

## EP-07 Precision Photoelectric Effect

### Introduction:

The photoelectric effect experiment was suggested by Einstein in 1905, and it provided convincing experimental verification of quantum theory. The actual phenomenon of photoemission of electrons from metals was observed by Hertz in 1887. However, Hertz's experimental data proved to be incompatible with the wave theory of light. Einstein postulated that not only is light emitted and absorbed in discrete bundles, as proposed by Planck, but it is propagated that way as well. In the photoelectric effect experiment, the velocity of electrons leaving the surface of a metal being irradiated by monochromatic light depends upon the wavelength of light and not the intensity of the radiation. With the EP-07 Precision Photoelectric Effect, you will be able to repeat the essential part of the experiment that served to establish the quantum theory of radiation. In this experiment, the photocathode is irradiated by a source of monochromatic radiation and a potential is applied to the tube so that the resulting electric field between the anode and the cathode 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 wavelength gives a linear relationship, the slope of which can be used to calculate Planck's constant.



### Specifications:

Phototube:	R727 mounted inside the amplifier case Response: 185 to 650 nm Peak Response: 340 nm
Tube current:	Low (0-200 nA) High (0-20 $\mu$ A) Backing volts
Experiments:	1a - photoelectric effect 1b - illumination/current relationship 1c - energy in photons 1d - Planck's constant 1e - energy distribution 2 - energy distribution
Display:	LCD
Filters:	470 nm, 580 nm and 630 nm are included

### Front Panel Controls:

Experiment rotary switch (left of meter) - three position (off, 1a-e, and 2):

- 1) Use this switch to turn the unit on, when it is connected to a wall outlet via the adapter.
- 2) Select experiment by choosing 1a-e or 2.

Meter reading rotary switch (right of meter) - three position (low 0-200 nA, high 0-20  $\mu$ A, and backing volts):

- 1) Select the digital meter to read very small current through the tube (0-200 nA).  $1 \text{ nA} = 1 \times 10^{-9} \text{ A}$ .
- 2) Select the digital meter to read larger current through the tube (0 -20  $\mu$ A).  $1 \mu\text{A} = 1 \times 10^{-6} \text{ A}$ .
- 3) Select the digital meter to read the backing voltage applied to the tube. The backing voltage is adjustable from 0 to -1.8 V. When experiment 2 is selected, this switch position monitors the 0 to +20 V applied to the tube from the external sockets.

Adjust backing volts rotary control:

When in experiment 1, using this switch adjusts the backing voltage applied to the tube from zero to about 1.8 V. The application of this voltage to the tube (backwards) is to reduce the current passing through the tube to zero nanoamps (nA). When experiment 2 is selected, this control has no function.

External sockets:

When experiment 2 is selected, an external voltage not exceeding 20 V DC can be connected to these sockets to perform the experiment dealing with the forward current characteristics of the phototube when illuminated. Although an external voltage is applied to the sockets, the adapter must still be connected to a wall outlet to supply power to the unit.

**Meter:**

The digital meter is on when the power is on.

Experiment 1 - Reads the selected current flow through the phototube of 0-20  $\mu\text{A}$  or 0-200 nA. Reads backing volts applied to the tube as adjusted by the front panel control from 0 to -1.8 V.

Experiment 2 - Reads 0-20  $\mu\text{A}$  current flow through the phototube or reads the adjustable forward volts from 0 to +20 V as applied to the tube from external sockets.

**Fitting color filters:**

Two pairs of guides are fitted to the rear face of the instrument, just in front of the light source. If a filter is inserted, the light that reaches the cell contains all the wavelengths that pass through the filter.

**CAUTION:** It is important that during an experiment, no other light than the light through the filter reaches the phototube. You may wish to use a cardboard box to cover the light source and the area around the phototube opening during the experiment, so that unwanted ambient light does not enter the apparatus. If a mercury arc light source is utilized, a plain glass filter is required to remove ultraviolet light content from the light, while leaving the shortest visible wavelength present for violet (about 390 nm).

