PHYS 330: The Photoelectic Effect and determination of Planck's constant

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I. INTRODUCTION

The objectives of this experiment are to study the photoelectric effect and use it to determine the energy-to-frequency relation of a photon, which is related by Planck's constant.

The photoelectric effect is the emission of electrons from the surface of a metal when electromagnetic radiation (such as visible or ultraviolet light) shines on the metal. At the time of its discovery, the classical wave model for light predicted that the energy of the emitted electrons would increase as the intensity (brightness) of the light increased. It was discovered that it did not behave that way. Instead of using the wave model, treating light as a particle (photon) led to a more consistent explanation of the observed behavior.

Historically, the photoelectric effect played a central role in the birth of quantum physics. In 1905, Albert Einstein proposed that light comes in discrete quanta (photons), and that the energy of the emitted electrons depends on the frequency of the light rather than its intensity. This radical idea challenged the classical wave picture and laid the foundation for quantum theory. However, the scientific community remained skeptical until Robert Millikan, after a decade of painstaking experiments with carefully designed apparatus, confirmed Einstein's linear relation between photon frequency and electron energy. It was only after this experimental verification that Einstein was awarded the 1921 Nobel Prize for his explanation of the photoelectric effect. Millikan himself later received the 1923 Nobel Prize.

The apparatus you will use in this lab is a modern descendant of these classic experiments In this lab, you will study the effect of varying the light intensity and the light's frequency on the energy of the emitted electrons and the magnitude of the photo-current (the rate of photons). You will use this to determine Planck's constant.

Reading: Knight 4$^{\text{th}}$ edition with Modern Physics: (1) Chap 37.6 The Discovery of the Nucleus, The Electron Volt, and (2) Chap 38.1 The photoelectric effect.

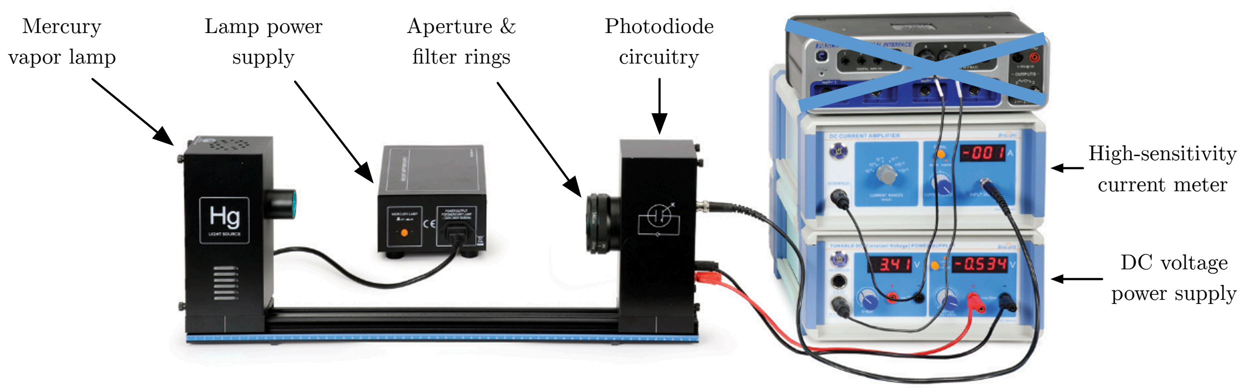

FIG. 1. The PASCO Scientific Photoelectric effect apparatus used in this lab. (We won't be using the crossed-out electronic unit.)

II. THEORY

Einstein's quantum physics prediction is that light behaves as individual energy packets called photons. The energy of a photon is proportional to the "frequency" f of the electromagnetic radiation:

$$E_0 = hf \ . \tag{1}$$

The constant of proportionality h is Planck's Constant.

The electrons in a metal are bound inside a potential energy well (see Figure 2) with depth ϕ, which is also called the "work function" of the material. The potential well is formed by the metal's atomic lattice structure via. condensed matter physics effects. When light shines on the metal, the energy of the photon is absorbed in its entirety by the electron. Now, if the electron has energy greater than ϕ (i.e. $E_0 > \phi$), it *can* escape the metal. By energy conservation, the *maximum* kinetic energy of the escaped electron (also commonly called a "photoelectron" to indicate its origins) just outside the metal $K_{\max}$ is given by

$$K_{\max} = E_0 - \phi \ . \tag{2}$$

This is the maximum kinetic energy because, after absorbing the photon, the electron can loose some or all of its energy to the metal lattice (for example, as heat) before escaping the metal. If $E_0 <= \phi$, then no electrons can make it out of the metal.

