

PHOTOELECTRIC EFFECT

OBJECT: To verify the photon theory of light as applied to the photoelectric effect.

EQUIPMENT LIST: RCA 934 phototube, two Fluke 37 multimeters, Hewlett-Packard 6235A Triple Output Power Supply, Halogen Table Lamp, set of light filters.

BACKGROUND: *Historical Note:* The photoelectric effect was accidentally discovered by Heinrich Hertz in 1887 during the course of the experiment that discovered radio waves. It remained unexplained until 1905 when Albert Einstein postulated the existence of quanta of light -- photons -- which, when absorbed by an electron near the surface of a material, could give the electron enough energy to escape from the material. Robert Milliken carried out a careful set of experiments, extending over ten years, that verified the predictions of Einstein's photon theory of light. Einstein was awarded the 1921 Nobel Prize in physics: "For his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect." Milliken received the Prize in 1923 for his work on the elementary charge of electricity (the oil drop experiment) and on the photoelectric effect. Hertz died (at age 36) before the first Nobel Prize was awarded.

Theory: In the photon explanation of the photoelectric effect, photons, carrying an energy $h\nu$, can free electrons from the surface of a material if the photon energy is greater than the work function W of the material. The work function is the minimum energy required to release an electron from the material. When an electron in a material absorbs a high enough energy photon, it gains enough kinetic energy to escape from the substance. This is called the photoelectric effect. Einstein's theory predicts that the kinetic energy E of the electron **once it has escaped from the material** is directly proportional to the photon's frequency.

$$E = h\nu - W \quad (1)$$

In this equation h is the Plank constant, ν is the frequency of the light, and W is the work function. We see that W is equal to the photon energy required in order to extract

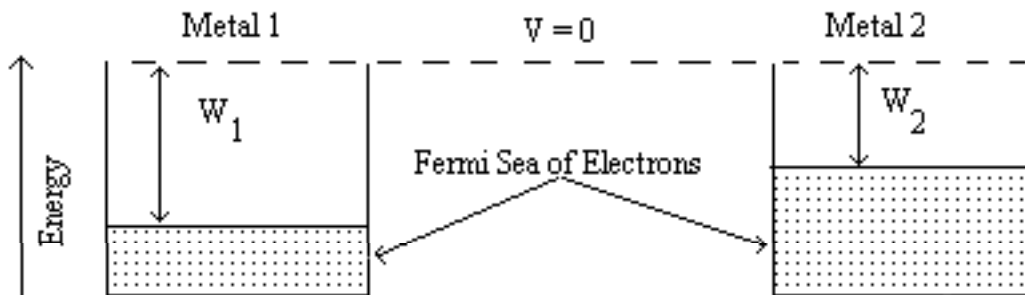


Figure 1 The work function of two metals

an electron from a substance with zero final kinetic energy. Figure 1 illustrates the concept of the work function of a metal. In a metal, the valence electrons are not bound to the metallic ions but can wander freely throughout the metal and can be thought of as a (Fermi) sea of electrons filling a box to a certain height. The work function is the minimum energy to remove an electron from the top of this sea to a point far from the metal.

Note in Eq. (1) that the kinetic energy of an emitted electron is linearly proportional to the photon energy; the latter must exceed the work function to cause photoelectron production.

In this experiment you will expose a metal electrode to light of various frequencies to verify that the electron energy is linearly proportional to the photon frequency as predicted by Eq. (1). From the intercept you will get a value for the work function and from the slope a value for the Planck constant.

We are accustomed to thinking of light in terms frequency but rather wavelength or energy. The conversion factor is:

$$E_{\text{photon}} = \frac{hc}{\lambda} = \frac{1240}{\lambda} \quad (2)$$

where E_{photon} is in eV and the wavelength is in nm. For the visible range of 400 to 780 nm, the energy ranges from 3.1 to 1.6 eV.

Experimental Technique

The experiment requires a multi-chromatic source of light, and the ability to measure the light frequency and the photo-electron energy. The frequency measurement is easy: start with light of a broad spectrum and use optical filters to create approximately monochromatic beams at a number of different frequencies.

