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Scientific Explanation of the Photoelectric Effect Using Common Objects

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Abstract

In this study, a tool that can explain laboratory-scale photoelectric effect events was designed. So that having a tool that can explain the photoelectric effect will make it easier for users to study the nature of light as a particle. This tool is designed according to its function which will know that the photoelectric effect event is not affected by light intensity but is influenced by the frequency of a light source and the wavelength that shines on a metal so that electrons will move from a negative source towards a positive voltage source. A gadget for this experiment was built uses phototubes and cheap LEDs as light sources instead of traditional mercury lamps. Multiple LEDs operating in the wavelength range 470–631 nm can be used to measure the Planck constant to an accuracy better than 10%. By varying the intensity of the LEDs, it is possible to monitor the energy of the electrons and photocurrent with respect to the amount of light. The results show that the voltage applied to the photodiode leg (cathode) has a different value for each color spectrum and the output voltage obtained for each different wavelength, the less light intensity received by the photodiode, the smaller the output voltage value.

Keywords: LEDs, photoelectric effect, Planck constant, science,

INTRODUCTION

The description of the photoelectric effect by Albert Einstein earned him the Nobel Prize in physics 100 years ago (Friedman, 2022). This theory is fundamental to our comprehension of light, and many beginning physics courses include experiments to illustrate it (Falk, Eichler, Windt, & Hütt, 2022). The phototube, a variable voltage source, current, and voltage meters, as well as a light source that can create a variety of narrow light spectrums (Ghufron & Prayogi, 2023), such as a mercury amp or an incandescent bulb (Schirripa, Leccese, & Leccisi, 2019), are all conventional components of the setup for these presentations (Krotkus, Kasemann, Lenk, Leo, & Reineke, 2016).

Since then, numerous studies have been carried out using a variety of methods and ways to calculate this amount (Darminto et al., 2023). Among them are those based on using the photoelectric effect, employing a watt balance, and using light-emitting diodes (LEDs) of various colors (Silviana & Prayogi, 2023). From an educational perspective, the determination of Planck's constant is appropriate to perform using LEDs due to its straightforward circuit arrangement (Checchetti & Fantini, 2015), the appealing and fascinating color illumination (Prayogi, 2023b), the easy and simple steps to be carried out (Turnbull, Chugh, & Luck, 2021), the absence of sophisticated equipment (Checa & Bustillo, 2020), and most significantly, the ability to perform using inexpensive devices (dos Santos, Medola, Cinelli, Garcia Ramirez, &

Sandnes, 2021). The incandescent source has a low intensity by nature, especially at shorter wavelengths (Waymouth, 2017), in contrast to the mercury source (Balaram, 2019), which is more expensive and potentially hazardous due to its high temperature (Prayogi, Cahyono, & Darminto, 2022), the output of ultraviolet light (Janda et al., 2015), and course, the presence of mercury vapor (Dutta Gupta & Agarwal, 2017). The understanding of the photoelectric effect has important implications for modern physics and technology. This concept helps explain how light has particle properties and plays an important role in developing light detection technologies, digital cameras, and even solar cells.

In this article, a practical method for demonstrating the photoelectric effect with LED light sources was presented. It should be noted that, in contrast to our use of LEDs, some systems use the LED "turn-on" voltage as a measure of the photon energy. The wavelength of red (660 nm), green (520 nm), yellow (593 nm), and blue (470 nm) LEDs (631 nm) were employed. The LEDs are useful for time response studies because of their brightness and their quick on time of less than 1 μs. Other light sources make it difficult to carry out these investigations. Furthermore, it is less expensive to use because it only requires a basic tool.

