Physics 197 Lab 9: Photoelectric Effect

Equipment:

Item	Part #	Qty per Team	# of Teams	Total Qty Needed	Storage Location	Qty Set Out	Qty Put Back
Hg Light Source	OS-9286 A	1	6	6			
h/e Apparatus	PASCO AP-9368	1	6	6			
Filter Set yellow, green, 5 ND lines	PASCO AP-9368	1	6	6			
Digital Multimeter and probes	Extech	1	6	6			
Lens/Grating Assembly	PASCO AP-9368	1	6	6			
Timer		1	6	6			

Layouts:


Figure 1, Experiment A, B, h/e Apparatus

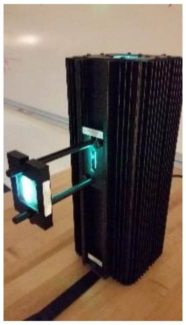


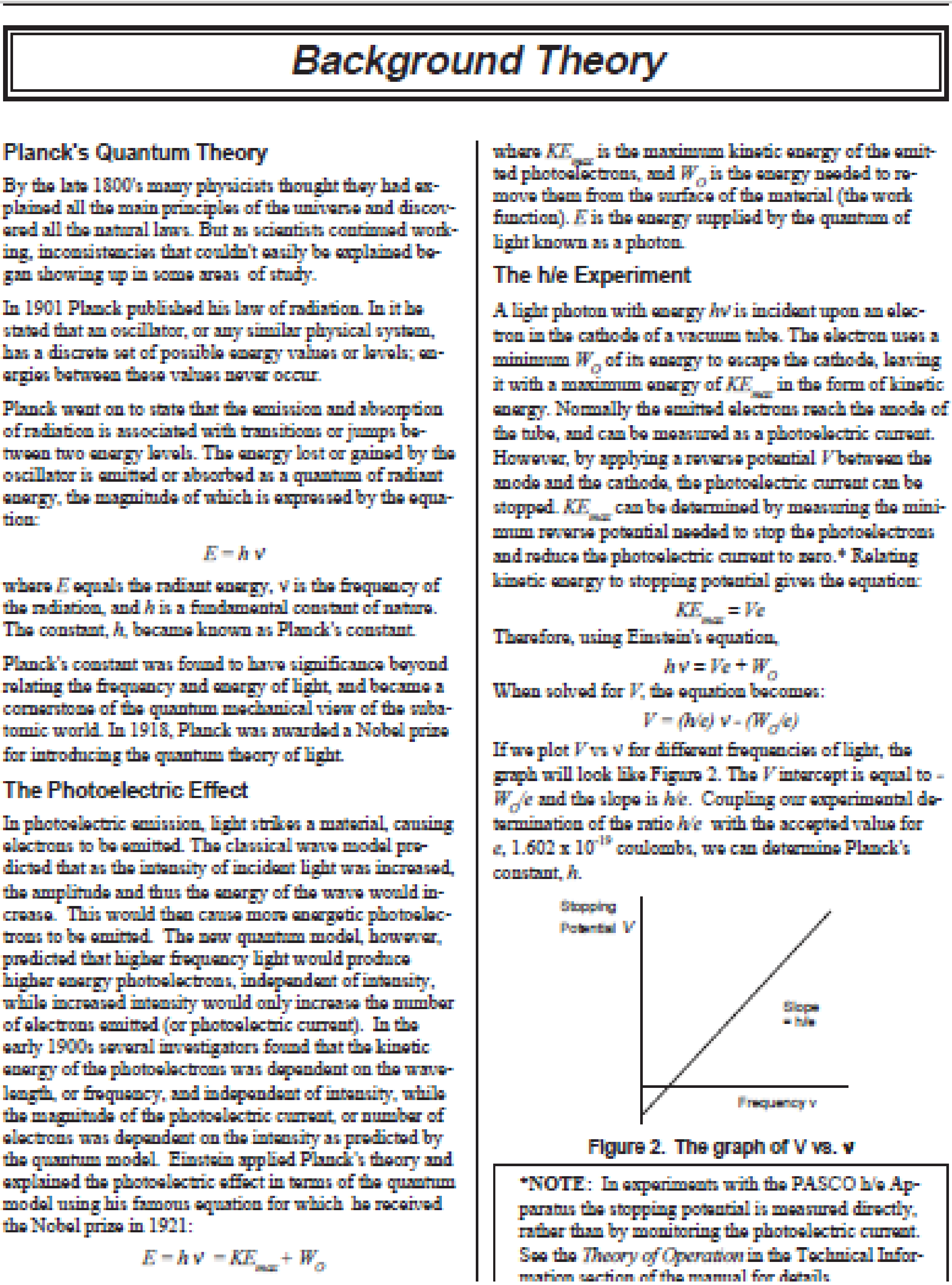
Figure 2, Mecury Lamp


Figure 3, Receiver, Hg Green Line


Figure 4, First and Second Order Spectrum from Mercury Lamp

Summary:

In this lab, students will investigate the photoelectric effect using an apparatus designed to obtain a value for h/e (Planck’s constant divided by the electron charge). Light from a mercury lamp is separated with a diffraction grating and focused onto a slit. The yellow, green, blue, violet and ultraviolet transitions (seen in figure 4 in first and second order) have different energies, and therefore cause electrons to be emitted from a photocathode with different kinetic energies. These kinetic energies, the difference between the photon energy and the photocathode work function, are determined from the stopping potential. (This is determined indirectly by having a capacitor charge up from the photoelectrons, and measuring the steady state capacitor voltage). Students should find that the stopping potential is a strong function of the photon energy, but that changing the intensity of the light has a very small effect on the observed stopping potential.



Background Theory

Planck's Quantum Theory

By the late 1800's many physicists thought they had explained all the main principles of the universe and discovered all the natural laws. But as scientists continued working, inconsistencies that couldn't easily be explained began showing up in some areas of study.

In 1901 Planck published his law of radiation. In it he stated that an oscillator, or any similar physical system, has a discrete set of possible energy values or levels; energies between these values never occur.

