# Lab 1: Measuring Planck's Constant Using LEDs

Adapted from a lab procedure written by Martin Hackworth, University of Idaho

Objective: Scientists use Planck's constant (h) frequently. In this experiment, you make will measure the emission wavelength and turn-on voltages of several light-emitting diodes (LEDs) in order to determine the numerical value of Planck's constant.

Background Reading: McQuarrie, *Quantum Chemistry*, sections 1-2 through 1-4; or Warren, *The Physical Basis of Chemistry,* sections 5.2.1 through 5.3. Basically, you are looking for sources that give sound treatments of blackbody radiation and the photoelectric effect, and what these phenomena meant to the development of quantum mechanics.

Introduction: A blackbody, which is an idealized object that would absorb all radiation at all wavelengths, emits radiation in a specific, temperature-dependent manner, as seen in Figure 1:
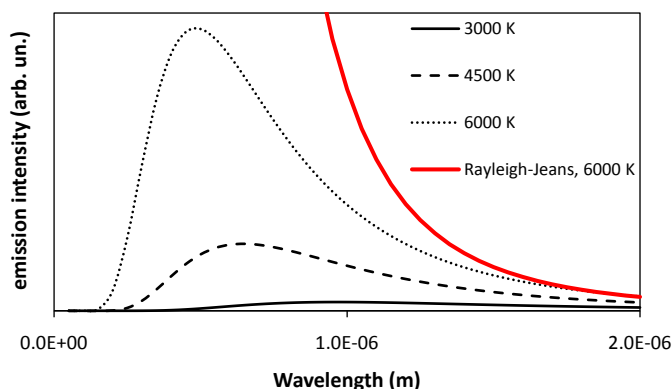
Figure 1. The emission intensity of an ideal blackbody at 3000 K (the temperature of a halogen lamp), 4500 K, and 6000 K (the temperature of the sun) as a function of wavelength. The red line shows the Rayleigh-Jeans Law prediction for blackbody emission at 6000 K.

This relationship between intensity and wavelength could not be adequately explained by classical physics. The Rayleigh-Jeans Law (developed 1900-1905), which was derived according to the laws of classical physics, was the best approximation according to classical physics and still very poorly reproduced the data, as seen by the red line in Figure 1. It diverges sharply with decreasing wavelength in the UV and shorter for the type of blackbody studied by physicists at the turn of the 20th century (essentially, an oven with a pinhole); therefore, the inability of classical physics to explain blackbody radiation became known as the *ultraviolet catastrophe*.

Around the same time as Rayleigh and Jeans, Max Planck postulated in that the only way to derive a function capable of reproducing the blackbody emission spectrum was to restrict the emission energies of the oscillating electrons that are responsible for blackbody emission to discrete values $E = hc/\lambda$, $2hc/\lambda$, $3hc/\lambda$,… where h is an arbitrary constant, c is the speed of light ($3.0*10^8$ m/s), and λ is the emission wavelength, so that c/λ is, of course, the frequency (ν) of the emitted light. Although Planck's

assumption was considered non-physical and even absurd at the time, the expression for blackbody radiation that was derived using this method correctly describes blackbody emission intensity and is one of the cornerstones of modern quantum mechanics.

Further confirmation of the quantization of energy came from Albert Einstein's explanation of the photoelectric effect in 1905. In this phenomenon, light causes the ejection of electrons from a metal surface only if the light has a higher frequency than some threshold value v_0 that is dependent on the identity of the metal. The ejected electrons are detected as current flowing in a circuit between the metal and a second electrode, and their kinetic energy is measured by applying a voltage across the two electrodes until current ceases to flow. The kinetic energy of the electrons ejected by a particular light source could be determined at this so-called stopping potential, V_s of that light source, because at this point,

$$K.E. = \frac{1}{2}mv^2 = -eV_s \tag{1}$$

where m, v, and e, are the mass, velocity and charge of an electron, respectively, and V_s is the necessary stopping voltage.

