MEASURING PLANCK'S CONSTANT WITH LEDS

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This paper will show you how to set up a simple and inexpensive laboratory experiment to measure Planck's Constant with Light Emitting Diodes (LEDs). The experiment demonstrates the connection between familiar LEDs and the photoelectric effect, a fundamental quantum mechanical phenomenon. The laboratory challenges consist of measuring the peak emission wavelength and threshold operating voltage of each LED. Both tasks can be accomplished with common, inexpensive, components.

Levels of Difficulty

The laboratory exercise can be configured at several levels, depending on the capabilities of the student and the instructor and on the availability of equipment (or funds) as summarized in **Table I**. Costs range from less than $20 to several thousand dollars and the level ranges from high school to advanced undergraduate laboratory. Note that the Basic Level can yield results of acceptable accuracy, within 20 % (your mileage may vary!).

Table I: Summary of the Level Options for the Planck's Constant/LED Laboratory

Level	Time	Level (1)			Cost	Equipment (2)					
		HS	**CC**	**CU**		**VM**	**CS**	**LG**	**MM**	**SM**	**XY**
Basic	1 hr	X			low	X	X	X			
Intermediate	1 hr	X	X		med.	X	X		X		
Advanced	3 hr		X	X	high (3)	X	X			X	X

Table I Notes:
(1) HS = High School, CC = Community College, CU = College or University
(2) VM = Voltmeter or multimeter, CS = Current Source, SC = Spectral Chart, LG = Lamp and Grating, MM = Manual Monochromator, SM = Scanning Monochromator and photodetector, XY = X-Y Recorder
(3) Unless you already have a monochromator and X-Y recorder. These can cost more than $1,000 each.

Background

In 1900, German physicist Max Planck (1858-1947) was trying to model the spectrum of electromagnetic radiation emitted by a warm (or hot) body. This *black body radiation* is what you see coming from the sun, the filament of an incandescent light, or a hot electric stove element. In order to make the observations agree with the theory, Planck had to assume that the electromagnetic radiation was grouped in equal discrete lumps of energy which we now call photons. The photons at each frequency have a discrete energy $E = hf$, where E is the energy of the photon in Joules, f is the frequency in Hertz, and Planck's constant $h = 6.626 \times 10^{-34}$ J-s.

In 1905, Albert Einstein explained the fundamental quantum mechanical principles behind *black body radiation* and also an even more puzzling phenomenon called the *photoelectric effect* in which light illuminating a metal cathode in a vacuum diode caused the ejection of electrons

with kinetic energies determined by the of the light frequency (or equivalently, the wavelength, see Eq. 2 below).

You will use the *photoelectric effect* to measure Planck's constant *h* with modern Light Emitting Diodes (LEDs) by measuring the threshold voltage *V* in Volts and emission wavelength λ in meters of several different colored LEDs. From this data, you will calculate Planck's constant. The operating relations are: 1) $E = hf$; (2) $f = c/\lambda$; (3) $E = eV$. The speed of light in a vacuum is c = 299,792,458 m/s (exactly an integer with no uncertainty or additional decimals–but why?). The elemental charge is $e = 1.60 \times 10^{-19}$ Coulomb.

Laboratory Activities (modify these procedures to suit your goals and resources)

Activity 1 (Basic-Intermediate): Measure the LED Threshold Voltage

Equipment: Several LEDs, current source, multimeter, biological optical detection system (eye)

Connect the LEDs in series to the current source as shown in the diagram at right. (Assign an index number to each LED for future reference. NOTE: the long lead of an LED is the positive lead. Do not exceed 40 mA because excess current will burn out the LEDs) Increase the current until all the LEDs glow noticeably, but no more. Measure and record the voltage *V* across each LED with the multimeter (shown connected to the third LED). Calculate the threshold energy *E* of each LED using one of the above equations. (The Appendix shows several alternate circuits.)

