Ph 3455

The Photoelectric Effect

Required background reading
Tipler, Llewellyn, section 3-3

Prelab Questions

1. In this experiment you will be using a mercury lamp as the source of photons. At the yellow line (578 nm) of mercury, the total power output of the lamp- (into all directions) is 0.3 W. The distance from the lamp to the cathode surface of the photoelectric effect device is 0.7 meter. Assume that the cathode has atoms with a work function of 1.46 eV and radius \(10^{-10}\) meter. Estimate the time lag for emission of photoelectrons that would be expected classically. (Example 3-7 in your textbook will be helpful in working this problem).

2. The mercury lamp you will use in this lab emits photons at the following wavelengths – 365 nm, 405 nm, 436 nm, 546 nm, and 578 nm. Assuming light with all these wavelengths is incident on a photocathode with a work function of 1.46 eV, what will the measured stopping potential \(V_0\)? Recall that the stopping potential is the voltage that needs to be applied to stop the flow of all photoelectrons from the cathode.

Introduction

The theory behind the photoelectric effect is explained very well in the required background reading (see above), so we will not repeat it in detail here. Recall that the basic idea is that for photons of frequency \(f\) incident on a photocathode, the current flow of electrons can be stopped by applying a stopping potential \(V_0\) of sufficient strength to stop the electrons with the highest kinetic energy:

\[
eV_0 = \left(\frac{1}{2}mv^2\right) = hf - \phi
\]

where \(\phi\) is the work function of the material in the photocathode. In the experimental setup described in the text, the voltage \(V_0\) is externally applied. In the apparatus you will use, things are done slightly differently. See Figure 1. Photons strike the large cathode surface of a vacuum photodiode. Some of the emitted photoelectrons from the surface strike the anode wire shown. Charge builds up on the anode. The anode and cathode have a capacitance, so a potential difference builds up between them; electrons continue to flow onto anode until the potential difference builds up to the stopping voltage. The final voltage between the anode and cathode is therefore the stopping potential of the photoelectrons. This apparatus lets you then measure this voltage directly, as shown. Internally, it has a built-in amplifier with an ultrahigh input impedance (> \(10^{15}\) \(\Omega\)) and unity gain (\(V_{out}/V_{in}=1\)). The resulting potential difference can be measured with a digital
voltmeter. The fact that the amplifier has a very high input impedance means that it requires very little current input to measure the voltage (a “perfect” voltage measuring device would draw zero current). But the fact that the amplifier draws a small current means that the actual measured voltage will be slightly less than the real stopping potential; this effect gets worse as the light intensity striking the photocathode goes down.

Figure 1: Schematic of the photoelectric experiment setup.

Apparatus
First familiarize yourself with the apparatus. A picture of the apparatus as it should be set up for you is shown in Figure 2.

Figure 2: The PASCO Photoelectric Effect Apparatus
Take a look at the apparatus and identify the following pieces:

- Mercury lamp; you should switch this on now (if it is not already on) so that it can start warming up.
- The light exits the mercury lamp through a small rectangular aperture of size 2.4 mm x 27 mm to make a well-defined beam.
- The next object in the optical path is a combined lens and diffraction grating. The lens is a 100 mm focal length lens that focuses the light onto the vacuum photodiode inside the photoelectric effect apparatus. It is followed by a diffraction grating (600 lines/mm) like the one you used in the atomic spectra lab. This grating is _blazed_ meaning it produces the brightest spectrum on one side only.
- The light then travels to the photoelectric head. It first encounters a rectangle with a white reflective mask; this mask allows you to see the ultraviolet line from the mercury source that is not normally visible. It is made of a special fluorescent material that makes the ultraviolet line appear as a blue line, and it also makes the violet line appear more blue. Light passes through this aperture into a light shield that you can flip out of the way (try it). This light shield should always be closed when you do measurements so that room light doesn’t get in the device.
- The photoelectric head also has voltage outputs, and it should already be connected up to a handheld digital multimeter and to a voltage probe attached to the computer data acquisition system.
- The vacuum photodiode that you will use in this experiment is contained in a shielded enclosure inside the photoelectric head, so you won’t be able to see its details. But we have an example of a similar vacuum photodiode laying on the instructor’s counter. Take a look at it and compare the internal parts to what you see in Figure 1.
- Take a look at Figure 3. It has a list of the five discrete wavelengths of light that you can get from the mercury lamp. You will guarantee that the light incident on the photoelectric effect is monochromatic by using the diffraction grating.
All values except wavelength for yellow line are from Handbook of Chemistry and Physics, 46th ed. The wavelength of the yellow was determined experimentally using a 600 line/mm grating.

**NOTE**: The yellow line is actually a doublet with wavelengths of 578 and 580 nm.

<table>
<thead>
<tr>
<th>Color</th>
<th>Frequency (Hz)</th>
<th>Wavelength (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yellow</td>
<td>5.18672E+14</td>
<td>578</td>
</tr>
<tr>
<td>Green</td>
<td>5.48996E+14</td>
<td>546.674</td>
</tr>
<tr>
<td>Blue</td>
<td>6.87858E+14</td>
<td>434.855</td>
</tr>
<tr>
<td>Violet</td>
<td>7.40858E+14</td>
<td>404.656</td>
</tr>
<tr>
<td>Ultraviolet</td>
<td>8.20264E+14</td>
<td>365.483</td>
</tr>
</tbody>
</table>

Figure 3: Wavelengths in the Mercury lamp spectrum and pictures of the orders from the diffraction grating.

