Photoelectric Effect

Modern Physics Lab - Rochester Institute of Technology*

Introduction

The photoelectric effect is one of the earliest experiments that demonstrated the particle like ("corpuscular") nature of light. It shows that the energy of a photon depends only on the frequency of the light, and not on the intensity of the light. In this experiment, the photoelectric effect is observed at a variety of wavelengths in the visible and ultraviolet range. The data is used to experimentally determine the ratio of Planck's constant to the charge on an electron, h/e.

Pre-Lab

1. Read this entire document; the pre-lab assumes things discussed in later sections.
2. What is the work function of a metallic surface, and how is it different from the ionization energy of an isolated metallic atom? Which is larger?
3. Your data will allow you to determine V_s as a function of ν. Using Equation 4, what should you plot, and how might you determine ϕ and h/e from your plot?
4. Look up the emission wavelengths for a Mercury Vapor lamp. Cite your source. Do these agree with the approximate values shown in Appendix A?
5. During the second week, use your pre-lab time to start the analysis of the data taken during week 1.

Theory

Electrons are only loosely bound to the atoms of a metal. When struck by light of sufficient energy, some electrons are ejected from the surface of the metal. These are known as *photoelectrons*. The binding energy of the electrons to the surface of the metal is known as the *work function* and is typically denoted as ϕ. If incident light has energy greater than the

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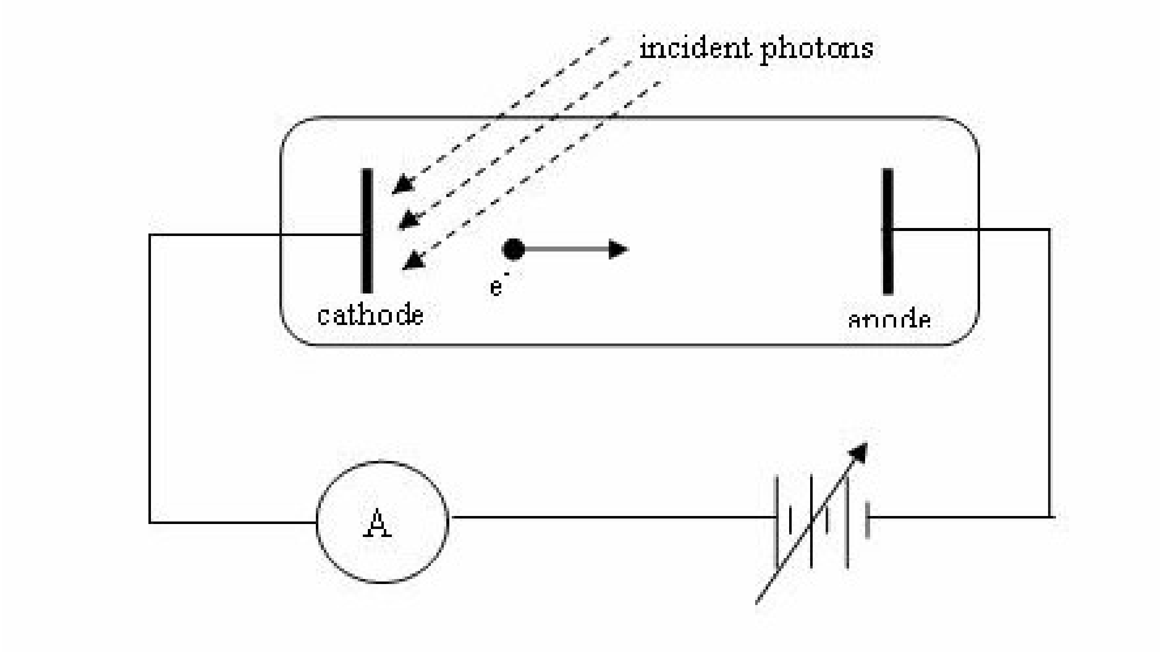

Figure 1: The photoelectric effect vacuum tube and basic circuit.

work function of the metal, electrons are ejected. The kinetic energy K of the electron is simply the incident energy of the light minus the work function of the metal. In order to study the photoelectric effect, the kinetic energy of the photoelectrons must be determined.

The apparatus used in this experiment is diagrammed in Figure 1. Photoelectrons are produced when light shines on a cathode metal surface within an evacuated tube.

The electrons are ejected from the cathode with kinetic energy K. The photoelectrons travel toward the anode, and thus produce a measurable current through the ammeter **A**. A variable voltage is provided, as shown in the figure. With the polarity shown, electrons are decelerated by the negative potential at the anode. If the voltage is large enough, it will completely stop the electrons, and thus no current flows. The stopping potential V_s is defined to be this voltage; where the kinetic energy of even the most energetic electrons is nullified, thus $K = eV_s$.

