

# Experiment 3: The Photoelectric Effect\*

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## Abstract

In this experiment, you will determine the value of Planck's constant and demonstrate that the experiment is consistent with the photon theory of light.

## 1 Introduction

In photoelectric emission, light strikes a material causing electrons to be emitted. The classical wave model of light predicts that as the intensity of incident light is increased, the amplitude and thus the energy of the wave increases. This then causes more energetic photoelectrons to be emitted.

In the early 1900s several investigators found that the kinetic energy of the photoelectrons was dependent on the frequency of the incident light and independent of its intensity, while the magnitude of the photoelectric current, or number of electrons was dependent on the intensity. In the end, it was Einstein's application of Planck's quantum model that explained the photoelectric effect (and earned Einstein the Nobel prize in 1921). The quantum model requires energy to come in "packets" or *quanta*. The amount of energy carried by a quantum is directly proportional to its frequency. Einstein described the photoelectric effect mathematically as,

$$E = h\nu = KE_{\max} + \phi. \quad (1)$$

Here, a light photon with energy  $h\nu$  is incident upon an electron in the cathode of a vacuum tube. The electron uses a minimum  $\phi$  of its energy to escape the cathode (this is the work function of the metal), 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<sup>1</sup>. Relating kinetic

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\*Adapted from *Instruction Manual and Experiment Guide for PASCO Scientific Model AP-9368 and AP-9369 h/e Apparatus*.

<sup>1</sup>In this experiment we will be measuring the stopping potential directly, rather than by monitoring the photoelectric current

energy to stopping potential gives the equation:

$$KE_{\max} = eV. \quad (2)$$

Then the stopping potential,  $V$ , can be written as:

$$V = \frac{h}{e} \nu - \frac{\phi}{e}. \quad (3)$$

If a plot  $V$  versus  $\nu$  is made for several different frequencies of light, the graph will be linear with a  $V$  intercept equal to  $-\phi/e$  and a slope of  $h/e$ . Coupling such an experimental determination of the ratio  $h/e$  with the accepted value  $e = 1.602 \times 10^{-19}$  C, Planck's constant,  $h$ , can be determined.

In this experiment, we will be investigating both the intensity and frequency dependence of the photoelectron energy  $KE_{\max}$ , as well as determining Planck's constant,  $h$ . In section 3.1 you will select two spectral lines from a mercury light source and investigate the maximum energy of the photoelectrons as a function of the intensity. In section 3.2 you will select different spectral lines and investigate the maximum energy of the photoelectrons as a function of the frequency of the light. You will then use this data to calculate  $h$ .

## 2 Equipment

$h/e$ Apparatus, (AP-9368)	$h/e$ Apparatus Accessory Kit, (AP-9369)
Mercury Vapor Light Source, (OS- 9286)	Digital voltmeter
Pasco Photometer	Computer with GPIB card

## 3 Procedure

Thoroughly read and understand the provided equipment manual *Instruction Manual and Experiment Guide for PASCO Scientific Model AP-9368 and AP-9369  $h/e$  Apparatus* (hereafter referred to as the *Manual*) before beginning this experiment.

Set up the apparatus as described in the "Equipment and Setup" section of the *Manual* (see Figure 1).

### 3.1 Dependence of $KE_{\max}$ on intensity

1. Adjust the  $h/e$  Apparatus so that only one of the spectral colors falls upon the opening of the mask of the photodiode. If you select the green or yellow spectral line, place the corresponding colored filter over the White Reflective Mask on the  $h/e$  Apparatus.
2. Place the Variable Transmission Filter in front of the White Reflective Mask (and over the colored filter, if one is used) so that the light passes through the section marked 100% and reaches the photodiode. Record the DVM voltage reading. Press the instrument discharge button, release it, and observe approximately how much time is required to return to the recorded voltage. DUE TO PREVIOUS STUDENTS' NEGLIGENCE OF THE EXPERIMENT, WE NO LONGER HAVE THIS FILTER.

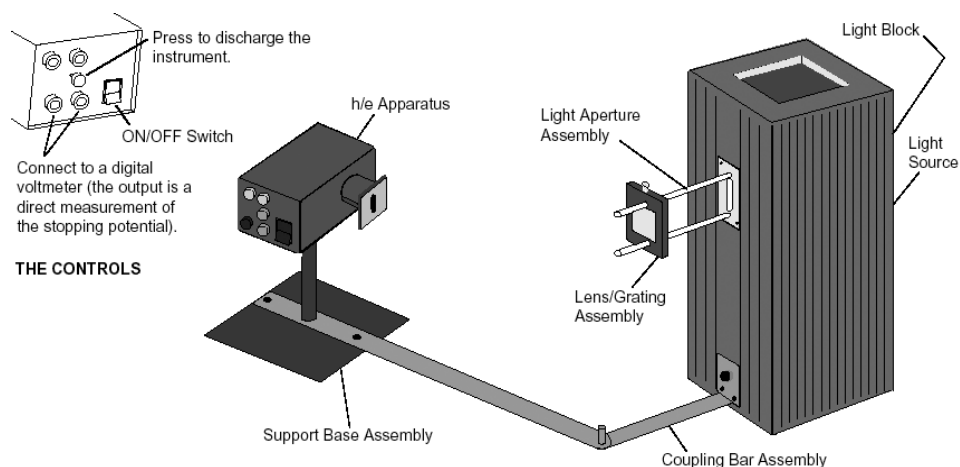


Figure 1: Equipment setup using a mercury vapor light source and the  $h/e$  apparatus.

