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Our Understanding of Light, the Photoelectric (PE) Effect and the Birth of Modern Physics

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Foundations New Orleans 2019
Physics Lab Packet
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"But what is light really? Is it a wave or a shower of photons? There seems no likelihood for forming a consistent description of the phenomena of light by a choice of only one of the two languages. It seems as though we must use sometimes the one theory and sometimes the other, while at times we may use either. We are faced with a new kind of difficulty. We have two contradictory pictures of reality; separately neither of them fully explains the phenomena of light, but together they do."

Albert Einstein and Leopold Infeld, *The Evolution of Physics*

IS LIGHT A *PARTICLE*? OR IS LIGHT A *WAVE*?

PARTICLE: In physics, a particle is a small, localized object to which can be ascribed several physical properties such as volume or mass. Particles vary greatly in size or quantity, from subatomic particles like the electron, to microscopic particles like atoms and molecules, to macroscopic particles like powders and other granular materials. Shoot a well-aimed particle at something and, if it has the right mass and momentum, it will strike the object with a localized impact and possibly set it in motion by transferring its energy to that object.

WAVE: In physics, a wave is an oscillation accompanied by a transfer of energy that travels through a medium (space or mass). It transfers energy through matter (such as sound waves which transfer energy through air molecules) or through space (such as electromagnetic waves, which do not require a medium with mass). Some waves flow around things and reform, as ocean waves do around piers. Ocean waves are created by energy passing through water transferred to the water by wind (hurricanes), or underwater disturbances such as volcanic eruptions or earthquakes (tsunamis).

LIGHT: Light does some very particle-like things, such as knocking electrons off of metal plates in such a way that it transfers energy to them, sending them in motion. But light also flows around objects and reforms its pattern, which is what waves do. In fact, its spectrum of colors is created when it travels at certain *wavelengths*.

Think of a champion bowler shooting a bowling ball (particle) toward bowling pins (electrons) and the motion that is imparted to the pins. Light has a similar effect on electrons when it shines upon a metal plate. But unlike the bowling ball, the intensity of the light doesn't affect the transfer of energy to the electrons; only the wavelength frequency does. What happens to the electrons makes it look as if they are being hit by particles, but the behavior of the light that is hitting them is definitely wavelike.

Thus, the mystery of light puzzled scientists for centuries.

Lab Background and Explanation: Foundations New Orleans begins with an explanation of how models of light were developed through 2000 years of observations, experiments and imagined explanations. Eventually the explanation arrived at the wave-particle duality model for light. Once developed, this explanation became foundational to all of modern Physics. Understanding this "duality" is required to consistently and coherently explain the "photoelectric effect" (PE). Numerous physicists puzzled over the photoelectric effect, where incident light could eject electrons from surfaces with varied but predictable energies. Other interesting behaviors relating to the incident light, the nature of surface and the electrical current at times seemed to both confirm and disconfirm light as a wave and light as a particle. This puzzle over the photoelectric effect lasted for more than half a century.

Finally, in 1905, Albert Einstein proposed an imaginative and brief explanation in a paper proposing a "wave-particle duality". This scientific insight required carefully collected observable behavior. Using data collected by the experimental physicist Phillipp Lenard, Einstein demonstrated that the photoelectric effect required a newly imagined scientific model for light that depicted the event in terms of *wave-particles* (called “quanta” by Einstein in his Nobel Prize Winning paper). The “quanta” will never be directly seen but are inferred by the behavior of charged particles escaping a surface, as detected by electrical measurements, due to an interaction of the surface with incident light.

Our focus will be to understand the photoelectric effect according to Einstein’s model. Together we will review the major observations and experiments that brought the dilemma of wave-particle duality to the forefront of early 20th century physics. Teams will gather electron ejection energy as a function of incident light frequency. The data will be collected across all teams and groups for analysis in the Concluding Session. Teams will also explore the capabilities of the simulation of the PE effect and the different values that can be measured and observed. Teams will gather data with stated expectations. Possible interacting values include light frequency (color), light intensity (brightness), electrical current (amperes), stopping voltage (Volts) required to stop the flow of electrons from the surface (and so therefore electron ejection energy).

In each lab, groups will organize and prepare the data collected for presentation. The two groups will then come together to discuss the results of the investigations. It will become obvious to all who have participated and reflected on the experiment that BOTH the wave and particle models of light are REQUIRED to explain all possible photoelectric experiments.