The stopping potential V_s is measured at several fixed wavelengths (frequencies); the light is supplied by a mercury vapor lamp. Mercury emission wavelengths are very well known, and are given in Appendix A. The light, which appears bluish, like mercury street lights, enters a grating monochromator. The monochromator has an adjustable grating which allows one of the specific wavelength mercury lines to be directed to the output slit of the monochromator. At the output slit, a photoelectric effect evacuated photocell is mounted. This consists of an evacuated tube containing a ring shaped anode and flat plate cathode behind it. The photocell is Leybold Heraeus part 55877, see attached specification sheet. According to Leybold's specifications, the cathode is potassium with an oxidized silver coating and the anode ring is a platinum-rhodium alloy. The anode is ring shaped so that the incident light passes through its center and strikes the cathode (primarily). The photoelectrons then travel towards the not-illuminated anode.

Classical theories have the energy of light proportional to its intensity. Quantum mechanical theories put the energy of light of frequency ν at $h\nu$, where h is Planck's constant. If we call the energy of the light E, the kinetic energy of the photoelectrons is given by

$$K = E - \phi \tag{1}$$

Since the kinetic energy is measured by the stopping potential, Equation 1 reduces to

$$eV_s = E - \phi \tag{2}$$

Thus if the stopping potential is independent of the intensity of the light, but depends only on its wavelength (frequency), then the quantum theory that photons carry energy $h\nu$ is confirmed. If monochromatic light is used, of frequency ν, the maximum kinetic energy of the photoelectrons, from Equation 1 is given by

$$K = h\nu - \phi \tag{3}$$

The kinetic energy is determined by measuring the stopping potential V_s, and thus

$$eV_s = h\nu - \phi \tag{4}$$

Apparatus

Now you will look inside the monochromator and figure out the optical path.

Make sure the UV filter is on the output of the light source. This lamp produces hazardous ultraviolet which will burn your skin and do permanent retina damage to your eyes!

The UV filter is a transparent filter that mounts in the output window of the lamp. When it is securely mounted, turn on the mercury vapor lamp. It may take a few minutes to warm up and light. The lamp has been aligned so as to put maximum intensity into the monochromator input slit, so do not disturb its mechanical placement. The optics within the monochromator are shown in Figure 2.

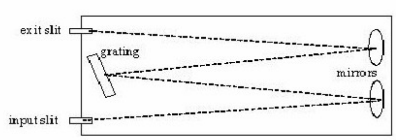

Figure 2: The monochromator used for the photoelectric effect experiment. The dotted line in this figure shows the optical path. A mercury vapor lamp at the input slit provides illumination. The photoelectric tube is mounted outside the monochromator after the exit slit. A crank at the lower left of the monochromator allows the grating angle to be adjusted, which changes the wavelength of light incident upon the exit slit.

Open the monochromator casing by unscrewing the access doors on top of it, and use an index card to trace the optical path. Locate the output slit and ensure the maxima of the intensity pattern is falling on it. The grating angle is adjusted with a knob at the lower left front. It makes a grinding noise when turned; this is the sound of gears engaging in the grating rotation mechanism. Align the green line[1] on the exit slit.

As you line up the green line on the exit slit, monitor the rotary dial reading. The value on the dial is the approximate value for λ. You may note that the dial does not read the exact value for λ that you expect. Thus it is only useful for getting into the right range. You will have to monitor the current output to more accurately align the monocromater.

The grating is large and very expensive, so do not touch it and NEVER try to clean it.

The wavelengths of Hg lamps are well known: use the known values given in Appendix A, and only use the dial to find the lines approximately. Additionally, many of the numbers have worn off this dial, you have to keep track of some digits in your head so that the blanks make sense. You need to learn how to do this while practicing with the green line, since the UV lines are not visible you cannot align them manually using an index card and your eyesight, as you are doing with the green line. Practice with this until you are confident you can align any mercury emission line onto the exit slit.

The photoelectric effect tube is in a light tight casing outside the exit slit, under a black rag to reduce stray light even further. There is an old, burned out, tube in a box on the table. Take that out and look at it, see the metal coated back surface and the ring which produces photoelectrons (the ring got fried in this tube). The tube used in the actual apparatus is identical, except the ring hasn't been destroyed.