**Phototube:**

The phototube is an essential part of the instrument. It is an evacuated glass tube containing an electrode shaped like a half cylinder. At the open mouth of the electrode, another electrode, in the form a straight rod, is positioned at approximately the focal point of the curved surface.

**Anode:**

Light enters the tube to illuminate the cathode. The anode is a metal rod to which the electrons flow. It is illuminated, as it is located in front of the cathode. The bombardment of the anode with photons causes the metal surface of the anode rod to release some electrons (unwanted Photoelectric Effect). Light is reflected from the glass envelope and from the curved cathode surface back onto the anode rod. This anode emission must be avoided because it will interfere with the normal migration of the electrons from the cathode surface to the anode. It will create an error when measuring the exact backing voltage required to stop the electron flow from the cathode to the anode. To reduce this error, a shield is fitted to the glass envelope of the tube to shield the anode rod from direct light. Reflections inside the tube cannot easily be avoided.

**Cathode:**

The curved surface of the cylinder is called the cathode. It is coated with a metal that easily releases electrons when light (or photons) strike the curved surface. When light strikes the metallic surface, the energy contained in a photon is passed to an electron which must rise to the surface of the cathode material. Then, the electron must overcome the tendency to remain on the surface. When the electron is released from the surface, it travels through the vacuum towards the anode rod. Current is flowing as electrons are released from the surface of the metal.

**The Purpose of the Photon Energy Experiment:**

To measure the energy of photons, we need to detect but not measure the current through the phototube. Photons of different energies excite electrons to different energies. The experiment is to determine the highest energy level to which the electrons have been excited by the photons. There will be only a small percentage of electrons from the cathode to the anode with these highest energies. A small reverse voltage (anode negative, cathode positive) is applied just high enough to completely stop the flow of electrons. This reverse voltage is called the backing voltage. When all the electrons stop flowing (zero current), the voltage has repelled the electrons, including the ones with the highest energy acquired from the photons.

Filters placed in the path of the light will pass frequencies below their cut off frequency. Most wavelengths of light will drive electrons from the cathode, but the wavelength of the particular filter is the shortest wavelength (highest frequency) of light that can pass to the phototube.

**Theory:**

The photoelectric effect occurs when light greater than certain threshold frequencies impinges on the surface of metal and causes electrons to be ejected from the surface of the metal. Assuming that light interacts with the surface of the metal as photons of wavelength,  $\lambda$ , the energy carried by the incoming radiation can be expressed by the following relationship:

$$E_p = h\nu$$

where

$E_p$  = quantum of energy of the photon

$h$  = Planck's constant ( $6.626 \times 10^{-34} \text{ J} \cdot \text{s}$ )

$\nu$  = frequency of light (Hz or  $\text{s}^{-1}$ )

When the photon impinges on a solid, the this energy is transferred. If the energy ( $E$ ) exceeds the characteristic energy that is required to remove an electron from the surface of the solid (solid's work function,  $\phi$ ), the resulting kinetic energy of the election,  $E_k$ , can be seen to be the balance of the transferred energy:

$$E_k = E_p - \phi$$

The experiment measures the point where the stopping potential acting on the electron just equals the kinetic energy:

$$E_k = Ve$$

where

$e$  = charge of an electron ( $1.609 \times 10^{-19} \text{ C}$ )

$V$  = stopping potential

Using the relationship between frequency and wavelength,  $\lambda$ , of the photon,

$$c = \lambda\nu$$

where

$c$  = speed of light ( $2.998 \times 10^8 \text{ m/s}$ )

$\lambda$  = wavelength (nm)

We can substitute and making the following rearrangements:

$$E_p = h\nu$$

$$E_k = h\nu - \phi$$

$$E_k = h \frac{c}{\lambda} - \phi$$

$$Ve = h \frac{c}{\lambda} - \phi$$

$$V = \frac{hc}{e} \cdot \frac{1}{\lambda} - \phi$$

Therefore, a plot of  $V$  versus  $1/\lambda$  will have a slope of  $hc/e$  and y-intercept  $\phi$ . Planck's constant can be estimated as  $h = (\text{slope} \cdot e)/c$ .

