The Photoelectric Effect

Physics Topics

If necessary, review the following topics and relevant textbook sections from Serway / Jewett "Physics for Scientists and Engineers", 10th Ed.

- Electric Potential and Electric Potential Energy (Section 24.1, 24.2)
- The Photoelectric Effect (Section 39.2)

Introduction

Albert Einstein was awarded only one Nobel Prize; contrary to what you might expect, he did *not* win his Nobel Prize for the theory of relativity. In fact, it was his explanation of a less well-known phenomenon called the photoelectric effect that earned him the prize.

The Experiment

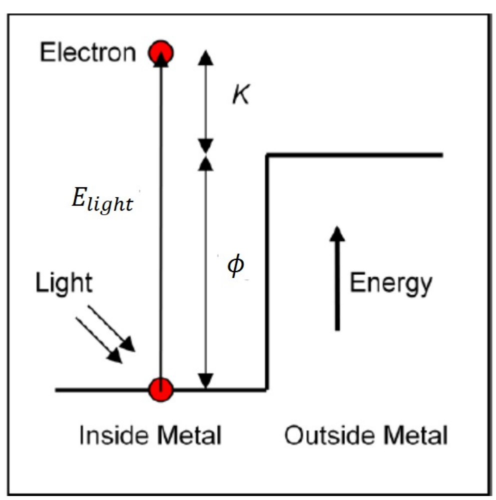
The photoelectric effect occurs when light is shined on a material (usually a metal); under certain conditions, the light can release electrons from the metal. These electrons can be detected, and their energy can be measured as explained below. In the late 19th and early 20th century, experiments were conducted measuring how the energy of the emitted electrons varied with intensity (brightness) of the incident light, as well as the wavelength (color) of the light.

Electrons are bound inside a metal. When light is shined on the material, the energy carried by the light can be used to release electrons. We call the minimum energy necessary to release the electrons the *work function* of the materal denoted as ϕ. The work function is a physical property of the material.

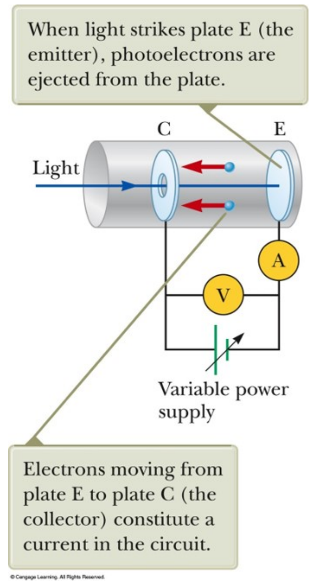
Because energy is conserved, we can write an equation tracking the energy throughout this process

$$E_{\text{light}} = K_e + \phi \tag{1}$$

where E_{light} is the energy of the light used to release a single electron, ϕ is the minimum energy needed to release an electron from the metal, and K_e is "leftover" kinetic energy of the electrons after they have been released from the metal.



We can measure the kinetic energy of the electrons by slowing them down with a potential difference applied between two plates. If the potential difference is small, electrons will be able to flow between the plates, causing a current (the "photocurrent"). If the potential difference is just strong enough, electrons will no longer be able to make it across the gap. Their initial kinetic energy will be entirely converted to potential energy: they will stop and turn around, and the photocurrent between the plates will drop to zero. The applied potential difference at which the photocurrent just stops is called the *stopping potential*, or *stopping voltage*, ΔV_{stop}. Conservation of energy relates it to the kinetic energy



From Serway "Physics for Scientists and Engineers with Modern Physics", 9th Edition

$$\Delta K + \Delta U = 0 \tag{2}$$

$$\cancelto{0}{K_f} + K_e - e\Delta V_{\text{stop}} = 0 \tag{3}$$

$$K_e = e\Delta V_{\text{stop}} \tag{4}$$

Comparing this with (1), we have

$$E_{\text{light}} = e\Delta V_{\text{stop}} + \phi \tag{5}$$

Models of Light

In the 19th century, most scientists understood light as a wave. All other known waves (like water waves, sound waves, etc...) have an energy related to their amplitude. If light behaved this way, we would expect a brighter light to release more energetic electrons.

On the other hand, Einstein hypothesized the light came in "bundles" called photons, with the energy of each photon related to its color. They proposed the energy of light is related to its *color* (its frequency f, or wavelength λ) through the equation

$$E_{\text{photon}} = hf = \frac{hc}{\lambda} \tag{6}$$

where h is Planck's constant $h = 6.636 \times 10^{-34}\,\text{J}\cdot\text{s} = 4.14 \times 10^{-15}\,\text{eV}\cdot\text{s}$, and c is the speed of light. A convenient combination is $hc = 1240\,\text{eV}\cdot\text{nm}$.

