EXPERIMENT 3

THE PHOTOELECTRIC EFFECT

Equipment List

Included Equipment
1. Mercury Light Source Enclosure
2. Track, 60 cm
3. Photodiode Enclosure
4. Mercury Light Source Power Supply
5. DC Current Amplifier
6. Tunable DC (Constant Voltage) Power Supply

Optical Filters, Apertures, and Caps
7. Filter Wheel (365, 405, 436, 546, 577 nm)
8. Aperture Dial (2 mm, 4 mm, 8 mm diameter)

Photodiode Enclosure Cap (not shown)
Mercury Light Source Enclosure Cap (not shown)

Cables and Cords
9. Power Cord (3) (110 V version shown)
10. BNC Connecting Cable, Photodiode Enclosure
11. Connecting Cable, Red
12. Connecting Cable, Black
13. Interface Cable (3) UI-5219

Safety Information

Warning: To avoid possible electric shock or personal injury, follow these guidelines:

• Do not clean the equipments with a wet rag.
• Before use, verify that the apparatus is not damaged.
• Do not defeat power cord safety ground feature.
• Plug in to a grounded (earth) outlet.
• Do not use product in any manner not specified by the manufacturer.
• Do not install substitute parts or perform any unauthorized modification to the product.
• Line and Current Protection Fuses: For continued protection against fire, replace the line fuse and the current-protection fuse only with fuses of the specified type and ating.
• Main Power and Test Input Disconnect: Unplug instrument from wall outlet, remove power cord, and remove all probes from all terminals before servicing. Only qualified, service-trained personnel should remove the cover from the instrument.
• Do not use the equipment if it is damaged. Before you use the equipment, inspect the case. Pay particular attention to the insulation surrounding the connectors.
• Do not use the equipment if it operates abnormally. Protection may be impaired. When in doubt, have the equipment serviced.
• Do not operate the equipment where explosive gas, vapor, or dust is present. Don't use it under wet condition.

• Do not apply more than the rated voltage, as marked on the apparatus, between terminals or between any terminal and earth ground.
• When servicing the equipment, use only specified replacement parts.
• Use caution when working with voltage above 30 V AC RMS, 42 V peak, or 60 V DC. Such voltages pose a shock hazard.
• To avoid electric shock, do not touch any naked conductor with hand or skin.
• Adhere to local and national safety codes. Individual protective equipment must be used to prevent shock and arc blast injury here hazardous live conductors are exposed.
• Remaining endangerment: When an input terminal is connected to dangerous live potential it is to be noted that this potential can occur at all other terminals.

Introduction

The photoelectric effect is the emission of electrons from the surface of a metal when electromagnetic radiation (such as visible or ultraviolet light) of the right frequency 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.
Instead it was discovered that the energy of the emitted electrons was directly proportional to the frequency of the incident light, and that no electrons would be emitted if the light source was not above a certain threshold frequency. Lower energy electrons were emitted when light with relatively low frequency was incident on the metal, and higher energy electrons were emitted when light with relatively high frequency was incident on the metal.

Background Information

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 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: $E = hv$ where E equals the radiant energy, v 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 hv with v as the frequency. 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_o). 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 his famous equation for which he received the Nobel Prize in 1921

$$E = hv = KE_{max} + W_o$$

Where KE_{max} is the maximum kinetic energy of the emitted photoelectron. In terms of kinetic energy,

$$KE_{max} = hv - W_o$$

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.

$$eV = hv - W_o$$

$$V = \frac{h}{e} - \frac{W_o}{e}$$

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 (see Figure 1).

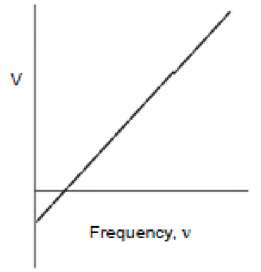
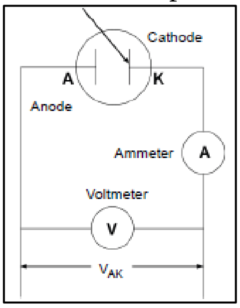


Fig. 1: Stopping Potential, *V*, versus Frequency

Principle of the Experiment

When incident light shines on the cathode (K), photoelectrons can be emitted and transferred to the anode (A). This constitutes a photocurrent. By changing the voltage between the anode and cathode, and measuring the photocurrent, you can determine the characteristic current-voltage curves of the photoelectric tube.



The basic facts of the photoelectric effect experiments are as follows:

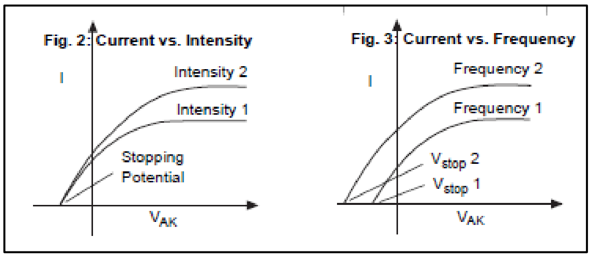
• For a given frequency (color) of light, if the voltage between the cathode and anode, V_{AK}, is equal to the stopping potential, V, the photocurrent is zero.

