The Photoelectric Effect
Spring 2023

Introduction

In early experiments that attempted to create radio waves, it was noticed that light shining on an electrode sometimes produced a visible spark. Later experimentation found that these sparks were created by the impact of light on an electrode, which caused the ejection of electrons. It was also found that these ejected electrons had kinetic energies that increased *linearly* with the frequency of the light used.

These observational results were explained by Einstein's photon model, which assumes that light behaves as a particle. This model predicts that the maximum kinetic energy, K_{max}, of ejected electrons depends only on the frequency of the incident light, and is independent of the intensity. Therefore, the higher the frequency of the light, the greater the energy of ejected electrons.

In contrast, the classical wave model of light predicted that K_{max} would depend on light intensity – the brighter the light, the greater the energy of the ejected electrons. Today's experiment will test both theories.

Theory

The apparatus consists of a mercury source behind a slit, a diffraction grating and a lens which images the slit in the wavelength of each mercury line on a phototube (**Figure 1a**). The photons strike a metal plate inside a capacitor, causing electrons to be ejected (**Figure 1b**). These ejected electrons charge the capacitor to roughly their highest energy, so the measured voltage (the *stopping potential,* V_{stop}) gives us a measurement of the energy of the ejected electrons.

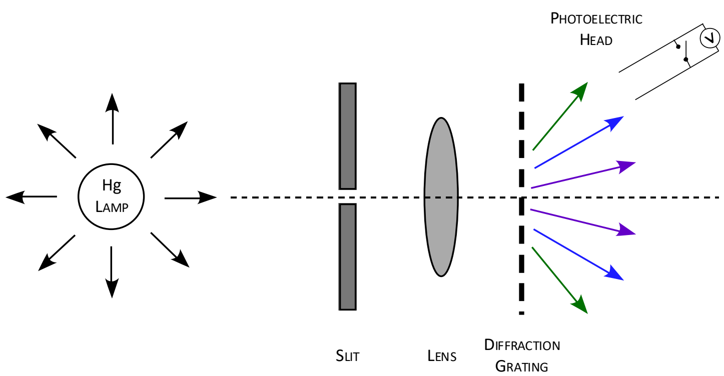

Figure 1a: The apparatus

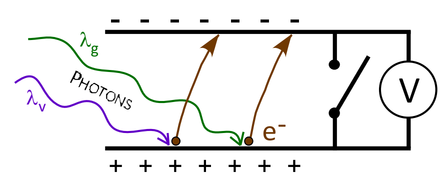

Figure 1b: Photoelectric head detail

Each photon has energy $E = hf,$ where f is the photon frequency and h is Planck's constant. When a photon strikes a metal surface, a minimum amount of energy, W (the work function), is needed to knock an electron off. The remainder is given up to the kinetic energy of the ejected electron.

$$hf = K_{max} + W$$

These electrons strike one of the capacitor plates and charge it up. Eventually, the capacitor voltage becomes large enough to stop further charging. This happens when

$$K_{max} = eV_{stop}$$

where e is the charge on an electron. Solving each for kinetic energy and combining gives us:

$$eV_{\text{stop}} = hf - W$$

We can measure V_{stop} and can calculate f for each of the given mercury wavelengths ($c = f\lambda$). Plotting eV_{stop} versus f should produce a linear relationship (*why?*), from which we can experimentally measure Planck's constant and the work function. The work function gives us a measurement of the binding energy of the electrons.

We will use the *electron-volt* as a convenient energy unit for the quantity eV_{stop}. An electron-volt (*eV*) is defined as the amount of kinetic energy gained (or lost) by a single electron accelerating from rest through an electric potential difference of one volt. That means that if you measure 1.234 *volts* for V_{stop}, the ejected electrons have gained an energy of 1.234 *eV*.

Experiment: *Caution – The mercury lamp is very hot. Do not turn off the lamp until everyone at the table is ready to leave!*

1. *Prediction*: You will be measuring the five colored lines listed below. Which color will have the smallest stopping potential? Record your prediction in your journal and briefly explain your reasoning.
2. Create a data table in your journal with the following columns. Leave enough room for *four* measurements of V_{stop} for each color:

Line Color	λ (*nm*)	f (*Hz*)	V_{stop} (*V*)	$\langle V_{stop} \rangle$ (*V*)	$\langle eV_{stop} \rangle$ (*eV*)

3. *Calculating Line Frequency*: The wavelengths of the brightest mercury lines that you will measure are listed below. Calculate the frequency of each line in units of Hertz (*Hz*). Keep four significant figures, show a sample calculation, and be careful with the units!