The observations made in the photoelectric effect experiments were at odds with classical physics. First, the kinetic energy of ejected electrons was found to be proportional to the difference between the frequency of light used, v, and v_0. If the intensity of the light source was increased, only the number of emitted electrons increased, rather than their kinetic energy. On the other hand, classical physics predicted that electrons should be emitted at any frequency of light, and that increasing the intensity of the light source would only increase the kinetic energy of the electrons. Einstein rationalized this discrepancy by assuming something very similar to Planck: namely, that light incident on a metal surface exists in quanta of energy hv. This meant that $E_W=hv_0$ was the energy necessary to eject an electron from the surface, while $K.E.=hv – hv_0$ appears as the kinetic energy of the electron. Combined with Equation 1, this means that

$$hv - hv_0 = -eV_s \tag{2}$$

The quantity hv_0 became known as the *work function* of a metal (E_W). Using the known value of e, Einstein was able to independently determine h. His value agreed very well with Planck's, suggesting that there is a natural basis for quantization and for the constant h.

An LED is composed of a chip of a semi-conducting material. The chip is doped with impurities, so that a p-n junction is formed. The positive side of the junction is the anode and contains excess holes (unfilled spaces in lower-energy orbitals), while the negative side is the cathode and has excess electrons. The presence of a sufficient power source causes electrons to flow toward the positive end of the power source, while holes flow toward the negative end. When an electron and hole meet, they recombine, so that the electron falls to a lower energy level and light is emitted. The color (frequency) of the light depends on the size of the band gap in the semiconducting material.

In this experiment, you will use LEDs of various colors to make your own measurement of Planck's constant. This is essentially a demonstration of the photoelectric effect in reverse. A quantum of energy is necessary to create the electron-hole pair, and is released again when the electron and hole

recombine. Because multiple states can be excited when the voltage across a diode is increased, photons of increasing energy are emitted with increasing voltage. This means that the light emitted by an LED spans a range of wavelengths that decrease with increasing voltage above the threshold voltage, V_0, which is numerically equal to the minimum energy necessary to create an electron-hole pair. The maximum wavelength, λ, occurs at V_0. As with Equation 2, a direct relationship between V_0 and λ can be established by relating kinetic energy to potential energy:

$$E = h\upsilon = \frac{hc}{\lambda} = eV_0 \tag{3}$$

This relationship rearranges easily to Equation 4:

$$V_0 = \frac{hc}{e}\left(\frac{1}{\lambda}\right) \tag{4}$$

Therefore, a graph of V_0 vs. $1/\lambda$ (a quantity also known as *wavenumbers*) is linear, and provides a convenient method for determining an experimental value for h.

<u>Procedure</u>: Construct the following circuit on a breadboard using a 5 or 6 volt power source, a 1 k ohm resistor, a 10 k ohm variable resistor (also called a potentiometer), and various LEDs. *A* and *B* denote the leads to a digital multimeter – clip the leads accordingly so that you are measuring a positive voltage in the circuit.
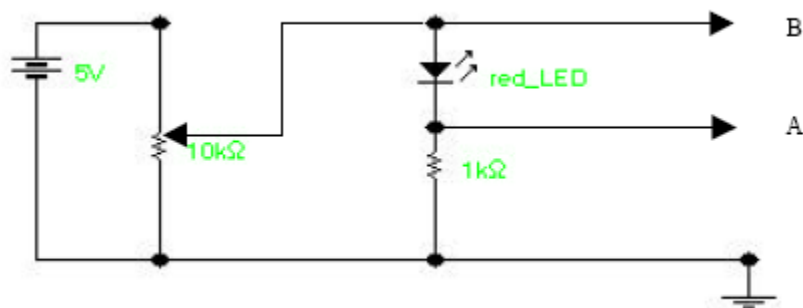
With the lights off, measure the minimum voltage across the LED that is required to faintly light the LED. This is a crude method for determining the turn-on voltage V_0.

A much better way to measure V_0 is to construct a current-voltage curve (*i-V*) curve for the LED. This is done by measuring the current flow in the circuit (simply switch the setting on the multimeter from volts to milliamps) at a variety of voltages. Measure *i* at a variety of voltages (try increasing the voltage in 0.3-0.5 V increments) between ~0 V and ~6 V for your LED light.

Use the Ocean Optics UV-Vis spectrometer to measure λ_{max} for the diode. This can be done using the fiber optic attachment and bringing it close to the LED. The voltage need not be at the minimum voltage measured above – it can be ≈100 mV greater, as long as a wavelength of maximum emission can be definitively identified.

