PHYSICS 258 Lab Manual[1]

Contents

[1]Updated: February 14, 2021

Lab 3

Photoelectric Effect

Learning Objectives

- To investigate the relation between light's frequency, intensity and energy.
- To explore the quantum nature of light.

Introduction

This experiment will investigate the effect of the frequency of light arriving at a photodiode on the stopping potential that one has to impose on the circuit in order to cancel the photoelectric current.

In order to select specific light conditions, the apparatus includes small filters that will select light of a specific wavelength to shine on the photodiode. These filters are labeled to identify the main wavelength they let through. It is therefore needed to find the corresponding frequency of each light setting using the relationship

$$c = \nu\lambda, \tag{10}$$

where c is the speed of light in vacuum, ν is the frequency of the light, and λ is the wavelength of the light.

For each wavelength, a corresponding stopping potential must be determined. When light shines on to the photodiode, it provokes a current that the highly sensitive ammeter records as positive. The value of the stopping potential is obtained by supplying just the right voltage to cancel the photoelectric current. The cancellation is achieved using the Tunable DC Power Supply. The value to be recorded is that of the voltage provided when the current reads 0. This is the stopping potential[3].

Theory

NOTE: This section is based on PASCO Instruction Manual 012-13943A.

Many people contributed to the discovery and explanation of the photoelectric effect. In 1865 James Clerk Maxwell predicted the existence of electromagnetic waves and concluded

[3] This voltage is not exactly the stopping potential. In the limits of this experiment, as the object of interest is the slope of the potentials as a function of the frequency, the approximation can be assumed. If you want more information on this topic, you are welcome to read Experiments in Modern Physics by Adrian C. Melissinos, copyright 1966, Hardcourt Brace Jovanovich.

that light itself was just such a wave. Experimentalists attempted to generate and detect electromagnetic radiation, and the first clearly successful attempt was made in 1886 by Heinrich Hertz. In the midst of his experimentation, he discovered that the spark produced by an electromagnetic receiver was more vigorous if it was exposed to ultraviolet light. In 1888 Wilhelm Hallwachs demonstrated that a negatively charged gold leaf electroscope would discharge more rapidly than normal if a clean zinc disk connected to the electroscope was exposed to ultraviolet light. In 1899, J.J. Thomson determined that the ultraviolet light caused electrons to be emitted from the metal.

In 1902, Phillip Lenard, an assistant to Heinrich Hertz, used a high intensity carbon arc light to illuminate an emitter plate. Using a collector plate and a sensitive ammeter, he was able to measure the small current produced when the emitter plate was exposed to light. In order to measure the energy of the emitted electrons, Lenard charged the collector plate negatively so that the electrons from the emitter plate would be repelled. He found that there was a minimum "stopping" potential that kept all electrons from reaching the collector. He was surprised to discover that the "stopping" potential, V, – and therefore the energy of the emitted electrons – did not depend on the intensity of the light. He found that the maximum energy of the emitted electrons did depend on the color, or frequency, of the light.

In 1901 Max Planck published his theory of radiation. In it he stated that an oscillator, or any similar physical system, has a discrete set of possible energy values or levels; energies between these values never occur. Planck went on to state that the emission and absorption of radiation is associated with transitions or jumps between two energy levels. The energy lost or gained by the oscillator is emitted or absorbed as a quantum of radiant energy, the magnitude of which is expressed by the equation $E = h\nu$, where E equals the radiant energy, ν is the frequency of the radiation, and h is a fundamental constant of nature. (The constant, h, became known as Planck's constant.)

In 1905 Albert Einstein gave a simple explanation of Lenard's discoveries using Planck's theory. The new "quantum"-based model predicted that higher frequency light would produce higher-energy emitted electrons (photoelectrons), independent of intensity, while increased intensity would only increase the number of electrons emitted (or photoelectric current). Einstein assumed that the light shining on the emitter material could be thought of as "quanta" of energy (called photons) with the amount of energy equal to $h\nu$. In the photoelectric effect, one "quantum" of energy is absorbed by one electron. If the electron is below the surface of the emitter material, some of the absorbed energy is lost as the electron moves towards the surface. This is usually called the "work function" (W_0). If the "quantum" is more than the "work function", then the electron is emitted with a certain amount of kinetic energy. Einstein applied Planck's theory and explained the photoelectric effect in terms of the quantum model using Planck's famous equation for which Einstein received the Nobel Prize in 1921: $E = h\nu = KE_{max} + W_0$, where KE_{max} is the maximum kinetic energy of the emitted photoelectron. In terms of kinetic energy, $KE_{max} = h\nu - W_0$.