The harder problem, the measurement of the electron energy, is accomplished through a nonstandard use of a photocell. In standard photocell operation, current is read from an anode that is held at a positive potential relative to a large area photocathode. When illuminated by light above the cut-off frequency, the photoelectrons flow from the cathode to the anode and create a detectable photocurrent.

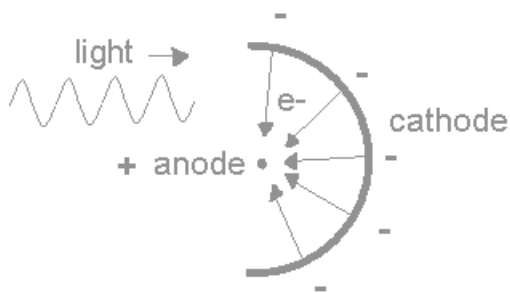


Figure 2. Normal Photocell Operation

In this experiment, we measure the electron energy by operating the photocell in reverse. The photocathode is connected to the positive terminal of a power supply and the anode to the negative. The photoelectrons are ejected from the cathode with energy according to Einstein's equation, and then slowed down by the "retarding voltage". When the retarding voltage times the electron charge is just equal to the maximum energy of the photoelectrons, the current ceases. This voltage is called the "stopping voltage", V_s , and measures the maximum photoelectron energy as $E = eV_s$ when $I=0$.

To verify the photoelectric effect and measure Planck's constant h , you should measure the stopping voltage versus the wave number $1/\lambda$ for several frequencies of incident light. Equation 1 predicts that the stopping voltages and wavelengths should be related as:

$$V_s(\lambda) = \frac{hc}{e} \frac{1}{\lambda} - \phi \quad (3)$$

The slope of this line (V vs. $1/\lambda$) gives the quantity hc/e . You can assume e and c are known and calculate h . The intercept of the line gives the quantity ϕ , from which you can calculate the work function and compare it to the expected value.

APPARATUS

The circuit, Fig. 3, for the photoelectric experiment centers around an RCA 934 phototube, which consists of two electrodes -- a cathode and an anode -- enclosed in a glass high vacuum tube. The curved cathode emits electrons when photons of sufficient energy strike the surface. The anode, at the center of the cathode's radius of curvature, will collect the electrons emitted by the cathode. The purpose of the circuit is to determine the kinetic energy of the electrons that escape from the cathode when **light of a single wavelength** strikes the cathode. This is done by applying a variable reverse voltage between the anode and cathode which is adjusted to stop the electrons from getting to the anode. The voltage V_{sp} that stops the electrons from making it to the anode is the "stopping voltage" which is a measure of the emitted electron's kinetic energy, E .

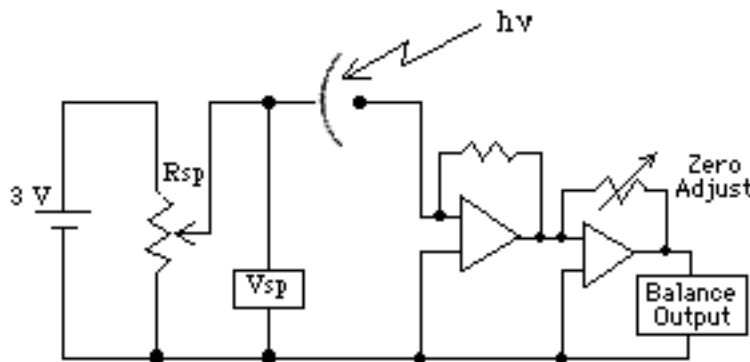


Figure 3

The circuit, shown in the diagram, consists of two parts. On the left is a voltmeter reading the retarding voltage. The potentiometer R_{sp} (labeled Stopping Potential Adjust on the apparatus) controls the retarding voltage. The range is adjustable from 0 to 3 volts. The relevant voltage lies in the range 1.5 V to 0.

The right-hand side of the circuit is a high-gain amplifier circuit, which gives an output, labeled "Balance Output" that indicates the amount of current flowing from the cathode to the anode. When the Balance Output is 0 V, the voltage V_s is stopping the free electrons.

