THE PHOTOELECTRIC EFFECT

SPECIFIC OBJECTIVES:

1. To understand a demonstration of the particle nature of light.

2. To determine Planck's constant, \( h \), from the ratio of \( h/e \) where \( e \) is the charge of an electron.

GENERAL DESCRIPTION:

The photoelectric effect is the liberation of electrons from the surface of a material by absorption of energy from light striking the surface. The simplest experimental arrangement for observing this effect is shown in Fig. 1. The cathode is illuminated with monochromatic light, and the current (resulting from photoemission of electrons from the cathode) is measured as a function of voltage.
The most important experimental observations are the following:

1. The kinetic energy of the photoelectrons (as determined by the reverse voltage needed to stop completely the flow of electrons from cathode to anode) is independent of the intensity of the light, but is a linear function of the frequency of the radiation.

2. There is a minimum frequency below which photoemission does not occur; the value of this minimum depends on the composition of the surface.

3. The saturation photocurrent is directly proportional to the light intensity.

The experimental observations of the photoelectric effect were first understood by Albert Einstein in 1905. He interpreted them in terms of the quantization of light first postulated by Planck five years earlier. In this model a beam of light is said to be composed of a number of light quanta, or photons, each with energy related to its frequency, \( \nu \), by \( E = h\nu \) where \( h \) is Planck's constant. Each photon acts like a "particle" of light.

The intensity of the light increases when the number of photons increases. The interaction of light with an electron in the photoelectric effect is modelled as a collision in which the electron can absorb the energy of the photon and destroy the photon.

To remove an electron from the surface of a material requires an amount of energy, \( W \), called the work function of the material. The higher the work function, the more tightly bound are the electrons. When an electron is emitted, by conservation of energy, the initial energy of the photon equals the resulting kinetic energy of the electron plus the energy lost in overcoming the work function. That is,

\[
hv = \frac{1}{2} mv^2 + W. \tag{1}
\]
The negative potential, $V_o$, needed to stop the electron flow is determined by setting the potential barrier, $eV_o$, equal to the electron's kinetic energy. Thus equation (1) can be rearranged to yield:

$$eV_o = h\nu - W.$$ 

If the reverse voltage is more negative than this cutoff voltage, $V_o$, no current flows. Note that, $V_o$ is a linear function of frequency, as observed experimentally. Measuring $V_o$ as a function of frequency should provide values for $h$ and $W$ as shown in figure 2.

*Figure 2*
EXPERIMENTAL DETAILS:

1. Refer to the Instruction Manual on page 6-7.

RESULTS:

1. Calculate h from your data and compare to the accepted value
2. Plot a graph of $V_o$ vs. $v$, estimate the slope and compare to the computer's value.
3. Explain why the photoelectric effect shows the particle nature of light.

COMMON PITFALLS:

1. Not writing a sufficient description of the experiment to show you understand what the computer is simulating.
2. Not reading the scale of apparatus correctly.
3. Misspelling "Planck".

SOPHISTICATIONS:

1. Why is it necessary to plot a graph of $V_o$ vs. $v$? Hint: would the computer fit a straight line to random data points?
2. Sketch a graph of $I$ vs. $V$ and indicate how it would change for the following conditions:
   i) The intensity of light is doubled.
   ii) The target material is changed to one with a smaller work function.
3. The photoelectric effect is a very powerful modern analytic tool. The rising portion of the graph of $I$ vs. $V$ is found not to be a smooth
curve. Instead, it has peaks which reflect the allowed energy levels in the target material. It is called UPS (Ultraviolet Photoemission Spectroscopy) or XPS (X-ray Photoemission Spectroscopy) depending on the wavelength of the light used. It is used to probe the electronic structure of materials. That is, to determine the allowed energy levels and the number of electrons in each level. In the basic experiment the data obtained are the number of emitted electrons as a function of their kinetic energy for each incident wavelength. In more sophisticated experiments, the data are obtained for different polarizations of the light and by looking in which directions the electrons are emitted.

A typical graph is shown schematically in figure 3. The important features of the data are the positions of the peaks and their amplitudes.