Several LEDs in series with a current source.
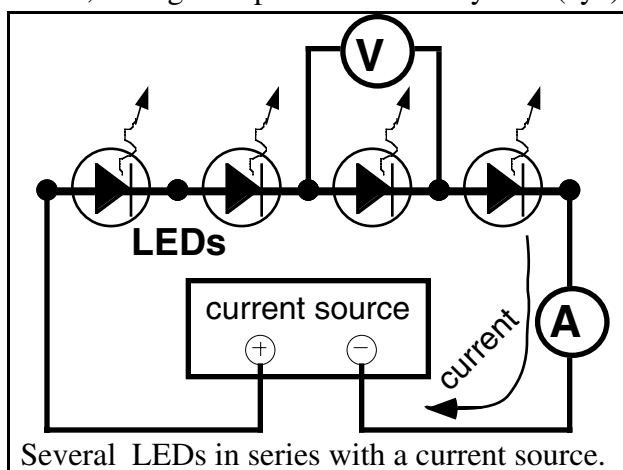
Activity 1 (Advanced): Measure the LED Threshold Voltage

Equipment: Several LEDs, current source, X-Y recorder.

Connect one LED to the power supply, resistor, and X-Y recorder as shown at right. Place a clean piece of paper on the recorder and set the origin near the lower left corner of the paper. Adjust the X-axis scale to 2.5 V full scale and the Y-axis to display (0.040 A × R) full scale. Engage the recorder servo and pen functions. Slowly increase the power supply voltage until the pen reaches the top of the paper (40 mA), tracing out the current-voltage (I-V) curve for the LED. Use a multimeter to mark off tick marks spaced by 0.5 V on the X axis of the graph.

For Recording the I-V Curve of an LED
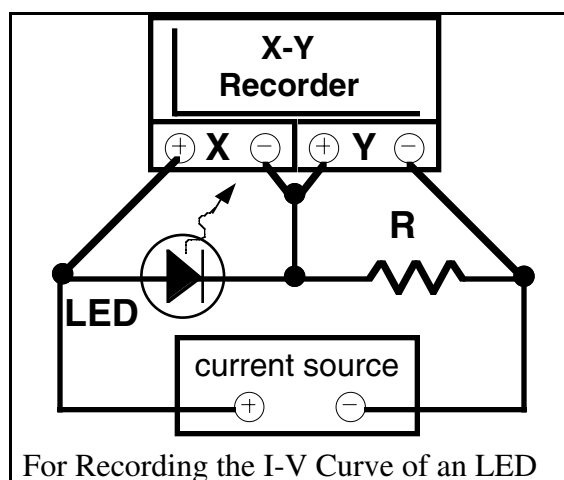
Repeat, making similar curves for each of the LEDs on the same piece of paper. draw a tangent line along the rising part of each I-V curve, extrapolating to Y = 0 (current = 0). Record the value of the X-intercept (V = 0) for each curve. This is the threshold voltage of the LED.

Activity 2 (Basic or Intermediate): Measure the LED Emission Wavelengths

Equipment: Several LEDs, power supply, white-light source, grating, wall, white paper, pen, meter stick, biological optical detector system

Illuminate the grating with the collimated beam from a white-light source (such as a slide projector). Position a wall (or viewing screen) so that the "rainbow" spectrum is clear and easy to view. Attach a large piece of white paper to the wall or screen. (We aren't allowed to write on the walls!) Mark the limits of the visible spectrum on the white paper with a pen, labeling these limits "400 nm" for the violet end and "700 nm" for the red end. (You may need to dim the room lights to see the spectrum clearly.