Pre-Lab Questions

Please complete the following questions prior to coming to lab. They will help you prepare for both the lab and the pre-lab quiz (Found on D2L).

1.) Light of wavelength 310nm is shined on a metal with work function $\phi = 1$ eV. What will be the maximum kinetic energy of the emitted electrons?

2.) Light is shined on a metal with work function 2.0 eV, and electrons are emitted creating a photocurrent. When a decelerating voltage of magnitude 1.0 V is applied, the current goes to zero (i.e. the magnitude of the stopping voltage is 1V). What is the wavelength (in nm) of the incoming light?

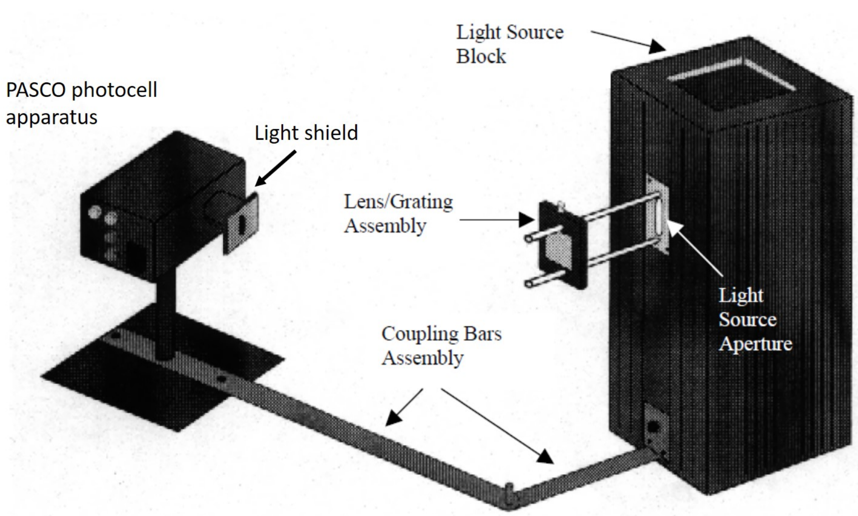
3.) According to the wave model of light, which would have a larger stopping potential (or would their stopping potentials be the same): bright green light of a single wavelength, or dim green light of the same wavelength? Explain your answer.

4.) According to Einstein's model of light, which would have a larger stopping potential (or would their stopping potentials be the same): bright green light of a single wavelength, or dim green light of the same wavelength? Explain your answer

5.) Blue light has a higher frequency than green light. According to Einstein's model of light, which would have a larger stopping potential: blue light or green light (or do you need more information to answer this question)? Explain your answer.

Apparatus

- PASCO photoelectric apparatus (light source and light block, photodiode apparatus, coupling bars, grating and lens assembly)
- Digital multimeter
- Cables with banana plugs (2)



A mercury vapor light source is enclosed in a black "box" to block any stray light. Light exits the box through the small slit, the light source aperature. The light is then split into component wavelengths with the use of the lens/grating assembly, with each wavelength traveling at a different angle. The five visible wavelengths are

Colour	Wavelength
Yellow	578.0 nm
Green	546.1 nm
Blue	435.8 nm
Blue/Violet	404.7 nm
Dark Violet	365.5 nm

Light can be detected when it enters a slit on the photodiode apparatus. The photodiode apparatus can be rotated on its axis, and can also be rotated around the light source in order to detect different wavelengths.

Rather than having to adjust the decelerating voltage until the current goes to zero, the photodiode apparatus contains electronic circuitry which allows you to measure the stopping voltage with the push of a button. Details about this circuitry are contained in the appendix.

Procedure

1.) Turn on the mercury vapor light source, and allow it to warm up for about 5 minutes.

2.) Turn on the multimeter and plug cables into the multimeter to measure voltage (in the V and COM) ports. Adjust the dial so that the meter is measuring DC voltage.

3.) Check the battery on the photodiode apparatus:

(a) Plug the black cable into the ground terminal on the photodiode apparatus.

(b) Plug the red cable into the "+6V MIN" terminal on the photodiode apparatus. If the multimeter reads below 6.0V, the battery on the apparatus should be replaced.

(c) Unplug the red cable, and plug it into the "-6V MIN" terminal on the photodiode apparatus. If the multimeter reads above -6.0V (i.e. between -6.0V and 0V), the battery on the apparatus should be replaced.