The introductory presentation, lab experiences and concluding presentations will allow participants to experience how science and modern physics is presently done. In addition to a pivotal laboratory that birthed modern physics as understood today all will have experienced and reflected on how science generates new knowledge and models.

There are unique insights available to those with an understanding of the photoelectric effect (and the modern view of light) in a wide variety of disciplines (including philosophy and theology). Every participant will have a broader view of science, philosophy and theology as a result of this collective effort.

Physics Lab Glossary (also helpful for FNO Chemistry Lab)

Current: The flow of electric charge measured in Amps. In the photoelectric effect experiment, if electrons (negatively charged particles) reach the negatively charged metal plate, a current will be detected.

Diffraction: the process by which a beam of light or other system of waves is spread out as a result of passing through a narrow aperture or across an edge, typically accompanied by interference between the wave forms produced.

Energy: The property that must be transferred to an object in order to perform work on it, make it move, or heat it. There are many types of energy, and energy can be transferred from one type into another. In the photoelectric effect experiment, energy from the incoming light is transferred to the electrons that ejects them from the metal. In the flame test experiment, energy is released in discrete amounts as the electrons jump between orbitals. In biology, energy is required in order to sustain life.

Frequency: The number of wave cycles that pass by a given point per second. Hertz (Hz) is the standard unit for frequency. The frequencies of visible light range from 4.3×10^{14} Hz to 7.5×10^{14}Hz.

Intensity: The brightness of the light. The intensity of a wave is related to its amplitude. Waves with greater intensity (or amplitude) carry more energy than waves with smaller intensity (or amplitude).

Interference: is a phenomenon in which two waves superpose (add together) to form a resultant wave of greater, lower, or the same amplitude.

Speed of Light: The speed at which light travels through a vacuum is 3.00×10^8 m/s. Scientists often use the formula, speed = frequency x wavelength, to convert frequency into wavelength or wavelength into frequency.

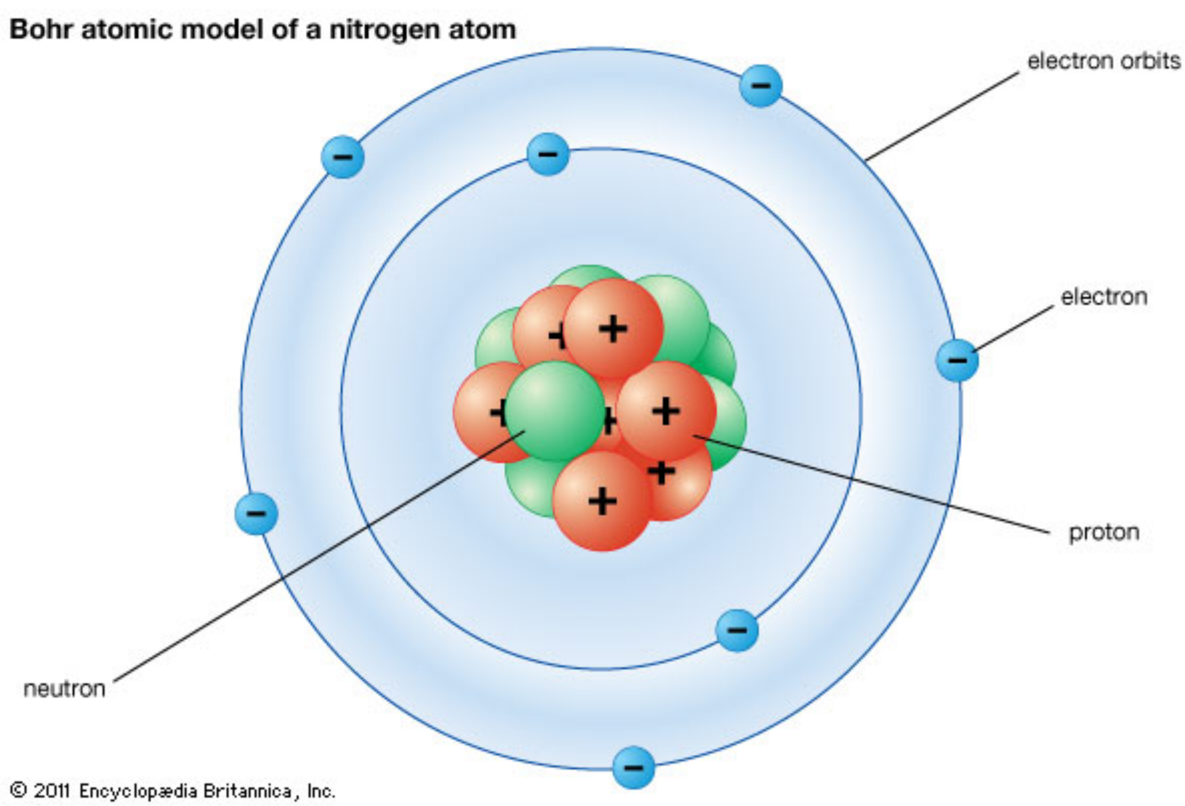
Visible Spectrum: Different colors of light correspond to different wavelengths (or frequencies) of light. The smallest wavelength that the human eye can detect is about 400 nanometers. The largest wavelength that the human eye can detect is about 700 nanometers. All of the colors that we see correspond to different wavelengths on this spectrum.