Week 1: Stopping Potential for Green, Yellow, and Blue

The photoelectric effect is demonstrated by locating a sharp change in slope of the photocell's I-V curve. The photocurrent does not go to zero for large retarding voltages, but instead approach a (negative) saturation value. This complicates the quantitative determination of V_s.

Align the green line on the exit slit, monitor the rotary dial reading. When you are convinced you have the green line on the output slit, close up the monochromator top and familiarize yourself with the electronics.

A simple dc power supply is set to 4 V maximum and is attached to a voltage divider box mounted on the front of the monochromator. The voltage divider potentiometer allows a fine adjustment from 0 to 4 V, this is the adjustable power supply shown in Figure 1. A positive voltage accelerates the electrons towards the anode, and an appreciable photocurrent can be observed. When the leads are reversed a negative voltage is applied, which decelerates the electrons; at just the right negative voltage the electrons are stopped and no photocurrent is observed. The voltage is monitored with a Fluke DVM.

[1]We start with the green line because it is easy to find, intense, and cannot be confused with one of the other colors (unlike the blue and violet lines which are hard to distinguish).

Start with a positive voltage of 4 volts. Turn on the Keithley electrometer, which is used to measure the photocurrent. You should have a photocurrent of between picoAmps and nanoAmps. Please note that this is a very small current, and it is very easy to get stray signals of this magnitude. You may observe that the current jumps around wildly if you move suddenly, shake leads, touch the apparatus, or otherwise provide any change to the grounding of the equipment or the mechanical stability of the optics.

When you have a reasonably stable signal of 50 to 500 pA, for an applied voltage of positive 4 V, gently adjust the monochromator grating a small amount. The photocurrent signal should rapidly decrease. Adjust it back, until you find the signal again, pass it, and the signal drops. This is the process used to align the optics for the (invisible) uv lines. Practice gently going past the line in both directions, monitoring the photocurrent signal and the dial reading, until you are confident that you can align the monochromator without actually looking at the green line with an index card inside.

Determine an appropriate procedure and collect data as a function of both positive and negative accelerating voltages. You want to first scan the whole range ± 4 V for a course spacing for voltage.

Plot your data as you take it. You should be able to "eyeball" the approximate the value for the stopping voltage. Once you have located the stopping voltage, take data every 0.1 V in a region of ± 1 V around it.

Repeat your data collection for both the yellow and blue mercury emission wavelengths. Note that many observers cannot distinguish, by eye, which is the blue or the violet. You have to trust your dial and signal method to find these lines, since your eye may mislead you as to which one is which. Note that the grating angle correlates directly with the wavelength, so that cranking the grating adjustment will increase (or decrease) wavelength monotonically; the lines must come in order.

Week 1 Check in

For one of your colors (I suggest blue since the signal is very strong) attempt either analysis 2 or 3 from the "Determining h/e from the stopping potential V_s" analysis section below. Get the stopping potential V_s with its uncertainty for your color of choice.

Week 2: Intensity Dependence of V_s and UV lines

Intensity Dependence of V_s

Classical physics predicts that the energy of light depends on its intensity, while quantum theories predict that the energy of the light depends only on its frequency or wavelength. In order to determine the validity of the quantum theory, the wavelength of light is fixed while its intensity is varied.

Optical density D is defined by

$$D = \log_{10}(I_o/I_\mathrm{T}) \tag{5}$$

where I_o is the incident intensity and I_T is the transmitted intensity through the neutral density filter. "Neutral density" means that the reduction in intensity is uniform across the spectral range of wavelengths. We assume that the photocurrent observed is directly proportional to the intensity. So we can use I to mean intensity and observed photocurrent current, interchangeably.

Make sure the UV filter is still be installed on the Mercury lamp. Align the monochromator for the violet line. Using the provided neutral density filter set, design and perform an experiment to determine if the intensity of light falling on the photocell has an impact on the stopping voltage. Place a neutral density filter holder in the beam path between the light source and the entrance slit to the monochromator. Use at least three different intensities (one set without the filter and two with different filters). Because the neutral density filters work on a log scale, do not go above $D = 1$.

When analyzing the stopping potential of each wavelength, you can just use the violet data without the filter.

UV Lines

Next you will measure the photocurrent behavior using the mercury ultraviolet lines. Turn off the mercury lamp. Remove the UV filter; this is the disk mounted in the output window of the lamp with several Allen set screws.

Do not turn on the lamp without UV protection! This lamp produces extremely strong UV radiation that will burn your skin and cause permanent retina damage to your eyes!

Slide the plexiglas tube into the larger tube permanently mounted at the inlet to the monochromator. Mount the the other end of the tube in the lamp output with the Allen set screws. Have your instructor verify that this is mounted correctly and will provide good UV protection. Then turn on the lamp.

