# Photoelectric Effect

Equipment

Mercury Lamp and Power Supply (in SE-6609)
Photodiode (in SE-6609)
Track (in SE-6609)
DC Current Amplifier (BEM-5004)
DC Power Supply I (BEM-5001)
850 Universal Interface (UI-5000)

Introduction

The photoelectric effect is the emission of electrons from the surface of a metal when electromagnetic radiation (such as visible or ultraviolet light) shines on the metal. At the time of its discovery, the classical wave model for light predicted that the energy of the emitted electrons would increase as the intensity (brightness) of the light increased. It was discovered that it did not behave that way. Instead of using the wave model, treating light as a particle (photon) led to a more consistent explanation of the observed behavior.

In this lab, you will study the effect varying the light intensity and frequency has on the energy of the emitted electrons and the magnitude of the photo-current. You will also determine Planck's constant.
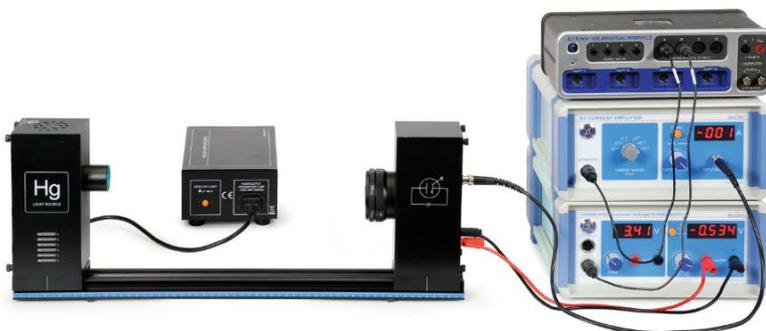
Predictions

1. If the light shining on the metal becomes brighter, will the kinetic energy of the emitted electrons increase?

2. If the light shining on the metal becomes brighter, will the number of electrons emitted per second (the photo-current) increase?

3. If the frequency of the light shining on the metal is increased, will the number of electrons emitted per second (the photo-current) increase?

4. If the frequency of the light shining on the metal is increased, will the kinetic energy of electrons emitted increase?

PASCO

5. Will all colors (frequencies) of light cause electrons to be emitted by the metal?

6. If light with the same frequency and same intensity shines on two different metals with different work functions, will both metals emit electrons?
    a. Will these electrons have the same kinetic energy?
    b. Will the photo-current be larger for the metal with the smaller work function?

Theory

The electrons in a metal are in potential energy wells (see Figure 1A). When light shines on the metal, the energy of the photon is absorbed by the electron and converted into potential energy and kinetic energy. If the photon has sufficient energy to raise the electron out of the potential well, the electron will be ejected from the surface of the metal with kinetic energy (K) equal to the difference between the photon energy (E) and the depth of the potential well (φ, the work function of the metal) (see Figure 1B).

$$K = E - \varphi \qquad (1)$$

The energy of the photon is proportions to its frequency:

$$E = hf \qquad (2)$$

where h is Planck's Constant.

If the energy of the photon is equal to the work function, the electron makes it out of the well with no kinetic energy and thus will not actually leave the surface of the metal. If the energy of the photon is greater than the work function, the electron makes it out of the well with some kinetic energy and the electron leaves the surface of the metal. If the energy of the photon is less than the work function, the electron does not make it out of the well.
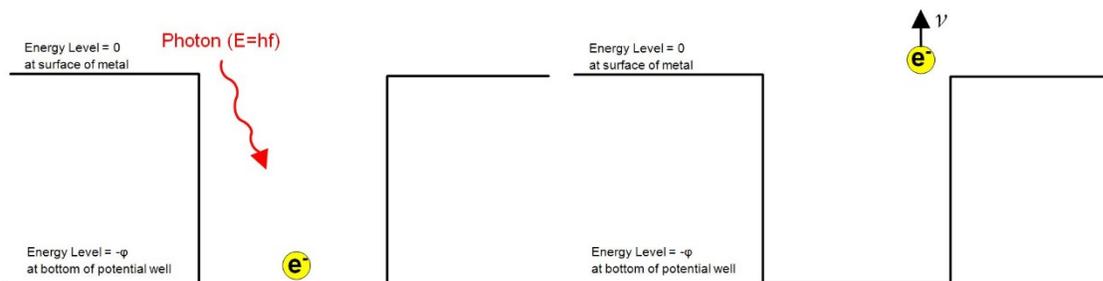

