

Experiment P – 1

The Photoelectric Effect

(Original by J. Gering; Revision 1/28/2014 by M.Hohlmann)

Introduction

The purpose of this experiment is to demonstrate the photoelectric effect and to measure the stopping potential when several wavelengths of light strike a photocell's cathode. The data allows the experimenter to calculate Planck's constant.

The discoverer of the photoelectric effect was Heinrich Hertz. In 1887 Hertz was the first person to produce electromagnetic waves (radio waves). He applied a high alternating voltage across the gap of two metal terminals and generated a spark. He detected the waves in a nearby coil of wire. He also noticed that light from any spark that fell on the terminals made it easier for the spark to jump the gap. Hertz did not pursue this further but others did. In 1900, Philip Lenard found that these 'rays' deflected in a magnetic field and they had the same charge-to-mass ratio as 'cathode rays' (i.e. electrons).

Concepts

Light is composed of quanta (bundles) of energy we call photons. Photons have energy, carry momentum but have zero rest mass. When light falls on certain metals, the photons will give their energy to the atom. If the photon's energy is sufficient, unbound electrons in the metal will absorb this energy and leave the metal's surface. If an anode collects these electrons a very small electrical current will flow.

Before Einstein explained the photoelectric effect in terms of the quanta of light, it was thought that one could increase the kinetic energy of the electrons (and thereby increase the photocurrent) simply by increasing the intensity of the light. However, this was found not to be the case experimentally.

When a small voltage is applied between the cathode and anode as in Fig. 1, this voltage will exert a force opposing the motion of the photo-induced electron toward the anode. If this voltage is increased to a value (V_0) so the photocurrent falls to zero, the amount of energy $e V_0$ will just equal the electron's kinetic energy. V_0 is called the stopping potential. By conservation of energy, the kinetic energy of the electron should equal the amount of energy given to the electron by the photon less the amount of energy necessary for the electron to leave the metal's surface. The surface binding energy is called the metal's work function and it is given the symbol ϕ . If the applied voltage increases beyond V_0 , then the photocurrent will be reversed and the ammeter will register a negative current.

In 1905 Einstein published a paper wherein he assumed that the energy quantization (used by Planck for blackbody radiation) was a universal characteristic of light. It is interesting to note that it was also in this year that Einstein published his Special Theory of Relativity. Relativity became so controversial that the Royal Academy of Sweden awarded Einstein the Nobel Prize for his explanation of the photoelectric effect rather than for relativity.

In his paper on the photoelectric effect, Einstein assumed the kinetic energy of light was given by $E = hf$ so that

$$eV_0 = hf - W \quad (1)$$

W is called the work function of the metal. It is sometimes also given the symbol ϕ . It is the amount of energy required for an incident photon to liberate an electron from the surface of the metal. Einstein's conceptual leap was in taking Planck's relationship and applying it to the nature of all light. This leap was actually quite daring because, at the time, there was no experimental justification for it. It can be argued that the Michelson-Morley experiment provided the experimental background for the postulates of special relativity. However, Einstein himself denied being familiar with the Michelson-Morley experiment prior to 1905. Even if this was the case, earlier work by Poincare and Fitzgerald also helped pave the way for special relativity.

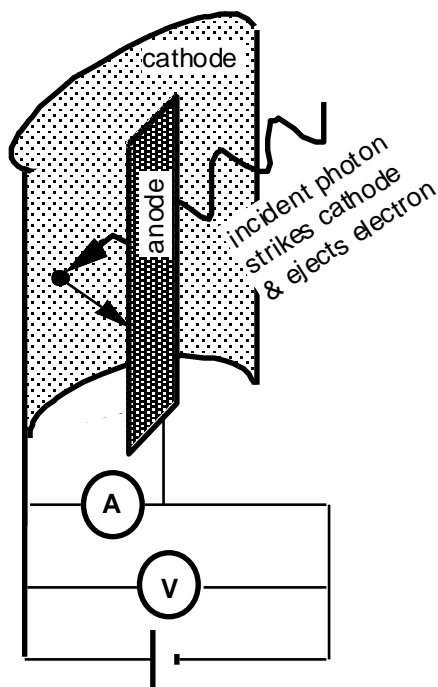


Figure 1. Schematic of the experiment.