There is one important precaution you must take. The op-amps in the high-gain amplifier have small DC offsets (non-zero output even when the input is zero). These offsets, which may drift in time, must be nulled (zeroed) by adjusting the second potentiometer, labeled "Zero Adjust". This adjustment, of course is done when no light is striking the cathode and should be independent of the setting of V_{sp} .

The light source is a high intensity halogen lamp which consists of an incandescent filament in an argon gas atmosphere that emits additional light at the short wavelengths. A number of different optical interference filters can be placed in the "well" at the instrument top to permit light of only a narrow band of wavelengths (about 10 nm wide). Each filter has an identification number which is used to find the approximate wavelength from the storage box. The precise wavelengths are obtained from the filter calibration curves found in a binder kept on the experiment table

On the experimental apparatus the following labels are used:

OUTPUTS: Stopping Potential Output: a BNC connection running to a voltmeter

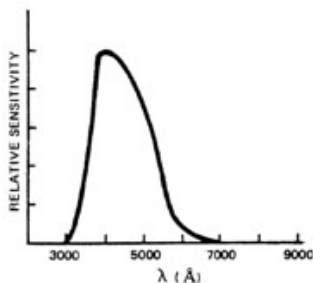
Balance Output: a BNC connection running to a voltmeter.

ADJUSTMENTS: Stopping Potential Adjustment: potentiometer controlling the applied V_{sp} . Zero Adjustment: potentiometer controlling the offset V_{offset} .

POWER REQUIREMENTS: A single power supply (SRS) supplies the required voltages -- +3V, +18V, and -18V. Note that one ground connection between the power supply and apparatus is sufficient. The second ground connection is redundant. Check all the connections before turning on the power supply!

LIGHT SOURCE: The tungsten-halogen lamp should be placed 4 inches above the top of the instrument where the entrance aperture is. A filter is placed on the aperture. The aperture should be covered with the plastic lid when not in use to keep dust out of the system. **The filters must be stored in their individual boxes and not left unprotected on the table. They break easily if dropped.**

PHOTOTUBE: The RCA 934 phototube uses a cathode of Cesium-Antimony, reported by the manufacturer to have a work function of ~ 1.7 V. You should verify this with your experiment. The sensitivity of the RCA 934 varies with wavelength as indicated below. Think how this will affect your results. **Include the answer in your report.**



Wavelength dependence of sensitivity of the RCA 934.

PROCEDURE:

1. Set up the apparatus. The aperture in front of the photocell faces up. The light source should be above it.
2. Check that the power supply and multi-meters are connected correctly. One of the meters measures the retarding voltage, the other measures the photocurrent (but set it to measure Voltage). Connect red to red and black to black to get the signs of voltages right.
3. Turn on the equipment. With the retarding voltage set to zero and no light on the photocathode set the “Zero Adjustment” knob so that the photocurrent is nearly zero <1 mV or so. Note the fluctuations in “dark current”.
4. Open up the Agilent Digital Multimedia Connectivity Utility software on the computer. Ensure the software is connected to the equipment in the bottom left of the screen. If it is not, make sure all equipment is turned on, then close and reload the program. Next click the play button in the center of the screen to launch the data taking program. Data logging can be started by pressing the green start button on either the bottom or top of the program. For each data point, it is best to let data accumulate for some time before using the orange tabs to select the region with the relevant data. Under the chart you will find a table labeled “Measurement between Markers (M2-M1)” where you can find the average, time interval, min, max, and standard deviation of the selected data. Additionally, data can be saved using the export function to either Matlab, Microsoft word, Microsoft Excel, or CSV formats. Note: If data logging is occurring but the chart is not updating, click on “Auto Scale” underneath the chart to update it.
5. Mount a filter, the green one is good to start. Turn on the mercury lamp and place it as close as possible to the filter. The current amplifier is protected so that off-scale readings will not harm it.
6. Adjust the retarding voltage and study the behavior of the photocurrent. You should be able to quickly find a voltage where the current stops changing. This is the stopping voltage.

