

## Lab 11: Photoelectric Effect (E11)

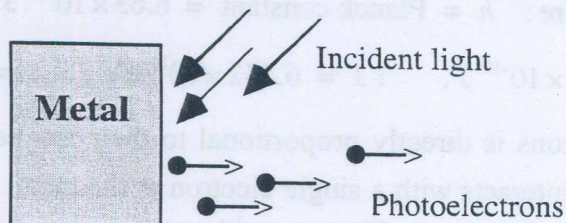
*Lab Reports for E10 and Prelab Questions for E11 are due at the beginning of this lab.*

### Objectives

- Understand how ejection of photoelectrons from a metal surface depends on the frequency and intensity of incident light.
- Measure Planck's constant and the work function for the cathode material.

### Theory<sup>1</sup>

The photoelectric effect is one of several processes by which electrons may be removed from the surface of a metal. It is found that when electromagnetic radiation is directed onto a metallic surface, electrons may be ejected from the surface. The ejected electrons are called photoelectrons.



The key experimental facts about the photoelectric effect are the following.

- (1) The emission of photoelectrons will not occur at all, if the frequency of the incident electromagnetic radiation is less than a certain frequency called the cutoff frequency. Below the cutoff frequency there would be no photoelectrons regardless of the intensity of the incident light.
- (2) The maximum kinetic energy of the ejected photoelectrons depends on both the frequency of the incident electromagnetic radiation and the metal itself.
- (3) If the frequency of the incident radiation is larger than the cutoff frequency, then the number of emitted photoelectrons is proportional to the intensity of the radiation.

Because classical electromagnetism is unable to explain these experimental facts, a quantum theory of light is required for a satisfactory explanation.

<sup>1</sup> Alan Giambattista, Betty McCarthy Richardson, Robert C. Richardson, *College Physics*, 2<sup>nd</sup> ed., McGraw-Hill, 2007, pp. 984-990.

### A. Electrons in Metals

Although the outermost valence electrons in a metal are free to move within a metal (that is why metals usually are good conductors), they are constrained within the metal by the surface itself. The binding energy of the electrons least tightly bound to the metal is denoted by the work function  $W_0$  of the metal. If energy greater than the work function is supplied to one of these electrons, that electron can be ejected from the metal surface. This process is known as the **photoelectric effect**.

### B. The Incident Light Rays

The electromagnetic light rays that strike the metal surface can supply the outer electrons with the energy they need to leave the metal. According to quantum theory, these apparently continuous electromagnetic waves are actually quantized, consisting of discrete quanta called **photons**. Each photon has energy  $E$  that depends only on its frequency  $f$  (or wavelength  $\lambda$ ) and is given by the following equation.

$$E = hf = \frac{hc}{\lambda}, \quad \text{where: } h = \text{Planck constant} = 6.63 \times 10^{-34} \text{ J}\cdot\text{s} = 4.14 \times 10^{-15} \text{ eV}\cdot\text{s}$$

$$1 \text{ eV} = 1.602 \times 10^{-19} \text{ J}, \quad 1 \text{ J} = 6.242 \times 10^{18} \text{ eV}, \quad c = 2.998 \times 10^8 \text{ m/s}$$

The energy of photons is directly proportional to their frequency. In the photoelectric effect, a single photon interacts with a single electron at the metal surface; it cannot share its energy among several electrons. Photons with a frequency  $f$  greater than the cutoff frequency  $f_0$  will cause the emission of photoelectrons, whereas photons with a frequency less than  $f_0$  will not cause the emission of photoelectrons.

### C. The Photoelectric Effect Equation

In photoelectric emission, light strikes a material, causing electrons to be emitted. The classical wave model predicted that as the intensity of incident light was increased, the amplitude and thus the energy of the wave would increase. This would then cause more photoelectrons to be emitted. The quantum model, however, predicted that higher frequency light would produce higher energy photoelectrons, independent of intensity, while increased intensity would only increase the number of the electrons emitted (or photoelectric current).

