The Photoelectric Effect: A Practical Approach
Molly Golladay
Allatoona High School, Acworth, GA

In this lesson, students explore the photoelectric effect by using light-emitting diodes (LEDs). Firstly, students will be introduced to the construction of an LED and how the p-n junction operates by exploiting the photoelectric effect. They will use this knowledge to produce a current in an LED using only a light source, and finally, they are expected to use a series connection of LEDs to measure Planck’s constant by producing a plot of voltage versus wavelength. While this activity is written for an honors-level physics course, it can be adapted for students at all levels.

Problem
How does the photoelectric effect demonstrate the particle nature of light?

Objectives
- To relate the photoelectric effect to real-world technology
- To verify the particle nature of light
- To determine an accurate method of finding Planck’s constant

Anticipated Outcomes
After completing this activity, students will be able to:
- explain the relationship between electrons and photons in a metal
- calculate the workfunction and threshold wavelength or frequency of a metal
- explain the importance of the photoelectric effect in modern electronics

Standards
NSE Standards

- **Content Standard A**: As a result of activities in grades 9-12, all students should develop:
  - Abilities necessary to do scientific inquiry
  - Understandings about scientific inquiry
- **Content Standard B**: As a result of activities in grades 9-12, all students should develop an understanding of:
  - Structure and properties of matter
  - Interactions of energy and matter
- **Content Standard G**: As a result of activities in grades 9-12, all students should develop an understanding of:
  - Science as a human endeavor
  - Nature of scientific knowledge
Georgia Professional Standards

- **SCSh1**: Students will evaluate the importance of curiosity, honesty, openness, and skepticism in science
- **SCSh2**: Students will use standard safety practices for all classroom laboratory and field investigations
- **SCSh3**: Students will identify and investigate problems scientifically
- **SCSh4**: Students will use tools and instruments for observing, measuring, and manipulating scientific equipment and materials
- **SCSh5**: Students will demonstrate the computation and estimation skills necessary for analyzing data and developing reasonable scientific explanations
- **SCSh6**: Students will communicate scientific investigations and information clearly
- **SCSh7**: Students will analyze how scientific knowledge is developed
- **SCSh8**: Students will understand important features of the process of scientific inquiry
- **SP3**: Students will evaluate the forms and transformations of energy.
  - Analyze, evaluate, and apply the principle of conservation of energy and measure the components of work-energy theorem by
    - relating transformations between potential and kinetic energy.
- **SP5**: Students will evaluate relationships between electrical and magnetic forces.
  - Determine the relationship among potential difference, current, and resistance in a direct current circuit.
- **SP6**: The student will describe the corrections to Newtonian physics given by quantum mechanics and relativity when matter is very small, moving fast compared to the speed of light, or very large
  - Explain matter as a particle and a wave

Materials/Supplies

- Variable voltage source
- Alligator leads
- 1000Ω resistors (1 per apparatus)
- Various LEDs: red, yellow, green, blue, violet, infrared
  - NOTE: Make sure that you have the LEDs that are actually colored light – not the ones that are simply colored plastic. These are more expensive.
- Multimeter
- Soldering iron and solder
  - NOTE: To prepare the set-up most effectively, you should solder together the resistor and LEDs in ROYGBV order – resistor, IR, red,…, violet – this makes it easier for students to keep the LEDs straight. While soldering, keep in mind that LEDs have specific polarity and current can only run in one direction. Do not clip the wires or solder too close to the LED – the alligator clips will be used to connect the LEDs using the wires.
Background

The photoelectric effect is one of the most famous examples illustrating the particle nature of light and leading to the development of quantum mechanics at the turn of the 20th century. It is for his explanation of this effect that Albert Einstein was awarded the Nobel Prize in 1921. Einstein’s paper on this effect was published in 1905 and is still the standard explanation taught in classrooms today.

When light is incident on a metal, electrons are emitted from its surface. At the time this was discovered, the wave theory of light was the only model available. According to the wave theory, if the intensity of light is increased, the energy of the emitted electrons should also increase. Additionally, the frequency of incident light should not affect the electrons. Finally, there should be a time lag between turning on the light and observing emitted electrons.

Of course, if you perform this experiment, none of these predictions turn out to be correct. Intensity does not affect the energy of the electrons. The frequency of the incident light does affect the electrons – the photoelectric effect only works for certain frequencies. And also, there is no time lag between turning on a light source and observing electrons.

Basically, the wave theory of light fails in every way to explain the photoelectric effect.