However, the current may not be exactly zero there, see below. Note that any adjustment knob, potentiometer, etc. has hysteresis. It's usually good practice to move knobs in one direction only for reproducible results. You may find it useful to make small adjustments in the “Zero Adjust” once you know the range of things. However, once it is set, be careful not to vary your zero by mistake in the middle of a measurement.

Before starting to take data, read section 4.3 Analysis of the Data in Melissinos (1'st edition pp 24-27 supplementary material). Because of various effects, notably photoemission from the anode, it is not a straightforward matter to determine the onset of photoemission from the cathode. Melissinos gives two different procedures for analyzing the photocurrent versus anode-to-cathode voltage data to obtain the stopping voltage, which produce comparable results with about 10% percent accuracy. Take sufficient data that will enable you to apply these methods of analysis.

6. Set balance output to zero before each measurement, while the aperture is covered by the lid. After the measurement verify that the balance output is still zero. If it isn't you must make a correction for the difference.

Measure, tabulate, and plot the phototube current (you will actually measure a voltage which is proportional to the photocurrent) as a function of the retarding voltage for each filter. Make a preliminary inspection of the curve and use this to guide efficient data

taking. Take fine steps near the “knee” where the current starts rising (where you need the precision). You only need coarser steps up the sharp rise, which is not so important for finding V_s . Make sure to extend the measurements beyond zero current in order to measure the effects of “reverse” current. Repeat the series of measurements at least four times for each filter to obtain the data necessary for a reliable estimate of the random errors of measurement. The photocurrent with the red filter is very small and the readings fluctuate ~ 1 mV, so do this one especially carefully. You may need to cover the box to prevent photocurrents from outside light in this case

7. Can you observe the saturation current at high accelerating voltages? This could help you normalize the results for different wavelengths (see discussion in Melissinos)

8. Devise a method to measure the dependence on the intensity of the light.

Example Data

An example of anode current vs. retarding voltage data for a number of wavelengths is shown below. This is from the first edition of Melissinos. Note that the polarity conventions may be different from yours. In these plots the retarding voltage increases to the left.

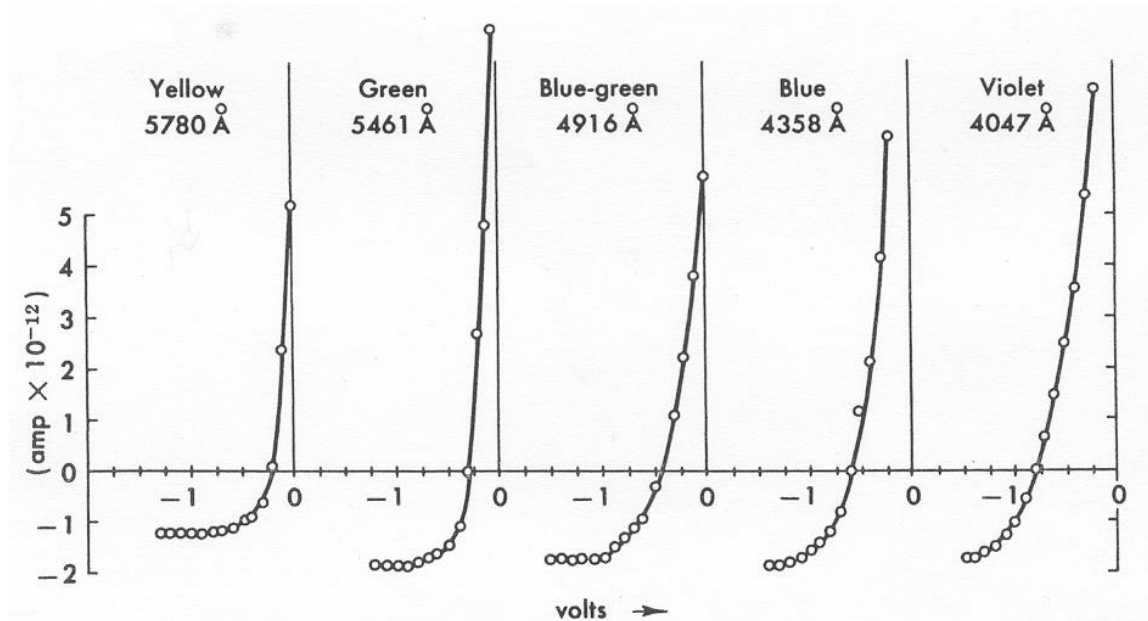


Figure 4. I-V curves for photodiode (from Melissinos, first Ed.)