If the collector plate is charged negatively to the stopping potential so that electrons from the emitter don't reach the collector and the photocurrent is zero, the highest kinetic energy electrons will have energy eV where e is the charge on the electron and V is the stopping potential:

$$eV = h\nu - W_0. \tag{11}$$

Alternatively, expressed as a stopping potential:

$$V = \frac{h}{e}\nu - \frac{W_0}{e}. \tag{12}$$

Einstein's theory predicts that, if the frequency of the incident light is varied, and the stopping potential, V, is plotted as a function of frequency, the slope of the line is h/e.

Apparatus and Calibration

The apparatus consists of one mercury lamp[4], one photodiode, one DC current amplifier, one tunable DC power supply, and the PASCO 850 Universal Interface, as shown below.

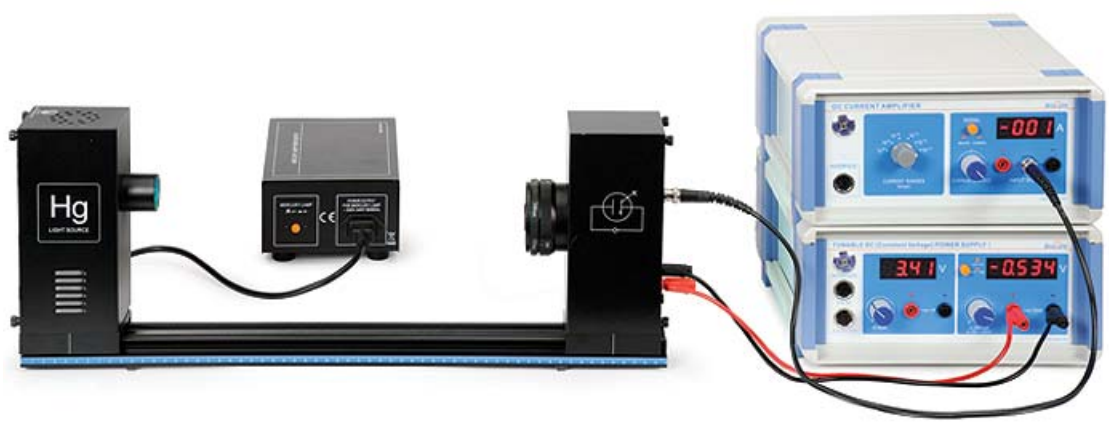

Figure 6: Experimental set-up: the photoelectric effect system, complete with DC Current Supply and DC Power Supply.

Before connecting up the apparatus, ensure that ALL ON/OFF switches are in the OFF position! Dial the voltage knobs to zero (counter-clock wise). Ensure that the window of the Mercury Light Source Enclosure is covered with the Mercury Lamp Cap and the window of the Photodiode covered with the Photodiode Cap.

Please do not switch on any power until your setup has been checked and approved by a TA or technician!

1. Place the mercury lamp on the track, 40 cm away from the photodiode (just slide the lamp on the track).

[4]The mercury lamp produces ultraviolet light that can damage eyes. Do not look into the lamp. Also, note that the lamp can become very hot.

2. Connect the lamp to its power supply.

3. Connect the BNC cable from the photodiode to the DC current amplifier. The BNC cable goes to the DC current amplifier port labelled **INPUT SIGNAL**.

4. Connect the cables from the photodiode to the tunable DC power supply. The red and black banana-plug cables connect to the DC power supply on the right-hand side.

5. Open the appropriate capstone file and click on the 'Setup View 1' and 'Setup View 2' tab for an image of the setup.

6. We want to work in the $-4.5 - 0\,\mathrm{V}$ range; make sure the orange button on the DC Power supply is 'out' and the dial turned counter-clockwise all the way.