**Procedure**

1. Your mercury lamp should have been on at least 10 minutes to warm up. Rotate the photoelectric effect head on its swinging coupling bar so that the zeroth order of the diffraction grating strikes the white reflective mask on the front of the photoelectric head. If the light image doesn’t appear well focused, you can adjust the position of the lens/grating assembly by the mercury head; adjust it by loosening the thumbscrew and sliding it along its rods.

2. Roll the light shield out of the way to reveal the white photodiode mask inside the apparatus. You now need to rotate the photoelectric head on its support rod until the input light is passing through the input rectangular aperture and is striking the holes into the photodiode. Once you have it adjusted properly; tighten the thumbscrew in the base support rod. Unfortunately, even when this thumbscrew is tight the apparatus can still rotate a little bit, so you have to be careful not to bump it. You may also need to adjust the lens/grating assembly a bit to achieve the sharpest possible image of the aperture on the window in the photodiode mask. Then roll the light shield back into place. Whenever you move to a different wavelength of light, you need to open the light shield and recheck that the light is striking the phototube inside the apparatus.
3. Turn the power switch of the photoelectric head ON. Now rotate the entire photoelectric head about the pin in the coupler bar until you see the colored maxima in first order. Swing to either side of the zeroth order and figure out which side the first order maxima appears to be brighter on (it will be brighter on one side since this is a blazed diffraction grating). Make sure that you can identify all five spectral lines listed in Figure 3.

4. Pick out one of the lines in first order (on the bright side) and make sure it is striking the photodiode following the procedure in step 2. Press the “PUSH TO Zero” button on the side of the photoelectric head. This will discharge any charge built up on the anode. Release the button, and then look at the voltage on the voltmeter. You will see it immediately jump up to some non-zero value and then, depending on the light intensity, it may take a few (sometime as long as 30 – 40 seconds) to settle at its final value. The final, stable voltage value on the voltmeter is the stopping potential for that wavelength of light. Notice that the fact that the voltage jumped essentially instantly up to a non-zero value after you released the zero button indicates that photoelectrons are immediately being emitted from the photocathode. There is no “time lag” as one predicts in the classical theory (like you worked out for prelab question 1).

5. First, you will investigate one of the important predictions of the quantum theory of the photoelectric effect. According to the photon theory of light, the maximum kinetic energy, $KE_{\text{max}}$, of the photoelectrons depends only on the frequency of the incident light, and it is independent of the intensity. So, in the quantum theory, we expect the measured stopping potential to be independent of intensity for a fixed frequency. In contrast, the classical wave model of light predicted that $KE_{\text{max}}$ would depend on light intensity. In other words, the brighter the light, the greater its kinetic energy. So, in the classical wave theory, we expect the measured stopping potential to increase as the light intensity increases for a fixed frequency.

6. To choose between the two models discussed in step 5, set up the apparatus to look at the blue 436 nm line in 1st order on the bright side. As usual, make sure the light is properly focused onto the photodiode, and make sure only the single spectral line is incident on it. Make sure to close the light shield. Find the device labeled “Variable Transmission Filter” on your desktop. Place the variable transmission filter on the white reflective mask (it attaches with a magnet) so that the light passes through the section marked 100% and reaches the photodiode. Press the “PUSH to Zero” button, and wait for the voltage on the digital multimeter to stabilize. When it has stabilized, record the voltage. Move the variable transmission filter so that the light is passing through the next section (80%) and redo. Continue for all five settings (100%, 80%, 60%, 40%, 20%) so that you have a measurement of the stopping voltage for all five intensities at this wavelength.

7. Now set up the apparatus for a different color (either green or yellow) and repeat step 6. For green or yellow you need to use the filters provided to limit other frequencies of light from entering the apparatus. Place the appropriate filter (green or yellow) on the white reflective mask, and then place the variable transmission filter on top of that. Make
measurements at all five settings so you have a second set of data of stopping voltage for all five intensities at a different wavelength.

8. Does your data support a quantum or wave based model of the photoelectric effect? Einstein will be unhappy with you if you make the wrong choice, so consult with your TA if your data doesn’t support his theory.