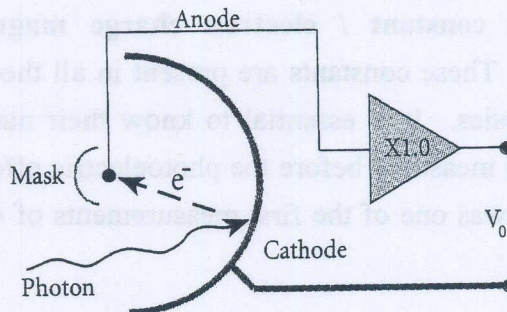
Einstein applied Planck's theory and explained the photoelectric effect in terms of the quantum model using his famous equation for which he received the Nobel Prize in 1921. The equation states that the maximum possible kinetic energy of ejected electron ( $KE_{max}$ ) is

equal to the energy of the incident photon ( $hf$ ) minus the minimum work needed to eject electron (the work function  $W_0$ ).

$$KE_{\max} = hf - W_0$$

The photoelectrons measured outside the metal surface will have kinetic energies ranging from 0 to  $KE_{\max}$ . One may notice that the photoelectric equation is basically another way to express the conservation of energy principle!

#### D. Measuring the Work Function and the $h/e$ Ratio Using a Photocell



Some photoelectrons travel toward the stopping electrode (anode) and, upon reaching it, constitute a current, which flows through the circuit. As we increase the voltage  $V$ , some of the less energetic photoelectrons will be repelled from the anode and the current will decrease. At some voltage  $V = V_s$  (the stopping voltage), the most energetic photoelectrons will be stopped just in front of the anode and current will cease to flow. For this condition:

$$eV_s = KE_{\max} \quad \left\{ e = \text{the charge of an electron} = 1.60 \times 10^{-19} \text{ C} \right\}$$

Therefore, using Einstein's equation,

$$hf = eV_s + W_0 \quad (1)$$

When solved for  $V_s$ , the equation becomes:

$$V_s = (h/e)f - (W_0/e) \quad (2)$$

If we plot  $V_s$  versus  $f$  for different frequencies of incident light, the graph will show the linear dependence, with the slope equal to  $h/e$  and the y-intercept equal to  $-W_0/e$ . The accurately measured value of the  $h/e$  ratio is equal to:

$$h/e = 4.136 \times 10^{-15} \text{ V}\cdot\text{s} \quad (3)$$

We are going to use a mercury vapor lamp as the light source for the photoelectric experiment. The light from the mercury lamp looks white. However, the mercury lamp does not produce a continuous spectrum (a rainbow) of all colors from red to violet. Instead, it produces only four lines (frequencies) in the visible range and one in the near ultraviolet. We will use a diffraction grating (like the one used in the diffraction grating experiment) to separate various frequencies (i.e., colors) of the light.

### E. Why the $h/e$ ratio is important?

The  $h/e$  (**Planck's constant / electron charge magnitude**) is the ratio of two fundamental constants. These constants are present in all theories of atomic, quantum, and elementary particle physics. It is essential to know their numerical values! The electron charge magnitude  $e$  was measured before the photoelectric effect was discovered. However, the photoelectric effect was one of the first measurements of  $h/e$  (and therefore the value of  $h$ ).

### How this apparatus works?

The photodiode tube and its associated electronics have a small capacitor, which becomes charged by the photoelectric current. When the potential on this capacitance reaches the stopping potential of the photoelectrons, the current decreases to zero and the anode-to-cathode voltage stabilizes. This final voltage between the anode and cathode is therefore equal to the stopping potential of the photoelectrons.

