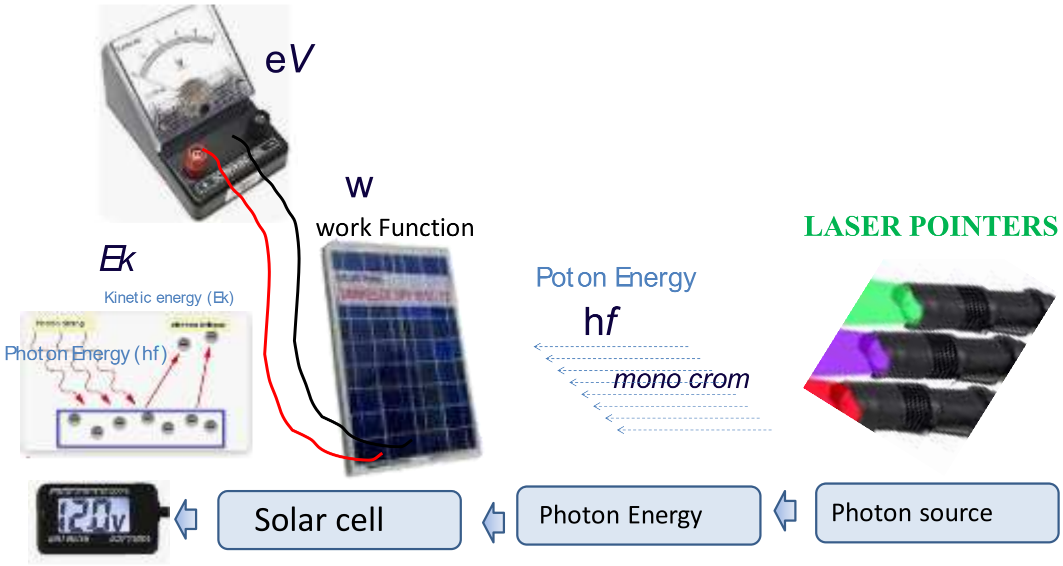

Fig. 1 *Schematic of the Photoelectric Experiment*

The experiment was carried out using an experimental method, employing equipment that was self-designed and assembled. A simple circuit was constructed using three laser pointer LEDs—red, green, and blue—as photon sources. The target was a semiconductor plate made of silicon that had been modernly modified into a mini solar cell of the 6V 1W type. A solar cell functions to convert solar energy into electrical energy (Arini & Chrisna, 2019). The laser pointers were used with known wavelength labels for each colour: red at 650 nm, green at 535nm, and blue at 405 nm, serving as the independent variables in this study. Laser beams are typically highly coherent, meaning the emitted light does not spread and has a narrow frequency range (monochromatic light) (Paschotta, 2008). Monochromatic light is widely used in optical applications today, with lasers being one of the most familiar examples (Shavira et al., n.d.). Meanwhile, the speed of light, 3.108m/s (Kurnia, 2021), and the electron charge, e = 1.6 × 10^{-19}C (Fitriana, 2022), functioned as control variables. A 3V battery was used as the power source for the laser pointers. The voltage data, as the dependent variable, were obtained from the output of each light colour as displayed on a digital multimeter.

The circuit system, along with the colored laser LEDs, was arranged inside a mini light-proof box designed to prevent external light from entering, ensuring the stability of the light intensity striking the solar cell as the target electrode. The colored lasers—three LED units—were used to ensure that the intensity of the light entering the solar-cell wafer remained stable.

This study employed an experimental method to determine Planck's constant through a simple photovoltaic approach. The experimental setup consisted of a circuit system integrated with colored LED laser light sources and a photovoltaic (solar) cell as the target electrode. All components were placed inside a mini light-proof box to eliminate the influence of external light, ensuring stable and uniform light intensity incident on the solar cell. The photovoltaic effect arises primarily in semiconductors, which exhibit medium electrical conductivity due to electrons occupying distinct energy bands—namely the conduction band and valence band—while the region without electrons is known as the band gap (Rudawin et al., 2020).