Figure 1A: Photon strikes the surface of the metal.   *Figure 2B: Electron absorbs the photon and is ejected from the metal with some kinetic energy.*

In this experiment, the kinetic energy of the emitted electron is measured by applying a potential difference (V) across the photodiode to just barely stop the electron from reaching the collector plate in the photodiode tube (Figure 2). The voltage is adjusted until the ammeter reads zero. The

kinetic energy is then equal to the potential energy, which is the charge multiplied by the potential difference:

$$K = eV \qquad (3)$$

Substituting equations (2) and (3) into equation (1) gives:

$$eV = hf - \varphi \qquad (4)$$

Solving for the potential difference yields

$$V = \left(\frac{h}{e}\right)f - \frac{\varphi}{e} \qquad (5)$$

If different frequencies of light are incident on the metal, the electrons will be emitted with different kinetic energies, and thus it will take different potential differences to stop the electrons.

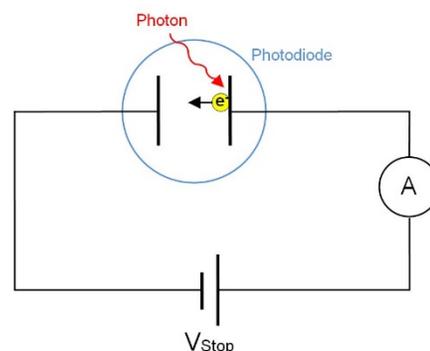A plot of V versus f will yield a straight line with a slope of h/e and a y-intercept of φ/e.

Figure 2: Photodiode Circuit

Setting the voltage equal zero and solving equation (5) for the frequency gives the x-intercept on the V versus f graph. Photons must have a frequency greater than this to cause electrons to be emitted from the metal. This is called the cutoff frequency.

$$0 = \left(\frac{h}{e}\right)f_{cutoff} - \frac{\varphi}{e} \qquad (5)$$

$$f_{cutoff} = \frac{\varphi}{h} \qquad (6)$$

Setup

1. Mount the mercury lamp and the photodiode case on the track as shown in Figure 3.

2. Connect the power cord from the Mercury Light Source enclosure into the receptacle labeled "POWER OUTPUT FOR MERCURY ~220V" on the Mercury Lamp Power Supply. Connect the Mercury Lamp Power Supply to an outlet.

3. Turn on the Mercury Lamp and let it warm up for at least 10 minutes. Leave the cover on the lamp to avoid looking directly into the lamp.

4. Connect a DIN-plug-to-DIN-plug cable between Channel A on the 850 Interface and the DC Current Amplifier (see Figure 4). Connect a DIN-plug-to-DIN-plug cable between Channel B on the 850 Interface and the DC Power Supply port labeled -4.5 V to 0 V (the lower port) (see Figure 5).

5. Do not connect any cords to the photodiode yet.

6. On the DC Current Amplifier, turn the CURRENT RANGES switch to 10^{-13}A. Press the Calibration button in to zero the meter. Turn the knob until the meter reads 000 A (see Figure 4).