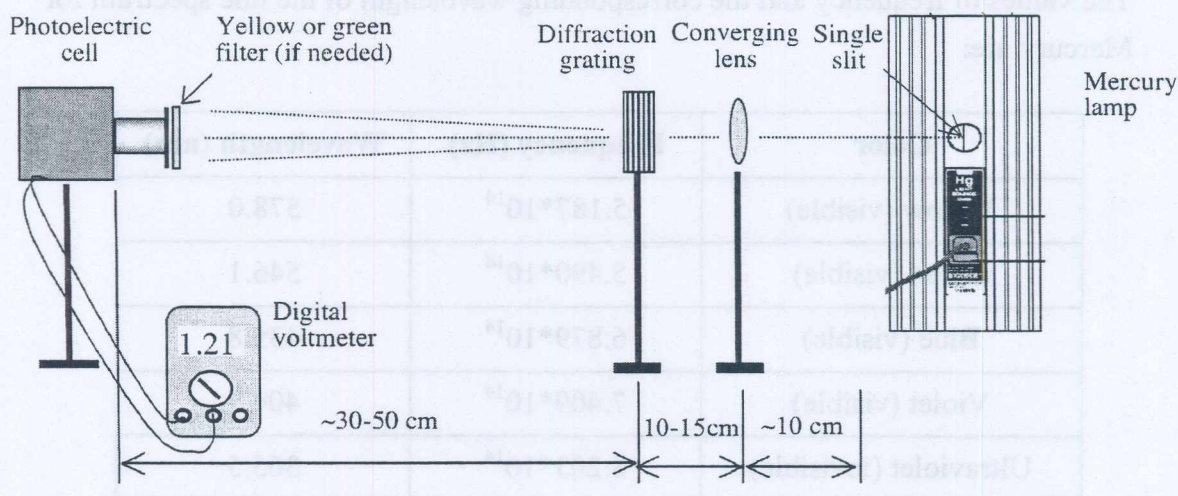
To let you measure the stopping potential, the anode is connected to a built-in amplifier with an ultrahigh input impedance ( $>10^{13} \Omega$ ), and the output from this amplifier is connected to the output jacks on the front panel of the apparatus. This high impedance, unity gain ( $V_{\text{OUT}}/V_{\text{IN}} = 1$ ) amplifier allows us to measure the stopping potential with an ordinary digital voltmeter. That amplifier does not actually amplify the voltage. Its sole purpose is to provide the ultrahigh input impedance.

Due to the ultra high input impedance, once the capacitor has been charged from the photodiode current, it takes a long time to discharge this potential through some leakage. Therefore, a shorting button "PUSH TO ZERO" enables the user to quickly remove the charge.

## Procedure:

### Activity 1: Measurements of the $h/e$ Ratio and the Work Function.

- 1.1. You will need to use the following pieces of equipment: mercury lamp with a single slit; small converging lens; diffraction grating; the photoelectric cell apparatus (also called the " $h/e$  apparatus") and a digital voltmeter.
- 1.2. First, assemble the pieces of the apparatus according to the drawing below:



- 1.3. The distances shown in the above picture are approximate. You will have to adjust them more precisely later during this experiment.
- 1.4. Make sure that a piece of the black cardboard with a single vertical slit is covering the front opening of the mercury lamp.
- 1.5. Turn on the mercury lamp and allow 2-3 minutes for warm up. **Do not turn off this lamp until the experiment is over.**

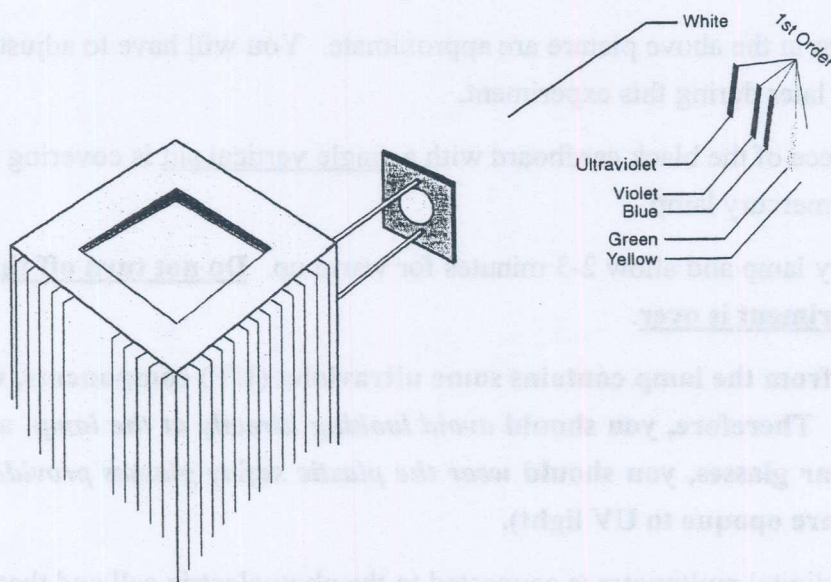
**CAUTION!** The light from the lamp contains some ultraviolet (UV) components, which can burn living tissue. Therefore, you should *avoid looking directly at the lamp*, and, if you do not already wear glasses, you should *wear the plastic safety glasses provided for you* (glass and plastic are opaque to UV light).

- 1.6. Make sure that the digital multimeter is connected to the photoelectric cell and that the multimeter is turned on and set to 2 V DC (V=) range.
- 1.7. Make sure that the photoelectric cell is turned on. Actually, the on/off switch turns on the high impedance amplifier.