METHOD

This study aims to determine the value of the Planck constant and the effect of the light intensity given to the photodiode on the output voltage and stop voltage. This laboratory-based research aims to determine the value of the stopping voltage and output voltage on the photodiode sensor after being exposed to light from the LED. The design of the tool uses an LED with a size of 60 mm and has four pins as a light source. Where to adjust the size of the intensity of the source will be regulated by Arduino Uno. The pins used on Arduino are pins 8, where pins 4 are pins that will be connected to LEDs and pin 2 is connected to a switch which functions 8 to change one color to another. While the light sensor used in the design of this tool is a photodiode sensor which functions as a converter of the amount of light into an electrical quantity so that the output voltage which is the output of the sensor can be read on the voltmeter.

In addition to the LED light source, the phototube used in the 1P39 vacuum is the equipment's lifeblood and the most important component. The latter is inserted into the plastic electronics enclosure cover and mounted there. Figure 1 shows how the tools were employed to study the photoelectric effect are constructed using their individual parts.

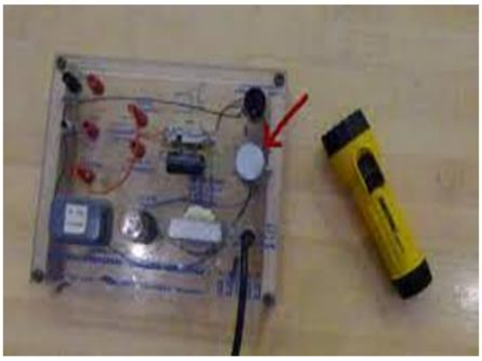

Figure 1. The equipment was utilized to demonstrate the photoelectric effect

The photocathode of the tube is filled with LED light at this distance. A hole through an iron bracket is used to mount the LED. With a push-on connector, connections to the LED was conducted. This configuration makes replacing the LED simple when doing the experiment. The phototube and LED are both covered by a light shield composed of a thin piece of alloy that blocks ambient light from entering the photocathode. This shield can be removed to enable students to see the light striking the photocathode (Zainuddin, Syukri, Prayogi, & Luthfia, 2022). The phototube's glass envelope is covered with a 3-mm strip of black electrical tape to protect the anode from the LED's direct light and stop it from generating erroneous electrons. The container contains all additional parts, including the batteries.

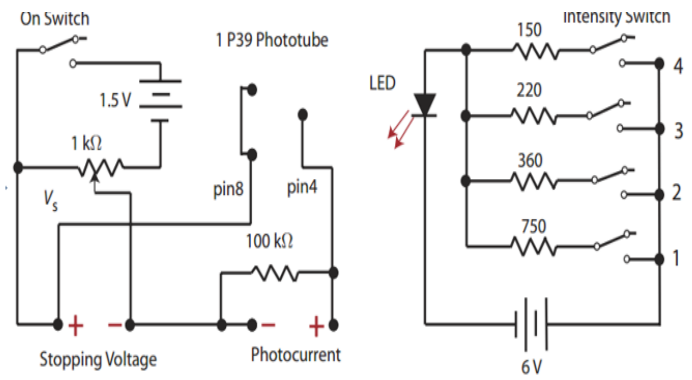

Figure 2. The photoelectric effect apparatus's circuit

The electrical circuit for this device is shown in Figure 2. The photocurrent and stopping voltage are measured using readily available digital meters. By reading across a 100-k resistor and using a digital meter set to the 200-mV range, a photocurrent resolution of 1nA is attained. Simply altering a resistor in series allows you to change the LED intensity. With a switch, one of four resistors can be chosen. To make the LED intensity correspond to the switch position, the resistance of each has been set.

RESULT AND DISCUSSION

When linked to a power source, a semiconductor device known as an LED operates like a light bulb and emits light (Zhu & Humphreys, 2016). The energy released during the emission of light is discrete and is known as a photon. It can come from any of the following sources:

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

The energy of each photon generated by an LED is determined by this equation, which also considers the frequency. The LED starts to emit light when the voltage reaches its minimum threshold, and the current is allowed to flow through it (Blackburn, 2020). The following formula expresses the relationship between energy and the minimum threshold voltage:

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

where e is an electron's charge, which has the value of 1.6022 x 10^{-19} C. Equation (1) and equation (2) are as the LED is turned on, equivalent and provide a linear relationship between frequency and voltage (Prayogi, Silviana, & Zainuddin, 2023b). You can demonstrate this correlation by:

