EXPERIMENT Q-3

Photoelectric Effect

Abstract

The value of Planck's constant, **h** is determined from observations of the photoemission of electrons from a metal surface.

References

Taylor, Zafiratos & Dubson, Modern Physics, 2nd Edition, 2004: Section 4.3
Reese, University Physics, Brooks/Cole, 2000: Section 26.5

Pre-Lab

Please do this section before coming to lab. By now you have done one or more labs that illustrate the wave nature of light. This experiment demonstrates how light sometimes behaves as particles, or "photons". The photoelectric effect occurs when you shine light on a piece of metal and electrons are ejected from the metal. When this happens, the rate at which electrons emerge is proportional to the intensity of the light. The curious thing is that electrons emerge only if the wavelength of the light is below a certain critical value, i.e. if the light is too red, no photoelectrons leave the metal, no matter how intense you make the incident light.

This behavior is understood by assuming that the incident light consists of photons, each photon carrying a definite amount of energy. This energy "quantum", **E**, is proportional to the frequency, **f**, of the light, i.e. **E = hf**, where the proportionality constant **h** is known as Planck's constant. It is also assumed that a certain amount of energy, ϕ, is required to remove an electron from the metal. ϕ is called the "work function". It is different for different metals; and is analogous to the "ionization energy" for an atom. If the energy brought in by the photon is less than ϕ, the light can't get an electron out of the metal no matter how many photons arrive. But, if the photon energy exceeds ϕ, each photon can eject one electron, and electrons leave the metal with a kinetic energy, **KE**, equal to the excess energy brought in by the photon, i.e. $\mathbf{KE = hf - \phi}$. In lab you will experimentally determine the **KE** of photoelectrons for several different wavelengths of light. When you plot your results as a function of **f**, you should get a straight line of slope **h** and y-intercept ϕ.

How do you find the **KE** of an electron coming out of a piece of metal? Consider the phototube in Figure 1. It contains two metal plates, the cathode and the anode, and light causes electrons to be emitted from the cathode. The electrons come out of the cathode in a variety of directions, but some of them go toward the anode. As these electrons hit the anode, they produce a current in the ammeter. Now suppose you apply a voltage to the anode, making it negative with respect to the cathode. Then the anode will repel the electrons emitted from the cathode; they will slow down as they fly across the phototube. If you adjust the voltage, **V**, so the electrons are turned around just before reaching the anode, you can set up a conservation of energy equation. The equation states that the **KE** the electrons had when they left the cathode is equal to the electrical potential energy, $|\mathbf{eV}|$, they gain as they fly across the tube. Experimentally, you adjust the voltage to the value $\mathbf{V_{cut}}$ that just "cuts off" the anode current, and say that $\mathbf{KE} = |\mathbf{eV_{cut}}|$. The voltage $\mathbf{V_{cut}}$ is called the "cutoff voltage", or "stopping potential". Equate the two **KE** expressions, to get Einstein's photoelectron equation, by expressing $\mathbf{V_{cut}}$ as a function of **f** and ϕ.

To prepare for lab, read the **Procedure** section below and feel free to ask questions!

Apparatus

- Shielded photobox
- Mercury lamp
- Interference filters - 405, 435.8, 546.1 and 577.7nm
- Computer with Excel
- Digital voltmeter
- Digital electrometer with input cable
- 1 BNC coaxial cable
- 1 BNC-to-banana adapter

Procedure

Examine the shielded enclosure, called the photobox (see Figure 1 below). The slot in one side allows light to reach the phototube mounted inside the box, and the diamond shaped cradle is used to hold interference filters in front of this slot. Open the box by unscrewing the two thumb screws. The breadboard is used, as you will see, to connect various components in the photobox together. Identify each of the components in the matching list below and identify the color of the wire that connects the component to the white plastic breadboard.