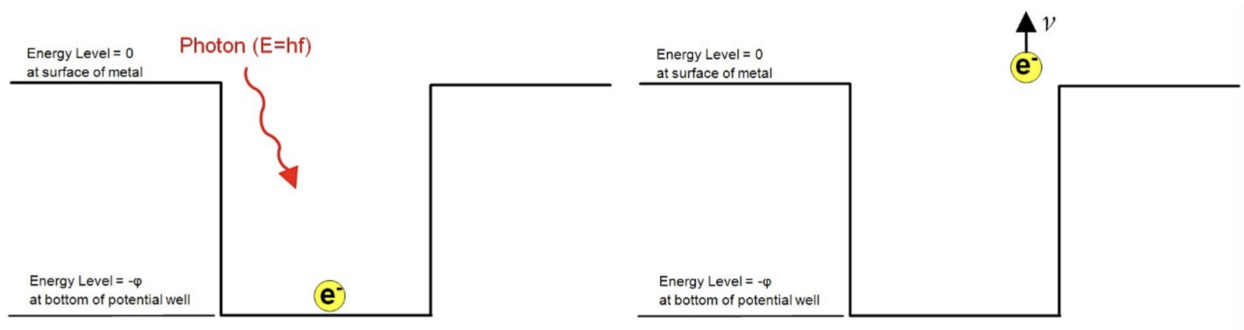

FIG. 2. Schematic of the "potential well" the electron finds itself in when inside a metal. The potential shown is in the absence of an electric field. (Left) A photon strikes the surface of the metal. (Right) An electron inside the metal absorbs the photon's energy, which is larger than the potential well depth, is able to escape the metal with speed v, and therefore has kinetic energy.

For a single photon energy E_0 incident on the metal, the photoelectrons will have a distribution of kinetic energies. In this experiment, we do *not* measure the kinetic energy of the photoelectrons; instead, we only measure their *maximum* kinetic energy. This is done by applying a potential difference ΔV across the photodiode, where the cathode of the diode is the metal plate the photons are incident on, and thus the source of photoelectrons, and the anode is the photoelectron collector plate. Following the convention for the sign of ΔV shown in Figure 3, a positive ΔV (i.e., positive voltage on the anode) is able to attract photoelectrons. Photoelectrons that reach the collector plate continue to flow to the positive terminal of the battery/power supply and thus forms a measurable current in the ammeter.

However, if ΔV is negative (i.e., negative voltage on the anode), photoelectrons inside the gap of the photodiode are repelled by the anode. Only photoelectrons with kinetic energy greater than electric potential barrier can make it to the anode. When ΔV is negative, this is called the electron rejection mode. The maximum electron kinetic energy can be measured by adjusting ΔV from zero to greater magnitude until it is just great enough to barely stop all electrons from reaching the collector plate. That is, the current measured by the ammeter just barely reaches zero. The applied potential at which this occurs is called V_{stop}. (Note: we have dropped the ΔV notation by assuming the cathode is at 0 V.)

The maximum electron kinetic energy $K_{\max}$ is then equal to the potential energy corresponding to V_{stop}, which is the charge of the electron, denoted by e, multiplied by V_{stop}:

$$K_{\max} = eV_{\text{stop}} \tag{3}$$

Using equations (1) and (2) in equation (3) gives:

$$eV_{\text{stop}} = hf - \phi \ , \tag{4}$$

which can be rearranged to:

$$V_{\text{stop}} = \left(\frac{h}{e}\right) f - \frac{\phi}{e} \tag{5}$$

Therefore, a plot of V_{stop} versus f will yield a straight line with a slope of h/e and a vertical-intercept of ϕ/e. Setting the voltage equal zero and solving equation (5) for the frequency gives the horizontal-intercept on the V_{stop} versus f graph. Light must have a frequency greater than this to cause electrons to be emitted from the metal. This is called the cutoff frequency, where $f_{\text{cutoff}} = \phi/h$.