Voltage: A measure of the difference in electric potential between two points in space, a material, or an electric circuit, expressed in volts. In the photoelectric effect experiment, voltage is the force that slows down the electrons as they are released from the metal surface. Since electrons are negatively charged, they are repelled by the negatively charged metal plate. As the voltage becomes more negative, it pushes against the electrons with greater force.

Wavelength: The distance traveled by a wave as it completes one full cycle. It is often measured from one peak of the wave to the next peak. For visible light, the unit of nanometers (nm) is often used when expressing wavelength. A nanometer is one billionth of a meter.

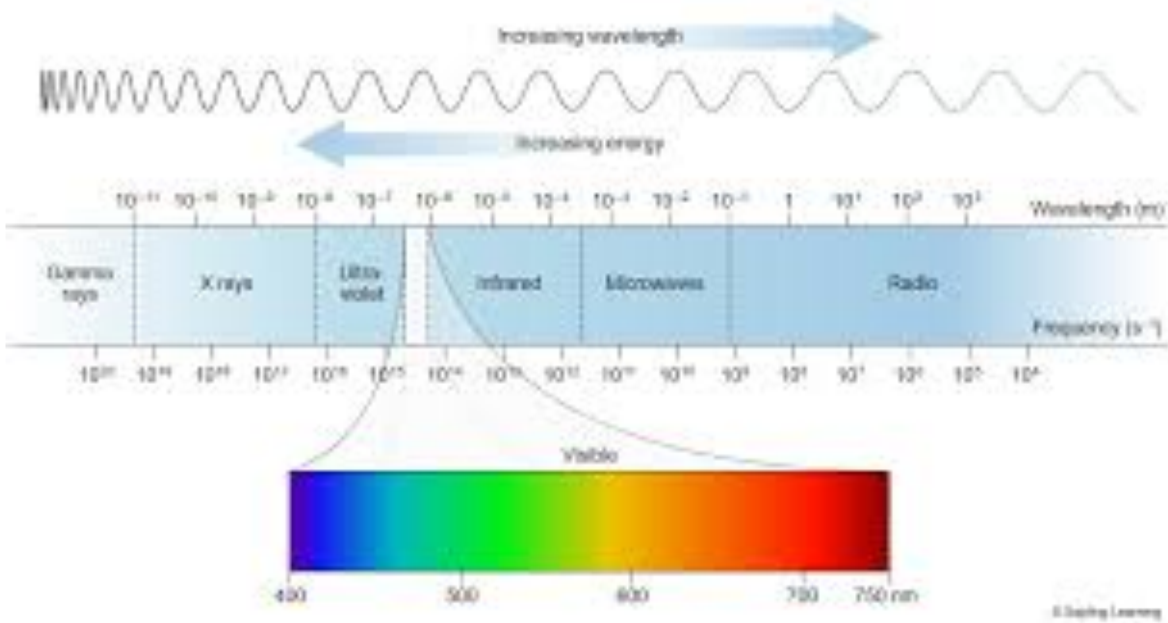
Simple Atomic Model

The nucleus is at the center of the atom and contains positively charged particles called protons and electrically neutral particles called neutrons. Electrons are negatively charged particles that orbit the nucleus in what is referred to as an electron cloud. The electric force of attraction between the positively charged nucleus and the negatively charged orbiting electrons holds the atom together. The solar system can be a useful model for understanding atoms. The sun is like the nucleus. The planets are like the orbiting electrons. The gravitational force that attracts the planets to the sun is like the electric force that holds the atom together. Atoms have the same number of electrons as protons. If an atom loses an electron, it becomes an ion. This process is called ionization, and it requires a certain amount of ionization energy.