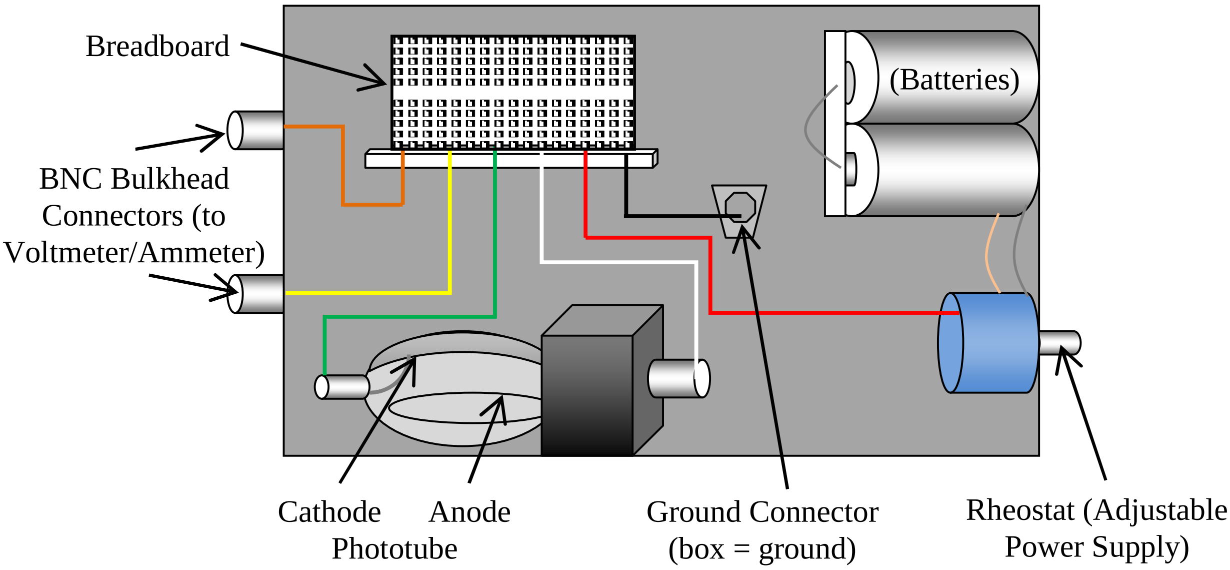

Figure 1: Inside the Photobox

Matching Exercise: After studying the photobox and its connections, write the color of wire connecting the breadboard to each of the photobox components in the space next to the component name:

Ground: ______________________________

Connections to external meters: ______________________________

Anode: ______________________________

Power Supply: ______________________________

Cathode: ______________________________

Be sure to indicate the connection colors in your lab notebook.

Method A: Simple Measurement of Cutoff Voltage

Suppose the anode and the cathode are not connected to anything and you shine light on the cathode. Photoelectrons will be ejected, and some of them will reach the anode, causing it to become negatively charged. As time passes and more photoelectrons are ejected, the charge on the anode will build up until it becomes large enough to repel the most energetic photoelectrons. At this point, the cathode-anode voltage will, ideally, be at an "equilibrium voltage" that is exactly equal to the theoretical cut-off voltage. To test this method of determining the stopping potentials, wire your circuit according to the schematic shown in Figure 1, using the Keithley 6514 Electrometer as a voltmeter.

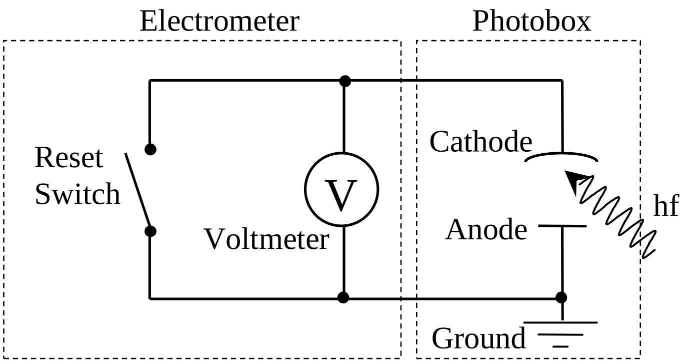

Figure 2: Simple measurement of Cutoff Voltage
(dotted boxes indicate each component)

1) Complete the wiring of the circuit in Figure 2, making connections inside the photobox using the breadboard, illustrated in Figure 3 (the connections shown in the figure are samples just to show you *how* you connect rows; they are not necessarily the specific connections you need to make). The breadboard has plug-in sockets, arranged in vertical rows of five sockets each. The five sockets in each row are all connected to each other. The photobox already has wires running from each component to different rows on the breadboard. To connect different components together, you use a short wire, known as a jumper, between their two rows. An electrometer is used to measure the cut-off voltage here because it comes closer than a standard lab voltmeter to approximating an "ideal" voltmeter, i.e. a voltmeter that has **infinite** resistance, so that no current will flow through it. ***QUESTION 1****: If the voltmeter is not ideal, but has some finite resistance, how will the observed "equilibrium voltage" compare to the theoretical "cutoff voltage"?*