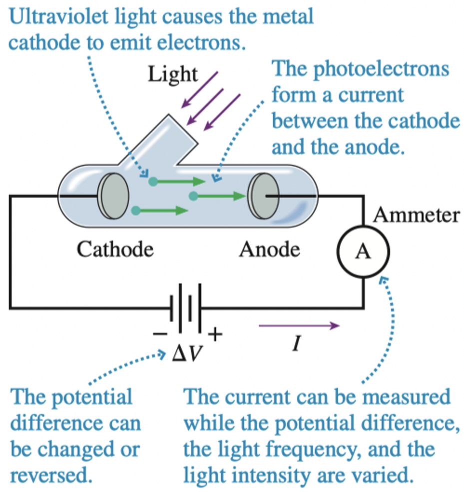

FIG. 3. The photoelectric effect circuit from Knight. The convention for the potential difference across the photodiode shown is positive ΔV for photoelectron attraction and negative ΔV for photoelectron rejection mode.

III. PRE-LAB QUESTIONS

1. What are the units of electrical current in base S.I units? Describe what an electrical current is in terms of this unit.

2. In figure 3, the electrons are flowing clockwise. Which direction is the current flowing (i.e., as read by an ammeter)?

3. In figure 3, if the potential difference of power source is negative (i.e. photoelectron rejection mode), what is the direction of the force an electron feels between the cathode and anode due to the electric field?

4. What is the expression for the potential energy of an electron in an electric field?

5. How is the unit of the electron-volt eV (a unit for energy) defined? What is its value compared to the SI unit for energy, which is Joules?

6. When in the electron rejection mode, if a potential difference of 1 V is applied across the photo-diode, what is the minimum kinetic energy an electron must have, in units of eV, when first leaving the cathode to reach the anode?

IV. EXPERIMENTAL SETUP

1. Mount the mercury lamp and the photodiode case on the track as shown in Figure 1.

2. Connect the power cord from the Mercury Light Source enclosure into the receptacle labeled "POWER OUTPUT FOR MERCURY ˜220V" on the Mercury Lamp Power Supply. Connect the Mercury Lamp Power Supply to an outlet.

3. Turn on the Mercury Lamp and **let it warm up for at least 10 minutes.** Leave the cover on the lamp and **avoid looking directly into the lamp.**

4. The outer metal housing of the Mercury Lamp can get hot. Avoiding touch it as this can burn you. You may be given a small fan to help cool the outer housing to avoid burns. In this case, wait at least 10 minutes after turning both the lamp and fan on and do not move the fan between measurements.

5. *Do not connect any cords to the photodiode yet.*

6. *On the DC Current Amplifier, turn the CURRENT RANGES switch to the* 10^{-13} A *range.*

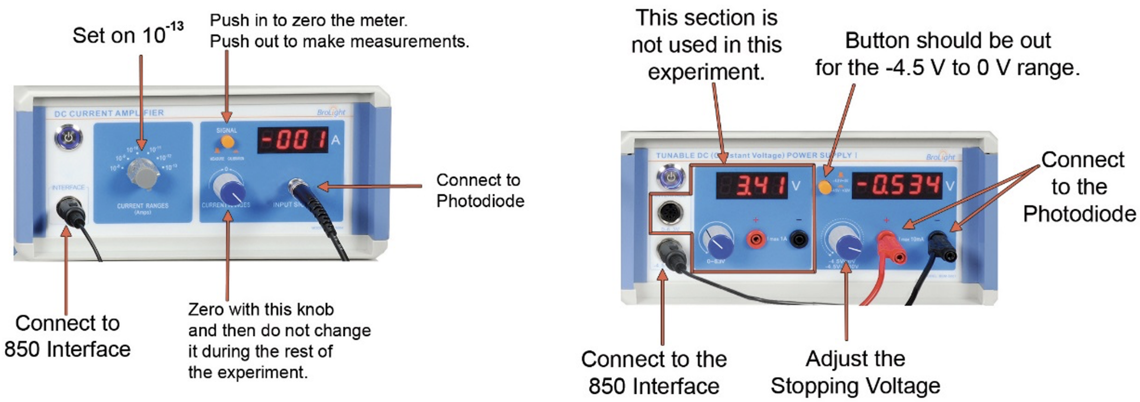

FIG. 4. (Left) The current amplifier settings. (Right) The DC Power Supply Settings. Note: these are just starting values and should be adjusted to match your conditions.

