Instruction Manual
for
EP-05 Photoelectric Effect

INTRODUCTION

This important experiment provided the first convincing experimental verification of the quantum theory and was suggested by Einstein in 1905. The actual phenomenon of photoemission of electrons from metals was observed by Hertz in 1887 and proved to be impossible using the wave theory of light. Einstein postulated that not only is light emitted and absorbed in discrete 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 photoelectrons. Plotting the stopping potential as a function of the reciprocal of the wavelength gives a straight-line plot, the slope of which can be used to calculate Planck's constant.

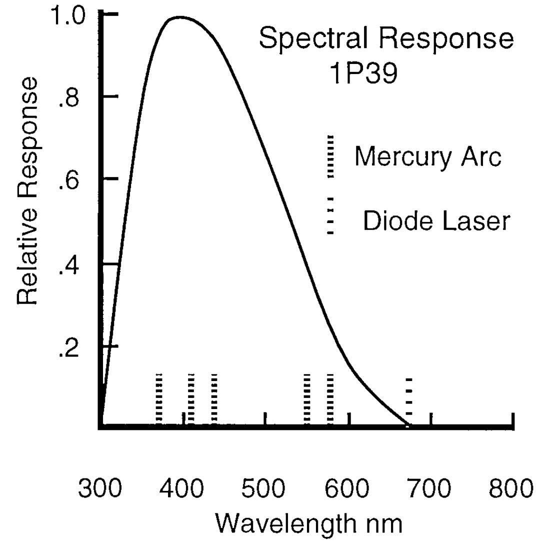
For accurate results, the measurement of very small photocurrent is required. In order to do this without introducing extraneous voltages; the amplifier should be placed close to the photodiode. Building the amplifier in the same case, only a few centimeters from the photodiode tube base fill this requirement nicely. The minimum detectable photocurrent is of the order of 5×10^{-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 λ436nm, λ546nm and λ590nm. 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/λ. If an ES-12 Diode Laser is available, it can be used to provide an excellent monochromatic wavelength at λ670nm.



The relative response of the 1P39 Vacuum Phototube used in the apparatus is shown in the above figure. The Laser is near the end of the tube's sensitivity, but because it is so bright there is enough photocurrent for a measurement.

The Mercury and Diode Laser lines are drawn on the ordinate axis. The following description assumes the use of a fluorescent lamp for the lines at λ436 nm and λ546 nm, and a tungsten lamp with the red filter for a λ590nm wavelength, 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 digital 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. Put the blue filter over the aperture. Turn on the fluorescent lamp.

3. Set the zero by turning the "VOLTAGE" knob to its full clockwise position, about 3 Vdc. Adjust the "ZERO" so that the meter reads zero.

   If the zero drifts between readings, the radiation intensity on the photosurface is too high and a phenomenon known as fatigue is occurring on the photosurface. Reduce the intensity by moving the source away from the aperture. 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 checked before and after the measurements.

5. Turn the "VOLTAGE" knob to its counter-clockwise limit. The voltmeter should read zero or very close to it. 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 so if the meter goes off scale, the photosurface won't be harmed. The meter won't be harmed either; the amplifier limits the current delivered to it.

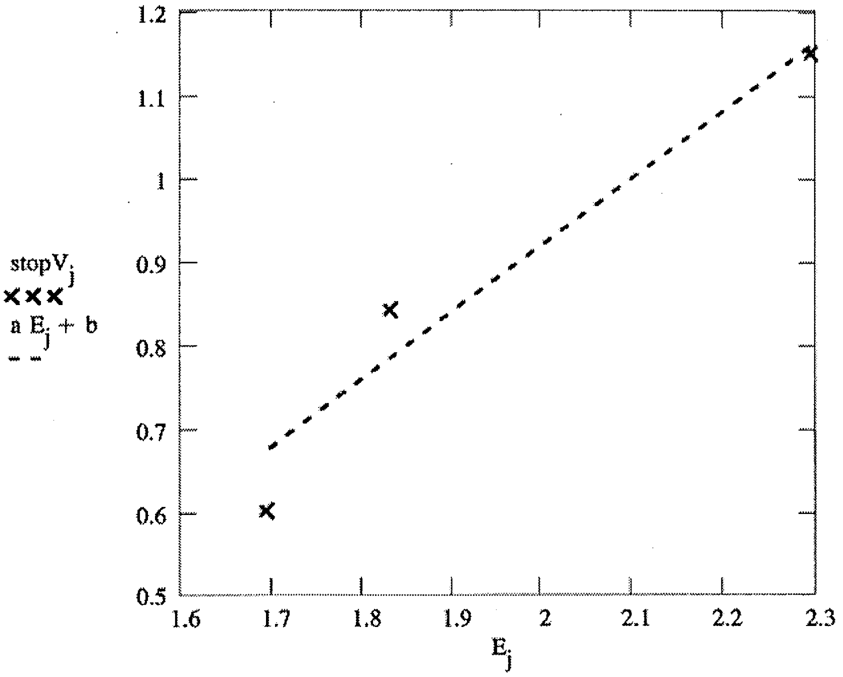
6. Measure the output current as a function of Stopping Voltage. As the voltage increases, fewer and fewer electrons have enough energy to leave the cathode, and the current drops. The critical point on the curve is the voltage at which the current just falls to zero.

