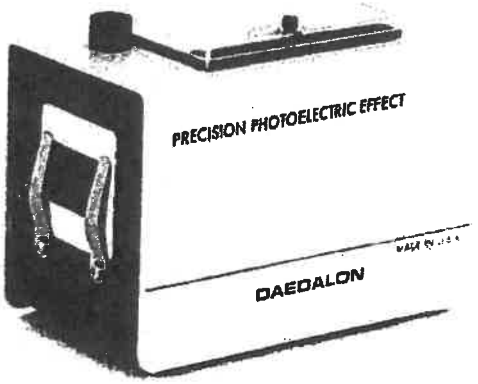
Instruction Manual

EP-07 Precision 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 incompatible with 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 being irradiated by monochromatic light depends upon the wavelength and not 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-07 Photoelectric Effect, 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

www.daedalon.com
800.299.5469
info@daedalon.com
Daedalon
The Science Source Company®

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 this stopping potential as a function of the reciprocal of wavelength gives a linear relationship, 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, fills this requirement nicely. The minimum detectable photocurrent is on the order of 1pA.

Operation

Light sources

The relative response of the phototube used in the apparatus is shown in fig. 1. The apparatus includes three filters to provide spectral separation, if monochromatic sources are not available. A fluorescent and a tungsten lamp can be used, although the results are not as good as with monochromatic sources. The Daedalon ES-18 Mercury Arc with an ES-19 Lamp Holder may also be used. This small lamp gives a pure mercury spectrum without the phosphor radiation from the fluorescent lamp.

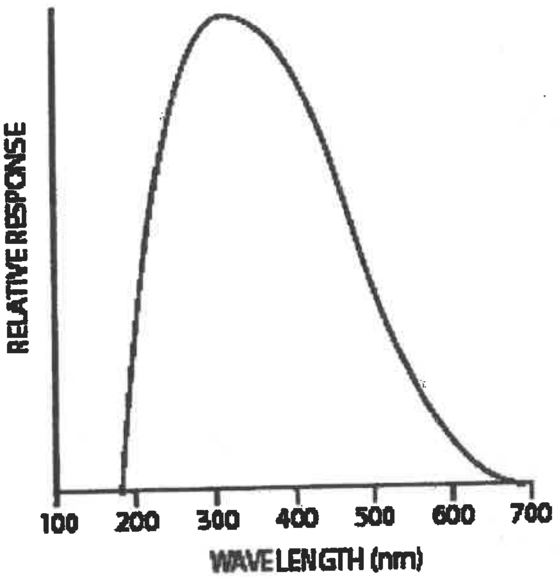


Figure 1

In general, when using sources of mixed wavelength, it is the shortest (highest energy) wavelength that will determine the observed stopping potential. Table 1 gives the resulting wavelengths possible with modern fluorescent, tungsten, and mercury arc sources are used in conjunction with the included gel filters and borosilicate glass (not included).

Table 1. Operational wavelengths of common light sources with supplied gel filters

	λ	operational λ using:		
filter	passed	tungsten	fluorescent	mercury arc
red	590	590		
green	546		546	546
blue	405		405	405
borosilicate glass	300			365
none				254

Best results are obtained with pure, monochromatic light from lasers. Common laser pointers are very effective sources, and are widely available in an increasing number of wavelengths. Most common are 635 or 650nm red, 535nm green, and 405nm blue pointers.

Set-up and data collection

The phototube is very sensitive to small amounts of stray radiation, particularly wavelengths shorter than those being measured. Ideally, the experiment should be performed in the dark. The unit is equipped with a red LED lightsource for illumination of the current meter. While the LED will not interfere with the performance of the apparatus, be sure not to allow its light to be reflected back into the tube. Even a hand in front of the unit will reflect sufficient light from the LED back into the tube to affect readings at longer wavelengths. If circumstances do not allow for a darkened room, construct a cardboard light shield around the phototube end of the apparatus and the light source.

When using light sources driven by unregulated supplies, fluctuation in photocurrent may be observed as output from the light source changes. If this occurs, and a regulated supply is not available, sufficient data must be taken to produce an average measurement.

Phototubes are subject to tradeoffs inherent in their function. The tube used in the Daedalon EP-07 has extremely low dark current, but is subject to a reverse current, arising from the flow of electrons from the anode to the cathode. Typically, stopping potentials are measured in a photoelectric experiment by increasing the voltage between the anode and cathode until electrons are repelled from the anode. This neglects reverse current, however, as it is acting in concert with the stopping potential to impede electron flow. For this reason, it is necessary to identify the point at which the photocurrent curve departs from the reverse current curve (fig.2). The sensitivity of the EP-07 is such that this departure is readily visible by carefully watching the sweep of the current needle, keeping in mind the transition from a constant slope of reverse current vs. voltage to the photocurrent vs. voltage curve.