### Operation:

#### LIGHT SOURCES:

The apparatus may be used with a colored filter (e.g., red, green or blue) if a monochromatic source is not available. A fluorescent or tungsten lamp can be used, although the results are not as good as with monochromatic sources. The ES-18 Mercury Arc Small may also be used along with the ES-19 Bracket for ES-18. This ES-18 small lamp gives a pure mercury spectrum without the phosphor radiation from a fluorescent lamp. In general, when using sources of mixed wavelength (nm), it is the shortest (highest energy) wavelength that will determine the observed stopping potential. The operational wavelength with no filter and a mercury source is 254 nm. 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 red (635 or 650 nm), green (532 nm) and blue (405 nm).

Filter	$\lambda$ passed	Operational $\lambda$ using:		
		Tungsten	Fluorescent	Mercury Arc
Red	590	590		

Green	546		546	546
Blue	405		405	405
Borosilicate glass	300			365
None				254

**General notes on running experiments:**

- 1) Select TUBE CURRENT on the meter switch to monitor the current through the phototube. Begin by selecting the 0-20  $\mu\text{A}$  range, and as this reduces almost to zero, select the very sensitive 0-200 nA range. If the current exceeds 200 nA, the display will be out of range. Select the higher range again.
- 2) The light source will be illuminating through the aperture at the rear of the instrument. The light source will become warm, which is normal. However, do not allow the light source to run for very long periods of time unattended or overheating may occur.
- 3) If the current is over-range, select the higher current range. Leave the meter switch on TUBE CURRENT and increase the backing volts using the black knob until the current (electron flow) through the tube reads close to zero microamps. Then, select the low range again adjust voltage to achieve 0.0 nanoamps through the tube.
- 4) Without disturbing anything, select BACKING VOLTS and observe the exact voltage that is being applied to the phototube in reverse to stop all electrons from reaching the anode. Note the wavelength of the filter used and the backing volts reading.

**Investigations:****Experiment 1a - Photoelectric Effect**

- 1) Select experiment 1 and power up the instrument.
- 2) Turn the ADJUST knob counterclockwise to set backing volts to zero.
- 3) Set the meter switch to read TUBE CURRENT high (0-20  $\mu\text{A}$ ).
- 4) Set up a light source (e.g., incandescent light or mercury arc lamp) so that it faces the aperture at the back of the unit. The meter will show current flowing through the tube, which is caused by photons from the light source striking the cathode and driving off electrons.

**Experiment 1c - The Energy in a Photon Depends on the Frequency of the Light**

When light from the light source is passed through a color filter, it is possible to determine the energy of the electrons by applying a small voltage to the tube in the reverse direction to determine the voltage that stops all the electrons from traveling from the cathode to the anode. When the current is no longer flowing, the value of this voltage is a measurement of the level of energy of the most energetic electrons. This means that the electrons were excited by the photons of the highest frequency (shortest wavelength) component of the light beam entering the phototube. Each colored filter has a different wavelength associated with it. It takes a different backing voltage to stop the current created by different wavelengths. Therefore, the energy of the photon that was transferred to the electron depends on the wavelength of the light. By using the different filters and recording the backing voltage values for each color, it is possible to make a plot of backing voltage versus frequency. The plot will be a straight line. The energy of a photon is proportional to the frequency of the light, and the energy is higher for higher frequencies. A photon behaves like a particle when it transfers energy to an electron. A photon behaves like a wave when it reflects or diffracts to create interference patterns through slits or gratings.

Quick overview of the method:

With the light source illuminating the phototube on the back of the unit and a colored filter in place, observe the current flowing and find the backing volts that just stop the current. Plot backing volts versus frequency for each light source/filter combination.