7. *With the light-blocking plug inserted into the Mercury Lamp, press the Calibration button IN. Turn the knob until the meter reads 000 A (see Figure 4). (In your lab report, answer what effects are we trying to counter when we zero the current meter.)*

8. Press the Calibration button to put it in the OUT position for measuring.

9. NOTE: For the rest of the experiment, do not change the knobs on the DC Current Amplifier.

10. You should check zero of your photocathode periodically by inserting the light-block plug into the mercury lamp.

11. On the DC Power Supply, make sure the button is out to select the -4.5 V to 0 V range (see Figure 4).

12. Connect the cables to the photodiode (see Figure 5)

    (a) *Connect the special BNC-plug-to-BNC-plug cable between the port marked "K" on the Photodiode enclosure and the BNC jack on the DC Current Amplifier.*

    (b) *Connect the red banana-plug patch cord between the port marked "A" on the Photodiode enclosure and the red banana jack on the right side of the DC Power Supply.*

    (c) Connect the black banana-plug patch cord between the black banana jack on the Photodiode enclosure and the black banana jack on the right side of the DC Power Supply.

13. During the experiment, you will be changing the aperture and the filters (see Figure5).

    (a) To change the aperture, pull out on the Aperture Ring and rotate it until it clicks into place.

    (b) To change the filter, do not pull out; just rotate the Filter Ring until it clicks into the next position.

V. MEASURING THE STOPPING VOLTAGE VERSUS LIGHT FREQUENCY, AND DETERMINING PLANCK'S CONSTANT, h

1. Select the 8 mm aperture and the 365 nm filter on the photodiode and use the 10^{-13} A range of the current amplifier.

2. Adjust the VOLTAGE ADJUST knob on the DC Power Supply until the current on the ammeter **just reads** zero. This voltage value is your stopping voltage V_{stop}. This is the voltage required to *just* stop all the photoelectrons from reaching the anode. The data table in your lab book should look something like Table I.

3. Making a V_{stop} is simple, but evaluating its uncertainty, in particular the uncertainty when a value has "just reached zero" in the presense of fluctuations, is more difficult. To help you justify your estimated uncertainty in determining your V_{stop} value, record the measured current for 4 ΔV values on *either side* of V_{stop}. The values on one side should clearly have reached zero current; the values on the other side should clearly be well above

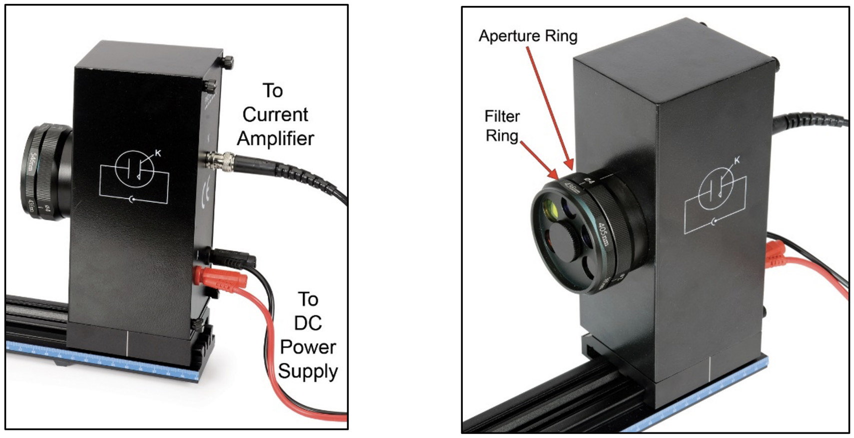

FIG. 5. (Left) Photodiode Connections. (Right) Filter Ring and Aperture Ring on Photodiode.

zero and increasing. Make a plot of this with error bars in each of your current values (estimated based on your uncertainty due to the current fluctuations). Use this plot to determine a possible range of ΔV values where the current *"just reaches zero"*.

4. Rotate the filter ring to the next longer wavelength filter, and adjust the VOLTAGE ADJUST knob until the current on the ammeter is zero for your next V_{stop} measurement

5. Repeat the above procedure (determining V_{stop} and its uncertainty) for all the different wavelength filters.

6. Put the cover back onto the Mercury Light Source.

Wavelength λ (nm)	Calculated light frequency using λ (units:)	Measured V_{stop} with estimated measurement uncertainty (V)
365	(Write this in your labbook)	(Write this in your labbook)
405	(Write this in your labbook)	(Write this in your labbook)
436	(Write this in your labbook)	(Write this in your labbook)
546	(Write this in your labbook)	(Write this in your labbook)
577	(Write this in your labbook)	(Write this in your labbook)

TABLE I: Sample data table for V_{stop} measurements for the different filters.