Planck went on to state that the emission and absorption of radiation is associated with transitions or jumps between two energy levels. The energy lost or gained by the oscillator is emitted or absorbed as a quantum of radiant energy, the magnitude of which is expressed by the equation:

$$E = h\nu$$

where E equals the radiant energy, ν is the frequency of the radiation, and h is a fundamental constant of nature. The constant, h, became known as Planck's constant.

Planck's constant was found to have significance beyond relating the frequency and energy of light, and became a cornerstone of the quantum mechanical view of the subatomic world. In 1918, Planck was awarded a Nobel prize for introducing the quantum theory of light.

The Photoelectric Effect

In photoelectric emission, light strikes a material, causing electrons to be emitted. The classical wave model predicted that as the intensity of incident light was increased, the amplitude and thus the energy of the wave would increase. This would then cause more energetic photoelectrons to be emitted. The new quantum model, however, predicted that higher frequency light would produce higher energy photoelectrons, independent of intensity, while increased intensity would only increase the number of electrons emitted (or photoelectric current). In the early 1900s several investigators found that the kinetic energy of the photoelectrons was dependent on the wavelength, or frequency, and independent of intensity, while the magnitude of the photoelectric current, or number of electrons was dependent on the intensity as predicted by the quantum model. Einstein applied Planck's theory and explained the photoelectric effect in terms of the quantum model using his famous equation for which he received the Nobel prize in 1921:

$$E = h\nu = KE_{max} + W_O$$

where KE_{max} is the maximum kinetic energy of the emitted photoelectrons, and W_O is the energy needed to remove them from the surface of the material (the work function). E is the energy supplied by the quantum of light known as a photon.

