

Photoelectric Effect

Goals

At the end of this experiment you will be able to:

- Describe qualitatively the photoelectric effect
- Describe the relation between the energy of light and the energy of the electrons emitted during the photoelectric effect,
- Explain how the photoelectric effect supports the concept that energy of light comes in packets (photons),
- Explain how your observations support the relation between a photon's energy and the frequency of light,

Introduction

A large number of devices detect the presence of light. These range from the “switches” which automatically turn on the street lights when it gets dark to the receiving end of the scanners at the grocery store check out counter to the detectors in a CD player. All of these devices work because light striking a material deposits energy in that material and causes a change in the motion of the electrons. The detection of this change helps determine how dark it is, how much your potato chips cost, and what sound should be produced by the stereo.

The basic process behind all of these devices is the photoelectric effect. This effect was first explained by Albert Einstein in 1905 and is cited as the reason for his Nobel Prize. (When Einstein was awarded the Noble Prize, the Theory of Relativity was very controversial, so it was not included as the reason.) We will study this photoelectric effect in this experiment.

WARNING The mercury lamps used in this experiment emit ultraviolet light and can cause eye damage. Do not look directly at these light sources.

A. Exploration

We begin by investigating the photoelectric effect in a manner similar to the way it was observed in Einstein's time. The apparatus is an electroscope which can indicate that it contains an electrical charge.

- A-1. To see how the electroscope works, get a charge on a rod by rubbing it with the fur. Then, touch the metal plate with the rod. Describe what happens to the electroscope.

- A-2. Explain your observation in terms of forces on like charges.

- A-3. Now, bring the ultraviolet light source near, but not touching, the metal plate. Describe what happens.

This result is the photoelectric effect. Light strikes the metal plate and the electroscope is discharged. Thus, the light must have caused the electrons to be emitted by the metal plate, leaving it without an electric charge.

- A-4. Now, complete additional experiments to determine if the color and/or intensity of light are important in causing these electrons to be emitted. Describe the experiments, the results and your conclusion below. (You can change the intensity of the light striking the metal plate by changing the distance between the light source and the metal plate.)

B. Background

We have not studied the photoelectric effect in class, so you will need a little background information to understand the measurements which you will need to complete. In this experiment we will look at a situation similar to the one that Einstein originally explained. It uses rather high-energy visible and ultraviolet light. In many devices today, particularly CD players and grocery store scanners, the energy of the light is much lower.

The photons of the light source have the energy;

$$E_{\text{photon}} = hf_{\text{photon}} \qquad h = 6.626 \times 10^{-34} \text{ J}\cdot\text{sec} = 4.136 \times 10^{-15} \text{ eV}\cdot\text{sec}$$

where E is the energy of the photon, f is the frequency of the light and h is Planck's Constant. The frequency of light can be found from the wavelength by:

$$f = c/\lambda \qquad c = 3.00 (10)^8 \text{ m/sec}$$

When an electron gets enough energy from a photon, the electron can be ejected from the metal. However, the electrons are bound in the metal so some of this energy must be used to overcome this binding. For bound electrons their maximum kinetic energy will be less than the energy of the light photon. Because interactions with the metal will differ from different electrons, not all of them will have the same *kinetic* energy even though they have absorbed the same total energy from the photon. We relate the kinetic energy of the ejected electron to energy of the photon as:

$$KE_{\text{max}} = E_{\text{photon}} - W_0 = hf - W_0$$

Here, E_{photon} is the energy of a photon, h is Planck's constant, f is the frequency of the light, KE_{max} is the maximum kinetic energy of the electron released from the metal, W_0 is the energy needed to eject an electron from the metal.

Using energy level diagrams the situation would look like the diagrams below.

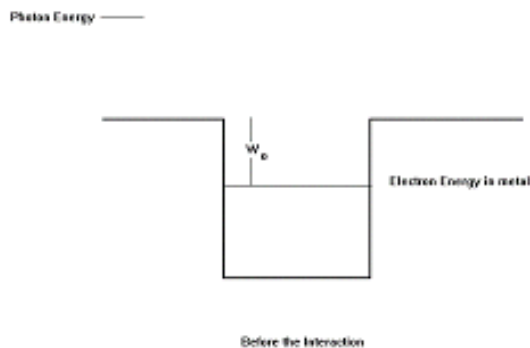


Figure 1: An energy diagram showing the energy of the electron in the metal and the energy of the photon before the photon is absorbed by the electron.

