

## 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, 2<sup>nd</sup> 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,  $\phi$ , is required to remove an electron from the metal.  $\phi$  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  $\phi$ , the light can't get an electron out of the metal no matter how many photons arrive. But, if the photon energy exceeds  $\phi$ , 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.  $KE = hf - \phi$ . 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  $\phi$ .

How do you find the  $KE$  of an electron coming out of a piece of metal? Consider the photocell 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 photocell. 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,  $|eV|$ , they gain as they fly across the tube.

Experimentally, you adjust the voltage to the value  $V_{\text{cut}}$  that just "cuts off" the anode current, and say that  $KE = |eV_{\text{cut}}|$ . The voltage  $V_{\text{cut}}$  is called the "cutoff voltage", or "stopping potential". Equate the two  $KE$  expressions, to get Einstein's photoelectron equation, by expressing  $V_{\text{cut}}$  as a function of  $f$  and  $\phi$ .

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

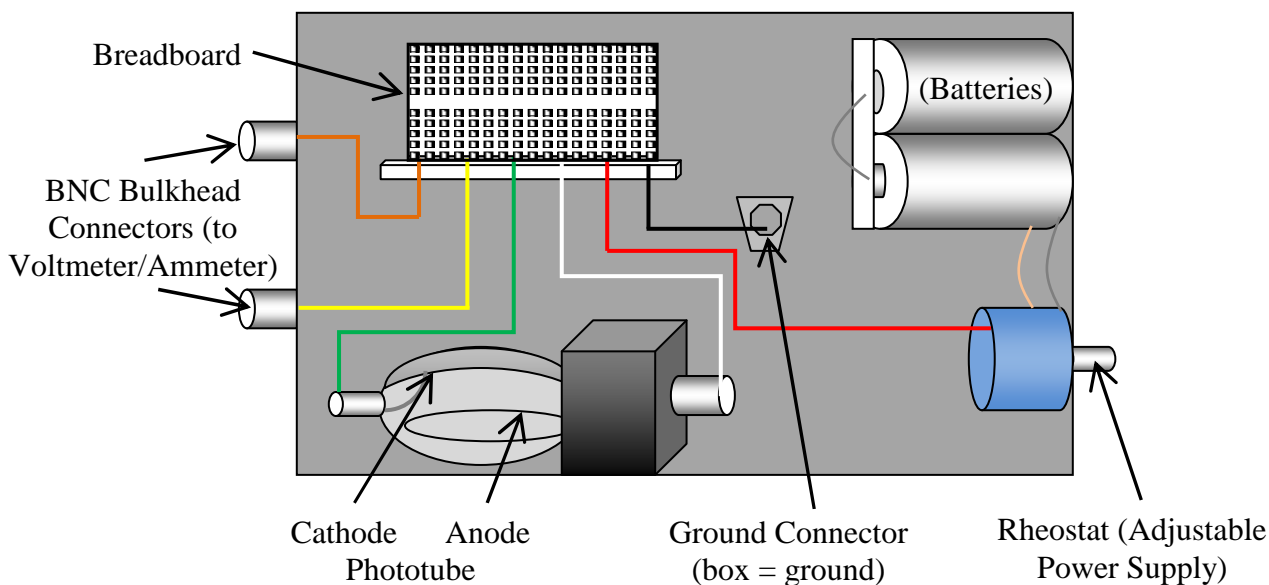
## Apparatus

Shielded photobox  
Mercury lamp  
Interference filters - 405, 435.8, 546.1 and 577.7nm  
Interface Box plugged into the Computer  
Computer with Photoelectric Effect software

Digital Voltmeter  
Digital Electrometer  
3 BNC Coaxial Cables  
2 BNC-to-Banana Adapters  
1 BNC T connector

## Procedure

Examine the shielded enclosure, called the photobox (see Figure 1 below). The slot in one side allows light to reach the photocell 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: \_\_\_\_\_