The electromagnetic spectrum

Light is often referred to as an electromagnetic wave. As a wave, it has frequency and wavelength. Here is a diagram showing the relationships between energy, wavelength, and color.



Appendix A
Geometric and Wave Optics Lab
(Introductory Demo by M. Foss)

Geometric and Wave Optics Lab

Developed by
University of Notre Dame — Abigail Mechtenberg
Physics Department — Adrian Valverde, Michelle Coeman
Debate: Philosophy and Science

Objectives

- To understand the behavior of light
- To observe light as a wave in refraction and diffraction
- To appreciate why Newton was incorrect to conclude that light is a particle based on his interpretation of Snell's law, but logically understandable because light travels as a deflected ray in the glass
- To appreciate why light can only be described as a wave in Snell's law of refraction and with the laser diffraction
- To appreciate why now we understand that light is a quantized packet of photon energy that behaves as a particle and as a wave

Diffraction, Geometric Optics and the Particle/Wave Debate

The understanding of geometric optics dates back to the development of lenses in ancient Egypt and Mesopotamia; the earliest philosophical descriptions include work by Plato and Euclid. A mathematical understanding of geometric optics can be dated back to the the work of Hero of Alexandria (c. 10-70 AD) on reflection, and the work of Ibn Sahl (c. 940-1000 AD) on refraction; it was codified in the work of Willebrod Snellius in 1621, as well as by Rene Descartes in 1637. This gives us two laws, the Law of Reflection and the Law of Refraction, which is also known as Snell's Law.

While this geometric description of light accurately describes the behaviour of light in many cases, it does not offer any explanation of its fundamental nature. Around the sixth century BC, there were two competing theories about light in ancient Greek thought. In one theory, light was thought to flow as particles. In another theory, light was sparkling waves called *eidola*. Even into the late 1600s and early 1700s, the debate raged between supporters of Isaac Newton's 1704 book *Opticks* and Christiaan Huygen's 1690 *Traite de la Lumiere*. On the next page is a table summarizing the two views at this time.

Brief History of Light as a Particle	Brief History of Light as a Wave
Newton was interested in light from very early on in his career; the work that first brought him to the attention of the scientific community was his experimental investigation of colour, & his invention of the 'Newtonian' reflecting telescope (work done in 1666-68, and published in 1672). However this work provided no theory of how light worked, and Newton made attempts at this for many years. For various reasons he favoured a particle theory of light – the explanation of light propagation in straight lines, except at interfaces, was then easily understood. Still, the light particles were acted upon by an invisible aether. Newton did not publish his theory until 1704, after the death of Huygens; he was by then the best-known scientist in Europe.	Huyghens made key contributions to mathematics, astronomy, & physics. However his most important contribution to science by far was his wave theory of light. He argued that the known properties of light, such as refraction, reflection and propagation in straight lines, could be understood by assuming that light was a wave in some invisible medium, analogous to waves moving in a fluid. Refraction could be understood if the waves traveled more slowly in a dense medium (like waves in shallow water). He gave the first theory of wave propagation, showing, amongst other things how they could be built up from 'elementary wavelets', radiated in circular patterns from multiple sources.
	- Written by Philip C. E. Stamp, 2011

In this cookbook lab write-up, students will do two parts. The first part will be looking at Snell's Law and understanding the geometric description of light as a ray. The second part will be looking at diffraction of light around a human hair and understanding Huygen's perspective on light as a wave. These two concepts being simultaneously true is the foundation for modern physics.

Part 1: Snell's Law

Geometric optics (or ray optics) considers the propagation of light in terms of a single line or narrow beam of light, through different media. It is a very useful way to consider optical systems especially when imaging is involved.
Geometric optics is based on the consideration that light rays:

- propagate in a rectilinear (straight-line) path in homogeneous (uniform) medium
- change direction and/or may split in two (through refraction and reflection) at the interface or boundary with a dissimilar medium (only two media are considered here: glass and air).