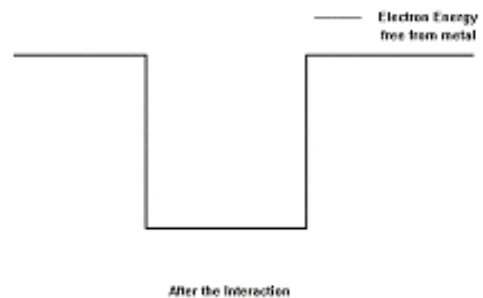


Figure 2: The energy diagrams after the photon is absorbed by the electron.

Modern device that use the photoelectric effect are frequently called photocells. These devices include a metal that will emit the electrons when light strikes it and another metal plate. The energy of photoelectrons can be changed by placing a voltage across the two metal plates. As the electron moves between these plates, it gains or loses energy which depends on the voltage applied to the plates. (An energy gain occurs when the electron is traveling toward the positive plate; a loss occurs when it is traveling toward the negative plate.). In next part of this experiment we will use this fact to determine the kinetic energy of the electrons.

A modern photocell with an appropriate electrical circuit are shown in Figure 3,

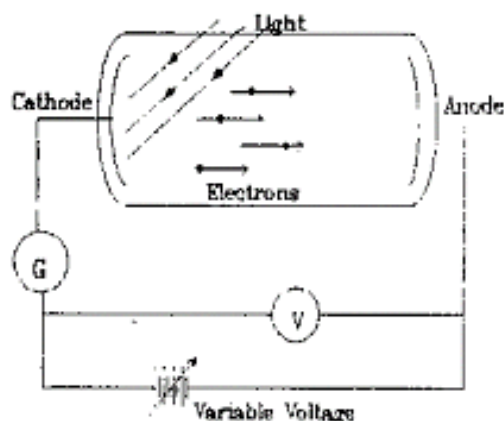


Figure 3: A schematic representation of a photocell.

The electrons will leave the metal with a kinetic energy. After they reach the other metal plate (anode in the Figure), they move through the circuit. Electric current is directly related to the number of electron passing a point per second. So, when the electrons have enough energy to pass from the cathode to the anode, we measure an electric current in the circuit.

We can slow the electrons in the region between the anode and cathode by applying a voltage between the anode and the cathode.

B-1. Which will be the positive and negative sides of this voltage so that the negatively charged electrons will be slowed in the region?

When the voltage is such that all of the kinetic energy of the electrons is transferred to the electric field, the electrons will stop before reaching the anode. Then, electric current is zero. Thus, the maximum kinetic energy of an ejected electron can be measured by finding the stopping voltage, V_0 :

$$KE_{\max} = \frac{1}{2} m v_{\max}^2 = eV_0$$

The stopping voltage, V_0 , is the minimum potential across the photocell required to stop all current through the photocell.

(Note on units: Electron volts are a good unit of energy to use here. The voltage gives us that measure. So, if you measure a stopping voltage of 10 Volts that converts to an energy of 10 eV.)

C. Visualizing the Photoelectric Cell

A computer program can give us a visual representation of the process that occurs in a modern photocell. Start the program *Photoelectric Effect*. At the top of the screen are sliders which allow you to change both the frequency (wavelength) of the light and the brightness. Along the right side you can change the voltage between the anode and the cathode. The little blue box on the lower right side is an “ammeter” and gives a relative measure of the number of electrons per second. Vary each of these parameters and describe what happens to the “electrons” and the current in the photocell.

C-1. Frequency of light

C-2. Brightness of light

C-3. Voltage between anode and cathode

C-4. Describe how the response of the electrons is similar to your observations in part A.

C-5. Describe how the response of the electrons and the current are consistent with the discussion in part B.