Steps:

- 1) Select experiment 1 and power up the instrument.
- 2) Set up a light source so that it faces the aperture at the back of the unit. Add the filter and secure with tabs on the back of the unit.
- 3) Select TUBE CURRENT low (0-200 nA) to see the current flow.
- 4) Increase the backing voltage to get exactly zero current flow at the low amps setting (0-200 nA).
- 5) When the current is at exactly zero, select BACKING VOLTS by turning the black knob to the appropriate position.
- 6) Read the backing voltage off the LCD display and record the value.
- 7) Note the wavelength of the filter used and the backing voltage required for the particular wavelength. Repeat steps 3-6 three times in order to obtain an average reading of the backing volts for the particular wavelength.
- 8) Change out the filter (new color/wavelength) and repeat the experiment until all the colored filters available have been utilized with the light source chosen (e.g., incandescent bulb or mercury arc).
- 9) Convert each wavelength to frequency ( $\text{Hz}$  or  $\text{s}^{-1}$ ). Sample calculations shown below. Make a plot of volts versus frequency. The graph should be a straight line.

Sample calculation for 670 nm:

$$c = \lambda \nu$$

$c$  = speed of light ( $3.00 \times 10^8$  m/s)

$\lambda$  = wavelength (m)

$\nu$  = frequency ( $s^{-1}$ )

$$3.00 \times 10^8 \text{ m/s} = 6.70 \times 10^{-7} \text{ m} (\nu)$$

$$\frac{3.00 \times 10^8 \text{ m/s}}{6.70 \times 10^{-7} \text{ m}} = \nu$$

$$\left(\frac{3.00}{6.70}\right) \times 10^{8+7} \text{ s}^{-1} = \nu$$

$$0.448 \times 10^{15} \text{ s}^{-1} = \nu$$

$$4.48 \times 10^{14} \text{ s}^{-1} = \nu$$

### **Experiment 1d - Planck's Constant**

Using the data collected for the various light source/filter combinations, make a plot of stopping voltage (V) versus  $1/\lambda$  ( $\text{nm}^{-1}$ ). Sample calculations are shown below for a plot with a line regression of  $y = 1183.4x - 1.1418$ .

Step 1:

Convert nm to m.

$$1183.4 \text{ nm} \times \frac{1 \text{ m}}{10^9 \text{ nm}} = 1.183 \times 10^{-6} \text{ m}$$

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

$h$  = Planck's constant ( $6.626 \times 10^{-34} \text{ J} \cdot \text{s}$ )

$c$  = speed of light ( $2.998 \times 10^8$  m/s)

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

$$h = (1.183 \times 10^{-6} \text{ m} \times 1.602 \times 10^{-19} \text{ C}) / 2.998 \times 10^8 \text{ m/s}$$

$$h = 6.32 \times 10^{-34} \text{ J} \cdot \text{s}$$

This represents an error of ~4.6%. The quality of the results obtained will depend heavily on the monochromatic nature of the light sources used and the care with which stopping voltages are obtained.

### **Experiment 2 - Characteristic Curve of the Phototube**

1) Select Experiment 2

2) Connect an adjustable power supply to the red and black sockets on the front of the unit. The power supply must be in the range of 0-20 V DC. Voltage is not a backing voltage in this experiment because voltage applied to the tube is in a forward direction to encourage electron flow from the cathode to the anode.

3) Shine an incandescent light source on the aperture at the back of the unit. Do not use filters.

4) Select TUBE CURRENT high (0-20  $\mu\text{A}$ ).

5) Gradually increase the applied voltage from zero to about 20 V DC.

6) Plot the relative phototube current in microamps against the applied forward voltage to obtain the characteristic curve of the phototube.

### **Warranty and Parts:**

We replace all defective or missing parts free of charge. Additional replacement parts may be ordered. We accept MasterCard, Visa, checks and School P.O.s. All products warranted to be free from defect for 90 days. Does not apply to accident, misuse or normal wear and tear. Intended for children 13 years of age and up. This item is not a toy. It may contain small parts that can be choking hazards. Adult supervision is required.