The h/e Experiment

A light photon with energy $h\nu$ is incident upon an electron in the cathode of a vacuum tube. The electron uses a minimum W_O of its energy to escape the cathode, leaving it with a maximum energy of KE_{max} in the form of kinetic energy. Normally the emitted electrons reach the anode of the tube, and can be measured as a photoelectric current. However, by applying a reverse potential V between the anode and the cathode, the photoelectric current can be stopped. KE_{max} can be determined by measuring the minimum reverse potential needed to stop the photoelectrons and reduce the photoelectric current to zero.* Relating kinetic energy to stopping potential gives the equation:

$$KE_{max} = Ve$$

Therefore, using Einstein's equation,

$$h\nu = Ve + W_O$$

When solved for V, the equation becomes:

$$V = (h/e)\,\nu - (W_O/e)$$

If we plot V vs ν for different frequencies of light, the graph will look like Figure 2. The V intercept is equal to $-W_O/e$ and the slope is h/e. Coupling our experimental determination of the ratio h/e with the accepted value for e, 1.602×10^{-19} coulombs, we can determine Planck's constant, h.

Figure 2. The graph of V vs. ν

*NOTE: In experiments with the PASCO h/e Apparatus the stopping potential is measured directly, rather than by monitoring the photoelectric current. See the *Theory of Operation* in the Technical Information section of the manual for details.

PreLab:

The basic purpose of this week's lab is to show that photons of different wavelength λ have different energies (given by E=hf=hc/λ). A vacuum photodiode has a photocathode with a Work Function φ (denoted as W_0 in the copied discussion above). If photons with energy less than φ hit the photocathode, no electrons are given off. If photons with energy greater than φ hit the photocathode, electrons are given off with kinetic energy hf-φ. If a stopping voltage V given by eV=hf-φ is applied, these electrons will be stopped. In the experiment, the stopping voltage V for different wavelengths of light can be measured and plotted to determine -φ/e (y-intercept at 0 frequency) and h/e (slope of V/f). The intensity of the light should have no effect on the stopping voltage, only on the amount of current given off. The experiment attempts to show this in a somewhat indirect way (charging up an internal capacitor), and thus the stopping voltage you measure will have some (but hopefully slight) dependence on light intensity.

Look up the values of Planck's constant h and the electron charge e and record them in your notebook. Calculate the ratio h/e.

Make a plot of the expected stopping voltage as a function of photon frequency for the five Mercury lines used in the experiment assuming a PhotoCathode Work Function of 1.5 eV (electron volts). The work function for the actual photocathode used in the experiment will be different, and so you will make a similar plot of your data which should have about the same slope (your measurement of h/e) but a different y-intercept (your measurement of the photocathode Work Function/e). The wavelengths of the mercury lines being used are 578 nm (yellow), 546 nm (green), 436 nm (blue), 405 nm (violet) and 365 nm (ultraviolet).

Setup:

1. Assemble the Apparatus as in Figure 1.

2. Turn on the mercury vapor lamp and let it warm up for at least a minute. Leave it on for the duration of the lab, but if it is turned off accidentally, leave it off for at least a minute before turning it back on. The coupling bar for the bottom angling apparatus slides up into the middle groove on the mercury lamp assembly.

3. The coupling bar for the bottom angling apparatus slides up into the middle groove on the mercury lamp assembly. The light apparatus at the top slides down in the outer groove. It needs to slide all the way so the slit lines up with the mercury vapor lamp. (See figure 2). The lens/diffraction grating assembly slides onto the posts of the light apparatus. The round lens faces towards the mercury vapor lamp, the square diffraction grating faces out. By sliding the lens/diffraction grating assembly on the posts, it should be possible to bring the merury lines into sharp focus where they are separated from each other (as in figure 4).

4. The receiver end is lined up to individual mercury lines by changing the angle on the angling apparatus and by rotating the receiver in its holder. Do not tighten the set screw until the receiver is aligned. Light needs go go through both the first and second slits in the receiver apparatus, which is seen by rotating the light baffle (barrel shaped tube) out of the way (as in figure 3) in order to expose the interior. Rotate the baffle back into place when the receiver is aligned. Note: Each new light band may require recalibration of the receiver by rotating the barrel assembly. As the angle changes, the amount of light coming through the photocathode hole varies.