9. As you were taking the above data, you should have noticed that it takes a little time for the anode to “charge up” and the voltage to stabilize at its final value. The time becomes longer as the light intensity gets weaker. In this step you will investigate that effect more quantitatively. Set up the apparatus again to look at the blue 436 nm line in 1st order on the bright side. Put the variable transmission filter into place and set it on the 20% setting. You will now record data for the voltage as a function of time using the computerized data acquisition system. On the computer desktop, click through the following folders: ClassNotes -> ph3455_stuff and click on the file voltage_vs_time.ds. A screen with a voltage versus time plot will pop up. By clicking on the start button it will record the voltage read by the voltage probe versus time; clicking on the stop button stops data-taking. If you want to delete an experimental data set you can do it by clicking on the appropriate tab under the “Experiment” pull-down menu. Press the “PUSH TO Zero” button on the photoelectric head, start data-taking, and then release the button. You should see the voltage jump quickly to a non-zero value and then it will more slowly build up to its final asymptotic value. When it appears to have stopped increasing, then stop data-taking. Move the transmission filter to the 40% setting and repeat. The second set of data will appear on the same plot. Print a copy of the plot to the printer for both partners to include in their lab report. You also want to print a second copy with the axes “zoomed” in to the area of interest. You can adjust the axes by left clicking on the graph; it will bring up a dialog box that allows you to change the axis ranges. For your second printout you want to focus (along the vertical axis) along the small range from where the voltage initially jumped to up to its final value. If you are unsure where it is you are to zoom, then consult with your TA.

10. Recall from the introduction that the relation between stopping potential and the frequency of the incident light is:

\[ V_0 = \left( \frac{h}{e} \right) f - \frac{\phi}{e} \]

so by measuring the stopping voltage as a function of frequency you will be able to verify the above relationship and extract a value for the work function \( \phi \) and the ratio of fundamental constants \( h/e \).

11. First do the measurements using the 1st order lines on the bright side. Remove the variable transmission filter. Measure the stopping potential for each of the five wavelengths of light (ultraviolet, violet, blue, green, yellow). Remember to make sure the light is focused properly on the photodiode for each line, and push the zero button before each measurement. Remember to use the green and yellow filters provided when you make the measurements with the green and yellow light.
12. Now move to the 2\textsuperscript{nd} order (on the bright side). Redo the measurements from step 11 but you only need to take data for the ultraviolet, violet, and blue lines; the green and yellow line data is not very reliable at these low intensities. This will give you a second set of data of stopping potential versus frequency.

13. Before leaving the lab please do the following:
   - Turn off the digital multimeter.
   - Turn the photoelectric head power switch to the OFF position.
   - Turn off the mercury lamp (unless there is another section coming in right after yours).
   - Put the filters back into their plastic bags for safe keeping.
   - Verify with your TA that you have all the data you need for your report.

\textbf{Report}

Your report should address all of the following points.

1. Introduction

2. Dependence of the maximum kinetic energy of photoelectrons on light intensity
   - Include tables of your measurements of the stopping potential versus light transmission for the two different wavelengths of mercury light. Make a plot for each case of stopping potential versus fractional intensity (you can combine the results on one plot with different plotting symbols for each wavelength).
   - Describe what both the wave and quantum based models of the photoelectric effect would predict for the above experiment. Which model did your data agree with and why? (Note: The high input impedance amplifier used in this experiment draws a small current, so the actual voltages you measured will be slightly less than the real stopping potential. This effect gets more pronounced as the light intensity striking the photocathode goes down. However, the effect is small enough that you should still easily be able to distinguish between the prediction of the wave and quantum based models.)

3. Measurement of charging time
   - Include your two plots of voltage versus time for the two different intensity settings (40\% and 20\%). From your plots, you should notice that the accumulated charge on the anode quickly jumps up to a value, and then slowly builds up with an exponential curve behavior to its asymptotic value. We will describe the time dependence with the following simple exponential build-up formula:

\[ V(t) = A(1 - e^{(-t/\tau)}) + V_{initial} \]
Here, $V_{initial}$ is the initial voltage that is jumped to quickly, and the time constant $\tau$ characterizes the time it takes to build up to the asymptotic value ($V_{initial} + A$). You can determine the value of $\tau$ by simply reading off your graph the time elapsed when the voltage reaches the value corresponding to $t = \tau$, that value is $A(1-e^{-1}) + V_{initial} = .63A + V_{initial}$. Determine the value of $\tau$ for both the 20% and 40% intensity settings.

- As described in your textbook, Philip Lenard first observed that the number of photoelectrons emitted from a metal surface per unit time is linearly proportional to the intensity of the incident light. Are your measurements above consistent with this observation? Explain why.

4. Relationship between stopping potential and frequency of incident light

- Make a table of your two data sets (one done in first order and one done in second order) for the relation between stopping potential and frequency of the incident light.

- Write down the proper equation that relates the stopping potential and frequency of the incident light. Discuss the reasoning behind this equation. What combination of fundamental constants does the slope measure? What does the intercept measure? Perform a least squares fit to each of your two sets of data to determine the best fit values of the slope and intercept. Do not use a canned fitting routine. Follow the procedure in section V of the handout on error analysis. Use the formulae there to determine the best fit value of the slope and intercept and their errors. Make a plot of each of your data sets and put the best fit line on there. (Note: the measured data points should be plotted as individual data points and they should NOT be connected by a jagged line to guide the eye. The best fit line should be shown as a continuous line, which, of course, will not go through every data point).

- Average the two values for the slope and two values for the intercept to quote your final values for the slope and intercept. Look up the accepted value for $h/e$ and compare it to the value you measured.

5. Conclusion