Color	**Wavelength (*nm*)**
Violet #1	365.0
Violet #2	404.7
Blue	435.8
Green	546.1
Yellow	578.1

4. Press the power switch on the side of the photoelectric head to turn it on. Record the letter (A – I) on the back of the photoelectric head on your apparatus sketch (*the results you get will depend on which photo head was used*).
5. *Measuring the Electron Energy Dependence on Frequency*: Light from the mercury lamp passes through a *blazed* diffraction grating (**Figure 2**), which maximizes the efficiency of the grating for specific wavelengths. A blazed grating produces images that are brighter on one side of the zeroth order image than the other. The apparatus has been set up so that the brighter images result from pulling the photoelectric head towards you. Use the following procedure to measure the stopping potential for each of the five colored spectral lines:

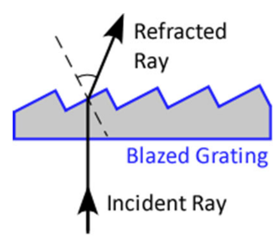

Figure 2: Grating detail

   a. Pull the photoelectric head towards you until the first violet line is aligned with the slit on the white reflective mask.

   b. Roll the cylindrical light shield of the photoelectric head out of the way and look inside to see the white photodiode mask. Loosen the thumbscrew on the support rod under the photoelectric head and rotate the head until the image of the violet line is centered on the window in the photodiode mask. Tighten the thumbscrew when you have the correct alignment and close the light shield. *Careful alignment is very important for your measurements; ask your instructor if you need assistance.*

c. Press and hold the **Zero** button at the center of the photoelectric head control panel until the voltmeter reading is 0, then release the button. Record the stopping potential in your data table when the reading on the voltmeter stops increasing. Repeat this step to collect *four* voltage measurements, zeroing between each measurement, and then calculate the average, $\langle V_{stop} \rangle$.

d. You will now see the ejected electrons dependence on the light frequency. Move the photoelectric head to the next line, and repeat the alignment and measurement procedure. Place the *green* filter so it covers the slit on the white reflective mask when measuring the green line, and the *yellow* filter for the yellow line (no filter is required for the violet and blue lines). These filters limit higher frequencies of light due to the second order image from entering the photoelectric head.

e. Fill in the values for $\langle eV_{stop} \rangle$ in your data table.

6. *Graph #1 – Plotting Frequency Dependence*: Enter your frequency and $\langle eV_{stop} \rangle$ values from your first data table into KaleidaGraph. The frequencies are on the order of 10^{14} *Hz*, so they need to be entered in a format the program can understand: *e.g.* 1.234×10^{14} is entered as **1.234E14** (Note: *E* stands for '*power of 10 exponent*', and can be uppercase or lowercase).

   a. Create a graph of $\langle eV_{stop} \rangle$ vs. *f*. Due to the large value of the frequencies, an error message will result if you choose the "Linear with Uncertainties" fit. Create a new general fit using the following function (refresh your memory about custom fits with *Finding the Best-Fit Function*):

   ```
   a*x+b; a=1e-15; b=1
   ```

   You should note that this is the same function as used in the "Linear with Uncertainties" fit, but the initial value of parameter 'a' has been changed.

   b. Apply your fit to the graph, add your names and print a copy for each person in your group. Calculate Planck's constant, the electron binding energy and their respective uncertainties. As always, specify the function, the units and the SSR!

7. *Ejected Electron Dependence on Light Intensity*: You will now test the classical wave theory assertion that light intensity affects the energy of an ejected electron. You will use a *transmission slide* to vary the intensity of a single color of light, instead of varying the light color (frequency).

   a. Create a new table in your journal, with the following columns. Again, be sure to leave enough room for four measurements of V_{stop} for each color:

Line Color	Relative Transmission	V_{stop} (*V*)	$\langle V_{stop} \rangle$ (*V*)	$\langle eV_{stop} \rangle$ (*eV*)

   b. Using just the yellow line (*with the yellow filter*), repeat the alignment and data collection procedure. Record four measurements of the stopping potential for *each* of the five opacities (100%; 80%; 60%; 40%; 20%) on the variable transmission slide.

   c. Calculate the average stopping potential and $\langle eV_{stop} \rangle$ for each of the five opacities.

8. *Graph #2 – Plotting Intensity Dependence*: Create a new graph of $\langle eV_{stop} \rangle$ vs. %Transmission. Here are some KaleidaGraph tips that will make your graph easier to analyze:

   a. Enter the Transmission as numbers (e.g., 100, 80, 60 …), *not* percentages!

   b. Change the limits of the vertical axis scale: set the minimum value to **0**, and the maximum to **2**.

   c. You don't need to add a best-fit line to this data. Add your names and print a copy of this graph for each member of the group

Discussion

- Record the curve fit from your graph, along with the appropriate units.
- Record your results for Planck's constant, the binding energy, and their uncertainties. Again, state the letter of the photoelectric head that was used.
- Discuss your prediction: did you correctly predict which color line would have smallest stopping potential?
- The published value of Planck's constant is $h = 4.136 \times 10^{-15}\ eV \cdot s$, and the manufacturer of the photoelectric head gives $W = 1.36\ eV$. Calculate the %difference, draw a number line and discuss the agreement with your calculated values of these quantities. *Check with your instructor that your results are consistent for the photoelectric head that you used!*
- Summarize your results from the light intensity experiment. What does this tell you about the effect of light intensity on the energy of ejected electrons?
- What is the photon model? How do your results from today's experiment support the photon model?

PLEASE TURN OFF THE MULTIMETER AND FLASHLIGHT WHEN FINISHED!