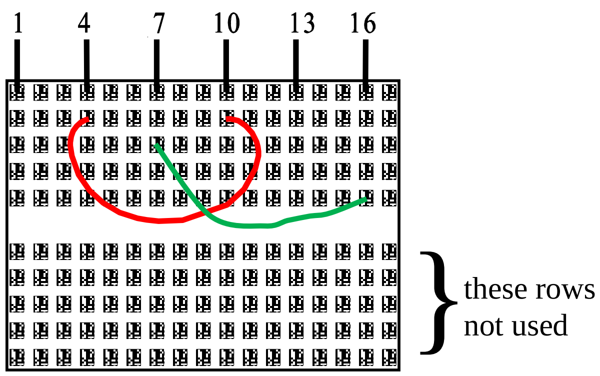

Figure 3: Sample connections on a breadboard (wires connecting row 4 to row 10 and row 7 to row 16). Note: these are sample connections, not actual connections you will actually make.

2) Use the coaxial cable provided with a BNC connector (with 2 locking pins/grooves) on one end and a Triax connector (with 3 locking pins/grooves) on the other to connect the electrometer to the photobox. The coaxial cable actually contains **two** wires, a central wire that is completely surrounded by a cylindrical outer conductor (see the *Commonly Used Lab Equipment* link on the physics 108 web page for details). The outer surrounding conductor is connected to the photobox (i.e. ground), thereby shielding the central wire. Note that the Triax connector connects to the back of the electrometer while the BNC connector connects to the photobox.

3) To begin taking data, place one of the filters into the square opening on the side of the photobox and slide the Mercury lamp over it until it stops at the end of the grooved slots. Turn on the lamp. **CAUTION:** *The Mercury Lamp emits ultraviolet light. Avoid looking directly at the lamp for prolonged periods.* Allow the lamp to warm up for a minute or so before taking data. Turn on the electrometer. To read voltage, the electrometer must read in the unit Volts (V) on the front panel display; if it reads “V.ZC” it is

set to "Zero Check" the voltage level. To read voltage, press the gray ZCHK button on the front panel and the display should read just “V”.

4) You should take sufficient trials with each filter to justify uncertainty. The reset switch in Figure 1 allows you to “zero” the meter to prepare for a new trial. On the Electrometer, the reset switch is the ZCHK button. Press this button to reset the voltage to zero, then press it again to begin a new trial. For each of the filters, record the equilibrium voltage for multiple trials. *Note: you do not need to wait for all digits on the meter’s display to stabilize before reading the measurement – in some cases this could take all day! For example, if the meter gives 0.81X Volts, where the X fluctuates between 2 (for a reading of 0.812 V) and 8 (for 0.818 V), you can report the reading as 0.815 V ± 0.003 V.*

5) Repeat this process for each of the four filters.

Method B: Measurement of Cutoff Voltage and I-V Curves

Method A above provides a quick way to check cutoff voltage, but does not give a more detailed picture of how photocurrent changes as a function of voltage. To learn more about photocurrent properties, we will use manipulate the cathode-anode voltage both to find cutoff voltage and to create a detailed current-voltage (I-V) graph for a window around the cut-off voltage.