These plots remind us of I-V curves for a diode. That makes sense! A difficulty in this experiment is that the equivalent of the diode threshold, the stopping voltage, is not sharp:

As the retarding voltage approaches V_s the anode current goes asymptotically to a constant value. This is partly because the electrons in the photocathode have a thermal energy distribution which broadens the work function. In order to define a numerical “stopping voltage” for a given wavelength, you will have to invent a convention for deciding where the current “turns on”.

The largest uncertainty in this experiment is that due to the technique for “defining” the stopping voltage for each filter. You should try at least two techniques, so that you can estimate how large the resulting uncertainties are. Possibilities are the point of maximum curvature (second derivative), or where it rises by a certain amount above the plateau or intersection of asymptotes. See the discussion in Melissinos first edition (supplementary material).

ANALYSIS:

- For each filter make a table and graph of photocurrent vs. retarding voltage.
- For each value of λ , find the stopping voltage from your graph and estimate its uncertainty. As explained above, the definition of the stopping voltage is somewhat arbitrary, so invent your own definition and use it consistently. The “knee” of the curve, or point of maximum curvature, is one measure.
- In your report, include a table of wavelength, frequency, and two estimates of stopping voltages for each of your filters. Also, indicate the stopping voltages on your graphs of photocurrent vs. voltage.
- Using a fitting program such as Origin, make a least squares fit of these data to a straight line using V_s as the y-axis and frequency or $1/\lambda$ as the x-axis. **Note that the stopping voltage is determined by the photons with the greatest energy. In plotting the graph you should use the wavelength corresponding to the shortest wavelength passed by the filter and not the wavelength of the center of the band.** You should use a weighted fit since some of your data points may be more accurate than others. To use it you must determine the uncertainties in your experimental measurements. You could do this in two ways. One is to observe the variation of the meter readings over a few seconds and write this down as an uncertainty in your reading. The other is to make several measurements and call the uncertainty the standard deviation of these measurements. Note that the error in the wavelength is not the width of the pass band of the filter, but a much smaller number corresponding to the width of the edge of the pass band. Include the fits in your report (you can use an appendix). Include estimated error bars on your data points.
- Repeat the fit for each technique for estimating the position of the “knee”. Interpret your data in terms of the photoelectric hypothesis. Determine the slope and the uncertainty in the slope. From these results determine the quantity h (units eV-s) and its uncertainty.
- Determine the work function of the cathode and estimate its uncertainty. Do you get sensible results?
- What are the key factors in the uncertainty? Can you improve your measurement?

Discussion

1. Compare your results with expectations from classical theory.
2. In this lab we apply a retarding voltage and then measure the current between the cathode and anode. Will your results depend on the work function of the cathode (Cesium Antimony has a work function of ~ 1.65 eV). How does the work function of the anode affect the results?
3. Your results depend on how you decided to define the stopping voltage. Consider the *systematic uncertainty* arising from this definition. What effect does this have on determining Planck's constant and the work function?
4. Is your result for Planck's constant consistent with expectation? If not, discuss possible reasons.
5. What is the effect of stray light on your measurements?
6. Explain why the photocurrent changes sign for large retarding voltages.
7. Discuss the effect on your results of the photocathode sensitivity variation with wavelength.
8. Discuss the sensitivity of your results to variations in light intensity.

READING:

- Eisberg and Resnick: Quantum Physics of Atoms, Molecules, Solids, Nuclei and Particles, New York; John Wiley 1974, pp. 31-37.
- Preston, Daryl W. *The Art of Experimental Physics*, (Wiley, 1991) pp. 166-180.
- Melissinos Experiments in Modern Physics, (Academic Press, 1996) pp. 18-27.