The Photoelectric Effect
Spring 2024

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 assuming that light behaves as a particle (see *Giambatista, et. al.* section*. 27.3*). 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 (also called the *stopping potential,* V_{stop}) gives us a measurement of the energy of the ejected electrons.

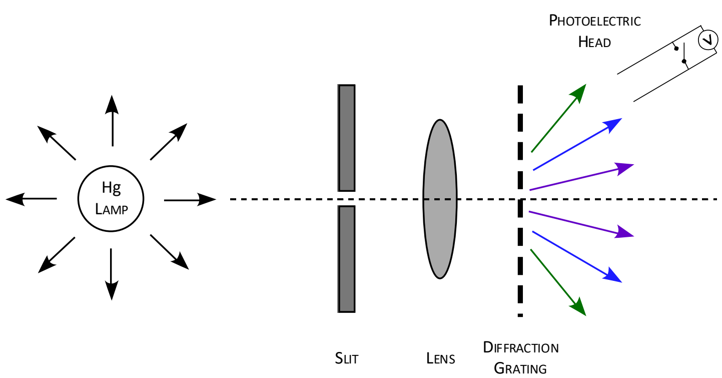

Figure 1a: The apparatus

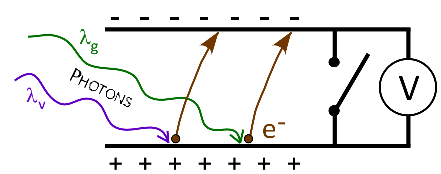

Figure 1b: Photoelectric head detail

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, ϕ (the work function), is needed to knock an electron off. The remainder is given up to the kinetic energy of the ejected electron.

$$K_{\text{max}} = hf - \phi$$

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

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

where e is the charge on an electron. Setting up this equality gives us:

$$eV_{\text{stop}} = hf - \phi \qquad \textbf{\{Equation 1\}}$$

We can measure V_{stop} and calculate f for each of the given mercury wavelengths ($c = f\lambda$). **Equation 1** is in the form of a straight line, ***y* = *(slope)x* + *b***. From the slope we can find Planck's constant and from the intercept we can find the work function, and hence 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. 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*)

2. *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

3. 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*).

4. *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:

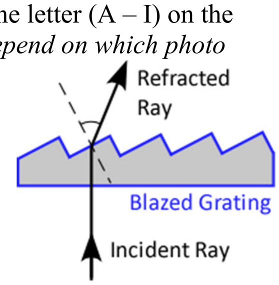

Figure 2: Grating detail

   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.

5. *Graph #1 – Plotting Frequency Dependence*: Plot $\langle eV_{stop} \rangle$ vs. f in Excel using the stopping potentials you just measured. Since it has been some time since you used Excel, here are a few reminders and tips:

   a. Enter frequency in the first column and $\langle eV_{stop} \rangle$ in the second. Large values are entered using scientific notation: 1.234×10^{14} is entered by typing **1.234E14** (note: *E* can be uppercase or lowercase!)

   b. Click one cell of the data you entered, select the *Insert* tab and then choose a scatter plot.

   c. Select the graph, then from the *Design* tab click the *Move Chart* button, and then choose *New Sheet*.

   d. Enter an appropriate title (containing the quantities that are plotted) and add axis labels (*Design* tab → *Add Chart Element* → *Axis Titles* → *Primary Horizontal* and *Primary Vertical*)

   e. Add a best-fit line by right-clicking on any data point and choosing *Add Trendline*. Click the button next to *Linear* and click the box next to *Display Equation on chart*. **Don't close the Format Trendline options section yet!**

   f. We wish to make our graph look like the one on the blackboard. The line fit can be extended beyond the end data points in Excel by increasing the *backward forecast*: In the *Forecast* section, type **6E14** next to ***Backward***, and then press *Enter*.

   g. Set the horizontal axis so that it starts at the origin: Right-click on any number along the horizontal axis and choose *Format Axis*. In the *Bounds* section type **0** next to ***Minimum***, and then press *Enter*.

   h. Increase the font size of the fit equation by selecting the equation box, clicking the **Home** tab, and changing the font size to **14**. Move the equation so that it does not overlap the best-fit line.

   i. Note that the value displayed for the slope only has *one* significant figure. Increase the number of digits displayed by right-clicking on the line equation and choosing *Format Trendline Label*. In the *Number* section, choose *Scientific* in the *Category* section, and change the number of *Decimal places* to **3** (note that this will give you a slope with *4 significant figures*). The intercept becomes formatted as Scientific as well.

      - If the number of significant figures did not change, unselect "Display Equation…" in the *Format Trendline* window, and then select it again.

   j. Finally, add your names to the header (click the *File* tab, then *Print*; under *Page Setup*, click the *Header/Footer* tab, then *Custom Header*), and print a copy of this graph for each member of the group.

6. Your data points should follow the best fit line well. If a point deviates significantly, check your calculations, and make sure you have measured the correct mercury line. Use the results of the linear fit from your graph to calculate Planck's constant and the work function.

   The published value of Planck's constant is $h = 4.136\times10^{-15}$ $eV{\cdot}s$, and the manufacturer of the photoelectric head gives the work function $\phi = 1.36$ eV. Calculate the % difference for each. *Check with your instructor that your results are consistent for the photoelectric head that you used!*

Now you will test the classical wave theory assertion that light intensity affects the energy of an ejected electron.

7. *Ejected Electron Dependence on Light Intensity*: 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 of the five intensities you will examine:

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*: Plot $\langle eV_{stop} \rangle$ vs. %Transmission. As before, here are some graphing tips that will make your graph easier to analyze:

   a. On a new Excel sheet, enter the %Transmission in the first column and $\langle eV_{stop} \rangle$ in the second. Enter the Transmission as numbers (e.g., 100, 80, 60 …), *not* percentages!

   b. Create a scatter plot of this data as before. Again, move the chart to a new sheet, and add a title and axis labels.

   c. You will again change the range of the vertical axis scale, as you did previously in step *5g*. This time, set the *Minimum* value to **0** and change the *Maximum* value to **2**.

   d. Do not fit a trendline to this data. Add your names to the header and print a copy of this graph for each member of the group.

Discussion

- Record the curve fit equation from the first graph, along with the appropriate units.
- Record your value of Planck's constant and the binding energy of the electrons in the phototube. Again, state the letter of the photoelectric head that was used.
- Briefly discuss the agreement between your measured and calculated values of h and ϕ for the photoelectric head that you examined.
- Do your data support the particle or the wave nature of light? Explain your answer. Be sure to discuss the differences between your two graphs, and how each graph supports – or doesn't – each theory of the behavior of light.

PLEASE TURN OFF THE MULTIMETER AND FLASHLIGHT WHEN FINISHED!