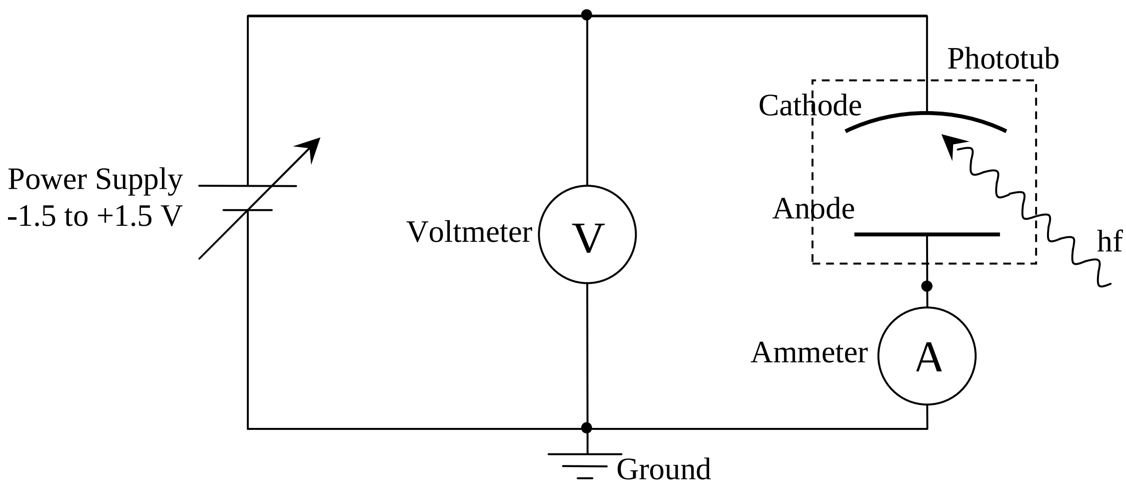

Figure 4: Circuit Schematic Diagram

All the electronic components (except the voltmeter and ammeter) needed to wire the circuit shown in Figure 4 are in the photobox. The circuit has a variable voltage power supply that allows you to vary the cathode- anode voltage from -1.5V to +1.5V. To vary the cathode-to-anode voltage, you turn the rheostat's knob, located on one side of the box.

The anode currents caused by the photoelectric effect can be very small (~10^{-12} amps), so the experiment is very sensitive to "noise" generated from a variety of sources, particularly using Method B. Some noise sources include changing currents in the building wiring, static electricity on your hair or clothes, shifting charged wires around, etc. To minimize this noise, the experiment has been designed to be totally contained within grounded metal enclosures, as shown in Figure 5. The point labeled "ground" in Figure 4 is the metal photobox itself. The voltmeter and ammeter are also shielded (their plastic cases surround metal ones), and are connected to the photobox via shielded BNC cables. In this way the photocell, voltmeter, ammeter, and their connecting wires are all enclosed in a grounded metal shield.

Follow the steps below, referring to Figure 5, to set up for data collection with method B:

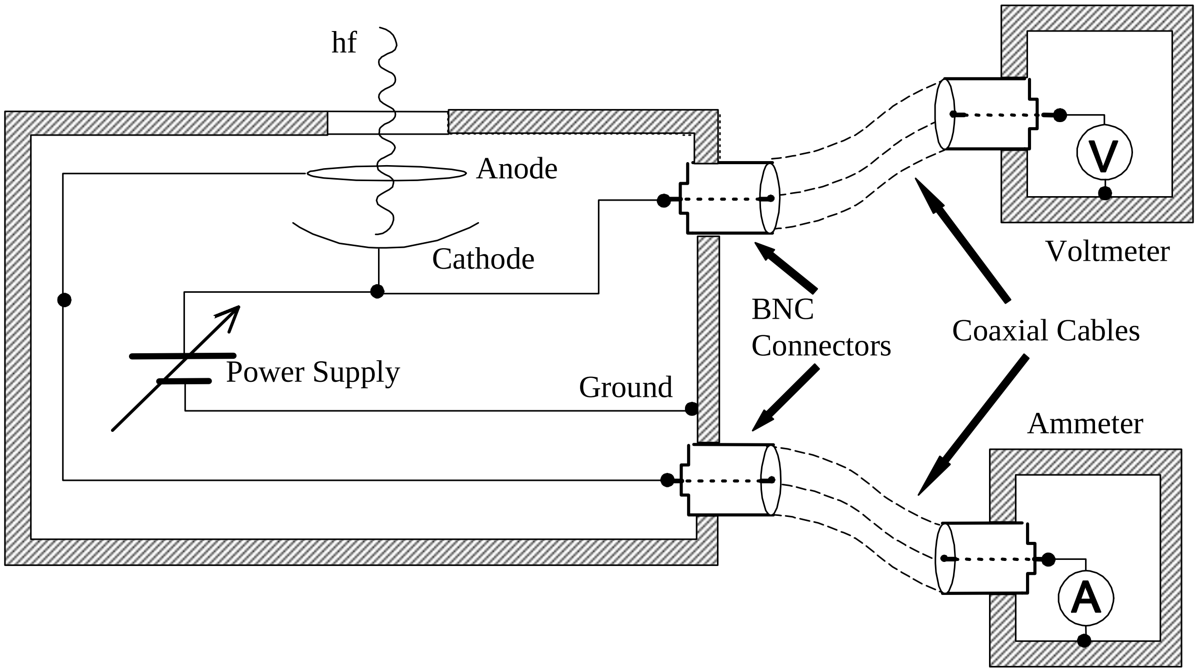

Figure 5: Another view of the Method B setup

1) On the breadboard, connect the phototube cathode to the variable power supply and to a BNC bulkhead connector with jumper wires. Connect this bulkhead to the yellow DMR-2500 multimeter DC Volt and COM inputs (you will need a BNC to BANANA adaptor to do so: see the *Commonly Used Lab Equipment* link and be sure the ground plug is connected to the COM input) and set the meter to measure DC voltages of up to 2 V.