7. Connect the PASCO 850 Universal Interface to record the experiment's applied voltage and measured current by plugging cables into the **Analog Input A** for current (from DC current amplifier) and **Analog Input B** for voltage at the interface outlet (from DC power supply), respectively.

8. Connect the USB cable from the PASCO 850 Universal Interface to the laptop running the PASCO Capstone software package.

9. Get your setup checked by a TA or technician.

10. Remove the cap on the lamp and turn on the lamp. Turn on the power of the *DC Current Amplifier*. **Important:** Allow the lamp and *DC Current Amplifier* to warm up for ∼**10 minutes**, with its protective cap removed.

11. Turn on the power supplies and the PASCO interface.

Calibration: Do leave the cap on the photodiode during the initial calibration step.

1. Push the orange $\boxed{\text{SIGNAL}}$ button of the *DC current amplifier* 'in' so that it is in the $\boxed{\text{CALIBRATION}}$ position.

2. In the Capstone file, press the 'Part 1' tab to see the ammeter which is more sensitive than the display of the current amplifier.

3. Press the red 'preview' button on the Pasco file.

4. On the *DC Current Amplifier*, turn the $\boxed{\text{CURRENT RANGES}}$ switch to $10^{-13}\,\mathrm{A}$.

5. Adjust the $\boxed{\text{CURRENT ADJUST}}$ knob on the amplifier until the display on the Capstone software shows zero.

6. Then press the $\boxed{\text{SIGNAL}}$ button again so that it moves to the $\boxed{\text{MEASURE}}$ position.

The system is calibrated and ready for data acquisition.

Procedure Part 1: Planck's constant h

We will measure the stopping voltage that is required to stop photoelectrons that were created at different wave lengths (365, 405, 436, 546, and 577 nm). We will use this information to extract Planck's constant h. The measurement will be performed at lamp-photodiode distances of 20 cm, 30 cm, and 40 cm.

The recording mode in the Pasco software should be the Keep Mode. In this mode, the software measures the voltage and the current when you press Preview, but it only actually records data when you press the Keep Sample button.

Remove the photodiode protective cap.

1. Verify the lamp-photodiode distance of 40 cm.
2. Select the aperture of ⌀2 mm.
3. Select the wavelength of 365 nm.
4. Adjust the Voltage knob on the *Tunable DC Power Supply* until the *Current Amplifier* reads zero. This cannot be achieved entirely, as the current always suffers some fluctuation, but take the value of the voltage when the current is approximately wavering both slightly positive and negative. When you are satisfied with your value, press Keep Sample.
5. Turn the filter and repeat the previous step for wavelengths 405, 436, 546, and 577 nm. Make sure to press Keep Sample if you are satisfied with your stopping voltage.
6. After acquiring all your data, press STOP. Take a snapshot of the graphical display for your records.
7. Export your data to a csv file. Make sure to keep lamp-photodiode distance and aperture diameter for your records.
8. Repeat the above measurement for a lamp-photodiode distance of 30 cm.
9. Export your data to a csv file. Make sure to keep lamp-photodiode distance and aperture diameter for your records.
10. Repeat the above measurement for a lamp-photodiode distance of 20 cm.
11. Export your data to a csv file. Make sure to keep lamp-photodiode distance and aperture diameter for your records.

Use the Capstone software to compute a linear relationship between the stopping potential and the frequency. The slope of this graph is the ratio $\frac{h}{e}$. This raw-data graph is to be regarded as a quick and approximate tool to see whether any values fall out-of-line. Appropriate error analysis is required to make sense out of these values. Note that the Capstone software does not provide such a tool.

Procedure Part 2: Measuring Current-Voltage Characteristics

In this part, we will be taking readings of the current as a function of the applied stopping voltages at a given wavelength.