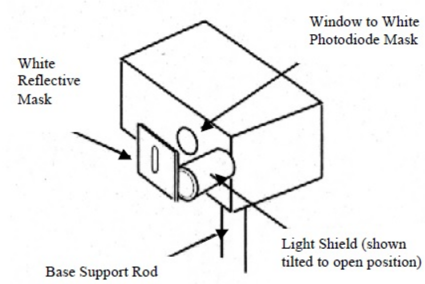
4.) Plug in the cables into the "OUTPUT" terminals on the photodiode apparatus using the same polarity as the multimeter (red to red, black to black)

5.) By holding your hand up close to the lens, you should be able to see five colors from the mercury light spectrum (three blue/purple lines, a green line, and a yellow/orange line). The pattern is repeated twice on each side of the apparatus. The lens/grating is manufactured to create light brighter on one side of the apparatus than the other. **Only take measurements on the brighter side.**

6.) Rotate the coupling bar so that the photodiode apparatus is directly across from the lens/grating. Adjust the position of the lens/grating so that the light is sharply focused.

7.) Rotate the coupling bar so that one of the wavelengths falls directly on the opening into the photodiode apparatus.

8.) Rotate the light shield out of the way and check that light of a **single color only** is entering the black openings inside the photodiode apparatus. If not, adjust the angle of the photodiode apparatus using a thumbscrew underneath it. You may also find it necessary to adjust the position of the lens/grating to focus the light.



9.) Once you are satisfied that a single wavelength of light is well-positioned and focused on the black openings inside the apparatus, rotate the light shield back into place.

10.) If you are measuring a yellow or green line, attach the magnetic yellow or green filter to the opening on the photodiode apparatus. This helps to filter out other wavelengths.

11.) You may now measure the stopping potential with the multimeter. It may take a few moments for the reading to stabilize (dimmer lines will take longer to stabilize). Should you want to take more measurements, you can push the "PUSH TO ZERO" button on the apparatus which will discharge the apparatus and cause it to start another measurement. Record your data with an estimate of uncertainty.

12.) Repeat steps 7 - 11 for all visible lines on the bright side of the light source. Record the light color, and the stopping voltage for each.

13.) When you have finished measurements, switch off all components of the apparatus. Don't forget to switch off the photodiode apparatus!

Analysis

1.) Using your measurements, plot your data in such a way that the result is a straight line. Plot two sets of data: one using the "first order" data (the 5 brighter lines closer to the center), and one using the "second order" data (the 5 dimmer lines further away from the center).

2.) Fit your data with a line. Using the slope and the intercept for each data set, determine Planck's constant h, and the work function (in units of eV) of the photocell ϕ. Pay attention to units!

3.) You should have two measurements of h and ϕ (one from the first order data, and one from the second order data). Use these two measurements to quote a final result (with uncertainty) for these two quantities.

4.) Compare your result for h with the accepted value including uncertainty. Is your result consistent with the accepted value (does the accepted value fall within your uncertainty range)? If not, determine the percent error by which your results differs from the expected result.

Wrap Up

The following questions are designed to make sure that you understand the physics implications of the experiment and also to extend your knowledge of the physical concepts covered. Your report should answer these questions in the noted section in a seamless manner.

1.) [Results & Calculations] In your data set, you should have observed the stopping voltage for each color twice (once for a bright first order line, and once for a dim second order line). Was the stopping voltage significantly different for the bright line as opposed to the dim line of the same colour? Comment on your observations.

2.) [Results & Calculations] Does your answer to the previous question support the wave model of light, or the Einstein/Planck model of light? Explain. (Re-read the pre-lab questions if necessary)

3.) [Discussion] The threshold frequency is the minimum frequency of light needed to release electrons from a material. Determine the threshold frequency for this apparatus. What is the associated threshold wavelength (the longest wavelength which releases electrons from the apparatus)? Quote your result with uncertainty. (You may need to review the rules for propagating uncertainty)

4.) [Discussion] Einstein hypothesized that light comes in packages of energy hf called photons. Does that mean that a bright light of a certain wavelength has the same total energy as a dim light of the same wavelength? Using the concept of photons, explain the difference between a bright light and a dim light.

Report

Labs will be completed in groups, you will enroll in a group with your lab partner at the beginning of each lab session. Each group will submit a single report through the assignment section on D2L.

- **Introduction**
  - What is the experiment's objective?
- **Theory**
  - You may be able to show a derivation of the physics you're investigating, or you may want to reference a source that provides a description/equation representing the physics you're investigating.
  - You may want to provide graphs that illustrate or predict how you expect the system under study to behave.
- **Procedure**
  - Explain the systematic steps required to take any measurements.

- **Results and Calculations**
  - Tabulate your measurements in an organized manner.
  - Based on your procedure, you should know what your tables
  - Provide examples of any calculations.
- **Discussion and Conclusions**
  - Discuss the main observations and outcomes of your experiment.
  - Summarize any significant conclusions.
- **References**
- **(Appendices)**

Appendix

Below is a circuit diagram for the electronics contained in the photodiode apparatus. This circuity allows one to measure the stopping voltage by connecting a voltmeter to read the "output".