Measuring Planck's Constant

By
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Historical Perspective and Physics Theory

Max Planck (1858-1947) was born in Kiel Germany and attended schools in Munich and Berlin. Planck was an early pioneer in the field of quantum physics. Around 1900 Planck developed the concept of a fundamental unit of energy, a *quantum*, to explain the spectral distribution of blackbody radiation. This idea of a basic quantum of energy is fundamental to quantum mechanics of modern physics. Planck received a Nobel Prize for his work in the early development of quantum mechanics in 1918. Interestingly, Planck himself remained skeptical of practical applications for quantum theory for many years.

In order to explain blackbody radiation, Planck proposed that atoms absorb and emit radiation in discrete quantities given by

$$E = \mathrm{n}hf$$

where:

- n is an integer known as a *quantum number*
- f is the frequency of vibration of the molecule, and
- h is a constant, Planck's constant.

Planck named these discrete units of energy *quanta*. The smallest discrete amount of energy radiated or absorbed by a system results from a change in state whereby the quantum number, n, of the system changes by one.

In 1905 Albert Einstein (1879-1955) published a paper in which he used Planck's quantization of energy principle to explain the *photoelectric effect*. The photoelectric effect involves the emission of electrons from certain materials when exposed to light and could not be explained by classical models. For this work Einstein received the Nobel Prize in Physics in 1921.

Niels Bohr (1885-1962) used Planck's ideas on quantization of energy as a starting point in developing the modern theory for the hydrogen atom. Robert Millikan made the first measurement of Planck's constant in 1916. The best current value for Planck's constant is $6.62607554 \times 10^{-34}$ J · s.

In this experiment, you will use light emitting diodes (LED's) to measure Planck's constant. You should be familiar with semiconductors and diodes from Modern Physics. To review: LED's are semiconductors that emit electromagnetic radiation in optical and near optical frequencies when a voltage is applied to them. LED's emit light only when the voltage is forward biased and above a minimum threshold value. This combination of conditions creates an electron hole pair in a diode. Electron hole pairs are charge carriers and move when placed in an electrical potential. Thus many electron hole pairs produce a current when placed in an electric field. Above the threshold value the current increases exponentially with voltage.

A quanta of energy is required to create an electron hole pair and this energy is released when an electron and a hole recombine. In most diodes this energy is absorbed by the semiconductor as heat, but in LED's this quanta of energy produces a photon of discreet energy $E = hf$. Because multiple states may be excited by increasing the voltage across a diode, photons of increasing energies will be emitted with increasing voltage. Thus the light emitted by an LED may span a range of discrete wavelengths that decrease with increasing voltage above the threshold voltage (shorter wavelength = higher energy). We are interested in the maximum wavelength that is determined by the minimum energy needed to just to create an electron hole pair. It is numerically equal to the turn on voltage of the LED. The relation between the maximum wavelength, l, and the turn on voltage, V_0, is

$$E = hf = \frac{hc}{l} = eV_0$$

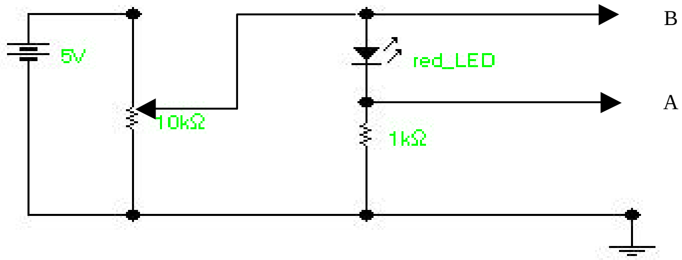
where:

- f is the frequency of the emitted photons,
- c is the velocity of light,
- e is the electronic charge, and
- h is Planck's constant.

The maximum wavelength of the LED can be measured to a resolution of a few nanometers with a good spectrometer. If the turn on voltage, V_0, is measured for several diodes of different color (and different maximum wavelength, l), a graph of V_0 vs. $1/l$ should be linear with a slope of hc/e. An experimental value of Planck's constant may then be determined by using the known values of the speed of light, c, and the charge of an electron, e, and computing h.

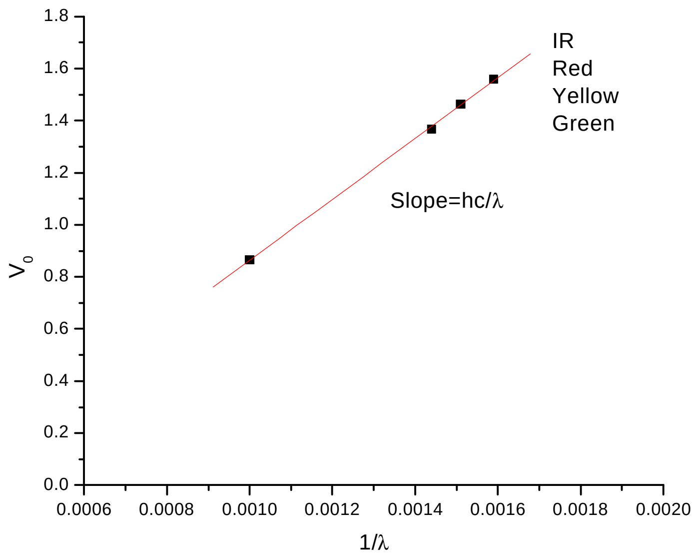
Procedure

The circuit that will be used to experimentally determine Planck's constant is illustrated below.



The A input to the 750 interface measures the voltage across the 1000 Ω resistor in series with the LED. This voltage is directly proportional to the current through the LED, and its value is numerically equal to the current in mA. The B input reads the total voltage across the LED and the 1000 Ω series resistor. The difference between these two voltages is the voltage across the LED.