Connect the LEDs in series with the power supply as in Activity 1 and adjust the current so that the LEDs have comparable brightness to the displayed spectrum. Compare each LED with the displayed spectrum and mark the white where the LED color best matches the spectrum color. Label each mark with the LED number.
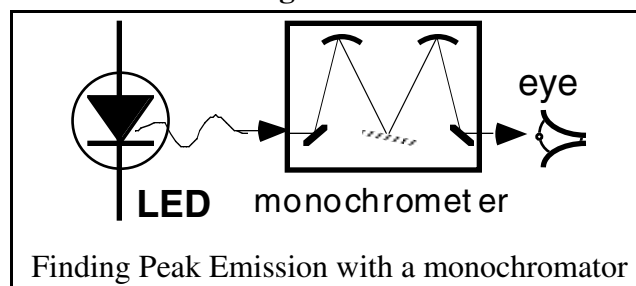
Projection Spectrometer
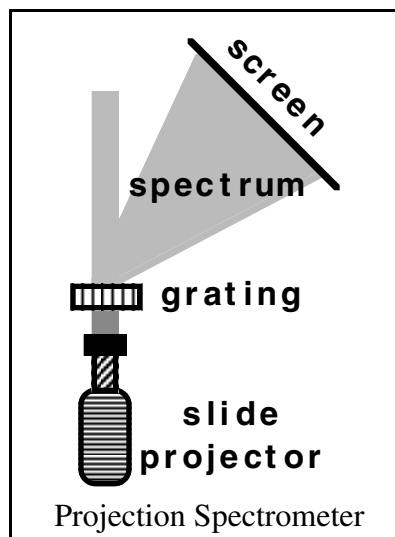
Measure and record the of the distances from the "400 nm" mark to the "700 nm" mark and to the spectrum marks using a meter stick. Use a linear interpolation method to calculate the wavelength λ of the spectrum mark for each LED. Calculate the optical emission frequency f of each LED from your wavelength data and one of the above equations. A good color wavelength chart like the one from Edmund can be used instead of the projected spectrum.

Note to teachers: This method is surprisingly accurate and challenges the students to work from basic principles of measurement.

Activity 2 (Intermediate): Measure the LED Emission Wavelengths

Equipment: Several LEDs, power supply, monochromator or spectrometer, biological optical detection system (or Photodetector and chart recorder)

Connect the LEDs to the current source and operate at a current of 20-40 mA. Position an LED close to the entrance slit of the monochromator or spectrometer, view the

Finding Peak Emission with a monochromator

spectrum through the output slit, and adjust for maximum brightness. Record the peak emission wavelength of each LED as detailed in the spectrometer or monochromator instructions. Calculate the optical emission frequency f of each LED from your wavelength data and one of the above equations.

This can be done with almost any viewing spectrometer with a wavelength scale or with a calibrated monochromator. The inexpensive STAR Project Spectrometer (see Table II) works particularly well, but I don't recommend Edmund's "pocket" spectrometer.

Activity 2 (Advanced): Measure the LED Emission Wavelengths

Equipment: Several LEDs, power supply, monochromator or spectrometer, photodetector, chart recorder or computer

Connect the LEDs to the current source and operate at a current of 20-40 mA. Position an LED close to the entrance slit of the mon o-chromator or spectrometer, and adjust for maximum signal at the photodetector. Record the emission spectrum of each LED as detailed in the spectrometer or monochromator instruc-tions. Find the peak intensity on each emission spectrum record and determine its wavelength. Calculate the optical emission frequency f of each LED from your wavelength data and one of the above equations. Infrared LEDs can be used in this version provided that the photodetector sensitivity extends to the IR LED wavelength.

Recording the Emission Spectrum of an LED
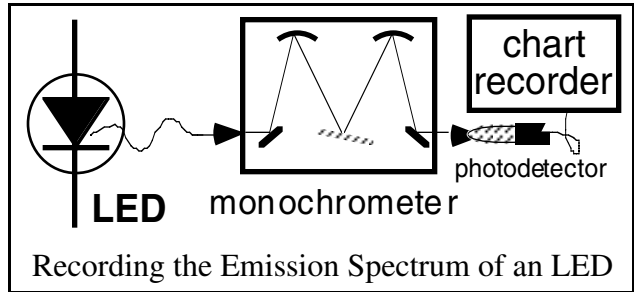
Activity 3: Data Analysis

Make a table listing the index number, the threshold energy E, and the emission wavelength λ of each LED. Plot a neat graph of this data and use your data or graph to calculate Planck's co n-stant h with the help of one of the above equ a-tions. Calculate the percentage difference between your value and the standard value given above.

The data in the graph at right was obtained using an X-Y recorder to measure threshold volt-age V and a scanning spectrometer to measure the peak emission frequency f. Note the data point is from an infrared LED like the ones used in TV remote controls, but you won't be able to measure its wavelength with the human eye! The blue LED is relatively new; blue LEDs were first made only in the last few years and soon we will have blue semiconductor lasers.