Although powerful in understanding the geometric aspects of optical systems, such as imaging and aberrations (faults in images) it does not account for effects such as diffraction and interference.
The two media of concern here are air and glass and the parameter that characterizes their optical property as far as geometric optics (and lenses) is concerned is their refractive index, n.
Refractive index, n relates to the speed of light in media and is defined

$$n = \frac{c_{\text{vacuum}}}{c_{\text{medium}}}$$

By definition the refractive index of a perfect vacuum is unity (i.e. exactly one). The refractive index bears a close relationship to relative permittivity, εr and can be understood to result from the interaction between matter and light's electric and magnetic fields.

Light incident upon a boundary between media with different refractive indexes will be reflected and transmitted. In addition, the transmitted light may be "refracted", i.e. it changes direction as described by Snell's law.

For a light ray travelling from air to glass (see figure 4) Snell's law can be expressed as

$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$$

Where the angles are as defined in the following figure and n_1 and n_2 are the refractive indices of air and glass respectively.

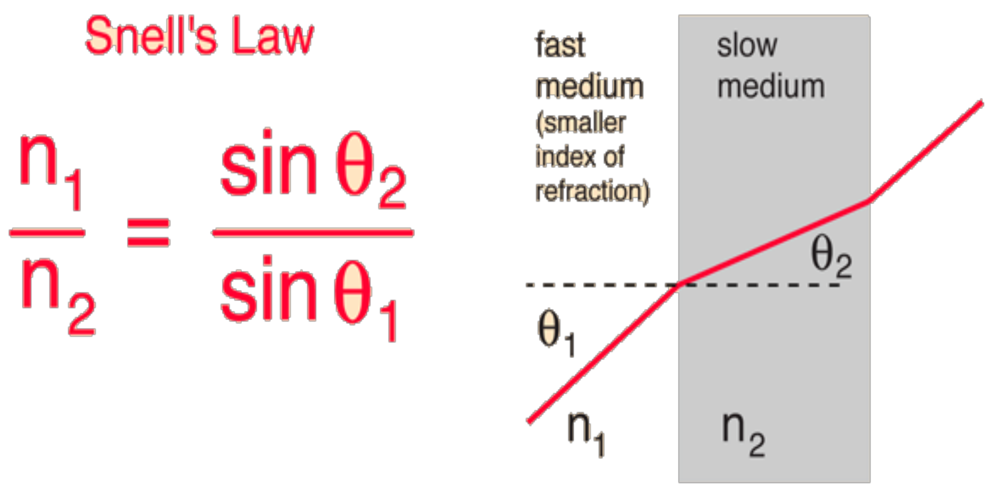


Figure 1.[Source: http://hyperphysics.phy-astr.gsu.edu/hbase/geoopt/refr.html]

Part 2: Diffraction of Light around a Human Hair

Wave optics considers the propagation of light in terms of a wave. It is a very useful way to consider optical systems that do not travel in a straight easily predictable manner. For example, the sun casts a shadow where some of the light does not hit behind an object, but when wave optics are considered the light does bend slightly around the edges of the object. On large objects much greater than the wavelength of the light, one sees only a shadow. BUT with objects that are smaller or on the same order of magnitude as the wavelength of the light, then one observes an amazing diffraction pattern (there is NO SHADOW).

In this lab, with a laser, wave optics is based on the consideration of the following:

- light propagates as a plane wave in air
- a light wave bends around an object creating constructive and destructive interference similar to water waves. Constructive interference creates bright spots and destructive interference creates dark spots. Both together create a diffraction pattern.

Understanding diffraction patterns is incredibly useful in wave optics.

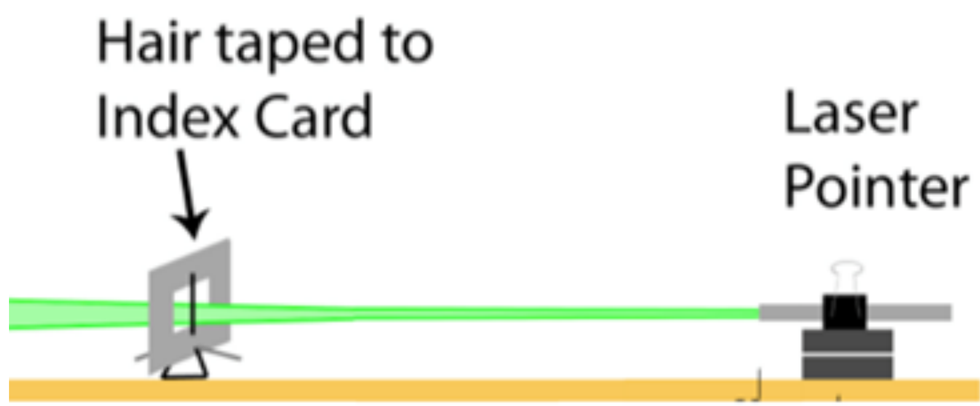


Figure 2. This is a side view of this lab apparatus for diffraction of light around human hair.

