# Photoelectric Effect

## 1. Objectives

The objectives of this experiment is to show that that light behaves like a particle when it interacts with matter, such as electrons on a metal surface. The associated phenomenon, called the photoelectric effect, is used to estimate the value of **Planck's constant** $h$.

## 2. Theory

NOTE:  The theory used in this lab is covered in <u>Serway & Jewitt</u> "Principles Of Physics" Fourth Edition, Chapter 28.2, pages 942-947.

### 2.1  Introduction

Our first laboratory experiment demonstrated that visible light can exhibit interference and diffraction much like water waves.  Similar experiments performed in the mid-19th century convinced most physicists to abandon Newton's particle model of light and favor wave theories. However, near the start of the 20th century, new experiments found problems with the wave theories as well. One failure involved the **photoelectric effect:** when light strikes a metal surface, electrons can be emitted.  Two observations puzzled scientists. First, *the energy of the emitted electrons depends only on the wavelength of the incident light*. Second, *light above a certain wavelength produces no electrons at all.* Neither of these observations could be explained by wave theories of light.

In 1905 Einstein used the energy-quantization equation E = *hv* to explain the photoelectric effect.  This equation is attributed to physicist Max Planck who earlier proposed that radiation could only escape a blackbody cavity if its energy was an integer multiple of *hv,* where v is the frequency of the radiation and *h is* an experimentally-determined constant now known as "Planck's constant" with a value of 6.626 x 10$^{-34}$ J-s. Newer experiments confirmed Einstein's predictions, and in 1921 he was awarded the Nobel Prize primarily for his discovery of the law of the photoelectric effect.  Energy quantization became a fundamental part of quantum mechanics.

### 2.2  Quantum Mechanics and the Photoelectric Effect

According to quantum theory, light interacts with matter as discrete packets of energy called **quanta** (now called **photons**) and each quantum has a total energy E = *hv*. When a photon strikes an atom, it can transfer its energy to an electron.  Unlike classical theories, this energy transfer must be all-or-nothing: the electron gains *hv* of energy or none at all. If an electron in a metal gains enough energy from photon

capture, it can escape the metal entirely and be emiited as a **photoelectron**.

The formula E = $hv$ predicts that monochromatic  light should produce many electrons of exactly the same energy.  Because the photoelectron must spend some kinetic energy to escape the metal, the precise amount of energy lost this way depends on the photoelectron's path and reaches a minimum value at the surface of the metal.  This "minimum escape energy" is called the metal's **work function** $\Phi$ .  The kinetic energy of an electron released from near the surface is therefore $hv - \Phi$ .    Any other photoelectrons must have less than this energy.

In our experiment, a source of light strikes a metal surface called **photocathode**, producing a steady current of photoelectrons.  The electrons are ejected towards a detector which is kept at a negative electric potential -V relative to the metal.  The negatively-charged electrons are repelled by the negatively-charged detector. As the magnitude of the potential is increased, only the most energetic electrons can reach the detector.  When V is exactly strong enough to reduce the electron current to zero, it is called the **stopping potential.**  Conservation of energy therefore requires:

photoelectron energy - energy lost escaping  =  energy required to overcome repulsion

Using our notation:
$$hv \ - \ \Phi \ = \ e \, V_{STOP}$$

where $e$ is the electronic charge, 1.602 x 10$^{-19}$ coulombs, and $V_{STOP}$ is the magnitude of the stopping potential.  In terms of the wavelength $\lambda$ of the incident photon:

$$V_{STOP} \ = \ h \, c \, / \, (\lambda \, e) \ - \ \Phi \, / \, e$$

If $V_{STOP}$ is plotted as a function of  $c \, / \, (\lambda \, e)$,  Einstein's theory predicts a straight line with slope $h$ and y-intercept $(-\Phi / e)$ . *Thus we can find an empirical value for h and the work function Φ of our photocathode simply by measuring stopping voltages.*

Note that  $V_{STOP}$ depends only on the *maximum* kinetic energy of the emitted electrons. The mercury lamp in our experiment produces several wavelengths of light, but only the shortest-wavelength (and thus highest-energy) photons will determine stopping voltage. In this experiment, we will use four sources of light and use a computer or calculator to find the best linear fit to the data.


## 3. Experimental Details

### BEFORE YOU BEGIN: IMPORTANT PRECAUTIONS

*- Do not look directly at any of the lasers or the mercury arc lamp.  The mercury lamp produces ultraviolet radiation which is difficult to see but can damage your eye.*

*- The mercury arc lamp and photodetector are fragile, so please handle them carefully!*

In this experiment, four light sources (red, green, blue, ultraviolet) of known wavelengths are aimed at a metal surface, causing it to emit electrons.  The maximum kinetic energy of these electrons is then measured and plotted as a function of light frequency. Quantum theory predicts a linear relationship that does not depend on the intensity of the light source. From the best-fit line formed by these four data points, one determines experimental values for Planck's constant and the metal's workfunction.