October 96, SPD

h = 5.76 E-34 Js
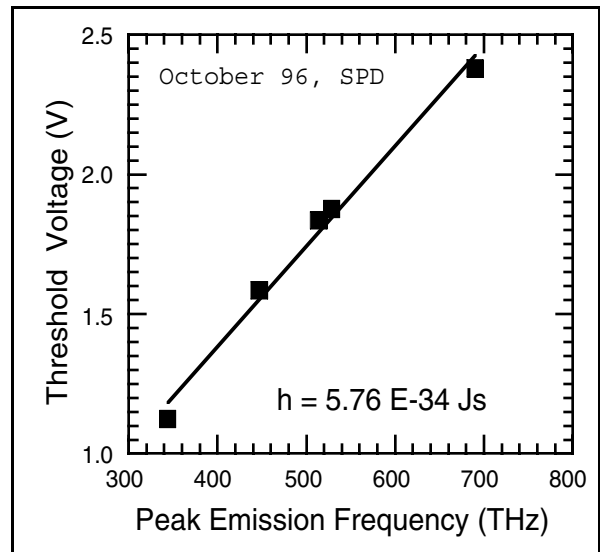
Questions

1) What was Albert Einstein awarded the Nobel Prize for?
2) List some limitations and possible sources of error inherent in the experimental method.
3) Suggest ways to improve the accuracy of the measurement.

Other Notes

LEDs have been used for decades in many devices: electronic displays, remote controls, electronic circuitry, and communications. The rich cousin of the LED, the Laser Diode (LD) has found use in a wide variety of devices: compact disc players, telephone communications (by fi-ber-optics), laser printers (however not all laser printers have lasers inside!), and bar-code scan-ners. Hardly and *hour* goes by when you don't use an LED or LED. The "laser revolution" does not involve large killer-lasers (à la Buck Rogers, Luke Skywalker, and Ronald Reagan), but it involves the ever-shrinking LDs which can now be made by the thousands on a single chip.

Equipment

The basic equipment is inexpensive, less than $20 in parts plus a multimeter, and measur e-ments can be completed in about an hour. In addition, more sophisticated versions of the project

can be constructed if you already have a good spectrometer and an X-Y recorder. **Table II** is a list of key parts and where to purchase them.

Table II: Summary of Parts Needed

Item	Level	Comment	Vendor (2)	Part no.	Cost
LEDs (get LEDs with clear, untinted lenses if available)	All	R Y O G B (1)	Digikey Mouser Radio Shack	various	about $0.50 each, ($2.50 for blue)
Breadboard	All	not necessary	any		$11 ea.
Elec. Components	All		any		up to few $
Multimeter	All	go digital!	any		$20 and up
Plastic Spectrometer	Basic, Inter.	excellent!	STAR	PS14/OA160	$18-$23 ea.
Diffraction Grating	Basic, Inter.	cheap	Edmund	C52,991	$16 for 15
Spectrum Chart	Basic, Inter.	use a text	Edmund	A36,423	$17 ea.

Table II Notes:

(1) R = red, Y = yellow, O = Orange, G = Green, B = Blue. Other colors may be available. Get "water clear" lenses, meaning nontinted and nondiffusing, if available, otherwise get "clear", meaning tinted but nondiffusing.

(2) Digikey (800) 344-4539, www.digikey.com; Mouser Electronics (800) 346-6873, www.mouser.com; Edmund Scientific (609) 573-6250, www.edsci.com; Pasco (800) 772-8700, www.pasco.com. The STAR Spectrometer can be obtained from plastic from Learning Technologies (800) 537-8703, www.starlab.com (Model PS-14, $22 in plastic or $55 for ten cardboard models), or from the Astronomical Society of the Pacific (800) 335-2624, www.aspsky.org (Model OA-160, $25). You can find some of these items from other vendors.

Bibliography

"Determining Planck's Constant Using a Light-Emitting Diode", by Dennis Sievers and Alan Wilson, *The Science Teacher*, Vol. **56**, no. 2, p. 44 (February 1989). This paper gives a nice introduction and detailed instructions on measuring the LED threshold voltages.