Note: The circuit diagram is NOT a photorealistic drawing of how to hook-up the circuit.

Method

The major challenge in this experiment is in measuring a very small (sub-nanoAmp) current while applying a D.C. voltage to the very thing we are trying to measure. If we view the ammeter shown in Fig. 1 as a traditional meter with a very low internal resistance, then it would be extremely easy to damage the ammeter since it represents the path of least resistance for the power supply. The currents to be measured are in the range of tens to hundreds of picoAmps. A power supply capable of delivering a current of 0.5 Amp would destroy an instrument designed to measure 10^{-12} Amp.

Fortunately, picoammeters and electrometers have extremely high internal resistances, usually 10^{13} to 10^{15} Ohms and the photocell represents an *open* circuit for the applied stopping voltage. This internal resistance is more properly called *input impedance*. By the way, an

electrometer is a more general-purpose instrument capable of measuring very small charges and voltages as well as currents.

Another approach is to use a current-to-voltage converter. One model constructed locally consists of two operational amplifiers mounted in a tan plastic box. The box also contains a small AC to DC transformer to power the op-amps. The amplifier provides approximately a amplification factor of 10,000. Therefore, one microamp of current corresponds to approximately 0.1 Volt. Op amps are integrated circuits, which also have high input impedances (10^9 Ohms). By putting two op amps in series the input impedance can be increased to a value high enough to measure picoAmp sized currents. This procedure calls for the use of a converter/amplifier. A voltage is read from an digital multimeter and it corresponds to some number of microamps. Typically the user must establish the correspondance with a known current standard.

Laboratory *standards* are sources of current, voltage or resistance (or length, mass or time) which are known to very high precision and accuracy. They are calibrated regularly (usually yearly) and their accuracy can be traced back to the standards kept at NIST (the National Institute of Standards and Technology). NIST's standards (atomic clocks, etc...) are termed primary standards. A very few laboratories in the U.S. maintain secondary standards. Unfortunately, a local standard is not available to unambiguously calibrate the current-to-voltage converter for this experiment. Fortunately, we are interested in measuring the stopping potential when the current falls to zero. An attempt to measure zero is called a null measurement. The beauty of a null measurement is that any precise, though uncalibrated instrument can be used!

With the recent purchase of a Keithley picoammeter, the use of the current-to-voltage amplifier has been discontinued.