The laser pointers, each emitting a different wavelength, served as photon sources to vary the incident light frequency. The output voltage generated by the photovoltaic cell for each light colour was measured using a digital multimeter and recorded as the dependent variable. Similar experimental approaches using light sources of different wavelengths to determine Planck's constant through voltage–wavelength or voltage–frequency relationships have been widely implemented in physics education laboratories (Anwar et al., 2018; Mogi et al., 2021). Data analysis was conducted by plotting the relationship between the output voltage and the inverse wavelength (1/λ). Linear interpolation was applied to obtain the gradient of the resulting graph, which was subsequently used to calculate Planck's constant based on the principles of the photovoltaic and photoelectric effects (Nelson, 2003; Singh, 2008). This approach enables students to empirically construct scientific understanding using affordable and easily accessible experimental tools.

RESULTS AND DISCUSSION

After experimenting, data on wavelength and the resulting voltage were obtained. Ten data points were collected for each light colour, as presented in Table 1.

Table 1. Eksperiement Results

No	Voltage (Volt)		
	Red	**Green**	**Blue**
1	0.710	0.820	0.910
2	0.720	0.810	0.900
3	0.710	0.810	0.900
4	0.710	0.820	0.890
5	0.710	0.860	0.890
6	0.720	0.860	0.900
7	0.830	0.850	0.890
8	0.850	0.850	0.910
9	0.810	0.840	0.860
10	0.800	0.860	0.820
Average	**0.757**	**0.838**	**0.887**

Based on the data regarding the influence of light colour on the voltage value, it can be seen that the voltage exhibits slight fluctuations or variations, although relatively small. This behaviour is attributed to the nature of semiconductors, as stated by Hammach (2018), who explained that 1 MeV electron irradiation results in an anomaly in short-circuit current degradation (Jsc). The current initially decreases, followed by a recovery phase, and then decreases again as the electron influence increases.

This behaviour is commonly caused by semiconductor type inversion in the active region of the solar cell.

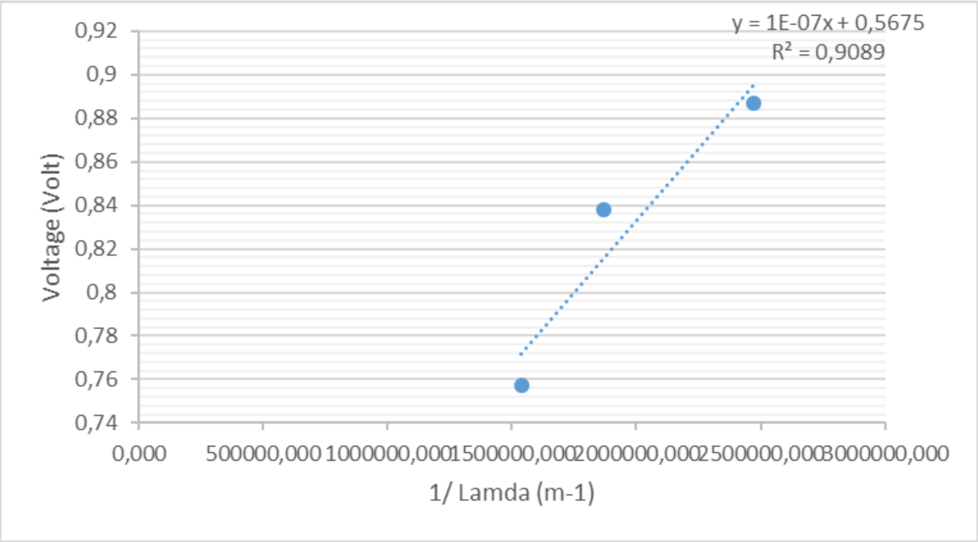

Fig. 2 *Graph of the Relationship Between Voltage and 1/Wavelength*

The experimental data in Fig. 2 were analysed using the linear regression method to obtain the gradient *m* (Firdaus, 2017). The regression analysis produced a gradient value of 1.327×10^{-7} with a slope error of 4.201×10^{-8}. Using the speed of light *(c)* = 3×10^{8}m/s and the electron charge *(e)* = 1.6×10^{-19}C, the calculated Planck constant *(h)* was 7.09×10^{-35}Js. Meanwhile, the standard value of Planck's constant is 6.26×10^{-34}Js, differing by 5.49×10^{-34} with the accuracy percentage determined using the equation:

$$\text{Accuracy} = [(h\_exp - h\_std) / (h\_std)] \times 100\%$$

A deviation of one order of magnitude is reasonable in a laboratory experiment; absolute truth and 100% precision do not exist. What matters is that the value is obtained epistemologically—that the procedures followed align with the established concept, resembling Millikan's experiments and Einstein's early 20th-century explanations—allowing the experiment to be scientifically justified.