To justify the photoelectric effect, Einstein used a relatively new idea first proposed by Max Planck in 1900. To explain a similarly challenging paradox involving blackbody radiation (another famous quantum effect), Planck treated light as a series of ‘discrete packets’ he called quanta instead of as a wave. In using Planck’s theory, Einstein determined that the energy of these ‘discrete packets’ that we now call photons is related to the frequency of the light:

\[ E = hf \]  

where \( E \) is the kinetic energy of the photon, \( f \) is its frequency, and \( h \) is Planck’s constant. We now know that

\[ h = 6.63 \times 10^{-34} \text{ Js} \]

Once photon energy has been quantized, the photoelectric effect becomes a simple example of energy conservation.

When light energy is incident on a surface, it is essentially adding that energy to the surface; specifically, to the electrons on the surface. Some energy is required to actually remove the electron – this is called the workfunction of the material. If there is any energy left over once the electron has been removed, it is turned into kinetic energy and the electron will then move.

We can therefore write:

\[ E_{\text{photon}} = \Phi + KE_{\text{electron}} \]  

\( \Phi \) is used to represent the workfunction.
There are several methods of verifying this equation. One involves connecting a photocell to a voltmeter and shining monochromatic light of various wavelengths on this photocell while measuring the voltage that results from the electrons jumping off the photocell, creating a current through the voltmeter. A variation on this traditional experiment is to connect the photocell to a voltage source and adjusting the source until the voltage in the photocell drops to zero, meaning that the field is strong enough to keep the emitted electrons from jumping off the photocell. Both of these methods involve recognizing that the kinetic energy of the emitted electrons results in a potential difference. Equation (2) can therefore be rearranged:

\[ eV = hf - \Phi \]  

where \( e \) is the elementary charge and \( V \) is the stopping potential. By using the equation in this form, if a plot of \( V \) vs. \( f \) is generated, the slope of the line is \( h/e \) and the workfunction is related to the y-intercept of the line.

Einstein’s solution to the photoelectric effect problem completely resolves the issues created by using a wave model of light. By treating light as a particle, we can understand how intensity does not affect electron energy: one photon causes one electron to be emitted; more photons just means more electrons, but each one still has the same energy. We can also explain the fact that the effect is not observed for all wavelengths: if the photon does not have enough energy to overcome the workfunction, the electron will not be removed from the surface. Finally, there is no reason for there to be a time lag, because again, the electron is released as soon as the photon reaches the surface. This is definitive proof of the particle nature of light.

The photoelectric effect is useful in many practical applications, but the most obvious one is the light-emitting diode. An LED is a type of device that uses a p-n junction. A p-doped material is placed in contact with an n-doped material, which forces current to travel in a single direction. When an electron travels across this junction (from n to p), its energy decreases suddenly. This excess energy is released as a photon. Because the same energy drop occurs for every electron that crosses the junction, the photon frequency is uniform, producing monochromatic light. LEDs, therefore, can be viewed as a sort of ‘reverse’ photoelectric effect, where a current produces light instead of light producing a current. Since this is the case, by measuring the voltage across LEDs connected in series, Planck’s constant can be determined to a high degree of accuracy.

**Plan**

- Introduce equipment (~10 minutes)
  - Explain how the strip of LEDs works
    - **NOTE**: Make sure to highlight how important it is that the lead coming out of the voltage source is ALWAYS connected to the resistor. Otherwise, one or more of the LEDs will be ruined, which can get costly.
Reiterate basic safety rules involving electricity (unplug when not in use, how to use a multimeter to measure voltage)

- Students follow procedure detailed in lab handout (~70 minutes)
  - Results can be printed out or submitted by email/flash drive as necessary
- Closure (~10 minutes)
  - Groups should compare results for their measurements of Planck’s constant
- Extension/Adaptations
  - If graphing software is not available and students are plotting their points by hand, it is advisable to let them finish their graphs at home, due to time constraints.
  - An excellent visual to accompany this lab is the Photoelectric Effect Simulation created by phet (available at http://phet.colorado.edu/en/simulation/photoelectric). For on-level students, it may be advisable to allow them to explore this simulation prior to the lab. For honors/AP students, this simulation can be used as an extension in-class for students that finish early and at home for students who need supplemental review.

Assessment/Rubrics
A copy of the student handout follows this document. The handout may be graded in the fashion of your choosing, for completion and/or correctness on a select number of conceptual questions.

A few questions on homework or in-class assignments should relate back to Anticipated Student Outcomes. This will prepare students for a minimum of one question on the summative assessment for this unit. Sample questions:

- Why is the photoelectric effect important? Explain your reasoning using at least two specific examples.
  - Solution: The photoelectric effect is important because it verifies the particle nature of light and supports the wave-particle duality. Also, it is useful in modern electronics such as the light-emitting diode.