It is also possible to collect readings of I vs. V and graphically determine the stopping voltage, as in fig.2. Monitor jacks are provided on the rear panel of the unit for this purpose. Photocurrent is converted to voltage at the monitor jack at a rate of 10mV/nA.

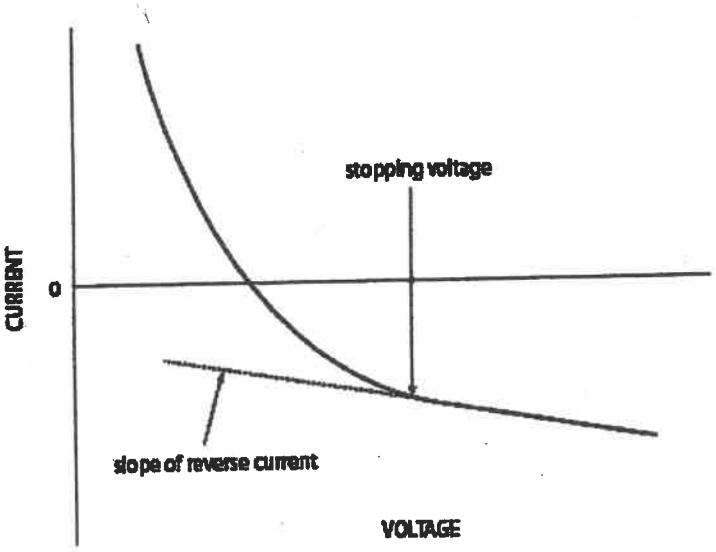


Figure 2

Procedure

The nature of the photoelectric experiment is one of extremely low currents and very high amplifications. The quality of results from the EP-07 is directly related to the care and precision with which data are collected.

I. Determination of Planck's constant

1. Set up the apparatus on a table so that the aperture in front of the photodiode faces the light source. The aperture is 7cm above the bench top, so the box or source may have to be raised to line them up.
2. Connect a digital voltmeter to the red and black banana jacks on the rear 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 the EP-07 on. Allow the unit to warm up for about five minutes. If using a mercury arc light source, turn it on at this time, as well. Mercury arcs may take up to 30 minutes to stabilize.
4. Determine the wavelength desired and have ready any necessary filters. Prepare the work area for working in darkened conditions.

5. Turn out the lights. Select the 60nA scale. Turn the VOLTAGE knob to its full counterclockwise position. Adjust the ZERO so that the meter reads zero.

6. Insert any filters and turn on the light source. Move the apparatus and light source realtive to each other until the reading on the output meter is 30nA. You may find it necessary to diffuse the source, particularly when working with lasers. This is best done with white paper over the laser.

Calibration of EP-07

Note: To determine the stopping potential, two methods are possible: 1. decreasing voltage until the needle transitions from a very slow sweep to a faster one (as it changes from reverse to forward current), or 2. increasing voltage until the fast sweep transitions to slow. It is recommended that both methods be used, as they may produce different voltages. Averaging these data produce excellent results.

Approach the transition from either end

7. Turn the VOLTAGE knob to its maximum. Switch to the 1nA scale. At this time, the needle may be positioned with the ZERO knob to any point in the scale that is most convenient to observe (roughly 1/4 scale is usually best).

8. Manipulate the VOLTAGE knob to coarsely observe the transition zone between slow and fast sweep. Focus on this zone. Return the VOLTAGE knob to a high level, so that the needle is below the transition. Using infinitesimal adjustment, decrease the voltage, keeping in mind figure 2. You will observe very, very slight, consistent movement of the needle as voltage is slowly decreased. The sweep of the needle will then be "felt" to minutely increase in response to the VOLTAGE knob. At this point, record the voltage.

Measurement

Note: A small amount of capacitance exists between the elements of the phototube. When adjusting voltage, a small amount of current may be visible in the needle as this capacitance charges or discharges. This may be accounted for by very slow adjustment of voltage or by waiting briefly (~1s) for current to stabilize.

9. Repeat this measurement using an increasing voltage, watching again for the subtle transition between sweep rates. Take as many measurements, switching between methods, as practicably possible. If collecting both I and V measurements, be sure to take as many points as possible around the transition zone, and several at high voltages where reverse current dominates.

10. Repeat steps ~~4-8~~ 7,8,9 for each wavelength.

← Here may be the issue that led to a shifted slope on the $V_{stopped}$ vs freq plot.

II. Independence of stopping voltage on intensity

To verify Einstein's prediction and Millikan's experiment that stopping voltage is a function of wavelength and not intensity, repeat the experiment using a different starting intensity in step 6, and compare your results.