• When the voltage between the cathode and anode is greater than the stopping voltage, the photocurrent will increase quickly and eventually reach saturation. The saturated current is proportional to the intensity of the incident light. See Figure 2.

• Light of different frequencies (colors) have different stopping potentials. See Figure 3

• The slope of a plot of stopping potential versus frequency is the value of the ratio, *h/e*. See Figure 1.

• The photoelectric effect is almost instantaneous. Once the light shines on the cathode, photoelectrons will be emitted in less than a nanosecond.



Part I – Measuring Current-Voltage Characteristics 1

Measuring Current-Voltage Characteristics of Spectral Lines - Constant Frequency, Different Intensity

This section outlines the instructions for measuring and comparing the current versus voltage characteristics of one spectral line at three different light intensities.

Preparation for Measurement

1. Cover the window of the Mercury Light Source enclosure with the Mercury Lamp Cap. Cover the window of the Photodiode enclosure with the Photodiode Cap.

2. Adjust the distance between the Mercury Light Source enclosure and Photodiode enclosure so that the general spacing is between 30.0 cm to 40.0 cm. NOTE: The recommended distance is 35.0 cm.

3. On the Mercury Lamp Power Supply, press the button to turn on MERCURY LAMP. On the Tunable DC (Constant Voltage) Power Supply and DC Current Amplifier, push in the POWER button to the ON position.

4. Allow the light source and the apparatus to warm up for 10 minutes.

5. On the DC (Constant Voltage) Power Supply, set the Voltage Range switch to **-4.5V – 30 V**.

On the DC Current Amplifier, turn the CURRENT RANGES switch to $\mathbf{10^{-11}}$ A. (If 10-11A is not large enough, please turn the CURRENT RANGES Switch to 10^{-10}A.)

6. Push in the SIGNAL button to the “in” position for CALIBRATION.

7. Adjust the CURRENT RANGES knob until the ammeter shows that the current is zero.

8. Press the SIGNAL button so it moves to the “out” position for MEASURE.

Measurement - Constant Frequency, Different Intensities

2 mm Aperture

1. Gently pull the aperture dial away from the Photodiode Enclosure and rotate the dial so that the 2 mm aperture is aligned with the white line. Then rotate the filter wheel until the 436 nm filter is aligned with the white line. Finally remove the cover cap.

2. Uncover the window of the Mercury Light Source. Spectral lines of 436 nm wavelength will shine on the cathode in the phototube.

3. Adjust the **-4.5V– 30V** VOLTAGE ADJUST knob until the current on the ammeter is zero.

Record the voltage and current in Table 1.

4. Increase the voltage by a small amount (for example, 2 V). Record the new voltage and current in Table 1.

5. Continue to increase the voltage by the same small increment. Record the new voltage and current each time in Table 1. Stop when you reach the end of the VOLTAGE range.

4 mm Aperture

1. Cover the windows of the Mercury Light Source Enclosure and the Photodiode Enclosure.

2. Gently pull the aperture dial and rotate it so that the 4 mm aperture is aligned with the white line. Then rotate the filter

3. Uncover the window of the Mercury Light Source. Spectral lines of 436 nm will shine on the cathode in the Photodiode Enclosure.

4. Adjust the **-4.5V– 30V** VOLTAGE ADJUST knob so that the current display is zero. Record the voltage and current in Table 1.

5. Increase the voltage by a small amount (e.g. 2 V) and record the new voltage and current in Table 1. Continue to increase the voltage by the same small increment and record the new voltage and current each time in Table 1. Stop when you reach the end of the VOLTAGE range.

8 mm Aperture

1. Cover the windows of the Mercury Light Source Enclosure and the Photodiode Enclosure.

2. Gently pull the aperture dial and rotate it so that the 8 mm aperture is aligned with the white line. Then rotate the filter wheel until the 436 nm filter is aligned with the white line. Finally remove the cover cap.

3. Uncover the window of the Mercury Light Source. Spectral lines of 436 nm will shine on the cathode in the Photodiode enclosure.

4. Adjust the **-4.5V– 30V** VOLTAGE ADJUST knob so that the current display is zero. Record the voltage and current in Table 1.

5. Increase the voltage by a small amount (e.g. 2 V) and record the new voltage and current in Table 1. Continue to increase the voltage by the same small increment and record the new voltage and current each time in Table 4. Stop when you reach the end of the VOLTAGE range.

6. Turn off the MERCURY LAMP power switch and the POWER switch on the other pieces of equipment. Rotate the filter wheel until the 0 nm filter is aligned with the white line. Cover the windows of the Mercury Light Source Enclosure and Photodiode Enclosure.

Table 1: Current and Voltage of Spectral Lines

λ = 436 nm 2 mm dia.	V (V)												
	I (x 10^{-11} A)												
λ = 436 nm 4 mm dia.	V (V)												
	I (x 10^{-11} A)												
λ = 436 nm 8 mm dia.	V (V)												
	I (x 10^{-11} A)												

Analysis

1. Plot the graphs of Current (y-axis) versus Voltage (x-axis) for the one spectral line, 436 nm, at the three different intensities.