Repeat this procedure, swapping your LED for an LED of a different color.

Data Analysis

Determining V_s *from an* i-V *curve*: Prepare an *i-V* curve for each of your LEDs. Then, perform a linear least-squares fit <u>on the linear part of your *i-V* curve only</u> – do not use the part of the curve that is non-linear! You will be making a judgment call on when the curve becomes linear – be sure to explain this in the Experimental section of your lab report. (Did you do it visually? Did you calculate the slope between each successive point and choose only the points that yielded equal slopes? It is your decision, and your responsibility to communicate this, as well as consider the benefits and drawbacks of your method.) Once you have your linear fit, extrapolate back to find the *x*-intercept – this is your estimated V_0 using the *i-V* curve method.

Determining a value for Planck's constant: Prepare two plots based on Equation 4 above: one in which you use the V_0 value measured by visual inspection, and one using the V_0 value measured from extrapolating your *i-V* curves for each LED light. (Caution: is the slope of this plot *h*, or will you need to do some calculations before you get a value for *h*?) Be prepared to compare and contrast the two methods, the values of Planck's constant they yield, and the potential error associated with each.

Lab report: Consult the lab report guide for general requirements and formatting. Required items specific to this experiment can be found below.

Introduction: Don't forget to cite all of your references!
- Briefly discuss the phenomenon of blackbody radiation, and the attempts of classical physics to derive expressions that explained the blackbody radiation profile. Then, discuss how Planck successfully reproduced that radiation profile with his own mathematical expressions.

- Discuss the photoelectric effect, how it was explained by Einstein, and explain how it relates to the LEDs used in this experiment.

- Explain how electrical current flows through a diode (the behavior is different than found in a resistor). Diagrams can be useful in your explanation, but be sure to also include an explanation in words. Describe why a voltage is necessary for an LED to emit light. Also, give 2-3 examples of materials used to make LEDs of different colors, along with the size of their band gap (you may find a table helpful here, but it is not required).

Experimental: Briefly summarize the experimental procedure. Include any equations used to analyze the data, along with defining each term.

Results and Discussion:
All graphs and tables must have proper formatting, captions, and a narrative explanation as outlined in the lab report guide. Include the following specific points in your lab report, in addition to the general guidelines:

- A data table with rows for each LED and columns for the color, λ_{max} (in nm) and V_0 required for light emission. All tables must have proper formatting, captions, and a narrative explanation as outlined in the lab report guide.

- *i-V* curves for each LED. Plot all of the curves on the same set of axes; just change the line style to distinguish between LEDs. Don't forget to explain this method, and how you decided which points to include in your extrapolation of the linear part.

- A graph of V_0 vs. $1/\lambda_{max}$, generated by computer graphing software. Show the linear regression trendline as calculated by your own linear regression spreadsheet (do NOT set the intercept to zero). Calculate the relative error in the slope and R^2 for the line; report these values in your narrative. (i.e. "the slope of the trendline was calculated to be $1.645 \pm 0.8414*10^{-33}$ J·s, with an R^2 value of 0.9246.") Do NOT restrict the intercept of the trendline to zero.

- Show your calculation of Planck's constant from the trendline equation in the Appendix, including values and **units** for each quantity. Be sure to show how the units cancel to give the appropriate units for h. Perform this calculation for both methods for determining V_0. The speed of light and charge on electron must be reported to at least 4 significant figures, while V_0 and λ_{max} must be reported to the appropriate significant figures based on the precision of the voltmeter and spectrometer, respectively. Report Planck's constant to the appropriate number of significant figures.

- Use the relative error in the slope of your line as calculated by linear regression to determine the error associated with your measurement of h. Discuss potential sources of error.

- Compare and contrast the values of h determined by both methods for finding V_0, as well as the relative error of each value. Are both values of h the same within error, or not? Discuss which method is most reliable, if it is possible to tell this from your data, and whether this fits your expectations.

- Calculate the percent error from the accepted value of Planck's constant (cite your source for this "accepted" value); discuss the accuracy and reliability of your measurements. A good rule of thumb in many physical chemistry experiments that are not done with precision instruments is that within 10% is good agreement, while within 2% is very good to excellent.