Analysis

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 energy is expressed by Einstein's relationship:

$$E_p = h\nu$$

where

E_p = the quantum energy of the photon
h = Planck's constant
ν = the frequency of light

When the photon impinges on a solid, this energy is tranferred. If E_p exceeds the characteristic energy that is required to remove an electron from the surface of the solid (the solid's work function, ϕ), the resulting kinetic energy of the electron, E_e, can be seen to be the balance of the transferred energy:

$$E_e = E_p - \phi$$

Our experiment measures the point where the stopping potential acting on the electron just equals this kinetic energy, so that substituting and rephrasing in terms of wavelength,

$$eV = hc/\lambda - \phi$$

where

e = the electron charge
V = the stopping potential
c = the velocity of light.
λ = the wavelength of light

Rearranging,

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

Therefore, a plot of V versus $1/\lambda$ will have slope hc/e and y-intercept ϕ. Planck's constant can then be estimated as

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

Sample results

Table 2. Sample results using laser pointers (405, 535, 650nm) and Daedalon ES-18 Mercury Arc (unfiltered, 254; borosilicate glass filter, 365nm).

	wavelength (nm)				
obs	254	365	405	535	650
1	3.44	2.25	1.813	1.09	0.522
2	3.42	2.43	1.812	1.14	0.637
3	3.18	2.1	1.664	1.22	0.58
4	3.47	2.16	1.72	1.21	0.577
5	3.2	2.21	1.737	1.17	0.636
6	3.36	2.29	1.695	1.21	0.602
7	3.3	2.36	1.805	1.31	0.581
8	3.33	2.2	1.65	1.072	0.582
9	3.37	2.26	1.618	1.013	0.56
10	3.39	2.15	1.68	1.12	0.61
mean	3.346	2.241	1.7194	1.1555	0.5887

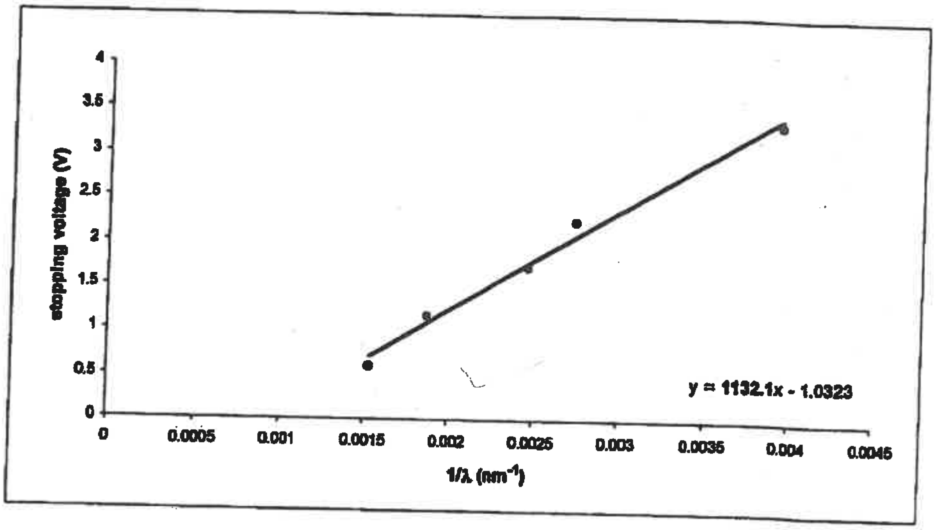


Figure 3. Stopping voltage vs. wavelength for sample data. Note that wavelengths and resulting slope are in nm.

Typical data are shown in table 2 and resulting regression in figure 3. Note that our slope is in nm, not m. To calculate Planck's constant, we need the velocity of light,

$$c = 2.998 \times 10^{8} \text{m/s}$$

and the charge on the electron,

$$e = 1.602 \times 10^{-19} \text{coulombs}$$

so that in this example,

$$h_{calc} = (1.132 \times 10^{-6} * 1.602 \times 10^{-19}) / 2.998 \times 10^{8} = 6.05\times10^{-34} \text{ joule-seconds}$$

The accepted value of Planck's constant is 6.626×10^{-34} J·s, or ~3.4% error. Remember that the quality of your results depend heavily on the monochromaticity of the light sources being used and the care with stopping voltages are determined.

Specifications

Phototube:	R727 mounted inside the amplifier case
Amplifier:	Ultra low leak currenk input FET; Dual FET meter op-amp
Current Sensitivity:	1 pA minimum
Spectral Separation:	provided by red, green, blue gel filters
Dimensions:	17 x 9 x 11 cm (3.5 x 6.7 x 4.0 in.)

$\sigma_x \sigma_p$