16. PLANCK'S CONSTANT

STRUCTURED

Driving Question | Objective

What is the value of Planck's constant and how can it be determined experimentally? Given the quantization of light energy and the relationship between photon energy and frequency, perform an experiment using the light emitted from monochromatic LEDs to determine the value of Planck's constant.

Materials and Equipment

- Data collection system
- PASCO Voltage–Current Sensor[1]
- PASCO AC/DC Electronics Laboratory[2]
- Wire leads[2] (5)
- Resistor, 330-Ω[2]
- Battery, D-cell (2)
- LED, blue (450–500 nm)
- LED, green (501–565 nm)
- LED, yellow/amber (566–620 nm)
- LED, red (621–750 nm)
- Spectrometer (optional)

[1] www.pasco.com/ap19

PASCO Voltage–Current Sensor

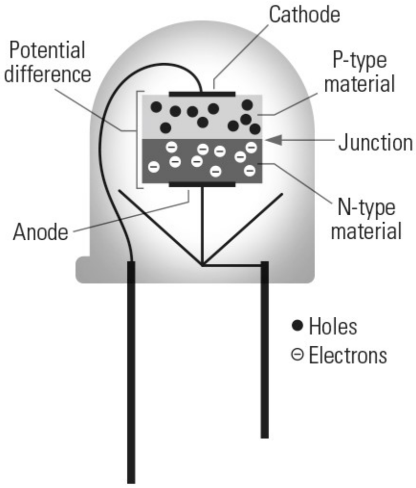
[2] www.pasco.com/ap04

PASCO AC/DC Electronics Laboratory

Background

A light-emitting diode (LED) is a simple *p–n junction* semiconductor device that converts electrical energy into light energy. LEDs consist of two semiconductor materials: *n-type*, where an excess of free electrons exists, and *p-type*, where a depletion of electrons, known as "holes," exists. The junction between the materials creates a *depletion region*.

The depletion region acts as an insulator blocking the flow of electrons across the junction. When a large enough potential difference (known as the "turn-on" voltage ΔV_0) is reached, electrons in the n-type material are given enough energy ($E_{\text{electron}} = e\Delta V_0$) to cross the p-n junction and join with the holes in the p-type material. At this point, current begins to flow through the LED.



The holes are at a lower energy state than the electrons. When an electron joins a hole, the electron moves to the lower energy state and one photon is emitted by the electron–hole pair. The energy lost by the electron E_{electron} when it combines with a hole is equal to the energy of the emitted photon E_{photon}. Assuming that light behaves with particle nature and has quantized energy ($E_{\text{photon}} = hf$), an equation describing both energies can be formulated:

$$E_{\text{electron}} = E_{\text{photon}}$$

$$e\Delta V_0 = hf \tag{1}$$

where e is the fundamental charge of an electron ($e = 1.60 \times 10^{-19}$ C), ΔV_0 is the potential difference (the "turn-on" voltage) required for an LED to just begin emitting light, f is the frequency of the emitted photon, and h is Planck's constant ($h = 6.63 \times 10^{-34}$ J·s).

Equation 1 states that the potential difference ΔV_0 (turn-on voltage) required for an LED to just begin emitting light is proportional to the frequency of the emitted light.

Additionally, frequency f is proportional to the speed of light in a vacuum ($c = 3.00 \times 10^8$ m/s), and inversely proportional to the photon's wavelength λ.

$$f = \frac{c}{\lambda} \tag{2}$$

In this activity, you will use this relationship between potential difference (turn-on voltage) and photon frequency from an LED to determine an experimental value for Planck's constant.

RELEVANT EQUATIONS

$$e\Delta V_0 = hf \tag{1}$$

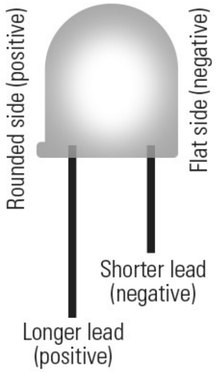
$$f = \frac{c}{\lambda} \tag{2}$$

Safety

Follow these important safety precautions in addition to your regular classroom procedures:

- Do not stare at the LEDs when they are fully lit as this may be harmful to your eyes.
- Do not use LEDs that emit ultraviolet light, which can cause permanent eye damage.
- Do not apply voltages to the LEDs above approximately 2.8 V as this can cause permanent damage to the LEDs.
- Voltage must only be applied to LEDs in the "forward-biased" orientation with current flowing from the positive lead to the negative lead. Connecting the LED incorrectly can damage it.