Questions

1. How do the curves of current versus voltage for the one spectral line at three different intensities compare? In other words, how are the curves similar to each other?

2. How do the curves of current versus voltage for the one spectral line at three different intensities contrast? In other words, how do the curves differ from each other?

Part II – Measuring Current-Voltage Characteristics 2 Measuring Current-Voltage Characteristics of Spectral Lines - Different Frequencies, Constant Intensity

This section outlines the instructions for measuring and comparing the current versus voltage characteristics of three spectral lines, 365 nm, 405 nm, and 436 nm, but with the same light intensity.

Preparation for Measurement

1. Cover the window of the Mercury Light Source enclosure with the Mercury Lamp Cap. Cover the window of the Photodiode enclosure with the Photodiode Cap.

2. Adjust the distance between the Mercury Light Source enclosure and Photodiode enclosure so that the general spacing is between 30.0 cm to 40.0 cm. NOTE: The recommended distance is 35.0 cm.

3. On the Mercury Lamp Power Supply, press the button to turn on MERCURY LAMP. On the Tunable DC (Constant Voltage) Power Supply and DC Current Amplifier, push in the POWER button to the ON position.

4. Allow the light source and the apparatus to warm up for 10 minutes.

5. On the DC (Constant Voltage) Power Supply, set the Voltage Range switch to **-4.5V – 30 V**. On the DC Current Amplifier, turn the CURRENT RANGES switch to $\mathbf{10^{-11}}$ A. (If 10^{-11}A is not large enough, please turn the CURRENT RANGES Switch to 10^{-10}A.)

6. Push in the SIGNAL button to the “in” position for CALIBRATION.

7. Adjust the CURRENT RANGES knob until the ammeter shows that the current is zero.

8. Press the SIGNAL button so it moves to the “out” position for MEASURE.

Measurement - Different Frequencies, Constant Intensity

365 nm Wavelength

1. Gently pull the aperture dial and rotate it so that the 4 mm aperture is aligned with the white line. Then rotate the filter wheel until the 365 nm filter is aligned with the white line. Finally remove the cover cap.

2. Uncover the window of the Mercury Light Source Enclosure. Spectral lines of 365 nm will shine on the cathode in the Photodiode Enclosure.

3. Adjust the **-4.5V– 30V** VOLTAGE ADJUST knob so that the current display is zero. Record the voltage and current in Table 2.

4. Increase the voltage by a small amount (for example, 2 V). Record the new voltage and current in Table 2.

5. Continue to increase the voltage by the same small increment. Record the new voltage and current each time in Table 2. Stop when you reach the end of the VOLTAGE range.

405 nm Wavelength

1. Cover the window of the Mercury Light Source Enclosure.

2. Rotate the filter wheel until the 405 nm filter is aligned with the white line.

3. Uncover the window of the Mercury Light Source enclosure. Spectral lines of 405 nm will shine on the cathode in the Photodiode Enclosure.

4. Adjust the **-4.5V– 30V** VOLTAGE ADJUST knob so that the current display is zero. Record the voltage and current in Table 2.

5. Increase the voltage by a small amount (e.g. 2 V) and record the new voltage and current in Table 2.

6. Continue to increase the voltage by the same small increment and record the new voltage and current each time in Table 2. Stop when you reach the end of the VOLTAGE range.

436 nm Wavelength

1. Cover the window of the Mercury Light Source Enclosure.

2. Rotate the filter wheel until the 436 nm filter is aligned with the white line.

3. Uncover the window of the Mercury Light Source Enclosure. Spectral lines of 436 nm will shine on the cathode in the Photodiode enclosure.

4. Adjust the **-4.5V– 30V** VOLTAGE ADJUST knob so that the current display is zero. Record the voltage and current in Table 2.

5. Increase the voltage by a small amount (e.g. 2 V) and record the new voltage and current in Table 2.

6. Continue to increase the voltage by the same small increment and record the new voltage and current each time in Table 2. Stop when you reach the end of the VOLTAGE range.

7. Turn off the MERCURY LAMP power switch and the POWER switch on the other pieces of equipment. Rotate the filter wheel until the 0 nm filter is aligned with the white line. Cover the windows of the Mercury Light Source Enclosure and Photodiode Enclosure.

Table 2: Current and Voltage of Spectral Lines

λ = 365 nm 4 mm dia.	V (V)												
	I (x 10^{-11} A)												
λ = 405 nm 4 mm dia.	V (V)												
	I (x 10^{-11} A)												
λ = 436 nm 4 mm dia.	V (V)												
	I (x 10^{-11} A)												

Analysis

1. Plot the graphs of Current (y-axis) versus Voltage (x-axis) for the three spectral lines, 365 nm, 405 nm, and 436 nm, at the one intensity.

Questions

1. How do the curves of current versus voltage for the three spectral lines at a constant intensity compare? In other words, how are the curves similar to each other?

2. How do the curves of current versus voltage for the three spectral lines at a constant intensity contrast? In other words, how do the curves differ from each other?