### 3.1 Apparatus

The apparatus consists of the following components:

- photocathode/ammeter apparatus
- mercury arc lamp and power supply
- red laser
- green laser pointer
- digital voltmeter
- color filters

The photocathode and ammeter are contained in one unit labeled "Photoelectric Effect." No computers or software are necessary for the experiment, but it may be helpful to use a program such as Excel or Maple to analyze the data afterwards.

### 3.2 Calibrating the Equipment

Connect a digital voltmeter to the black and red plugs labeled "Voltage" on the photocathode/ammeter unit and turn both of them on.  Turn the "Voltage" knob on the photocathode fully counterclockwise.  The digital voltmeter should read within a few millivolts (mV) of zero.  (If it does not, check the connections and/or ask your TA.)

Calibrate the ammeter by turning the "Zero" knob until the ammeter reads zero.  If possible, dim or turn off any light sources that could potentially affect the photocathode.

### 3.3 Experiment: Ignore rest of this section  See revised procedure on data sheet

Turn on the mercury arc lamp and let it warm up for a minute or two.  Aim the lamp at the photocathode.  Move the lamp closer or farther away as necessary until the ammeter reads close to 10 nanoamps.  (1 nanoamp = $10^{-9}$ A)

Slowly turn the voltage knob clockwise to increase the stopping potential of the detector. If the digital voltmeter is connected properly, its readings will increase.  Watch the ammeter carefully and continue turning until the ammeter reads zero.  Record the voltmeter reading in the **V 1** column and **ultraviolet** row of the data sheet.
It can be difficult to determine exactly when the photoelectron current drops to zero, so the measurement should be repeated two more times.  First, move the lamp away from the detector and recalibrate the ammeter using the "Zero" knob, then measure the stopping voltage again and record the results in the **V 2** and **V 3** columns.  Write down the average of all three voltmeter readings in the **V (average)** column.

Now place the blue filter over the photocathode and repeat the process.  Be sure to recalibrate the ammeter with the "Zero" knob between each measurement.  You may need to move the lamp closer to the photocathode to produce a 10 nanoamp current.

The unfiltered mercury arc naturally produces several wavelengths of light, but only the shortest-wavelength components determine the stopping voltage, as discussed in the theory section.  The blue filter blocks ultraviolet light but allows 405 nm light to pass.

Once three readings have been taken, repeat the procedure with a green laser pointer and then the red laser from the Interference and Diffraction experiment.  Note that moving either laser farther away does not significantly reduce the intensity of light entering the photocathode, so you will have to find another way to produce a 10 nanoamp current!  If the laser is too powerful, try placing one or more strips of ordinary paper in front of the photocathode.  Be sure to hold the laser as steady as possible.

### 3.4 Analyzing Data

Calculate **c / ( λ*e )** for each wavelength of light and fill the values in on the data sheet.  Recall that the speed of light is **2.998 x 10$^8$ m/s** and the magnitude of the charge of an electron is **1.602 x 10$^{-19}$ coulombs**.

Plot the results of your experiments as four points on the chart included with the data sheet using **V (average)** as the y-axis and **c / ( λ* e )** as the x-axis.  The points should lie close to a straight line, as predicted by theory.  The slope of this line is predicted to be **h** (in joules) and the y-intercept is predicted to be **- Φ (**in electron-volts).

To determine the best fit, open Excel on the lab computer and select **Excel Workbook**.  Enter the x-values in the first column and the y-values in the second.  Click and drag to select all of the data, click on the **Chart Wizard** icon in the toolbar and choose **XY Scatter.**  Now select **Chart > Add Trendline** , select **Linear**, and click on **Options** and check **Add Equation to Chart**.  Then select **Format > Selected Data Labels** from the menus at the top**,** click on the **Number** menu, and select **Scientific** with two decimal places to change the display format.  The equation of best fit will appear on your graph.  Use this equation to find **h** and **Φ** and record them on the data sheet.

### 3.4  Evaluating Error

The error in the measurement of a number is defined ( **measured** - **correct** ) / **correct** .

The National Institute for Standards and Technology maintains a table of standard values for physical constants at http://physics.nist.gov/cuu/Constants/index.html .   At the time of this writing, *h* is listed in MKS units as:

### 6.626 068 96(33) x 10$^{-34}$  joule * second

where the (33) indicates that the last two digits "96" are uncertain to +/- 33 .  Assuming

the NIST result is correct, write the error in your measurement of *h* on the data sheet.


## 3.6  Just for Fun !


**Problems With the Wave Model**

Nineteenth-century theories predicted that the energy of emitted electrons increases as the **intensity** of incoming light increases.  Einstein's photoelectric theory predicts that higher intensity light produces more electrons, but the energy of each electron is unchanged.  Verify these predictions for yourself.

Repeat one or more of the previous experiments, but increase the intensity of light so that, with zero voltage applied, the ammeter reads 20 nA instead of 10 nA.  For each color of light, how does the stopping voltage at 20 nA compare to the 10 nA result?