To perform the experiment, the voltage probes are connected to the first two analog inputs of the 750 interface and the Pasco Data Studio program is used to record the voltages as the potentiometer is turned from its minimum (fully counterclockwise) to its maximum (fully clockwise) position. In this way, thousands of data points may be acquired in a few seconds. After the data is collected, it is scanned to determine the least value at which the resistor voltage becomes nonzero. This is the turn on voltage, V_0, for that particular LED. By using different LED's of different color (different maximum wavelength, l) and by measuring the corresponding value of V_0, a table of data of V_0 versus $1/l$ can be developed. A graph of V_0 versus $1/l$ is plotted which has a slope of hc/e, from which h is determined. A typical graph of V_0 versus $1/l$ for several LED's is shown below.



Diode	V_0 (volts)	λ_{max}
IR	0.866	1000
Red	1.367	695
Yellow	1.464	660
Green	1.560	630

Apparatus

PC
Pasco 750 interface
Voltage probes
Breadboard
1000 Ω ½W resistor
5V DC regulated power supply
10kW potentiometer
large LEDs (blue, green, red, yellow)
infrared LED of known wavelength (if available)
connecting wires
Gratner spectrometer with grating.

1. Connect the 5V power supply to the breadboard. Use the convention black (-) and red (+).

2. Connect the red probe of the test lead in A to its place on the breadboard and the black probe to the ground. Connect the red probe of the test lead in B to its place on the breadboard and the black probe to the ground.

3. Switch on the power supply and the 750 INTERFACE box.

4. Click on the Data Studio icon on the computer screen and choose the appropriate port for the 750 INTERFACE box (COM1 or COM2).

5. Start the Data Studio program .

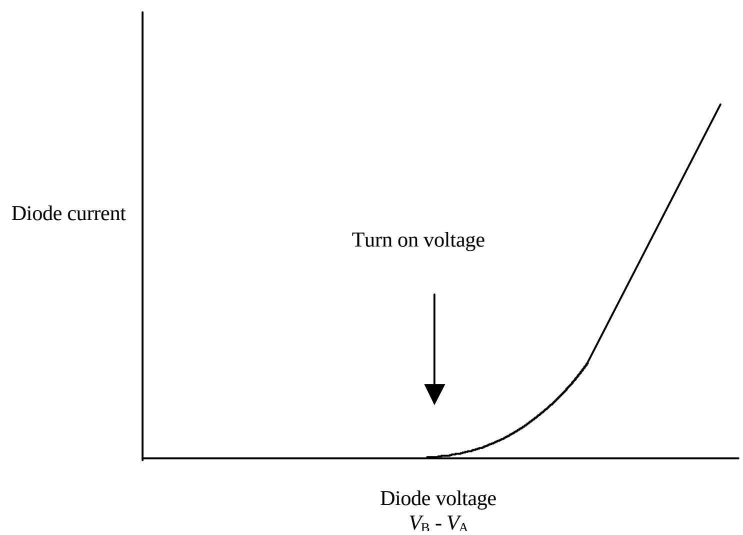
6. Move the pointer to the y-axis label and hold the left mouse button and choose Port 1 on the menu that appears. Execute a similar procedure for the x-axis label, only choose Port 2 for the x-axis.

7. Press and hold the right mouse button; a new menu should appear. While holding the mouse button, move the pointer to the arrow beside "Display" and then choose "Set All Max, Min" from the Display submenu. In the box that appears, type 5.0 in the area for max, 0 for min, and then click "ok".

8. Repeat procedure 7 except choose "Collect" and "Data Rate". Move the pointer to the circle in front of the number 500 and click once; click "ok".

9. Check the 10 kW potentiometer to see that it is turned fully counterclockwise. To take data, click the "Start" button. Immediately after

clicking the Start icon, turn the screw in the center of the potentiometer from fully counterclockwise to fully clockwise over the course of about 5 seconds. The turn should be smooth, and you should be in the fully clockwise position by the time 5 seconds has elapsed. A typical graph is shown below.



10. Turn off all lights in the room, and using the hand held spectrograph, look at the LED making sure to line it up with the slit on the right hand side of the spectrometer. You should see a band of light that covers a range of wavelengths. Read the maximum wavelength and record the value in the data table. Return the potentiometer to the fully counterclockwise position.

11. Return to the Data Studio program and bring up the data table by clicking and holding the right mouse button and select the "Window" option. From the Window submenu, choose "Data Table A".

12. Scan the data table for the first place at which the numbers in columns 2 and 3 are both nonzero. Subtract the smaller number from the larger number in that row and record this value as the turn on voltage for that LED in the data table below.

13. Place the next LED in the circuit and repeat steps 9-12. Do this for each additional LED you have until you have data for all of them. You will not be able to measure the maximum wavelength for the infrared LED; its value is 1000nm.

Data

Slope of turn on voltage versus 1/ *l* graph __________ V· m
Experimentally determined value for h _______$\times 10^{-34}$ J· s

Calculations

1. After exiting Data Studio, start the Graphical Analysis program by clicking on its icon.

2. Enter your data points by choosing the "Input New Data" option and input the information for which the program will prompt you. Plot $1/\lambda$ on the horizontal axis with units of 1/m and the turn on voltage on the vertical axis with units of *V*. (Remember your wavelengths are in nm, so if the wavelength is 500nm, then 1/ l is 2.00 x 10^6 m^{-1}, and should be entered as 2.00e6). Enter the graph title when prompted for it, and choose Automatic Scaling, Start at 0 for both axes. Print a copy of the graph for each person in the group.

3. The value for the slope will be given along the top of the graph. The slope is the value for *m*. The value for Planck's constant is the slope of your graph multiplied by e/c where e is the electronic charge (1.6022 x 10^{-19} C) and c is the velocity of light (2.998 x 10^8 m/s).