![Graph showing number of electrons emitted as a function of energy.](image)

**Figure 3.** Schematic of Number of Electrons Emitted as a function of Their Energy.
a) Did the electrons in peak (1) or (2) come from deeper inside the target atoms? i.e. from lower energy levels?

b) Are there more electrons in the level associated with peak (1) or (2)?
(This ignores any complications due to unequal yields.)

c) How can you tell (without the label) that the upper trace is for light of a higher frequency? Why is there an extra peak?

d) If you keep increasing the frequency, will you keep getting more peaks? If not, why not?
INSTRUCTION MANUAL
for
EP-05 PHOTOELECTRIC EFFECT with AMPLIFIER

INTRODUCTION

This important experiment, which provided the first convincing experimental verification of the quantum theory, was suggested by Einstein in 1905. The actual phenomenon of photo emission of electrons from metals was observed by Hertz in 1887 and proved to be impossible to explain using the wave theory of light. Einstein postulated that not only is light emitted and absorbed in discrete but tiny bundles, as proposed by Planck, but it is propagated that way as well; flying through space like a hail of shot at the velocity of light. This conjecture nicely explained the photoelectric effect experiment. In this experiment, the velocity of the electrons leaving the surface of a metal when irradiated by monochromatic light depends upon the wavelength and not upon the intensity of the radiation. When Einstein made his suggestion, there was not sufficient quantitative evidence to confirm or deny his equations. Very precise measurements were subsequently made with the result that the theory was completely verified. With the Daedalon EP-05 Photoelectric Effect with Amplifier, you will be able to repeat the essential part of the experiment that served to establish the quantum theory of radiation...In the experiment, the photocathode is irradiated by a source of monochromatic radiation and a potential is applied to the tube so that it opposes the energy of the emitted photoelectrons. The voltage required to just stop the current flow is proportional to the energy of the photoelectron. Plotting the stopping potential as a function of the reciprocal of the wavelength of the radiation gives a straight line plot, the slope of which can be used to calculate Planck's constant.

For accurate results, the measurement of very small photocurrent is required. In order to do this without introducing extraneous voltages, the amplifier should be placed close to the photodiode. Building the amplifier in the same case, only a few centimeters from the photodiode tube base, fulfills this requirement nicely. The minimum detectable photocurrent is of the order of 5 x 10^-10 A, which is quite good for such a simple apparatus.

The apparatus includes three filters to provide spectral separation. If monochromatic sources are not available, the filters with a fluorescent and a tungsten lamp can be used, although the results are not as good as with a monochromatic source.

OPERATION

These instructions assume that a white fluorescent lamp and a tungsten lamp are used with the supplied filters. The mercury arc spectral lines show through the
white phosphor of the fluorescent lamp and can be separated with the filters. The red wavelength can be obtained with the red filter and a tungsten lamp.

The filter combinations yield almost monochromatic radiation at $\lambda$436nm, $\lambda$546nm and $\lambda$580nm. A more reliable result can be obtained if a low pressure Mercury Arc and a set of interference filters are available to separate the spectral lines. Five wavelengths can be used to plot the line relating the stopping potential and $1/\lambda$. If a He-Ne Laser is available, it can be used to provide an excellent monochromatic measurement at $\lambda$638nm.

The relative response of the 1P39 Vacuum Phototube used in the apparatus is shown in the adjacent figure. The mercury and He-Ne Laser lines are drawn on the ordinate axis. The following description assumes the use of a fluorescent lamp for the lines at $\lambda$436nm, and $\lambda$546nm and $\lambda$580nm which is the short wavelength cutoff of the red filter supplied with the apparatus.

**Procedure**

1. Set up the EP-05 Photoelectric Effect Apparatus on a table so that the aperture in front of the photodiode faces the fluorescent lamp. The aperture is 7 cm above the bench top, so the box or source may have to be raised to line them up. The phototube is very sensitive to small amounts of stray radiation, particularly shorter wavelengths than those being measured. Sunlight is very rich in these wavelengths so it is often useful to construct a cardboard light shield around the box and the light source. The line power outlet should have a good ground connection to reduce any hum pickup.

2. Connect a voltmeter to the red and black banana jacks on the top panel of the case. They are connected across the photodiode and measure the stopping potential across the tube. A digital voltmeter is best for this measurement, since the accuracy of the reading affects the accuracy of the result.

3. Turn on the fluorescent lamp. If you are performing the experiment with a Mercury arc lamp rather than a fluorescent lamp, take care; Mercury Lamps with quartz envelopes, emit ultra violet radiation that is harmful to your eyes. Place the blue filter over the
photodiode aperture. This filter will pass the blue wavelength at \(\lambda 436\)nm.

4. Cover the aperture with a black piece of cardboard or metal to set the zero adjustment on the amplifier. Your hand is not opaque enough. Turn on the amplifier and adjust the right hand "Zero Adjustment" knob until the meter reads zero. The amplifier is quite stable but, since the measurement is made at the scale zero, any drift causes an error. The zero adjustment should be frequently checked during the measurements.