- 1.8. Adjust the position of the converging lens to get a sharp, white image of the single slit (the one in front of the mercury lamp) on the small white reflective mask of the photoelectric cell.
- 1.9. The light from the mercury lamp looks white. However, the mercury lamp does not produce a continuous spectrum (a rainbow) of all colors from red to violet. Instead, it produces only four lines (frequencies) in the visible range and one in the near ultraviolet. This is called **line spectrum** for Mercury.

The values of frequency and the corresponding wavelength of the line spectrum for Mercury are:

Color	Frequency (Hz)	Wavelength (nm)
Yellow (visible)	$5.187 \times 10^{14}$	578.0
Green (visible)	$5.490 \times 10^{14}$	546.1
Blue (visible)	$6.879 \times 10^{14}$	435.8
Violet (visible)	$7.409 \times 10^{14}$	404.7
Ultraviolet (invisible)	$8.203 \times 10^{14}$	365.5

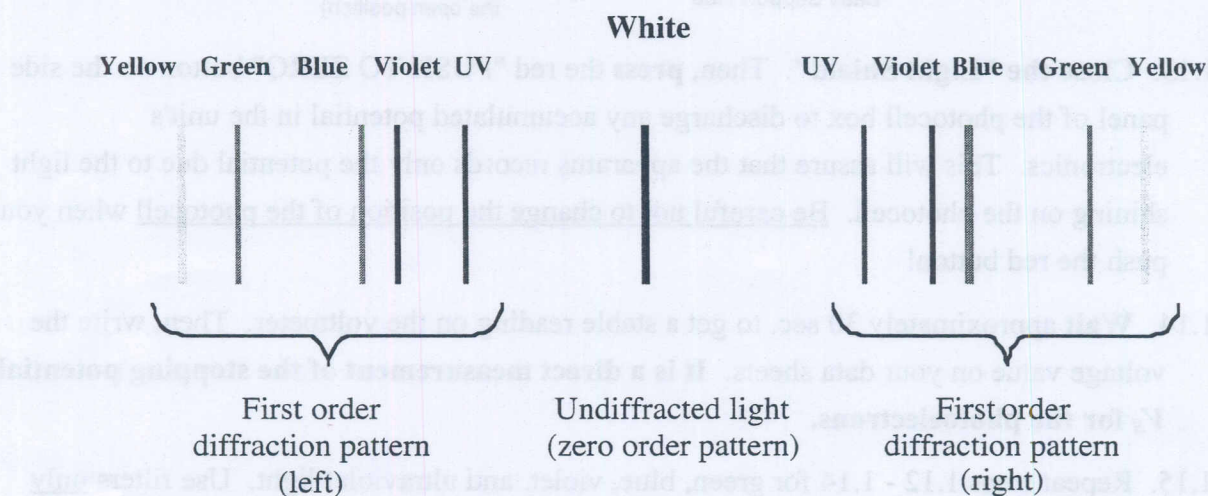


- 1.10. **The diffraction grating separates these lines**, so we will use only one color (i.e., one wavelength) at a time. Please recall your observations from the last part the "Diffraction

Grating" experiment. To make the separation of lines even better, **use yellow and green filters for yellow and green lines, respectively**. These filters have magnets built in, so they can be easily attached to the front of the white reflective mask (see the text and the picture below).

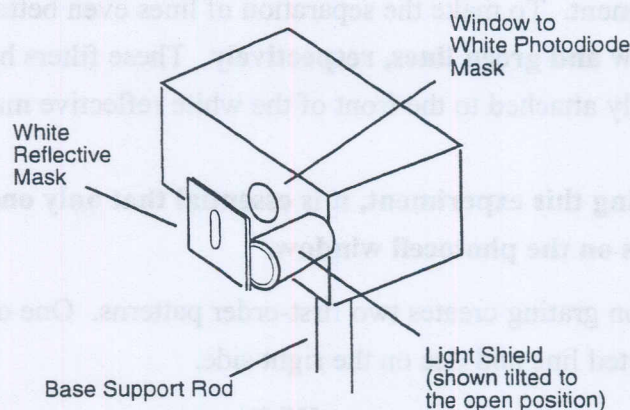
**When making this experiment, it is essential that only one color (i.e., one frequency) falls on the photocell window.**

- 1.11. The diffraction grating creates two first-order patterns. One on the left side of the white, undiffracted line and one on the right side.