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

Equation (4) shows that the y- and x-axes are linear when seen as a straight line with the equation y = mx + c, which is obtained by rearranging equation (3). This may be demonstrated by plotting a graph with the frequency of an LED on the x-axis and the minimum threshold voltage on the y-axis.

$$V_o = hf/e \quad (4)$$

The relationship between these two axes in a graph of minimal threshold voltage vs frequency yields a straight-line slope, and the size of Planck's constant can be determined by multiplying this slope by the charge of an electron (Prayogi, Silviana, & Zainuddin, 2023a).

The photocathode is illuminated with monochromatic light of a wavelength in the traditional photoelectric effect experiment, and the voltage needed to squelch its most energizing electron emissions is measured (Ramadhan et al., 2023). The famous Einstein equation results from the conservation of energy principle and the assumption that light is quantized:

$$eVs = hv\text{-}Wo \quad (5)$$

where e is the electronic charge, Vs is the stopping voltage, h is Planck's constant, v is the frequency of the light, and Wo is the minimum energy needed to release the electron from the photocathode (Prayogi, 2023a).

As the monochromatic light source for the experiment, each LED is used. The stopping voltage (Vs) is then changed until the photocurrent just barely reaches zero, and this stopping voltage value is noted for each wavelength (LEDs). Even though the LEDs are not truly monochromatic light sources, they are more than sufficient for this experiment's precision. Since their spectral width often has a wavelength of less than 20 nm, this approximation is appropriate. Therefore, less than 5% of the peak's wavelength (or frequency) spread is present.

Typical data captured with the LEDs at their highest intensity is shown in Figure 3. A straight line was used to fit the data points, and its slope was determined to be h/e. Planck's constant determined by our measurements is 6.19 ± 0.44 x 10-34 J.s. The estimated uncertainties of 5% in the determination of Vs and the LED wavelengths led to the assigned uncertainty of 7%. Planck's constant has a reduced value according to our measurement of 6.22 x 10-34 J.s. The photocathode's ability to reflect light and simultaneously emit erroneous electrons from the anode are the most likely causes (Hamdani, Prayogi, Cahyono, Yudoyono, & Darminto, 2022).

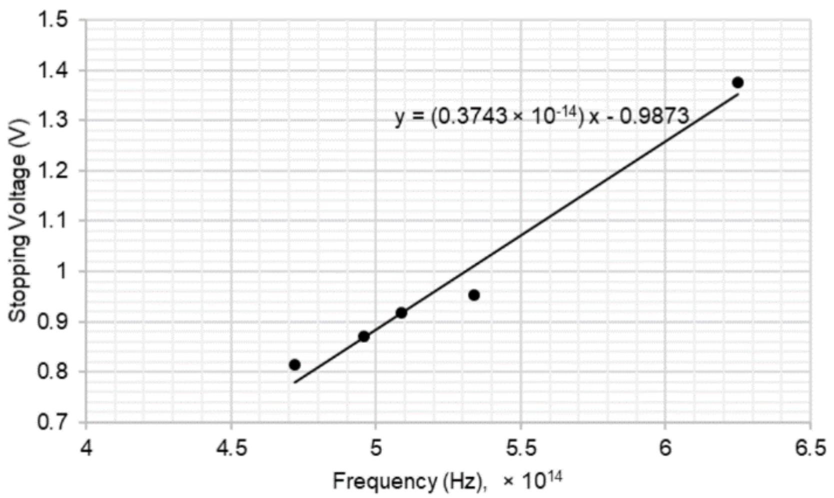

Figure 3. The function of LED frequency and stopping voltage. The ordinate intercept's size is determined by the work function, and the slope of the plot is h/e

Measuring the photocurrent and stopping voltage (V_s) for a range of intensities is another simple experiment that may be carried out with this equipment. The findings utilizing the green LED are displayed in Figure 4. These results demonstrate that while the stopping voltage does not change with incident light intensity, the photocurrent does. Because the energy of the released electrons is independent of the light's intensity, this conclusion unequivocally proves that light energy is quantized (Zhao et al., 2021). Another example of this is a straightforward experiment where the phototube is lighted using a 945-nm LED's infrared output.