Procedures

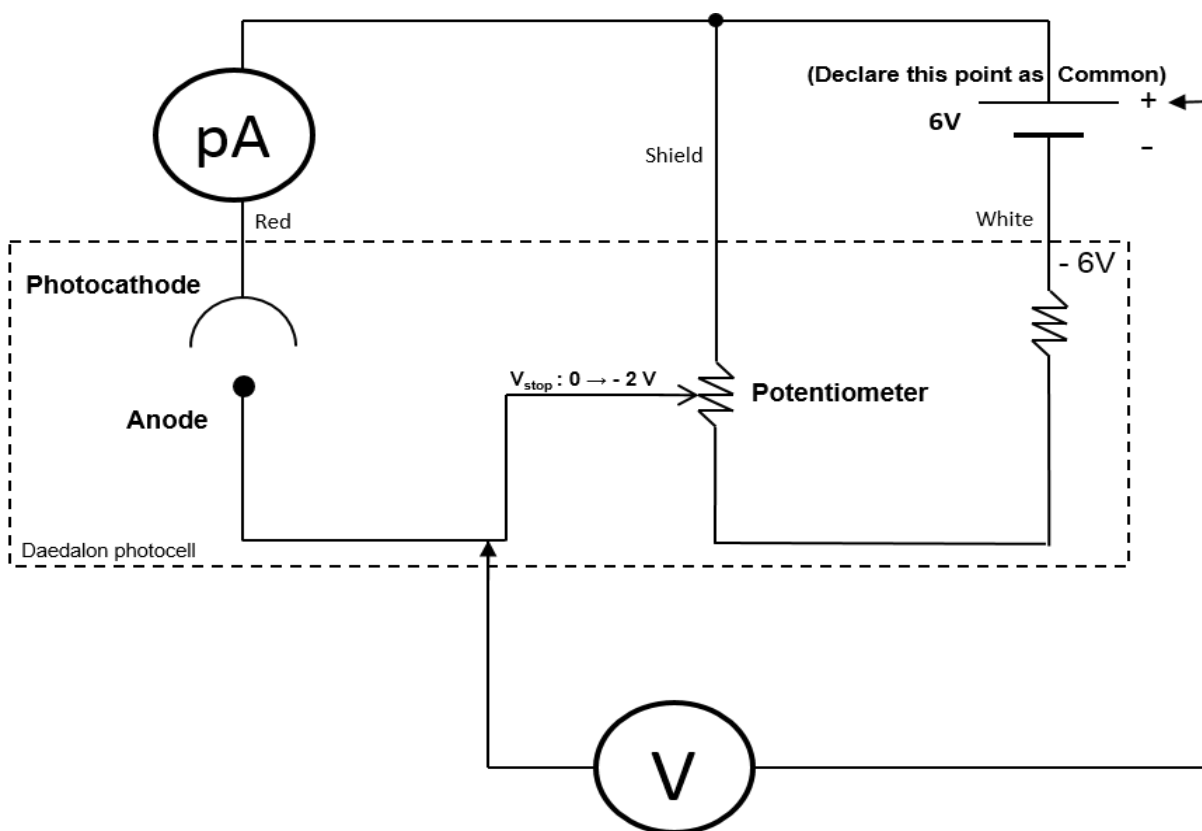
Part 1 Direct Observation of the Photocurrent

- 1) Turn on the mercury lamp. It requires an hour for this mercury vapor lamp to deliver a relatively constant level of brightness. **Safety Note:** Always point the mercury lamp toward a wall and do not gaze directly at the exit hole. The mercury spectrum contains visible and ultra-violet light. UV light promotes the developments of cataracts in the eye. Avoid exposure. Usually, a glass window is placed in front of the exit hole on the lamp housing. Alternatively, newer mercury bulbs have a glass outer bulb. In this case no glass window is needed. Depending upon the unit used, the transformer and/or the housing around the mercury lamp may get warm or hot.
- 2) Connect the Daedelon Corp. photocell directly to the Keithley picoammeter (pAM). Note that the maximum allowable current and voltage for this device is 20 mA and 40 Volts. You need to adapt the BNC input connection on the back of the pAM to banana cables. Remove the two small jumper cables on the photocell. Then connect the pAM directly to the photocell's anode and cathode to close the circuit.

- 3) Set the pAM to read microamps. With room lights ON, point the photocell's window toward the ceiling lights. Record the photocurrent to ± 1 nA. .
- 4) Shine the unfiltered mercury lamp light onto the photocell to get a much larger value of the photocurrent. Record this value.

Part 2 Measuring the Stopping Potential and h

- 1) Disconnect all wires leading to the picoammeter.
- 2) Connect a DC power supply to an electrical outlet but leave the unit off. Set its current limit switch (if available) to 0.5 A. Also, set its voltage setting to 6 Volts (if this feature is available; do NOT use the 60V setting!). Turn the voltage control knob to its lowest (i.e. zero) setting. Adjust the current limit knob on the DC power supply to its mid-range position.
- 3) There is a variable potentiometer integrated into the Daedalon photocell device which we will use to adjust the stopping potential (be careful because it is very easy to bump the photocell.) The knob on the photocell adjusts the potentiometer. Turn the knob counter-clockwise to set the potentiometer to its lowest setting to before connecting any other wires.
- 4) Connect the following measurement circuit to apply an adjustable stopping potential V_{stop} to the anode.



Note that the 3-terminal potentiometer and the resistor are already integrated into the Daedalon photocell device (also see the diagram on the device itself). Use the Keithley as your pA meter and a regular digital multimeter as a voltmeter to measure the stopping potential.