The difference between the Planck constant obtained in this study and the standard value is not without cause. The presence of a semiconductor coating or silicon layer protected by a transparent cover with a certain thickness leads to a shift in the wavelength of the laser light, thus altering the actual wavelength from the value stated on the product label.

One of the causes of this wavelength shift is refraction by the solar panel's cover glass layer, which is typically made of transparent materials such as glass or mica. Depending on its thickness, this layer refracts the incoming laser beam, causing some of the light to be transmitted deeper into the layers and some to be reflected, resulting in energy loss. The transmitted portion acts as a secondary light source of degraded laser light. This refraction occurs because the laser beam passes through two media with different refractive indices—air and glass. As cited in Kurniawati and Suryani (2023), refraction occurs when light travels through one medium and then enters another with a different density. Refraction is the bending of light upon encountering a boundary between two media.

The secondary light then enters deeper layers, including a transparent adhesive layer above the anti-reflective coating— a thin film with an optical refractive index situated above the semiconductor layer. These layers refract the laser beam further, shifting the wavelength value and ultimately degrading the λ printed on the product label. Consequently, the wavelength value cannot be perfectly accurate, although the shift may be very small.

This wavelength shift indirectly affects the measured voltage and ultimately shifts the calculated Planck constant from the standard value of 6.4×10^{-34}Js. However, using this simple experimental setup, a Planck constant of 7.09×10^{-35}Js was obtained. This represents a deviation of 5.69×10^{-34} Js, equivalent to an 8.89% error. In addition to the shift caused by refraction, the wavelength values stated on the laser pointer labels are also questionable; the researcher tested the red and blue wavelengths and found noticeable discrepancies.

Through the well-known light interference experiment by Thomas Young (1773–1829), where coherent conditions were achieved using a single light source (Pramono et al., n.d.), with the number of gratings (N) as the independent variable and the change in grating and screen distance as dependent variables, the average wavelength was found to be 726nm for red light and 454nm for blue light. This significant difference indicates that the wavelength listed on the laser pointer product does not match the actual value.

An accuracy value of 1.21E+03% was obtained. Meanwhile, the work function *(W)* was determined from the intercept of the equation $y = 1E{-}07x + 0.5675$. The constant term $b = 0.5675$, with $b = -W/e$, yields $W = b \times e = 0.5675 \times 1.60 \times 10^{-19} = 9.09 \times 10^{-20}$Js or 0.57 eV, which represents the threshold energy or work function of the solar-cell material. This threshold energy is much lower than that of metals listed in Table 2, indicating the basic nature of the semiconductor plate in a solar cell—namely, silicon or silicon wafer. This energy corresponds to the band gap between semiconductor materials, known as the excitation potential barrier.

Table 2. Work Function Metals (Sulistiyawati et al., n.d.)

Metals	**Symbol**	**Work Function (eV)**
Cesium	Cs	1.9
Kalium	K	2.2
Natrium	Na	2.3
Lithium	Li	2.5
Kalsium	Ca	3.2
Tembaga	Cu	4.5
Perak	Ag	4.7
Platina	Pt	5.6

CONCLUSION

In conclusion, a photoelectric effect experiment was successfully conducted using a simple apparatus consisting of three laser pointers—red, green, and blue—directed at a solar cell to produce an electric voltage. Through linear regression analysis of the resulting graph, the gradient value was used to determine Planck's constant, yielding a value of 7.09×10^{-35}Js. This result showed a deviation of 5.69×10^{-34}Js, with a relative error of 8.89%. This deviation was attributed to several factors, including the refraction effects caused by the glass layer and adhesive coating on the surface of the semiconductor plate used to protect the solar cell.

The threshold energy obtained in this experiment, in the context of the photoelectric effect, was significantly lower than the threshold energy of metals listed in Table 2. This reflected the fundamental nature of the semiconductor plate in a solar cell—namely, silicon or a silicon wafer. This energy corresponds to the band gap of the semiconductor material, known as the excitation potential barrier in photovoltaic terminology.

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