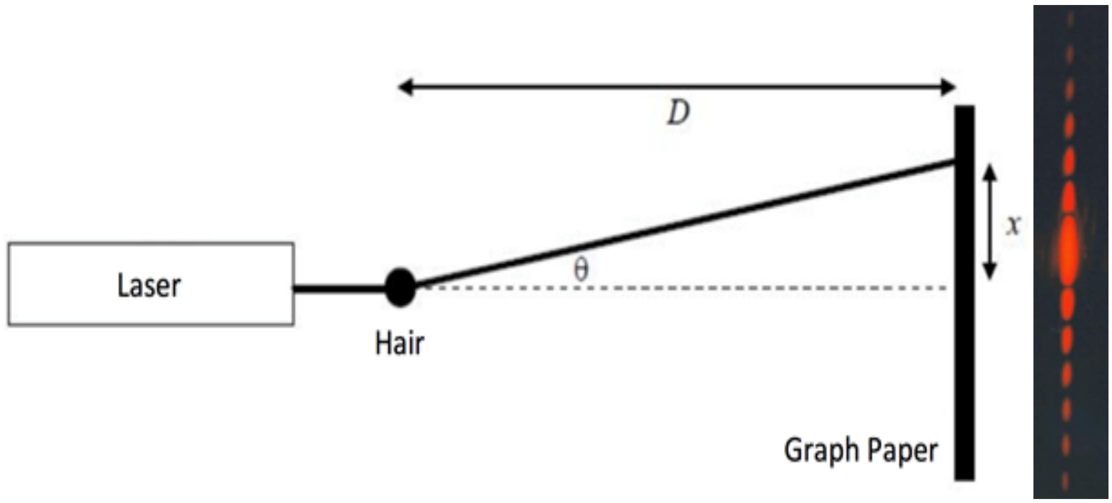


Figure 3. This is a top view of this lab apparatus for diffraction of light around human hair.

As can be seen in Figures 2 and 3, a light wave bends around the hair and creates constructive and destructive interference. The angle from the hair to the bright spots defines θ. The distance, D, defines the length from the hair to the graph paper at the point of a bright spot. The distance x, defines the length from the center of the diffraction pattern on the graph paper to one of the bright spots.