7. Measure the voltage for zero current five times. The meter 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 λ546nm. 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 λ590nm 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.



$$h := a \cdot \frac{1.602 \cdot 10}{2.998}$$

$h = 4.326$

Accepted value 6.626

Figure Two

Typical results are shown in Figure Two. The value of Planck's constant has the right order of magnitude but is very much too low. The limitation is because we have only three points to determine the slope and that the wavelengths used were not very monochromatic.

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:

$$E=hc/\lambda$$

$$\text{Thus} \quad e\,(V + \varnothing\,) = hc/\lambda$$

where
e = the electronic charge
V = the stopping potential
$\varnothing$ = the work function of the metal of the photosurface
λ = the wavelength of the light
h = Planck's constant
c = the velocity of light.

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

$$V = (\,hc/e)\,(\,1/\lambda)$$

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

$$h = (\text{Slope}*e)/c$$

The slope can be determined from the plotted data, or by fitting a least squares line to the points. Since almost all hand calculators have a least squares program installed, it is worth using it to fit your points. This is how the line in figure two was calculated.

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

$$h = .81 \times 10^{-6} \times 1.602 \times 10^{-19} / 2.998 \times 10^{8}$$

$$= 4.3 \times 10^{-34} \text{ Joule Seconds}$$

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

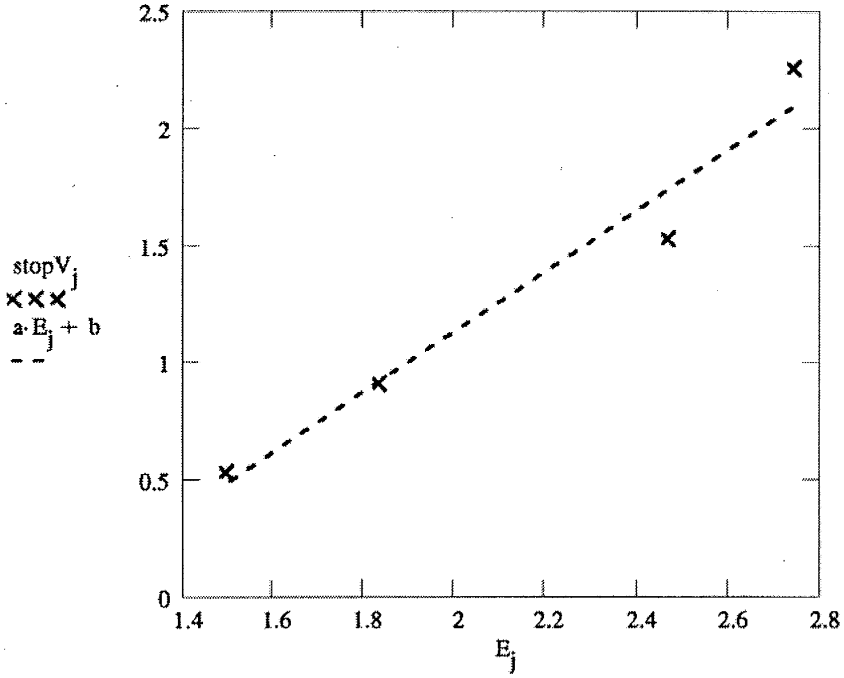
Alternative Light Source

Better results can be obtained using a Daedalon ES-18 Mercury Arc with an ES-19 Lamp Holder. This small lamp gives a pure mercury spectrum without the phosphor radiation from the fluorescent lamp. It will add another useful wavelength because the unfiltered arc emits an ultraviolet line at 365 nm.

A Daedalon ES-12 Diode Laser supplies the red radiation.