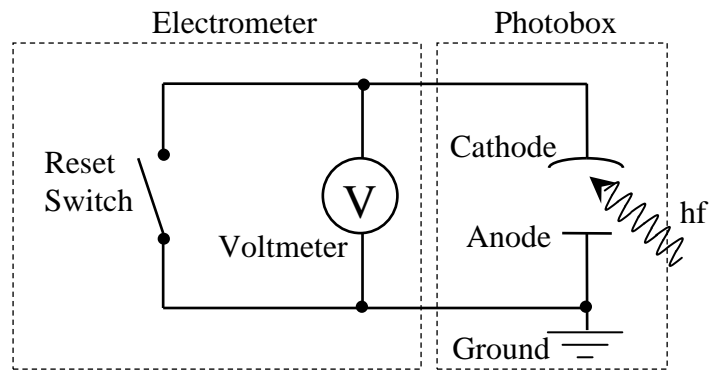
Power Supply: \_\_\_\_\_

Cathode: \_\_\_\_\_

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

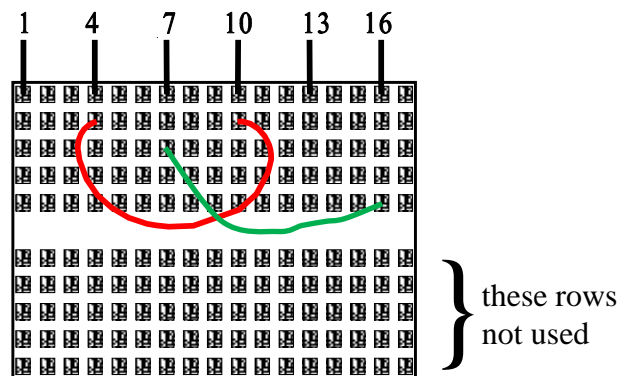
## Method A: Simple Measurement of Cutoff Voltage

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 anode 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 1, making connections inside the photobox using the breadboard, illustrated in Figure 2 (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

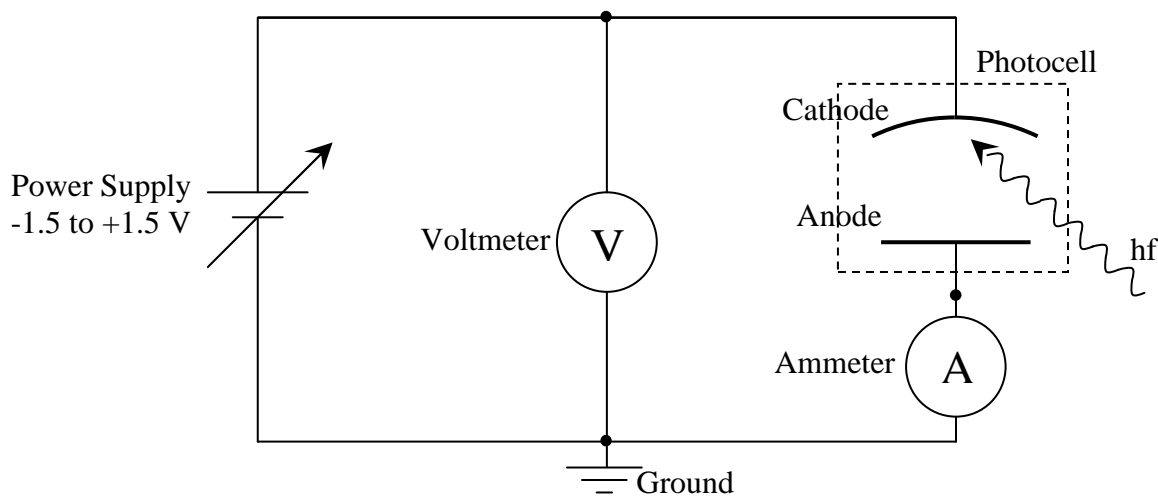
set to "Zero Check" the voltage level. To read voltage, press the gray ZCHK button on the front panel and the display should read just "V".

