Lab 3: Photoelectric Effect

Introduction

At the turn of the 20th century, physicists were striving after an understanding of the nature of light. Max Planck had discovered that if he assumed that atoms in a blackbody could only have energies equal to integer multiples of Planck's constant h times the light frequency f, then he could accurately model the light spectrum emitted from the blackbody. Planck himself felt that this was only a mathematical trick and not connected to physical reality. Albert Einstein thought differently.

From his earliest years in physics, Einstein believed that matter was discrete: that it is made of atoms. He took the idea that nature is quantized to the next level. Einstein won the Nobel Prize for his explanation of the Photoelectric Effect.

When light of a certain frequency shines on a metal, electrons in the metal can escape. With no voltage applied, some of those electrons reach a collector (anode), which creates a current when the emitter (cathode) and collector (anode) are connected via circuit. If a positive voltage is applied between the emitter and collector, more of the ejected electrons can make it across the gap between the emitter and collector, and thus the current increases. If a negative voltage is applied, a current will be measured only as long as the electrons have enough energy to overcome the extra barrier to jumping the gap. In either case the work done on the electrons by the potential is equal to $e\times V$ (charge of the electron times the voltage).

If the reverse bias voltage is increased until even the fastest electrons are drawn back to the emitter, the voltage at which none of the electrons reach the collector is the stopping voltage, V_0. In this case, the work done on the electrons is equal to $e\times V_0$. The kinetic energy of the most energetic electrons is equal to the work done on them:

$$eV_0 = \tfrac{1}{2} m v_{\max}^2 = \left(E_k\right)_{\max} \tag{1}$$

Einstein hypothesized that the energy of a light beam is not spread out uniformly like it was a continuous wave, but instead was concentrated in quanta of energy (photons), each having an energy hf, where f is the frequency of the electromagnetic wave. When a photon collides with an electron in a metal surface, the photon gives up all of its energy to the electron, and electron has the chance to escape the surface, that is if it has enough energy. The work function of the material, ϕ, is the amount of energy that the electron needs to just barely get out of the metal. This means that the most energetic electrons that escape the material have the energy, E_{max}:

$$\left(E_k\right)_{\max} = hf - \phi\ . \tag{2}$$

This means that

$$eV_0 = hf - \phi \tag{3}$$

gives the relationship between the stopping potential and the frequency of the photons incident on the emitter.

For our setup, we will use light emitted from a mercury emission tube. The excited mercury gas in the tube emits light of very specific wavelengths. We then use light filters to select out those specific wavelengths of light. We have band pass filters with central pass wavelengths of 405 nm, 436 nm, 546 nm, and 580 nm, which correspond to the visible peaks in the mercury spectrum.

Procedure

Check your setup with Dr. Flater before you turn on the power supply, ammeter, and mercury lamp. Set the ammeter scale to AUTO.

1. Turn on the mercury lamp. Don't ever look into mercury lamp, since it gives off some UV light. Also note that the Mercury lamp gets quite hot, so avoid touching the metal case surrounding the lamp.
2. Choose one of the filters and place it between the mercury lamp and the phototube. Don't ever touch the surface of any of the filters. If you do, let Dr. Flater know so she can try to remove your fingerprints.
3. Connect your setup in forward bias. Use the MATLAB script provided you to vary the voltage over the full range of the power supply (0 to 32 V). Make sure you estimate the uncertainty in the voltage and the current, in order to use it later in your uncertainty analysis.
4. Switch the leads on the front of the power supply for reverse bias mode. You will now be applying negative voltages between the emitter and collector in the phototube. Use the MATLAB script to go through a range of negative biases. Note that you probably don't need to go any lower than -2 V for reverse bias. The voltage at which the current plateaus is the "stopping voltage" for the particular color light you are looking at.
5. Repeat the data-taking process for each filter at least 3 times and also repeat for each of the filters.
6. When you are done with a particular data-taking session, make sure you turn off all equipment and cover the filter opening and mercury lamp opening with their respective caps.

Analysis

1. Make a plot of average phototube current *vs.* bias voltage for all filters, remembering that voltages applied when in reverse bias are negative. Note you should only have one plot for each filter.

2. Estimate the saturation current for each of the current vs voltage plots you created. If you did not reach a plateau in the current for a given filter, estimate the value at which the current saturates. What do the values of saturation current tell you about the light reaching the cathode at each wavelength? Are all the light intensities the same? Why or why not? Develop a quantitative argument for your answer and describe your argument in your report.
3. You will need to determine the stopping potential for each current vs voltage curve. Because there is there is small amount of photoemission from the anode, there is produces an additional negative current which will shift your current vs voltage curve downwards. You need to determine where the current transitions from the lower plateau to the steeply-increasing current region. Come up with two different methods to estimate the stopping voltage. Use each of these two methods on each of your current vs voltage curves. As long as you use the same method on all four curves, the plot of stopping voltage vs light frequency should have the same slope even if the actual values of the stopping voltage are different than what you determine. Using two methods will help validate that you get the same slope of the stopping potential vs frequency regardless of method.
4. Make a plot of stopping voltage *vs.* light frequency for all the wavelengths tested, for both methods chosen in the previous step. If you put the plots from both methods on the same set of axes, it will be easier to compare between methods. Use your two stopping voltage *vs.* frequency curves to determine the value of h/e. How does your value compare to the expected value? Also use your data to find work function of the cathode material. What material do you think the cathode is made of? (Note that you may need to search on the internet for a wider range of work function values for different materials.)

Write-up: Introduction and Summary

Introduction (15 pts)

In this first section of the main body of your paper, you will introduce your reader to the physical concepts being tested in the experiment. You should also summarize some of the background information and theory pertinent to this experiment. This section should be written in your own words, based on your own understanding of the experiment.

Summary (10 pts)

You should reiterate the main points in this final section of the report. Briefly describe the experiment performed, the results obtained, and what these results mean. There should not be any new information in the conclusion section; you are just summarizing what you already discussed in the rest of the manuscript.

Grading rubric:

Background section:

15 pts A thorough discussion of the relevant background for the experiment, including with a detailed explanation of the relevant physics in the experiment.

12 pts Includes a discussion of background theory, but may have not described some key aspects.

10 pts Some physical theory, with some significant missing ideas and connections.

5pts Poor or remedial overview of background theory. OR Ideas lifted heavily from the lab handout.

Summary section:

10pts A complete self-contained summary of the experimental details, key results, and key conclusions from the report.

8 pts A full summary of the report, but missing on a few key details. May include interpretations and/or conclusions that are not found in the rest of the report.

5pts Gives a basic overview of the report, but is missing summaries of many of the key interpretations and conclusions.

3pts Lacks specific interpretations and conclusions that are important for the report. Adds on conclusions that have little or nothing to do with the rest of the report.