3. Because we no longer have this filter, we must do something else. Take two polarizers from the optics kit (make sure to put these back!) As you rotate the two polarizers with respect to one another, the intensity will change. Since, this is not calibrated we must measure the relative intensity.
4. Using the Pasco OS-8020 high sensitivity photometer and fiber optic probe, measure the relative intensity of the light with this configuration of the polarizers and be sure to record it. The photometer's manual will explain how to make a relative measurement
5. Move the Variable Transmission Filter so that the next section is directly in front of the incoming light. Use the program "photoelectric effect dmm.exe" to measure the voltage and standard deviation. Record these numbers and the approximate time to recharge after the discharge button has been pressed and released.
6. Repeat step 5 until you have tested all five sections of the filter.
7. Repeat the procedure using a second color from the spectrum.

### 3.2 Dependence of $KE_{\max}$ on frequency

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 photodiode.
2. For each color in the first order, measure the stopping potential with the program "photoelectric effect dmm.exe". 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. Record the average DMM value, and the standard deviation.

Color	Wavelength (nm)
Yellow	578
Green	546.074
Blue	435.835
Violet	404.656
Ultraviolet	365.483

Table 1: The visible/near-visible mercury spectrum. All wavelengths except that for yellow are taken from the *Handbook of Chemistry and Physics, 46th ed.* from CRC Press. The yellow wavelength

## 4 Analysis

### 4.1 Wave Model vs. Quantum Model

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. For this, plot the average stopping potential with error bars and determine the slope of this line. Is your value for the slope consistent with zero? Do you have a good fit? Why or why not?
2. Describe the effect that different colors of light had on the stopping potential and thus the maximum energy of the photoelectrons.
3. Give a brief explanation (probably in your experimental section) describing how you measured the light intensity, as well as a brief explanation of GPIB (this is how the DMM is connected to the computer).

### 4.2 Determination of $h$

1. The wavelengths of the lines in the spectrum of mercury are given in Table 1. Determine the frequency of each spectral line. Plot a graph of the stopping potential vs. frequency using the uncertainty calculated from your data.
2. Determine the slope and  $V$ -intercept of the best-fit line of your data. Do you have a good fit? Why or why not? Interpret the results in terms of the  $h/e$  ratio and the  $\phi/e$  ratio. Calculate  $h$  and  $\phi$ .
3. In your discussion, report your values and discuss your results with an interpretation based on a quantum model for light.

## 5 Useful formulas

Sample Mean:

$$\bar{x} = 1/N \sum x_i \quad (4)$$

Sample variance:

$$s^2 = \frac{1}{N-1} \sum (x_i - \bar{x})^2 \quad (5)$$

Standard deviation:

$$s = \sqrt{(s^2)} \quad (6)$$

To find the best-fit to a straight line  $y_i = a + bx_i$  we want to minimize

$$\chi^2 = \sum \left[ \frac{1}{\sigma_i} (y_i - a - bx_i) \right]^2 \quad (7)$$

Solution for least-squares fit to a straight line  $y_i = a + bx_i$ .

$$a = \frac{1}{\Delta} \left( \sum \frac{x_i^2}{\sigma_i^2} \sum \frac{y_i}{\sigma_i^2} - \sum \frac{x_i}{\sigma_i^2} \sum \frac{x_i y_i}{\sigma_i^2} \right) \quad (8)$$

$$b = \frac{1}{\Delta} \left( \sum \frac{1}{\sigma_i^2} \sum \frac{x_i y_i}{\sigma_i^2} - \sum \frac{x_i}{\sigma_i^2} \sum \frac{y_i}{\sigma_i^2} \right) \quad (9)$$

$$\Delta = \sum \frac{1}{\sigma_i^2} \sum \frac{x_i^2}{\sigma_i^2} - \left( \sum \frac{x_i}{\sigma_i^2} \right)^2 \quad (10)$$

Variance in parameters

$$\sigma_a^2 = \frac{1}{\Delta} \sum \frac{x_i^2}{\sigma_i^2} \quad (11)$$

$$\sigma_b^2 = \frac{1}{\Delta} \sum \frac{1}{\sigma_i^2} \quad (12)$$

Is this a good fit? Use reduced  $\chi^2$ .

$\chi_\nu^2 = \chi^2 / (\text{numpoints} - \text{degrees of freedom})$ , for a straight line there are two degrees of freedom. Ideally,  $\chi_\nu^2 \sim 1$ . If reduced chi-squared is much greater than one you have most likely underestimated the measurement errors. If reduced chi-square is less than about 0.1, then you have overestimated the errors.