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  $\pm$  0.003 V.*

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

### Method B: Graphical Measurement of Cutoff Voltage

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 a computer to collect and graph current-voltage data for a window around the cut-off voltage.

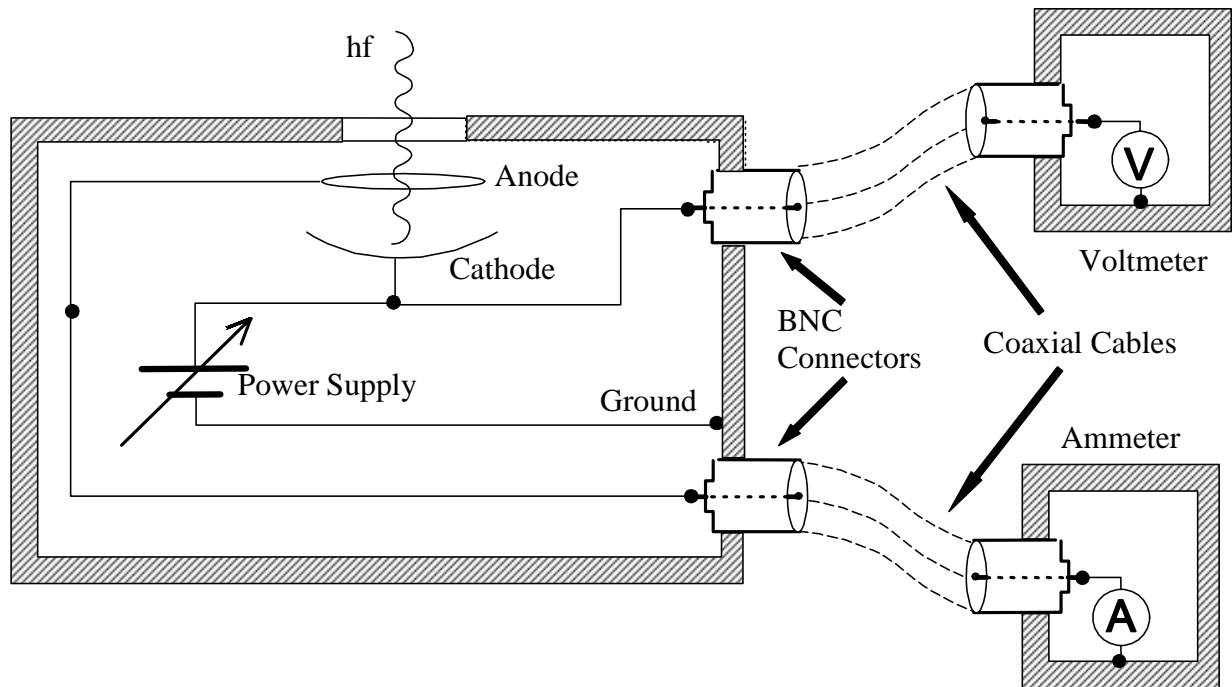


**Figure 4: Circuit Schematic Diagram**

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-to-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 ( $\sim 10^{-12}$  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 5 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 ( $\mu\text{A}$ ) 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. Connect the Y input of the computer interface box to the "2V Analog Out" on the back of the electrometer (the socket marked "COM" should be connected to ground), and use a BNC "tee" to connect the X input in parallel with the voltmeter.

4) 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  $V_{\text{cut}}$ , the "cut-off voltage" for this wavelength. At  $V=V_{\text{cut}}$ , 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  $V_{\text{cut}}$ ,

alternating with your lab partners, sometimes approaching the cut-off point from the positive side, sometimes from the negative. From your data, find  $V_{\text{cut}}$  and its uncertainty.