- Explain how an LED can be used to determine Planck’s constant.
  - Solution: As an electron moves across the p-n junction, energy is lost in the form of a photon, which is the ‘photoelectric effect in reverse.’ Knowing this, Einstein’s relationship can be used as long as the wavelength of the emitted light is known, as well as the voltage needed to cause the LED to light up.

- In a student’s experiment using sodium, incident light of wavelength 204 nm produces a voltage of 4V. What is the workfunction of sodium?
Solution: 2.09 eV, given these numbers. The actual workfunction of sodium is closer to 2.28 eV. More advanced students could be asked about potential sources of error as well as the calculation.

References


**LEDs and the Photoelectric Effect**

**Purpose:** 1. To describe the relationship between LEDs and the photoelectric effect  
2. To determine Planck’s constant  

**Materials:** LED solder strip, variable voltage box, multimeter

Light Emitting Diodes (LEDs) can be found everywhere you look, from TVs to computers. They emit light by converting electrical potential energy into light energy with far more efficiency than a standard luminescent light bulb. LEDs vary in color due to the fact that they are made of different materials.

Unlike conventional resistors, LEDs have a polarity – the flat side is the negative end and the round side is the positive end. Your LEDs have been soldered together so that the end with the resistor should be connected to the **POSITIVE** port on your box, and the end with the LED should be connected to the **NEGATIVE** port on your box. The 1000-Ω resistor is present because LEDs cannot take a lot of current. From positive to negative, you should have the following colors: red, yellow, green, and blue.

Listen carefully to the explanation of how to use the LED solder strip – if you subject an LED to a high current, it will be destroyed and your group cannot complete the lab (your solder strip is about $10 worth of LEDs).

**Part A: Making LEDs Light Up**

1. Connect the solder strip so that the red LED **only** lights up. Use the voltmeter to measure the voltage across the LED. At what voltage do you first see light?

2. Slowly turn the knob on the source, increasing the output voltage. What happens to the reading on the voltmeter?

3. Re-connect the solder strip so that the blue LED **only** lights up. Again, start with the source on the lowest voltage and then slowly increase it. At what voltage across the blue LED do you first see light?

4. Given your red measurements versus your blue measurements, in which LED does an electron lose the most energy?

5. Which color of light contains photons of greater energy?
6. Explain the relationship between voltage drop across an LED and the color of the light it emits.

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**Part B: LEDs in Reverse**

*For these questions, you will need to borrow a second strip. The ‘emitting’ LED on your strip should be connected to your voltage box (green in #1, 2, and red in #4), and the LED on the other strip should be connected to your multimeter (red in #1, 2, and green in #4).*

1. What is the voltage across the red LED when the green LED is not emitting?

2. What is the voltage across the red LED when the green LED is emitting?

3. Explain your findings.

4. What is the voltage across the green LED when the red LED is emitting?

5. Explain your observations from the previous question.

6. Predict what will happen if you shine blue light into the green LED.

7. Test this. Were your predictions correct?

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**Part C: Measuring Planck’s Constant**

1. Connect the solder strip to your source so that all four LEDs are lit. Turn the voltage down so that you can see most of the LEDs just barely emit visible light. Use the multimeter to measure the voltage across each LED.
2. Fill in the chart. You must put nm in m to find frequency!

<table>
<thead>
<tr>
<th>LED</th>
<th>λ (nm)</th>
<th>f (Hz)</th>
<th>$V_s$ (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>red</td>
<td>660</td>
<td></td>
<td></td>
</tr>
<tr>
<td>yellow</td>
<td>587</td>
<td></td>
<td></td>
</tr>
<tr>
<td>green</td>
<td>565</td>
<td></td>
<td></td>
</tr>
<tr>
<td>blue</td>
<td>430</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3. Explain why you know that the voltage you measured corresponds with the stopping voltage described in the photoelectric effect. You will need to discuss how an LED works in terms of the photoelectric effect.

4. Using Excel, generate a scatter plot of $V_s$ vs. $f$.

5. Fit a linear trendline to your data, display the equation on the graph. Print it out and attach it to this handout.

6. What is your measurement of $h$ based on your slope? Also calculate the percent error from the actual value.

6. Explain why we cannot discuss a ‘workfunction’ even though our graph has an obvious intercept.

7. Do you believe this is an accurate study of the photoelectric effect? Why or why not?

When you have completed this lab, staple your graph to this sheet and turn it in!