"The Inverse Photoelectric Effect," by S. D. Kropinak, (Canon-McMillian Senior High School, Canonsburg, PA), on the *Physics Infomall* CD ROM.

Most physics textbooks have a section on Planck's constant–just look in the index.

Visualizing Quantum Mechanics: Solids and Light, a project of the Kansas State University Research Physics Education Group led by Dean Zollman. http://BlueGiant.phys.ksu.edu/vqm/

Physics Infomall CD-ROM, compiled by the Kansas State University Research Physics Education Group and Published by The Learning Team of Armonk, NY.

The Art of Electronics, 2nd ed., by Paul Horowitz and Winfield Hill (Oxford University Press, Cambridge 1989.

Acknowledgments

APPENDIX: Current Source Circuits

A commercial current source capable of providing to 40 mA at 20 V would be ideal for driving up to 10 LEDs in series. Three alternate circuits that can be built with inexpensive parts are shown below. The voltage source must supply about 2.25 V per LED. If you want to drive five or more LEDs in series, use two 9 V batteries or a sufficient number of A, C, or D cells.

Simple Battery Series Circuit

The current should be 1 mA or less during threshold voltage measurement, so that the LEDs are operating near threshold. An ammeter can be inserted in series or the voltage across the resistor R (about 1 k Ω for four LEDs) can be measured to determine the current. This isn't strictly a current source as the current depends on the load from the LEDs, but by using a 10 kΩ potentiometer for the resistor R, you can adjust the current–less than 1 mA for measuring threshold voltage and 10 mA for measuring the spectrum or peak wavelength.
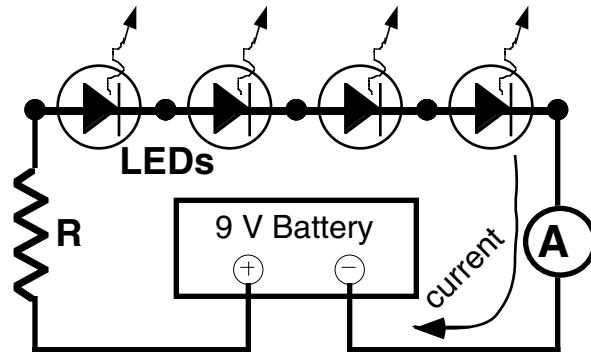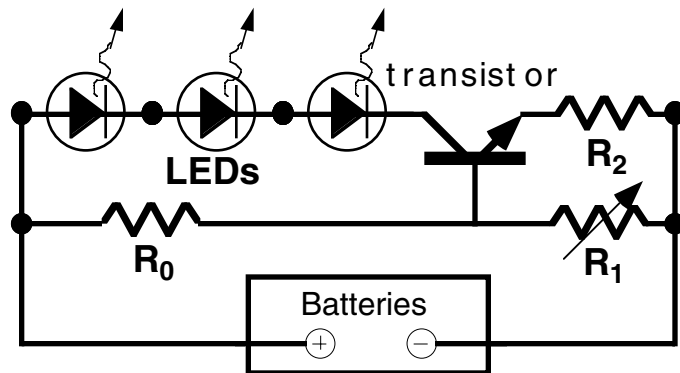

Transistor Circuit

The potentiometer R_1 controls the emitter current independent of the load (LED) resistance. A 2N2222 transistor is suitable if the LED current is limited to 20 mA. The LED current is approximately

$$I = \frac{(V_1 - 0.6V)}{R_2},$$

where V_1 is across R_1.

Recommended resistance values are R_0 = 1 kΩ, R_1 = 0-1 kΩ potentiometer, and R_2 = 250 Ω,. See Horowitz and Hill, Fig 2.22, for further details.

Op-Amp Circuit

The negative input current controls the current in feedback loop, independent of the load (LED) resistance. A good ±15 V electronic power supply is recommended. A 741 op amp is suitable as long as the current is limited to 20 mA.

$$I = \frac{V_1}{R_1}$$

Recommended resistance values are R_0 = 1 kΩ, R_1 = 0-10 kΩ potentiometer, R_2 = 680 Ω. See Horowitz and Hill, Fig 4.9 for further details.