1. Put the blue filter over the aperture. Turn on the mercury arc. This will give monochromatic radiation at 405 nm.
2. Set the zero by turning the "Voltage" knob to its full clockwise position, about 3 Vdc. Adjust the "Zero" so that the meter reads zero.
3. Turn the "VOLTAGE" knob to its counter-clockwise limit. The voltmeter should read zero or very close to it. Move the apparatus until the radiation is striking the center of the photodiode.
4. Measure the voltage for zero current five times. The meter remains at zero for stopping voltages higher than the critical value. The value you need is when the current just reaches zero.
5. Change the filter, replacing the blue filter with the green one. This isolates the green line at 546 nm.
6. Repeat the measurements.
7. Remove the filter and let the mercury arc shine onto the photocathode. The envelope of the mercury arc transmits ultraviolet radiation so that the line at 365 nm is radiated.
8. Repeat the measurement sequence.
9. Finally replace the mercury arc with the ES-12 Diode Laser. Place the red filter over the aperture to reduce stray light from entering the aperture. You will need to place a diffuser to spread out the laser beam. It produces monochromatic radiation at 690 nm.
10. Repeat the measurement sequence.

We now have four measurements to plot and the irradiation was more monochromatic. Typical results are shown in Figure Three. This is a much better result than obtained with the fluorescent lamp source.



$$h := \frac{(1.602)\ a\cdot 10}{2.998} \qquad h = 6.89$$

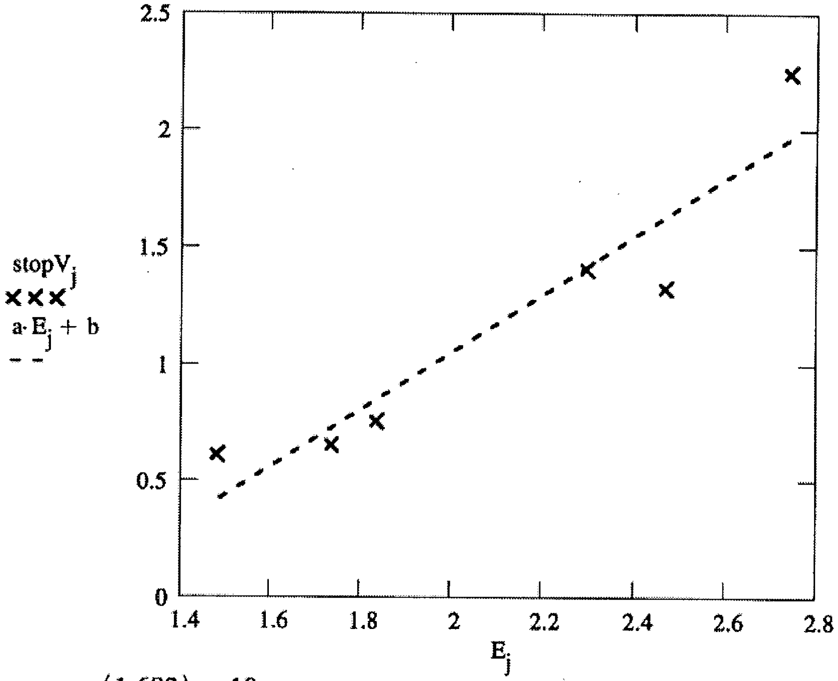
Accepted value 6.626

Figure Three

To further improve the result requires a set of interference filters to separate the mercury lines. These filters are quite expensive but do add two additional wavelengths. The filters supplied with the apparatus are not selective enough to separate all of the lines in the mercury spectrum. Interference filters are sharp enough so measurements can be made at 436 nm and 577 nm.

These filters have low transmission so a more intense mercury arc is required. The ES-18 was replaced by the ES-30 Low Pressure Mercury Arc. The interference filters were held in front of the aperture instead of the plastic filters and the measurements repeated. The laser was used for the red wavelength.

The results are shown in Figure Four. This is a very accurate measurement of Planck's constant for a short experiment. To get this accuracy, we have had to add enough additional material that the apparatus is no longer simple. Still, it is satisfying to see how good a result can be obtained.



$$h := \frac{(1.602)\ a\cdot 10}{2.998}$$

$h = 6.556$

Accepted value 6.626

Figure Four

The Work Function of the photocathode was not used in the derivation of Planck's constant. Its value is not needed. The characteristics of the photocathode are quite complicated and details are a trade secret of the manufacturer. A number of years ago, RCA described the S-4 surface, which is used in the 1P39 Phototube. It consists of a cesium-antimony "alloy". In the formation of this photocathode, an evaporated layer of antimony is treated with cesium vapor at 170°C. The resulting photocathode, which is believed to be a semiconductor Cs_3Sb, is characterized by high sensitivity in the visible spectrum. The Quantum efficiency is occasionally as high as 31% at 400nm, the wavelength of peak response.

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 and well worth reading.

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