  Always connect the positive lead to positive voltage, and the negative lead to negative voltage. An LED's positive electrode lead is longer than the negative lead, and the negative lead has a flat spot on the side of the plastic LED housing.

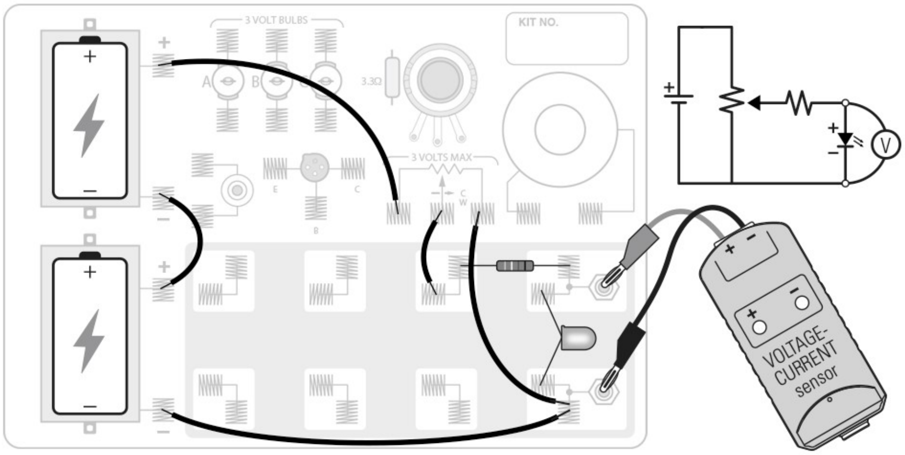


Procedure

SET UP

1. Assemble the circuit as shown, using two D-cell batteries, five wire leads, the on-board 25-Ω potentiometer, one 330-Ω resistor, and one of the LEDs. Be certain to connect the LED so it is forward-biased: the negative lead must be wired to the negative terminal on the battery.

NOTE: The potentiometer in your circuit is used to provide a variable voltage to the LED. Turning the dial clockwise increases the voltage to the LED; turning the dial anti-clockwise decreases the voltage.



2. Connect the voltage sensor leads in parallel across the LED in your circuit: red to the positive lead; black to the negative lead.

3. Connect the voltage sensor to the data collection system, and then create a digits display showing the voltage measured by the sensor.

4. Turn the dial on the potentiometer and observe the LED to make certain it emits light when the voltage is increased.

   NOTE: Do not stare at blue LEDs even when partially lit. If the LED does not emit light when the voltage is increased, check your circuit wiring and make sure all components are wired correctly and the LED is forward-biased.

COLLECT DATA

5. Record the color and output wavelength of the LED in your circuit in Table 1 in the Data Analysis section below. To obtain this data:

   - If you are using a spectrometer: turn the dial on the potentiometer all the way clockwise, and then use the spectrometer to determine the color and peak output wavelength of the LED.

   - If you are NOT using the optional spectrometer: obtain the LED's color and output wavelength from your instructor.

6. Adjust the potentiometer by turning it all the way anti-clockwise.

7. Begin recording data, and then slowly turn the potentiometer clockwise until the LED just begins to emit light.

   NOTE: When the LED just begins to emit light, it will be very dim and difficult to see. You may need to shroud the LED with your hands to help. You may also need to adjust the voltage up and down to accurately find the point at which it just begins emitting light.

8. Record the voltage measurement on your data collection system as the turn-on voltage for the LED in your circuit in Table 1, and then stop recording data.

9. Repeat the same data collection steps three additional times using a different color LED each time. Record the turn-on voltage, color, and output wavelength for each LED in Table 1.