2) On the breadboard, connect the phototube anode to the second BNC bulkhead connector. Connect this bulkhead to the Keithley electrometer. To set up the Keithley electrometer for use as an ammeter, press in the button labeled **I** on the front panel. Make sure the "Zero Check" is not pressed. You are going to use the least sensitive picoAmp range setting on the electrometer to take data: locate the downward-pointing Range selection button on the right of the front panel, press this button, watching the measurement units on the display, until it transitions from microAmps (µA) to nanoAmps (nA) to picoAmps (pA). Leave the electrometer on this first pA setting. *Note: The ammeter measures the current flowing from the cathode to the anode, which is proportional to the rate at which the photoelectrons ejected from the cathode reach the anode. An ammeter ideally has zero resistance, so the voltage indicated by the voltmeter is the same as the voltage drop between the cathode and anode. (Plug zero in for the resistance in Ohm's Law to convince yourself that a zero resistance yields no potential drop).*

3) Close the shielded box. Turn on the battery. Place the 405 nm filter over the slit, position the lamp over the slit and turn it on. Adjust the rheostat until the measured current is somewhere near, but below 0 pA (note: if the electrometer reads OV.RFLOW you are out of the readable range; turn the rheostat to find the readable range). At this point, take a set of data by hand: vary the voltage control until you reach V_{cut}, the "cut-off voltage" for this wavelength. At $V=V_{cut}$, all photoelectrons are turned around before reaching the anode, so the observed photocurrent vanishes. For just the 405 nm filter, take at least five trials to find V_{cut}, alternating with your lab partners, sometimes approaching the cut-off point from a negative current, sometimes from a positive current. From your data, find V_{cut} and its uncertainty.

4) For each filter, you should take 4 or 5 $\mathbf{V_{cut}}$ trials. Keep a continuous notebook record of the stopping potentials for each filter wavelength, justifying uncertainty.

5) When you have taken data for all four filters, you are ready to investigate the I-V properties of the phototube in more detail, doing so with the 577 nm filter. To do so, you are going to create a graph in Excel which represents the current vs voltage behavior of the tube from approximately -100 pA to the maximum positive current the phototube will produce. To begin, open Excel and set up a spreadsheet to collect your I-V data: create appropriate labels with units to enter cathode-anode voltage in column A and cathode-anode current in column B. Your final graph will contain 25 data points, so when you have set up the column labels, create a dummy graph (graph with no data points) in Excel by selecting/highlighting the column headers and enough blank cells below the headers to accommodate 25 data points. Then, *INSERT* a *SCATTER* chart with just points (no lines). The dummy graph should show up. Now, as you add data to the spreadsheet in the cells you highlighted, the points will automatically show up on the graph and the axes will auto-scale to make sure the points fit on the graph. Don't worry about formatting it now – you can format the final graph in the analysis later.

6) To get a basic idea of the I-V characteristics of the photocell, quickly and efficiently collect 10 to 15 (V,I) data points between a current of about -100 pA and the maximum positive current the phototube will produce. You will use these data points to decide which regions of the graph are more "interesting" than others – which regions contain changes in the behavior of the I-V curve that will require more investigation. Some notes about efficient data-taking:

- don't spend a lot of time trying to adjust the rheostat to obtain exact rounded voltages or currents: it just wastes time. For example, if you want a V, I point with a current near -70.00 pA, trying to set the rheostat so the current reads exactly -70.00 pA takes a lot of time and provides no more information than turning the rheostat quickly, seeing that it happens to read some value close to -70.00 pA (like -68.92 pA), recording the (V, I) data, then moving on. Just set the rheostat so that the data point is in the range in which you are interested, let the meters stabilize to a reasonable number of significant figures, record the (V,I) data in your Excel table and move on to the next data point.
- as you add points to the graph, keep an eye on the behavior of the I-V curve. Regions that appear more predictable require fewer data points; regions where you see a change in I-V behavior are regions you will want to focus on later.
- if you are spending more than a minute per data point, stop and figure out why. If you can't figure it out, discuss with an instructor.