5) You are now ready to begin taking data with the computer. Go to the Physics 108 folder: Desktop>Departments Folder>Physics Folder>Physics 108. Run the software by double clicking on the icon labeled **Lab Q-3 (Photoelectric Effect)**. Use the mouse to select from the option buttons listed on the left of your screen, starting by introducing your group. The tab menu just serves as a place to view your information; it is not a place to make changes. **WARNING:** *This software does the bulk of the work for you in this lab. However, if you do not follow the instructions carefully (both in this procedure and onscreen), you may find at the end of data acquisition that you have useless data, or no data at all.*

6) Choose the [New Filter] option. For each [New Filter] you must recalibrate the computer by entering the min and max voltages and currents. This sets the scales for the axes on the graph. As directed by the software, adjust the rheostat until the measured current is most negative, but readable - somewhere around -190 to -200 pA. Then follow the calibration instructions in the software carefully. *Note: it is VERY IMPORTANT that the rheostat is not moved from its minimum voltage value when you hit the [Set Min] button and at the maximum value when you hit the [Set Max] button. If this is not done, the graph axes will be improperly set and you will have to repeat the entire sequence.*

7) To make a graph of  $V_{\text{cut}}$  vs  $I$ , select [Acquire Data] and follow the instructions in the program. **Note: turn the rheostat as uniformly as possible at a relatively slow rate, particularly around the  $V_{\text{cut}}$  region.** As mentioned before, the currents you are measuring are very small and any jerkiness in turning the rheostat will have visible results on your graph.

8) For each filter, you should take 4 or 5  $V_{\text{cut}}$  trials. Cover the entire voltage range for just one trial as you did in Step 6 ; for the others, just concentrate on the region around  $V_{\text{cut}}$ , starting with a negative current near 0 pA and increasing the current until you reach  $V_{\text{cut}}$ . Keep a continuous notebook record of the stopping potentials for each filter wavelength, justifying uncertainty. You can save your data to an Excel spreadsheet by selecting [Send Data to Excel]. You can do this after each filter or at the end. **Warning:** *If you select [Send Data to Excel], complete the process. DO NOT CANCEL – the program will close and your data will be lost.*

9) When you have taken data for all four filters, select [Send Data to Excel] and save the data to your Paris folder or email the file to yourself. Be sure to send copies of the data to your lab partners. When your data is saved, select [Print Graphs] and select one graph from each filter to be printed. Choose a complete, smooth graph from each filter to print. When you get the printout, label each graph with the filter wavelength and the  $V_{\text{cut}}$  for that dataset. Note: you will need to copy this graph so each group member can tape a copy of the graph in his/her lab notebook.

## Sample Calculations

For one 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 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

You will start your analysis with Method B. Go into Excel and open your file. Notice that there is a blank column F. In it, you will calculate the frequency corresponding to the filter's wavelength. So, in cell F6, type in **freq** and in cell F7, enter the appropriate units. In cell F8, use an Excel formula to solve for frequency, using the wavelength given in cell B8. Be careful about units!! When column F is filled with frequencies, you will be able to plot  $V_{\text{cut}}$  vs  $f$  to find Planck's constant  $h$ . To do this, refer to the *Excel Tutorial* linked to from the physics 108 web page to create a similar XY-Scatter type graph.

Excel will automatically compute and plot the best-fit slope for this line, which you will need for calculating Planck's constant. Make sure to provide two or three significant figures for each quantity in the best-fit slope (you can right-click on the equation displayed to format the numbers). Refer to the *Excel Tutorial* link for additional instructions. You should also be able to use the graph to determine the work function,  $\phi$ , in electron volts for the metal used as the cathode by determining the y-intercept. Print your worksheet/graph and tape it into your notebook.

For method A, you can open a new Excel worksheet and enter your data as you did for method B (with no current, of course). You should also plot a graph of your  $V_{\text{cut}}$  vs.  $f$  ( $V_{\text{cut}}$  on the vertical axis) and determine the best slope as before. Print this second worksheet/graph and tape it into your notebook.

You should also calculate the max/min slopes for both methods. You may do this by hand, either algebraically, or graphically. Just be sure to show your work (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 that Excel uses all data points to calculate the best slope, but you will probably only use two points on the best-fit line for max/min. Carefully consider and clearly describe which points you should use.

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.

## Questions

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

3. You calibrated the setup for each filter when the minimum current was near -200 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?

**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...**