1. Switch the ammeter to 10^{-11} using the $\boxed{\text{CURRENT RANGES}}$ knob.
2. Set the voltage range on the power supply to $-4.5 \to 30\,\text{V}$ (orange button pressed).
3. Verify that the lamp-photodiode distance is 40 cm.
4. Calibrate the ammeter using the **Calibration** procedure described above, just with the 10^{-11} setting. Make sure to put the cap on the photodiode for the calibration procedure. Remove the cap afterwards.
5. Click on the 'Part 2' tab of the capstone file.
6. Reset your DC voltage to 30 V.
7. Rotate the filter wheel until the 436 nm filter and $\varnothing 2$ mm aperture are in place.
8. Press 'preview' and keep data at -2 V intervals until you reach 0 V.
9. Press 'preview' and keep data at -0.1 V intervals until the current on the amplifier reads zero, i.e., until you have reached the stopping potential at that particular frequency.
10. Stop recording and export the data to a csv file. Make sure to also record wavelength, distance, and aperture diameter.
11. Repeat the above measurement using the $\varnothing 4$ mm aperture. If the ammeter maxes out, use this voltage as the highest DC voltage and reduce it in -2 V steps until you reach 0 V. Then decrease the step size to -0.1 V until the current on the ammeter display reads zero.
12. Stop recording and export the data to a csv file. Make sure to also record wavelength, distance, and aperture diameter.
13. Repeat the above measurement using the $\varnothing 8$ mm aperture. If the ammeter maxes out, use this voltage as the highest DC voltage and reduce it in -2 V steps until you reach 0 V. Then decrease the step size to -0.1 V until the current on the ammeter display reads zero.
14. Stop recording and export the data to a csv file. Make sure to also record wavelength, distance, and aperture diameter.

Procedure Part 3 - Measuring Current-Voltage Characteristics

In this part, we will be taking readings of the current as a function of the applied stopping voltages at different wavelengths.

1. Verify that the lamp-photodiode distance is 40 cm.
2. Verify that you are on the 'Part 2' tab of the capstone file.
3. Reset your DC voltage to 10 V.
4. Rotate the filter wheel until the 436 nm filter and ⌀2 mm aperture are in place.
5. Press 'preview' and keep data at 2 V intervals until you reach 0 V.
6. Press 'preview' and keep data at 0.1 V intervals until the current on the amplifier reads zero, i.e., until you have reached the stopping potential at that particular frequency.
7. Stop recording and export the data to a csv file. Make sure to also record wavelength, distance, and aperture diameter.
8. Repeat the above measurement using a wavelength of 365 nm (⌀2 mm aperture). If the ammeter maxes out, use this voltage as the highest DC voltage and reduce it in 2 V steps until you reach 0 V. Then decrease the step size to 0.1 V until the current on the ammeter display reads zero.
9. Stop recording and export the data to a csv file. Make sure to also record wavelength, distance, and aperture diameter.
10. Repeat the above measurement using using a wavelength of 405 nm (⌀2 mm aperture). If the ammeter maxes out, use this voltage as the highest DC voltage and reduce it in 2 V steps until you reach 0 V. Then decrease the step size to 0.1 V until the current on the ammeter display reads zero.
11. Stop recording and export the data to a csv file. Make sure to also record wavelength, distance, and aperture diameter.

Data Analysis

Part 1

1. Determine the calculated slopes from Part 1 and use them to calculate the value of Planck's constant, h. Use proper error propagation and averaging methods. You can create a python script to load and fit your data files at different distances. Present h calculated for each measurement as well as the average value in a table. Don't forget to report all uncertainties.

2. Compare your calculated value of h to the accepted value, h_0 (don't forget to list your source in the references). Do not calculate a percent difference. Make a quantitative comparison that takes uncertainties into account.

3. What do you think may account for the difference, if any, between your calculated value of h and the accepted value?

4. What is the lowest frequency of light that will release electrons from the used photodiode?

5. What is the work function of the material used in the photodiode (don't forget to quote with uncertainty). Can you guess the diode's material?

Part 2

1. Plot the data as current versus voltage. Plot all three graphs in one figure. Do not try to fit the data of part 2.

2. Discuss the shapes of the curves obtained from Part 2. What conclusions can you draw from this data?

Part 3

1. Plot the data as current versus voltage. Plot all three graphs in one figure. Do not try to fit the data of part 3.

2. Discuss the shapes of the curves obtained from Part 3 and compare them to the plots obtained in Part 2. What conclusions can you draw from this data?