- 5) Double check to ensure that the power supply voltage is set to zero. Turn on the Keithley picoammeter and let it run through its initialization procedures. Then press the ZCH button. This removes the unit from its default 'zero check' mode and connects the picoammeter into 'local' mode for live current measurement. Whenever you change a connection in your circuit, the Keithley pAM should be put in safe mode, i.e. with zero check (ZCH) applied.
- 6) Shine the mercury lamp light onto the photocell. Use a black cloth to block room light from falling on the photocell or turn off the room lights and draw the black curtains around your station.
- 7) Extremely, and we mean *extremely* slowly, turn up the voltage on the DC power supply to a value of 6V. The stopping potential shouldn't increase at this point. Next slowly increase the resistance of the potentiometer. At this point the **stopping potential measured by the voltmeter should slowly increase to a negative value between 0 and -2 Volts** while the current decreases towards zero. If the current increases turn down the voltage immediately and check your circuit. Something is likely backwards. The (fairly expensive) picoammeter can only handle a maximum of 20 mA and 40 Volts. It becomes very difficult to read the current accurately as it approaches zero. Rather than just taking one measurement for the stopping potential in this range, it is better to take several readings as current approaches zero to make a plot of potential vs. current. This provides a much better approximation for the stopping potential.
- 8) The 'clicking' you will hear from the picoammeter are relays switching to automatically change the picoammeter's scale. If this autoscaling becomes a nuisance, you can press the up or down triangular buttons to manually set the picoammeter to an appropriate scale.
- 9) Continue in this fashion for all the available filters. Include those filters, which repeat a given wavelength. Past experience shows that the filters allow a spread of frequencies to pass through them. Moreover, the filters do not adequately block other lines in the mercury spectrum. For example, the green filters pass the yellow line. Some of these filters are cut-off filters designed for use with a mercury lamp. The darker filters are designed for use with white light. The darker filters will reduce the intensity of the light falling on the phototube. In your report, determine whether this affects the stopping potential for those wavelengths for which we have duplicate filters.
- 10) Plot a graph of stopping potential versus light frequency. From the slope determine an experimental value for Planck's constant. **Question:** What does the y-intercept of the graph correspond to? Since there will be a good bit of scatter to the points, use software (spreadsheet or other package) to compute the propagated error in the slope. Instructions for using Excel are presented below. Statistically compare your experimental value with the theoretical using error propagation.
- 11) Cite, categorize and discuss sources of experimental error in your report.

- 12) As this write-up presents a detailed procedure, do not waste time writing your own in your lab report. Also, you need not include an equipment list but do include a well-labeled sketch or photo of the apparatus for each experiment.

Appendix:

Lines in the Mercury Spectrum (nm)

404.7	violet	577.0	yellow
407.8	violet	579.0	yellow
435.9	blue	612.4	red
491.6	blue – green	623.5	red
546.1	green	690.8	red

Using Excel to calculate the errors in the slope and y-intercept

First, select a blank cell in the spreadsheet, then execute the Data Analysis... command in the Tools menu. In the pop-up window, scroll down to the Regression option, select it and click OK. In the second pop-up window, enter the range of cells which contain the y values and the x values. You can move the cursor back to the spreadsheet and trace over the cells to do this automatically. Then click OK. You may get an intermediate announcement having to do with where Excel is going to put the regression table. Ignore it and click OK. Excel then creates another spreadsheet with the regression results in a labeled table. The first entries at the bottom of the table contain the information you want, as follows.

	<i>Coefficients</i>	<i>Standard Error</i>
Intercept	y-intercept here	error in y-intercept here
X Variable 1	puts slope here	error in slope here

Note: if the Data Analysis... command is not visible, then the data analysis tool-pack hasn't been added to the copy of Excel you are using. This and other subroutines are usually copied onto the hard drive when Excel is installed but you must "add" them to Excel - just one time. To do this, execute the Add Ins... command in the Tools menu.

For data fitting, select the check box labeled Analysis ToolPak.