7. Press the Calibration button to put it in the OUT position for measuring.

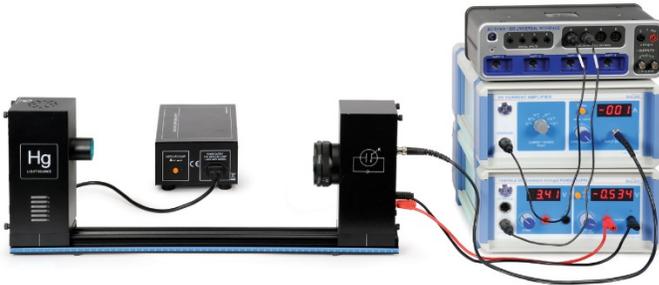**NOTE**: For the rest of the experiment, do not change the knobs on the DC Current Amplifier.
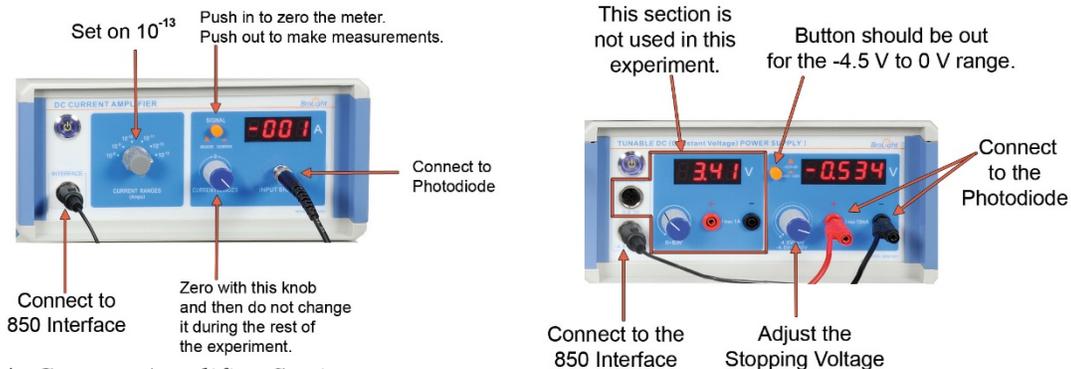

Figure 3: Complete Setup

Figure 4: Current Amplifier Settings

Figure 5: DC Power Supply Settings

8. On the DC Power Supply, make sure the button is out to select the -4.5 V to 0 V range (see Figure 5).

9. Connect the cables to the photodiode:
    a. Connect the special BNC-plug-to-BNC-plug cable between the port marked "K" on the Photodiode enclosure and the BNC jack on the DC Current Amplifier.
    b. Connect the red banana-plug patch cord between the port marked "A" on the Photodiode enclosure and the red banana jack on the right side of the DC Power Supply.
    c. Connect the black banana-plug patch cord between the black banana jack on the Photodiode enclosure and the black banana jack on the right side of the DC Power Supply.

10. During the experiment, you will be changing the aperture and the filters.
    a. To change the aperture, pull out on the Aperture Ring and rotate it until it clicks into place.
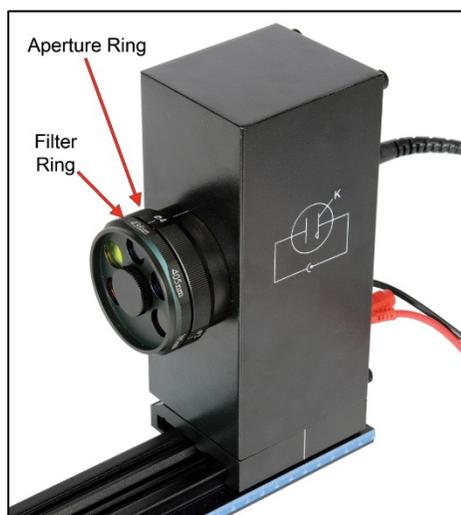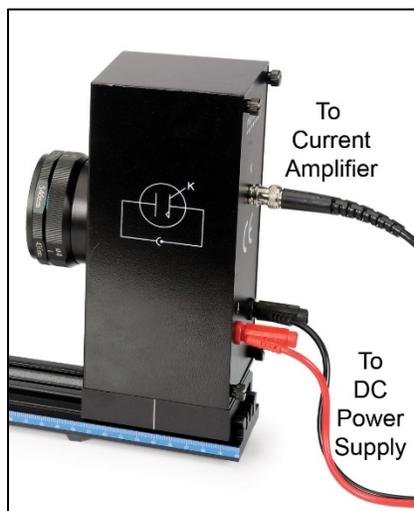   b. To change the filter, do not pull out; just rotate the Filter Ring until it clicks into the next position.