5. Turn the "Voltage Adjustment" knob on the middle of the panel to its counterclockwise limit. The voltmeter should read zero or very close to it. Uncover the aperture. Move the apparatus until the radiation is striking the center of the photodiode. The reading on the output meter is helpful in making the adjustment. The radiation intensity should be adjusted so that the meter is approximately 10 on the scale. Recall that the amplifier gain is high (1 mA on the meter is \(5 \times 10^{-5}\) A of photocurrent), so if the meter goes off scale, the photodiode won't be harmed. The meter won't be harmed either; the amplifier limits the current delivered to it.

6. Measure the output current as a function of Stopping Voltage. As the voltage increases, fewer and fewer electrons have enough energy to leave the cathode, and the current drops. The critical point on the curve is the voltage at which the current falls to zero.

7. Measure the voltage for zero current five times, resetting the zero after each setting. Be careful not to pass the zero current value. The curve remains at zero for stopping voltages higher than the critical value. The value you need is when the current just reaches zero.

8. Change the filter, replacing the blue filter with the green one. This isolates the green line in the mercury spectrum at \(\lambda 546\)nm. Repeat Steps 6 and 7. You will find that the stopping voltage is less than it was for the blue wavelength.

9. Replace the fluorescent lamp with a tungsten lamp. Check your light shields and place the red filter in the filter holder in front of the photodiode aperture. The short wavelength edge of the red filter is at \(\lambda 580\)nm and this will be the effective wavelength of the radiation passed through it. You will find the
stopping potential is much smaller than for the previous wavelengths.

If a He-Ne laser is used as a source, use the red filter. It has a wide band pass to longer wavelengths and will pass the laser radiation. It will also greatly reduce stray radiation that might strike the photosurface of the diode. The effective wavelength with the laser is \( \lambda = 638\text{nm} \).

Typical values for this experiment are shown in the next figure.

Interference filters can separate two additional lines in the Mercury spectrum, those at \( \lambda = 405\text{nm} \) and \( \lambda = 578\text{nm} \). A sodium arc lamp can also be used but the effective wavelength is not the bright lines at \( \lambda = 589\text{nm} \) but rather the faint, though more energetic line at \( \lambda = 586\text{nm} \). This line is so close to the mercury line at \( \lambda = 578\text{nm} \), that the plot is not improved much by the addition.

**DISCUSSION**

The classical physicist would propose that as the incident light energy decreases, the energy transferred from the incoming light to the electrons on the surface of the metal would allow progressively fewer electrons to escape until the flux went to zero. Einstein, however, correctly predicted that the energy carried by the incoming radiation is quantized; that is, it has a basic energy level or some multiple of it. Each photon either gives up its energy in whole, or not at all. This can be summarized by Einstein's relationship:

\[
E = \frac{hc}{\lambda}
\]

Thus

\[
e (V + \Phi) = \frac{hc}{\lambda}
\]

where

- \( e \) is the electronic charge
- \( V \) is the stopping potential
- \( \Phi \) is the work function of the metal of the photosurface
- \( \lambda \) is the wavelength of the light
- \( h \) is Planck's constant

6-10
C is the velocity of light.

This experiment measures the point where the stopping potential just equals the work function of the metal, so that

\[ V = \left( \frac{hc}{e} \right) \left( \frac{1}{\lambda} \right) \]

From a plot of \( V \) versus \( 1/\lambda \), the slope of the line can be determined. Since the slope equals \( hc/e \), then

\[ h = (\text{Slope} \times e)/c \]

The slope can be determined by drawing a line through the plotted data, or by using least squares fit of the data. Since almost all hand calculators have a least squares program built in, it is recommended that this statistical procedure be used. The example uses least squares. A plot of the sample data is shown in the adjacent graph.

To calculate Planck's constant, we need the value of the velocity of light.

\[ c = 2.998 \times 10^8 \text{ meter/second} \]

and the charge on the electron.

\[ e = 1.602 \times 10^{-19} \text{ Coulombs} \]

so that

\[ h = 1.13 \times 10^{-6} \times 1.602 \times 10^{-19} / 2.998 \times 10^8 \]

\[ = 6.01 \times 10^{-34} \text{ Joule Seconds} \]

The accepted value of Planck's constant is \( 6.626 \times 10^{-34} \) J.s. This value is typical of results that can be obtained.