5. When using the yellow line, the yellow filter is used to block out any higher energy light from the lamp or in the room. (Room lights should be turned way down for this experiment). When using the green line, the green filter is used. The ND (Neutral Density) filter bars are used for the charging time experiments to vary the light intensity in a known manner.

6. Attach the Digital Multi-Meter to the output of the receiver assembly, and make voltage measurments using the 2 V DC setting.

7. Perform a voltage check by connecting the negative lead to ground. Place the positive lead in the positive battery test terminal and verify a magnitude greater than +6 VDC. Remove the positive lead and insert into the negative battery test terminal and verify a magnitude greater than -6 VDC.

8. Record the model number of the PASCO assembly in your notebook.

Experiment A: Stopping Potential and Charging Time

1. Adjust the h/e Apparatus so that only the yellow color falls upon the opening of the mask (use the first order of the grating, the part where the colors are closer together). Magnetically attach the yellow filter to the mask.

2. Place the Variable Transmission Filter in front of the White Reflective Mask (and over the colored filter) so that the light passes through the section marked 100% and reaches the photocathode.

3. Once the voltage is stable (has not changed for more than 30 seconds), record the DMM voltage (which is the stopping potential) in a table. Press and hold the instrument discharge button. Release the button and start a timer simultaneously.

4. Observe how much time is required to return to the recorded voltage using the timer. Record this time in your table. Note: It should take at least 15 seconds to verify the voltage has returned to a stable value.

5. Move the Variable Transmission Filter so that the next section is directly in front of the incoming light.

6. Repeat Steps 3-5 until you have tested all five sections of the filter.

7. Repeat the procedure using the blue color from the spectrum, this time without the yellow filter.

Analysis

1. Describe the effect that passing different amounts of the same colored light through the Variable Transmission Filter has on the stopping potential and thus the maximum energy of the photoelectrons, as well as the charging time after pressing the discharge button.

2. Describe the effect that different colors of light had on the stopping potential and thus the maximum energy of the photoelectrons.

3. Defend whether this experiment supports a wave or a quantum model of light based on your lab results.

4. Explain why there is a slight drop in the measured stopping potential as the light intensity is decreased.   **NOTE:** While the impedance of the zero gain amplifier is very high ($10^{13}\Omega$), it is not infinite and some charge leaks off. Thus charging the apparatus is analogous to filling a bath tub with different water flow rates while the drain is partly open.

Experiment B: Determination of h/e

According to the quantum model of light, the energy of light is directly proportional to its frequency. Thus, the higher the frequency, the more energy it has. With careful experimentation, the constant of proportionality, Planck's constant, can be determined. In this lab you will select different spectral lines from mercury and investigate the maximum energy of the photoelectrons as a function of the wavelength and frequency of the light.

1. You can see five colors in two orders of the mercury light spectrum. Adjust the h/e Apparatus carefully so that only one color from the first order (the brightest order) falls on the opening of the mask of the phototube.

2. For each color in the first order, measure the stopping potential with the DMM and record that measurement in a table. Use the yellow and green colored filters on the Reflective Mask of the h/e Apparatus when you measure the yellow and green spectral lines. (It may be necessary to recalibrate the light band’s position within the photodetector assembly as described in setup step 4).

3. Move to the second order and repeat the process. Record your results in the table. (The second order spectrum may be brighter on one side than the other; use the brighter side).

Analysis

Determine the wavelength and frequency of each spectral line. (Note that the wavelengths are listed in the prelab). Plot a graph of the stopping potential vs. frequency. Determine the slope and y-intercept. Interpret the results in terms of the *h/e* ratio and the *φ/e* ratio. Calculate *h* and *φ*.

In your discussion, report your values and discuss your results with an interpretation based on a quantum model for light. Compare your value of h to the accepted value (provide a percent difference).

An example of the data which should be included in the graph is given below. This should be drawn carefully by hand including all 10 measured stopping potentials. The graph should be extended below y=0 to get the work function of the photocathode (divided by e) from the y-intercept.