The second order patterns are also visible and they are located further away from the undiffracted white line. The order of colors for the second order pattern is the same as for the first order pattern.

- 1.12. **Move** the photoelectric cell until the yellow light shines directly on the opening in the "White Reflective Mask" (see the picture below). **Rotate the photocell so that the same light that falls on the opening in the "White Reflective Mask" also falls on the window in the photodiode mask.** You need to open the "Light Shield" to be able to see the photodiode mask that is inside the black enclosure. Careful adjustment of the position and orientation of the photocell is essential to get good results!



- 1.13. **Close the "Light Shield"**. Then, **press** the red "PUSH TO ZERO" button on the side panel of the photocell box to discharge any accumulated potential in the unit's electronics. This will assure that the apparatus records only the potential due to the light shining on the photocell. Be careful not to change the position of the photocell when you push the red button!
- 1.14. **Wait** approximately 30 sec. to get a stable reading on the voltmeter. Then, write the voltage value on your data sheets. **It is a direct measurement of the stopping potential  $V_S$  for the photoelectrons.**
- 1.15. Repeat steps 1.12 - 1.14 for green, blue, violet, and ultraviolet light. Use filters only for yellow and green light.
- Note:** The white reflective mask on the photocell is made of a special fluorescent material. This allows you to see the ultraviolet line as a blue line, and it also makes the violet line appear bluer. You can see the actual colors of the light if you hold a piece of white paper in front of the mask.
- 1.16. Move the photocell to the other side of the zero order maximum (white line) and repeat measurements twice for all five colors. In other words, repeat steps 1.12 - 1.15 for the other set of the first order diffraction pattern.
- 1.17. Compare the values of the stopping voltage from both data sets. If your data from both runs are close to each other (ask your TA if you are not sure), then calculate the average values of the stopping voltage  $V_{S1}$ . *Hint:* for the UV line the stopping voltage should be  $\sim 2$  V.
- 1.18. After completing the measurements for all five lines, switch to the **second order pattern** and measure the second set of data. Calculate the average values of the stopping voltage for the second set of data  $V_{S2}$ .



- 1.19. Calculate the average values of the stopping voltage  $V_{SAV}$  using data sets #1 and #2.

$$V_{SAV} = (V_{S1} + V_{S2})/2$$

- 1.20. Make a graph of the average stopping voltage  $V_{SAV}$  vs. frequency  $f$ . Find and draw the best-fit straight line (do **not** just connect the points!) that approximates the behavior of your points (again, for both values of light intensity).

You should prepare the final version of the graph using a computer-graphing program (e.g., MS Excel that is available in all ITaP labs). These programs offer the 'linear fit' option to obtain the value of the slope and the y-intercept of the best-fit line.

- 1.21. Using the slope and the y-intercept values from the graph, calculate the values of the  $h/e$  ratio and the work function  $W_0$ . See equation (3). Be sure to include units.
- 1.22. Ask your TA for the signature on the data sheets, turn off the mercury lamp, turn off the photocell and turn off the digital multimeter.

### Your Completed Lab Report Should Include:

1. Your completed cover sheet.
2. Your answers to the Prelab Questions. (3 points)
3. Your completed Data Sheets. (5 points)
4.  $V_S$  vs.  $f$  graph with a straight line fit from *Activity 1*. (2 points)  
(Title and write your name and those of your partners on the graph.)
5. Your completed Analysis section. (2 points)

*In this section, you should briefly describe the observed phenomena. You should also explain how the final results were calculated from the raw data. Discuss sources of experimental error and their relative influence on your results. Essentially, this is your chance to prove that you truly understand the physics concepts illustrated by the laboratory experiment. This section of the lab report **must be typed** and should not be longer than one page.*

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Your Completed Lab Report Should Include:

- 1. Your completed cover sheet
- 2. Your answers to the Pre-lab Questions (3 points)
- 3. Your completed Data Sheets (2 points)
- 4. A  $V_{out}$  vs  $V_{in}$  graph with a straight line fit from Activity 1. (2 points)  
(This and your name and those of your partners on the graph.)
- 5. Your completed Analysis section (2 points)

In this section you should briefly describe the observed phenomenon. You should also explain how the final results were calculated from the raw data. Discuss sources of experimental error and their relative influence on your results. Essentially, this is your chance to prove that you truly understand the physics concepts illustrated by the laboratory experiment. This section of the lab report must be typed and should not be longer than one page.