1. Data analysis steps

1. Graph the stopping voltage versus frequency and apply a linear fit to the data. Include the graph with your report.

2. Determine Planck's constant with uncertainty from the slope of the line.

3. Calculate the discrepancy between the result and the accepted value (you can look for Planck's constant online).

4. Find the work function for the metal in units of eV from your fit.

VI. MEASURING STOPPING VOLTAGE VS. LIGHT INTENSITY

To investigate the effect that light intensity has on the energy of the emitted electrons, the intensity is varied by changing the aperture, while keeping the wavelength constant. We will do this for the 436 nm filter only.

1. Create a data table in your labbook with columns: (1) aperture diameter, (2) Stopping voltage V_{stop}.

2. Remeasure the stopping voltage for the 436 nm filter and 8 mm aperture. (Repeat the uncertainty determination.)
3. With the cover on the mercury light source, change the aperture from the 8 mm to 4 mm aperture on the photodiode tube.
4. Uncover the mercury light source and determine V_{stop} for this aperture size.
5. Change the aperture to 2 mm and find the stopping voltage again.
6. Make a plot, with error bars, of the stopping voltage versus **aperture area.** The rate of light reaching the cathode should be proportional to the aperture area.
7. Did the stopping voltage change as the rate of light (or rate of photons) striking the photocathode increase? You can do this quantitatively by fitting your data with a straight line and seeing if the fitted slope is consistent with zero.
8. What does the result indicate about the relationship between the kinetic energy of the electrons and the light intensity? Make quantitative arguments where possible.

VII. PHOTOTUBE CHARACTERISTICS: THE I VS ΔV CURVE

The "I-V curve" is a very common way to characterize electronic components. For example, it can be used to check if a component obeys Ohm's Law. You will do this for the phototube for two different aperture sizes.

1. With the cover on the mercury light source, change the aperture to 2 mm aperture on the photodiode tube and put on the 436 nm filter.
2. On the DC Power Supply, push the range button in to set the voltage range to –4.5 to 30 V. Set the voltage to -4.5 V to begin with.
3. Change the Current Range switch on the DC Current Amplifier to 10^{-12} A and zero it again.
4. Uncover the mercury light.
5. Make measurements of the current I vs different applied ΔV Between -4.5 V to 3.0 V, do this in 0.5 V increments. For > 5 V up to 30 V, you can do this in 2 V increments. You should have around 30 current measurements.
6. You may need to change the current range for these measurements if the current becomes too high for a given range. In this case, clearly indicate in your lab book when you have changed an instrument's setting.
7. You do not need to make these measurements very precisely. You're just trying to obtain the general behavior of the device.

	Measured current I (436 nm)	
Applied ΔV	Aperture diamter: 2 mm	8 mm
- 4.5 V	(labbook)	(labbook)
- 4.0 V	(labbook)	(labbook)
...	(labbook)	(labbook)
3.0 V	(labbook)	(labbook)
5 V	(labbook)	(labbook)
7 V	(labbook)	(labbook)
....	(labbook)	(labbook)
29V	(labbook)	(labbook)

Make plots of your I vs ΔV data for the two apertures on the same axes. There is no data fitting required. Comment on the shape of these curves and what you expect (hint: read the theory in Knight).

Comment on what characteristics of your I-V curve show that the phototube behaves like a diode. (This is why this device is often referred to as a "photodiode".) A photodiode can be used as a light sensor. Before the invention of semiconductors (e.g., silicon), these "vacuum tube diodes" were used as diodes and transistors in electronic circuits. This is why the early computers were the size of an entire room. Semi-conductor-based diodes and transitions can now be made ~ 10 nm in size with silicon.

VIII. FINAL QUESTIONS FOR YOUR LAB REPORT

1. If the light shining on the metal becomes brighter, will the kinetic energy of the emitted electrons increase?
2. If the light shining on the metal becomes brighter, will the number of electrons being emitted per second (the photo-current) increase?
3. If the frequency of the light shining on the metal is increased, will the number of electrons being emitted per second (the photo-current) increase?
4. If the frequency of the light shining on the metal is increased, will the kinetic energy of electrons being emitted increase?
5. Will any color (frequencies) of light cause electrons to be emitted by the metal?
6. If light with the same frequency and same intensity shines on two different metals with different work functions, will both metals emit electrons?
7. Will these electrons have the same kinetic energy?
8. Will the photo-current be larger for the metal with the smaller work function?
9. How did the current change when the light intensity was increased?
10. Was the stopping voltage different for different light intensities? How does the kinetic energy of the electron depend on the light intensity?