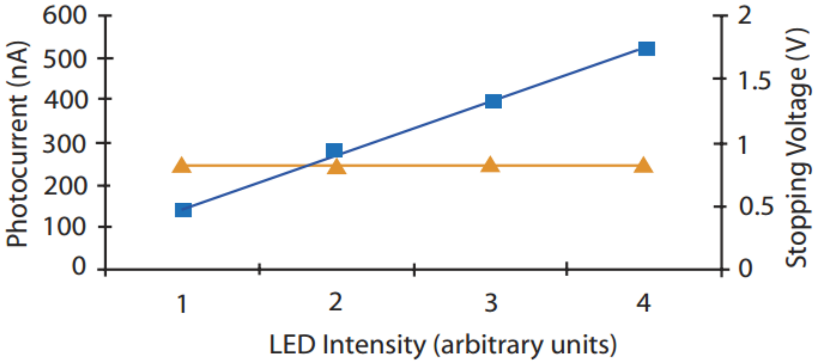

Figure 4. photocurrent (squares) and topping voltage (triangles) measurements for the green LED as a function of LED intensity (525 nm)

The presence of light coming from the LED can be confirmed using a photometer or digital camera. In fact, none of the four visible LEDs utilized for data collection can match the intensity of this LED (Prayogi, Cahyono, Iqballudin, Stchakovsky, & Darminto, 2021). Despite this, no photoelectrons were seen. The reason is that the infrared LED's energy per photon (1.31 eV) is lower than the photocathode's 1.4-eV work function.

The time response of the photocurrent can also be measured if a function generator and oscilloscope are provided. The LED is turned on and off at a rate of 20 kHz using a square wave supplied by the function generator. Another way to demonstrate the quantum character of light is to compare the time response of the resulting photocurrent to that of the incident light (Pan & Zhu, 2015). The experiment's electrical circuit is depicted in Figure 5. It should be noted that a 10-k resistor is provided in parallel with the 100-k current-measuring resistor to reduce the photocurrent measurement's intrinsic time constant.

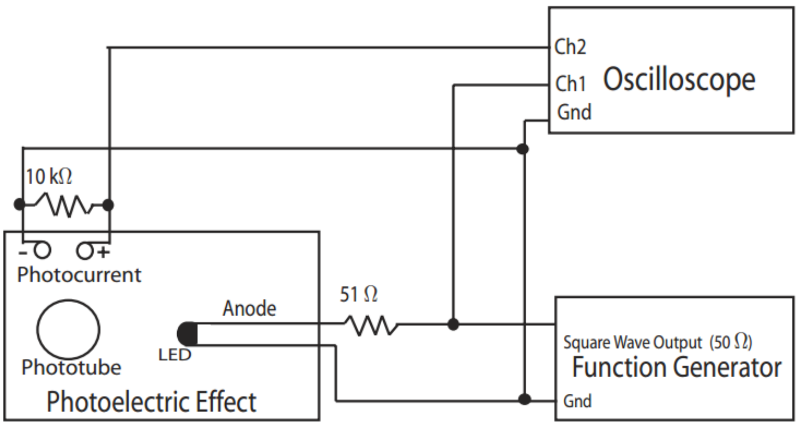

Figure 5. Measurement of the photocurrent time response using an electrical circuit

Figure 6 shows the LED and photocurrent waveforms measured. These waveforms clearly show that electrons leave the photocathode less than two seconds after the light first appears. This result contradicts the wave theory of light, according to an order of magnitude calculation. The LED requires 3 V at 20 mA, resulting in a 60-mW power draw. Each electron obtains a portion of the power provided by this electrical power if it is entirely converted to light and deposited on the photocathode as a wave (Prayogi, Silviana, & Hamid, 2023). The LED illuminates for around 20 μs and then dims for about 45 μs. The photocurrent reacts to the LED's light in less than two seconds and is negative (in electrons). It is set to zero for the stopping voltage (Prayogi et al., 2017).