D. The Real Experiment

The photocell should be connected as shown in the circuit in Figure 4. The connections are marked on the photocell box. (Instead of a battery we will use a small power supply set at approximately 3 volts.)

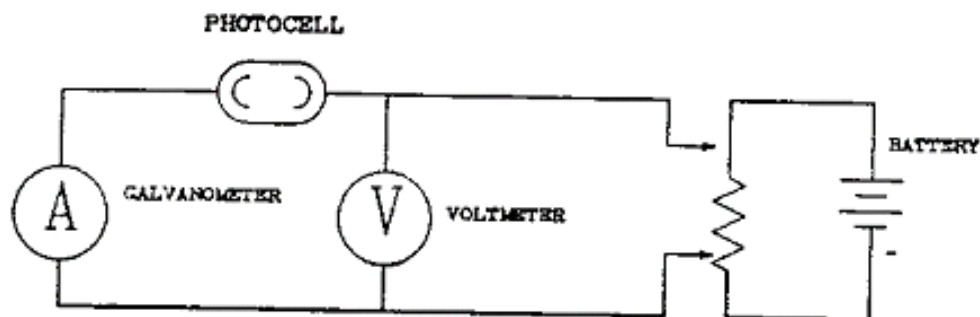


Figure 4: The circuit to use for the experiment.

When the equipment is set up as in Figure 4, the voltage applied by the battery will oppose motion of the photoelectrons. If the voltage becomes great enough the photoelectrons will be stopped. At this voltage, the kinetic energy of the electrons is equal to the electric potential energy applied by the power supply. Thus, the electrons do not move to the other metal plate and the current is zero. In this situation, the voltmeter gives the stopping potential, V_0 .

Procedure

The filter wheel on the photocell box limits the frequency (wavelength) of light that reaches the photocell. The numbers next to the filters indicate the wavelength in nanometers (10^{-9} meters). With the coarse and fine knobs on the photocell box set the voltage to zero volts and turn on the mercury light. You should see a reading on the galvanometer. The current is very small and the galvanometer readings are in arbitrary units, close to nano-amperes. You can now use the coarse and fine knobs on the photocell box to adjust the voltage until the current is zero.

- D-1. For each filter record the wavelength of the filter, the current at zero voltage, and the voltage needed to obtain zero current.

- D-2. To change the intensity of the light, use the slide that has gradations of gray in it. The numbers on the slide indicate the percentage of light transmitted through the filter. Before doing the experiment predict how the change in light intensity will effect the current at zero voltage to compare with the results in D1 (Greater, same or less)? Explain your answer.

D-3. How will you expect the voltage at zero current to compare with the results in D1? Explain your answer.

D-4. Do the experiment and record your results.

D-5. If your expectations in D3 and D4 do not agree with your results, discuss them with your instructor.

E. Conclusions

In drawing your conclusions you may wish to refer back to the animation. You may find it at <http://www.students.uiuc.edu/~dvorkin/PE.dcr>.

E-1. Describe how the computer visualization and the real experiment are consistent with each other. If you see any inconsistencies describe them as well.

E-2. Describe how the results of the experiment in part A is consistent with the experiment in part D.

- E-3. In the history of physics this experiment was important in demonstrating that photons of light exist and that their energies were proportional to the frequency of light. Write a paragraph describing how these results were demonstrated in the experiments that you did and the visualizations with which you worked.

Historical Note

Einstein's explanation of the photoelectric effect was published in 1905. However, almost no one believed he had explained it correctly. A few years later Max Born, a famous physicist of the time, said that Einstein was a talented physicist in spite of getting the photoelectric effect wrong. Eventually, enough experiments were completed to show that Einstein did not get it wrong and he was awarded the Nobel Prize for his efforts.

For Future Teachers

Electroscopes will be available in most school physics labs. To do this experiment you may need to attach a large piece of metal to the top. Zinc works well. The photocell apparatus comes in many similar forms and is also frequently available. A free version of the software that we used is available at <http://www.students.uiuc.edu/~dvorkin/PE.dcr>. The person who wrote this program is an undergraduate majoring in physics education.