7) When you have completed the quick initial set of data, decide which regions of the graph are adequately described by the data points you took and which regions could use more detail. Then, take additional points to add detail in the appropriate areas of the graph. Note: you can remove already existing data points from regions that you think are already adequately represented on the graph to make room for more data points in the more interesting areas of the graph, but **you must use exactly 25 data points in your final graph**.

8) As you investigate different areas of the I-V curve and add points to your spreadsheet, you may find it confusing or annoying that the points are not in increasing or decreasing order. You can reorder them at any time by sorting them: select the entire range of data in both columns (not including the headers, but all entered data in columns A and B and note: **DON'T just select one column to sort or you will not keep your (V,I) ordered pairs together!!**) Under DATA, click the symbol  to sort so that column A will range from most negative to most positive or  to sort from positive to negative. Since you selected both columns to sort, Excel will move the values in column B to keep them paired with their column A partners.

9) Be sure to send copies of the Excel sheet to your lab partners before you leave.

Sample Calculations

For the same wavelength from each method, use Einstein's photoelectric equation and the accepted value of Planck's constant to find the cathode work function. Note: you *won't* calculate Planck’s constant or the work function this way in the **Analysis** below, but will get all your results from graphs. Before you leave, make sure you understand how you will make the graphs in your analysis.

Dismantle the apparatus, unplug any equipment, and return the lab to its original state.

Analysis (to be done independently)

To analyze data for methods A and B, you will be creating graphs in Excel. You will start your analysis with method A. To do so, create a new Excel spreadsheet to with appropriate column labels, units, and data, starting in column A with wavelength, then frequency, then cutoff voltage. Create an equation to calculate frequency, then, create an XY-Scatter type graph with frequency on the x-axis and cutoff voltage on the y-axis (if necessary, refer to the *Excel Tutorial* linked to from Lyceum web to help you).

Use Excel to plot the best-fit line (called a “trendline”) for this line and calculate an equation for this line to determine the line’s slope, which you will need to calculate Planck's constant. Make sure to provide two or three significant figures for each quantity in the slope and intercept (you can right-click on the equation displayed to format the numbers). Refer to the *Excel Tutorial* link for additional instructions. Next, provide max/min lines to determine uncertainty in slope: for example, for the max line pick the two (frequency, voltage) points on the graph that allow you to create the line with maximum possible slope that still represents the overall trend of your data. Then, do the same to determine the minimum possible slope. You may do this either (i) by creating extra columns for max and min slopes in Excel or (ii) by hand, either algebraically or graphically. Just be sure to show all Excel work done or work done by hand (that includes drawing the max/min lines on your graph)! For hints, refer to the *Experimental Uncertainty Review* link on the physics 108 web page. Remember if you do the max/min lines in Excel that Excel uses all data points included in the y-column to calculate the best slope, so you will create additional columns for the max and min lines that contain only two points each to establish the max and min trendlines.

For method B, you can open a new Excel worksheet and enter your data as you did for method A. You should also plot a graph of your $\mathbf{V_{cut}}$ **vs. f** and determine the best and max/min slopes as before.

For each method, determine Planck's constant in eV-sec (with uncertainty) from the calculated slopes. Compare your two final results to each other and to a published value. Also, compare the work functions obtained from both methods (best values only – don’t worry about uncertainties). Don’t forget to include both graphs in your notebook!

Last, for the I-V data you took for a single filter in method B, create a graph that represents the I-V behavior of your phototube at that filter wavelength. Be sure to label the graph appropriately. Use this graph to answer question 4 below.

Questions

2. What is the longest wavelength that would cause photoemission from your cathode? What would happen if near infrared light (about 1200 nm wavelength) were incident on the cathode?

3. You began analyzing the I-V behavior of the phototube at about -100 pA. About how many electrons per second were ejected from your cathode at this current? Also, approximately how many photons per second are incident on the cathode, assuming this is a perfect system?

4. I-V curves for phototubes such as these have a characteristic bend near the cutoff voltage, often called the "knee". The I-V behavior is very different on either side of the knee; in fact, it usually appears that at the voltages greater than those in the knee region, the current begins to approach a maximum value asymptotically. Discuss why the behavior in this region is so different from I-V behavior in the region on the other side of the knee, specifically discussing the motion of electrons in the phototube under the applied voltage in each region.

Write a conclusion that summarizes and interprets your results. Suggest ways you could improve the results if you were to repeat the experiment, mention problems you had in lab, etc...