Find the UV lines using the dial and signal only. Take data for the two UV lines. It may take part of the second lab period to complete all six lines.

Analysis

Determining h/e from the stopping potential V_s

For each wavelength, plot photocurrent, which is proportional to light intensity, as a function of voltage. Determine the stopping voltage. For actual data, there is a small negative current for voltages below the stopping voltage; instead of zero photocurrent, a weak negative current exists. This is due to stray light hitting the anode and causing photoelectrons to be emitted from it; essentially, the tube is running backwards and anode is serving as cathode and vice versa. If the system is working well and optically aligned properly this reverse current is quite small.

For each wavelength, determine the stopping potential V_s. This is the kink or inflection point in the photocurrent versus voltage curve. The stopping potential can be determined three ways.

1. One can visually estimate the voltage at which the curve abruptly changes. This isn't a very "rigorous" method, but is a good check that the other methods give reasonable results.

2. The method of intersecting tangents. To do this, fit tangents to the curve both above and below the stopping potential, and where the tangents intersect is V_s. You will have to chop up your data to do this, so check the `Samplecode.py` on MyCourses for how to use the `np.where` function.

3. A numerical point by point derivative, where that the slope of the curve between each two successive data points is determined. You can either do this by calculating a point-by-point derivative in a spreadsheet, or by using the `np.gradient()` function in Python. With either method make sure you know how to calculate an uncertainty on the value.

   When these derivatives are plotted as a function of voltage, there is an abrupt change in derivative (slope) at the stopping potential V_s.

   This data should look like a sigmoid. A sigmoid (also called a s-curve or the logistic function) is a step shaped curve that is used to model data that behaves in a step wise manner. Similar to the Gaussian used elsewhere in this class, it is often used for phenomological reasons (that is we use it because it fits the data). If you would like to fit a sigmoid its function is given in Equation 6

$$S(x) = \frac{L}{1 + e^{-k(x-x_o)}} \tag{6}$$

   where L represents the height of the sigmoid, k reflects the steepness of the curve, and x_o is the location of the center of the curve (which is what we are interested in).

   Note: If you take a second numerical derivative of your data the result should look like a sharp peak. This should be reminiscent of a delta function. Coincidentally, the derivative of a step function (an infinetly sharp sigmoid) is in fact the delta function!

Determine stopping potential using each of these methods for at least two wavelengths and decide which method works well for you. Explain your choice (other than methoid 1 for obvious reasons). Use one method to determine the stopping potential for all wavelengths. Tabulate your results, including uncertainties. Compute the frequencies of the light and add those to your table.

Consider Equation 4. Since V_s in Equation 4 is a reverse voltage, it is the magnitude of the (negative) voltage you measured. Plot V_s versus frequency; find h/e, ϕ, and their uncertainties. Compare to the known values. Discuss any possible systematic errors you may have identified.

Only three points for plotting Vs vs Frequency?

Intensity Dependence of V_s

From your violet data, determine whether the energy of the light depends on its intensity. Or in other terms, how does the intensity of the light affect the analysis of your data? There are similar (but different) ways to accomplish this. Pick whichever method makes sense to you.

1. One thing you can do, is renormalize your measured intensities (photocurrents) by computing I_o from I_T for each scan where a filter was used, using Equation 5. In other words you are calculating a "theoretical" value for the intensity of the light before it passed through the filter. In an ideal world (where you know the exact value for D) every data set should have the same I_o.

2. The other method is to experimentally normalize each data set. Normalzing data involves taking a data set and dividing every value in that set by the largest value found in the data. That way the data peaks at "1". If you do this for every data set (dividing each by its own largest value) it becomes possible to quantitatively compare them. This method is useful if you don't have an exact equation to renormalize the data, or if you are suspicous that you don't have accurate values for something in the system (here that would be the values of the optical densities of each filter).

Plot the normalized data, I_o vs voltage, for all three violet scans, on the same plot. If all the data fall on one curve, it is conclusive proof that changing the intensity of light changes the magnitude of the photocurrent in direct proportion, but the energy of the emitted photoelectrons is unchanged. In other words, intensity determines the number of ejected photoelectrons, but not their energy.

Appendix A: Mercury Vapor Lamp Discharge lines

These values are approximate, rounded to the nearest angstrom. In reality there are some lines that are very close to each other (for example there are three yellow lines) but our equipment is not sensitive enough to distinguish these from each other.

color	λ (Å)
uv	3131
uv	3655
violet	4047
blue	4358
green	5461
yellow	5779