With greater care and more data, particularly additional wavelengths, better results could be achieved.
EP-05 PHOTOELECTRIC EFFECT

Typical values obtained using a ES-30 Low Pressure Mercury arc and interference filters to separate the lines are given in the following table:

<table>
<thead>
<tr>
<th>Wavelength ( \lambda )</th>
<th>( 1/\lambda )</th>
<th>( V_{\text{stop}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \lambda 405 )</td>
<td>2.469</td>
<td>1.316</td>
</tr>
<tr>
<td>( \lambda 436 )</td>
<td>2.295</td>
<td>1.217</td>
</tr>
<tr>
<td>( \lambda 546 )</td>
<td>1.832</td>
<td>.682</td>
</tr>
<tr>
<td>( \lambda 577 )</td>
<td>1.731</td>
<td>.547</td>
</tr>
<tr>
<td>( \lambda 600 )</td>
<td>1.667</td>
<td>.358</td>
</tr>
</tbody>
</table>

The data shown in the table were collected from two repetitions of the experiment on two successive days. These data were plotted and fitted with a least squares straight line as shown in the following figure. The value of Planck's constant from the slope of this line is

\[ h = 6.328 \times 10^{-34} \text{ J s} \]

which is a little closer to the accepted value than the earlier result. The data points are closer to the line as well so the correlation is higher, which makes the result more convincing.

The principal limitation on the value of Planck's constant in this experiment is the monochromaticity of the radiation directed to the photosurface. It can be seen from the above result, that interference filters are better than gel filters, but a double monochromator would be better yet.

The experiment was carried out with very great care for a number of metal surfaces by R.A. Millikan and published in Physical Review, 7, 355 (1916). If you have an interest in the history of Physics, this paper is important.

 WRJB–June 1989

\[ V_{\text{stop}} = -1.512 + 1.158 \times 1/\lambda \]

1.6 1.8 2.0 2.2 2.4 2.6

RECIPROCAL WAVELENGTH \times 10^{-6} m
APPENDIX: Predictions of the wave and particle models of light.

The photoelectric effect is an experiment that cannot be explained by the wave model of light, but is easily understood in the particle model. Interference is a complementary effect: it is easily understood in the wave model and cannot be explained in the particle model. Together the experiments force the presently accepted theory of wave-particle duality in which light is neither solely a wave nor solely a particle, but exhibits properties of each under the appropriate experimental conditions.

The relevant considerations in this experiment are how the intensity of light varies in each model and how energy is transferred from light to an electron. These facts and the predictions corresponding to the three experimental observations listed in the GENERAL DESCRIPTION are listed in tabular form below. The symbols used are:

I = intensity of light  
E \_o = electric field of the light wave  
N = number of photons  
h = Planck's constant  
v = frequency of the light  
E = energy transferred to each electron  
S = Poynting's vector  
q = charge on the electron  
T = time during which the light hits the surface  
W = work function of the material  
K.E. = kinetic energy of the electrons = E-W
<table>
<thead>
<tr>
<th>Consideration</th>
<th>Wave Model</th>
<th>Particle Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intensity</td>
<td>$I \sim E_0^2$</td>
<td>$I = N\nu$</td>
</tr>
<tr>
<td>Energy transfer</td>
<td>$E \sim qST$</td>
<td>$E = h\nu$</td>
</tr>
<tr>
<td></td>
<td>so $E \sim I^{1/2}T$</td>
<td></td>
</tr>
<tr>
<td>1. Maximum K.E.</td>
<td>complicated, but</td>
<td>K.E. = $h\nu - W$</td>
</tr>
<tr>
<td></td>
<td>for K.E. $\gg W$,</td>
<td>(independent of I)</td>
</tr>
<tr>
<td></td>
<td>K.E. $\sim I^{1/2}$</td>
<td></td>
</tr>
<tr>
<td>2. Minimum $\nu$</td>
<td>unexplainable</td>
<td>to get K.E. $&gt; 0$</td>
</tr>
<tr>
<td></td>
<td>predicts a minimum</td>
<td>hence a minimum</td>
</tr>
<tr>
<td></td>
<td>product of $I^{1/2}T$</td>
<td>frequency</td>
</tr>
<tr>
<td></td>
<td>at low intensity,</td>
<td></td>
</tr>
<tr>
<td></td>
<td>need a longer $T$ to</td>
<td></td>
</tr>
<tr>
<td></td>
<td>get the current</td>
<td></td>
</tr>
<tr>
<td>3. Saturation</td>
<td>complicated, but</td>
<td>number of electrons</td>
</tr>
<tr>
<td>photocurrent</td>
<td>for a fixed $T$, the</td>
<td>emitted is</td>
</tr>
<tr>
<td></td>
<td>saturation current</td>
<td>proportional to the</td>
</tr>
<tr>
<td></td>
<td>$\sim I^{1/2}$</td>
<td>number of incident photons</td>
</tr>
<tr>
<td></td>
<td></td>
<td>thus saturation current $\sim I$</td>
</tr>
</tbody>
</table>