Figure 6: Photodiode Connections   *Figure 7: Filter Ring and Aperture Ring on Photodiode*

11. In PASCO Capstone, create a table with a user-entered set containing the wavelengths of the filters.
    a. In the second column, create a calculation for the frequencies of the filters, $f = \frac{c}{\lambda}$, with units of 10^{14}Hz. Set the numerical format of this calculation to 3 decimal places.
    b. Add a third column for the voltage. Add a fourth column with a calculation called "Current Reading" with units of 10^{-10}A: Current Reading = [Current, Ch A(A), ▼]*10^{10}; Set the numerical format of this calculation to 3 decimal places.

12. Create a graph of Voltage vs. Frequency.

13. Set the Data Collection Mode to Keep Mode.

Data Collection

1. Select the 8 mm aperture and the 365 nm filter on the photodiode.

2. Remove the Mercury Light Source cover and press the Preview button on the Control Bar at the bottom of the page. Click in the first row of the Stopping Voltage in the table.

3. Adjust the VOLTAGE ADJUST knob on the DC Power Supply until the current on the ammeter is zero. Then click on Keep Sample on the Control Bar.

4. Rotate the filter ring to the next longer wavelength filter, click in the next row, and adjust the VOLTAGE ADJUST knob until the current on the ammeter is zero. Then click on Keep Sample on the Control Bar.

5. Repeat the procedure for all the filters. Then click on Stop.

6. Put the cover back onto the Mercury Light Source.

Analysis

1. Apply a linear fit to the data.

2. Calculate Planck's Constant from the slope of the line.

3. Calculate the percent difference between the result and the accepted value.

4. From the y-intercept, find the work function for the metal.

Questions

1. Which wavelength gave the emitted electrons the greatest kinetic energy? What color is this?

2. From the x-intercept, find the cutoff frequency. What wavelength (color) does the cutoff frequency correspond to?

Stopping Voltage vs. Light Intensity

To investigate the effect that light intensity has on the energy of the emitted electrons, the intensity is varied by changing the aperture, while keeping the wavelength constant.

1. Enter the stopping voltage into a table for the 436 nm filter and 8 mm aperture recorded in the first procedure.

2. With the cover on the mercury light source, change the aperture from the 8 mm to 4 mm aperture on the photodiode tube.

3. Uncover the mercury light source, click on preview, and adjust the VOLTAGE ADJUST knob until the current on the ammeter is zero. Record the stopping voltage in the table.

4. Change the aperture to 2 mm and find the stopping voltage again and record it in the table.

5. Find the average and the standard deviation of the stopping voltages.

6. The aperture diameter has been changed by a factor of four. Did the stopping voltage change as the light got brighter?

7. What does the result indicate about the relationship between the kinetic energy of the electrons and the light intensity?

Phototube Characteristics: How does the current change when the light intensity changes?

1. Create a graph of Current Reading vs. Voltage.

2. With the cover on the mercury light source, change the aperture to 2 mm aperture on the photodiode tube and put on the 436 nm filter.

3. Change the Current Range switch on the DC Current Amplifier to 10^{-12}A and calibrate it again.

4. Uncover the mercury light.

5. On the DC Power Supply, push the range button in to set the voltage range to –4.5 to 30 V. Set the voltage to -4.5 V.

6. Click Preview and wait for the readings to settle down. Then click on Keep Sample. Adjust the voltage slowly from –4.5 V to +30 V in steps small enough to define a smooth curve. Each time you pause to take a data point, wait until the readings are stable and then click Keep Sample. When you get to 30 V, click on Stop.

7. Change the aperture to 4 mm. This makes the light brighter. Repeat the procedure.

Questions

1. How did the current change when the light intensity was increased?

2. Was the stopping voltage different for different light intensities? How does the kinetic energy of the electron depend on the light intensity?

Check your predictions

Did you correctly predict what would happen? If not, what really happened? Identify which parts of the experiment apply to each question.