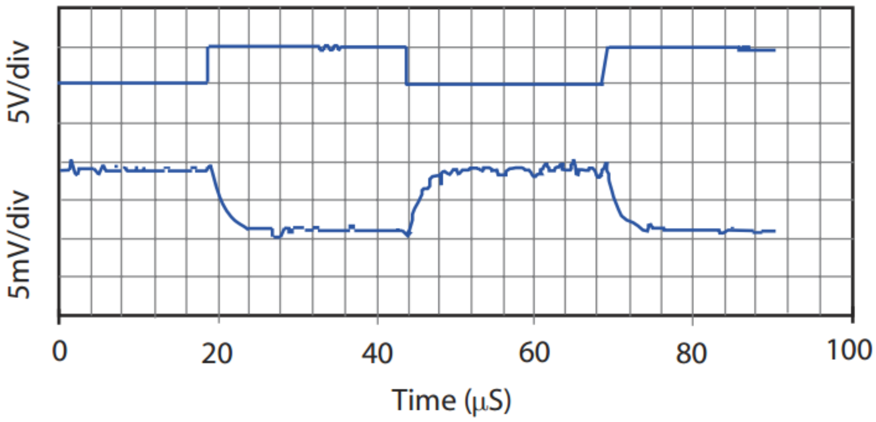

Figure 6. Oscilloscope images of LED voltage (top) and photocurrent (bottom) under the influence of a 0–5–V square wave from a function generator at 20 kHz

Each electron is restricted to a single atom in solids because their atoms are typically spaced 0.3 nm apart. Since the photocathode has a work function of 1.4 eV, it should take an electron at least 12 ms to absorb enough energy to leave it. However, liberated electrons are observed in less than 2 s, exceeding the projected wave speed by more than four orders of magnitude. The light must therefore be absorbed by the electrons in energy packets (photons) large enough to practically immediately set the electrons free.

In learning physics, the use of common objects or objects that can be found in general around students can help increase their understanding of the phenomenon of the photoelectric effect, including Concept Relevance Using common objects in photoelectric effect experiments can help students understand that this physical phenomenon does not only occur in the laboratory or in certain environments, but also in everyday situations. This increases the relevance of the concept in their lives. Student Involvement When students see common objects that they know and use every day used in experiments, it can increase their involvement in learning. They may be more interested in knowing why this phenomenon occurs in these objects and how it is related to light. Understanding the Experimental Process, the use of common objects allows students to understand and follow the experimental process intuitively more easily. They can see how light affects these objects and causes the photoelectric effect. Improving Memory Connection with known objects can help improve students' memory of the concept of the photoelectric effect. They tend to more easily remember information related to their everyday experiences. Reducing Abstraction Physics concepts, including the photoelectric effect, can be abstract and difficult to understand for some students. An in-depth understanding of the photoelectric effect allows students to link classical physics concepts with more modern quantum concepts. This also has important implications for the development of technologies related to the use of light and electronic materials.

CONCLUSION

In summary, the research demonstrates that Planck's constant was effectively discovered using only a straightforward analytic and straightforward experimental design. The undergraduate students found this to be fascinating as a starting point for their experiment on the fundamental explanation of the quantization of energy in modern physics as they investigate the relationship between energy and frequency of LEDs. Moreover, this demonstrates that a basic examination of the data and a practical presentation using a variety of appealing LED colors may aid in their better understanding of the idea of quantization. However, the rudimentary equipment used in this work indicates that the calculation of Planck's constant may be done using just commercially available LEDs, which are readily available and relatively inexpensive. Compared to certain basic physics experiments, which necessitate rather sophisticated equipment and ongoing maintenance, this shows cost-effectiveness in terms of short-term budgeting

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