Data Analysis

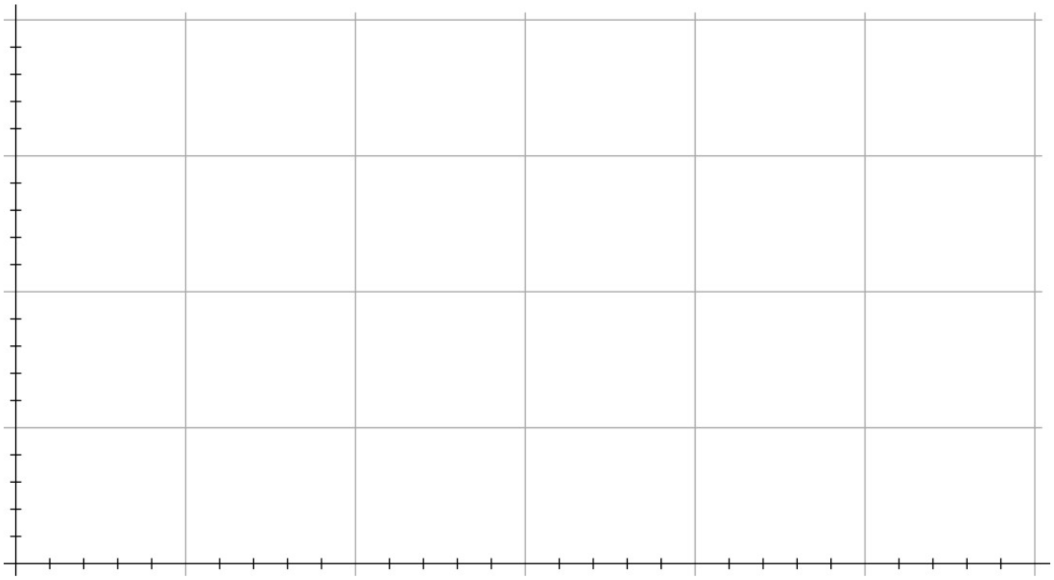
Table 1: LED voltage and frequency data for determining Planck's constant

LED Color	Output Wavelength (nm)	Turn-On Voltage (V)	Output Frequency (Hz)

1. Calculate the output frequency of each LED using its recorded Output Wavelength value and Equation 2. Record each Output Frequency value in Table 1.

2. Plot a graph of *turn-on voltage* versus *output frequency* in the blank Graph 1 axes below. Be sure to label both axes with the correct scale and units.

Graph 1: Turn-on voltage versus output frequency for various monochromatic LEDs



3. Draw a line of best fit through your data in Graph 1. Determine and record the equation of the line here:

   Best fit line equation: ____

4. Use the slope from the best fit line to determine an experimental value for Planck’s constant:

$$\text{slope} = \frac{h}{e}$$

Planck’s Constant h (J·s): ______________________________

Analysis Questions

1. What is your experimental value for Planck's constant, and how did you determine this value from your data?

2. What are factors that might have caused error in your measured value for Planck's constant? Explain how each factor you list could have been avoided or minimized.

3. The actual value for Planck's constant is $h = 6.63 \times 10^{-34}$ J·s. Calculate the percent error between your experimental value and the actual value.

$$\text{Percent error} = \left|\frac{\text{Actual} - \text{Experimental}}{\text{Actual}}\right| \times 100$$

Synthesis Questions

1. A solid state laser emits light at 532 nm from the laser LED within it. What minimum potential difference applied across the LED is required for light to be emitted from the laser diode?

2. A blue LED (λ = 472.2 nm) emits 3.89×10^{16} photons per second. In a few sentences, explain the process by which you would determine the power output in watts.

3. The *photoelectric effect* is a process in which energized electrons are ejected from the surface of a metal when light strikes it. The maximum kinetic energy K_{max} of each ejected electron is equal to the difference between the energy of one photon E_{photon} incident on the metal and the minimum amount of energy needed to free the electron, known as *work function* φ:

$$K_{\text{max}} = E_{\text{photon}} - \varphi$$

Assuming that the energy of an ejected electron is always positive and non-zero, below what wavelength must the incident light be for electrons to be ejected from an aluminum surface? Assume $\varphi_{\text{aluminum}} = 6.54 \times 10^{-19}$ J. Show your work.