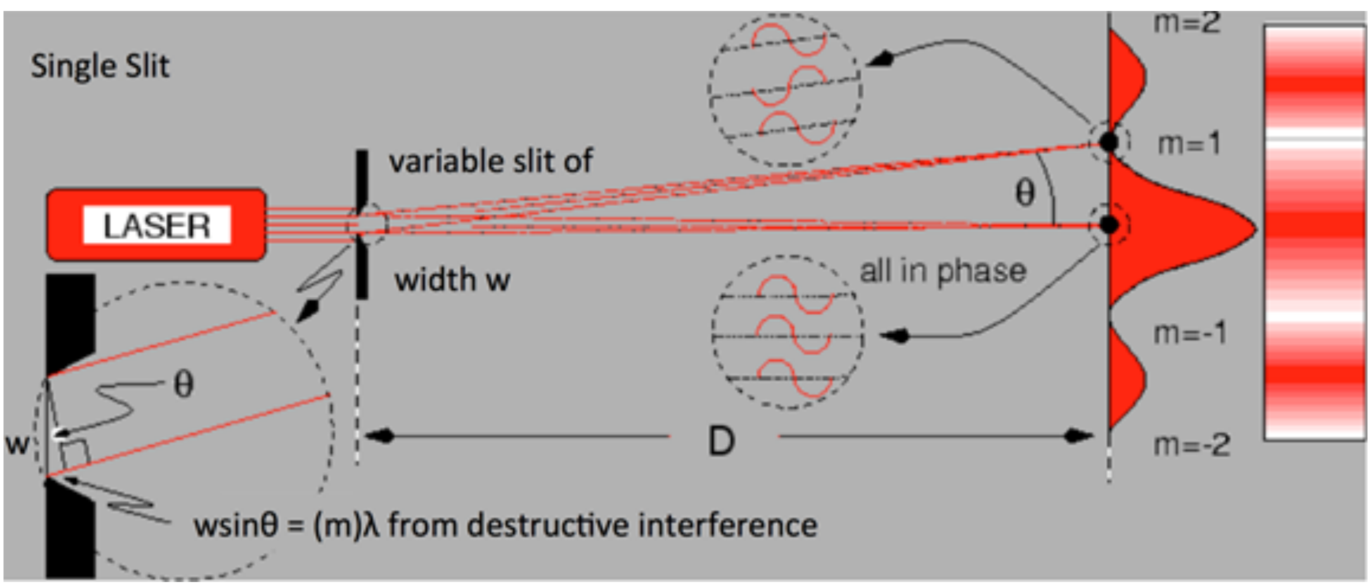


Figure 4. Comparing the two pathways that light travels in a single slit and calculating the difference distances each light pathway travels (to understand if they will be in-phase or out-of-phase).

The vital physics with measuring the width of hair is to assume that light bends around the hair with similar physics as light bends in a single slit with a small width on the order of magnitude of the wavelength of the light.

$$\sin(\theta) = \frac{\text{pathway distance difference}}{w}$$

$$w\sin(\theta)_{\text{constructive}} = (m + 1/2)\lambda$$

[4]

$$w\sin(\theta)_{\text{destructive}} = m\lambda$$

If this is all the information for this experiment, then there is no solution. However, students can measure the distance from the hair to the screen, D. Also, the height from center of maximum to each dark spots, x. Now basic trigonometry can be implement,

$$\tan(\theta) = \frac{x}{D}$$

Taking equations 4 and 5 allows students to be able to calculate the width, w, of human hair using a laser with a known wavelength of light, **λ**, and using the small angle approximation for tan **θ** and sin **θ**.

Experimental Questions:

1. **What is the index of refraction *n* of the glass in Part 1?**
2. **What is the thickness of the hair you used in Part 2?**

Experimental Design:

1. Based on the two experimental research questions, decide how many things will be varied and how many trials you want to measure for presentable statistics.

Analysis Pathways:

1. Use an analysis regression methodology (excel trendline with R2) to calculate the uncertainty of *n* and *D*.

2. Compare your measured values with known value for these physical results and estimate a percent error.

References:

Edited Figure 1: http://hyperphysics.phy-astr.gsu.edu/hbase/geoopt/refr.html
Edited Figure 2:
http://physicsed.buffalostate.edu/pubs/StudentIndepStudy/EURP09/Young/diagram.jpg
Figure 3:
http://skipper.physics.sunysb.edu/~physlab/doku.php?id=phy124:interference
Figure 4: http://www.physics.rutgers.edu/ugrad/labs/1lw_html_39a42d08.png

Appendix B
PASCO Photoelectric Effect (PE)
3 Experiments

Photoelectric Effect Apparatus & Equipment

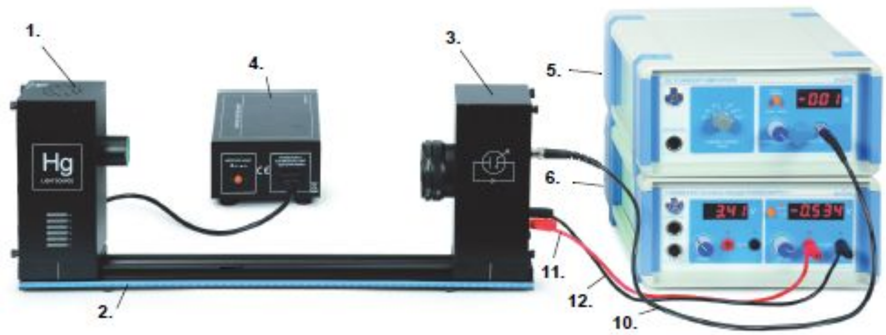
Directions: Familiarizing yourself with the equipment used in any science experiment accomplishes two important goals:

1. Provides you with guidance that helps you to use the equipment safely.
2. Familiarity with the equipment aids in performing experiments appropriately, efficiently and productively.

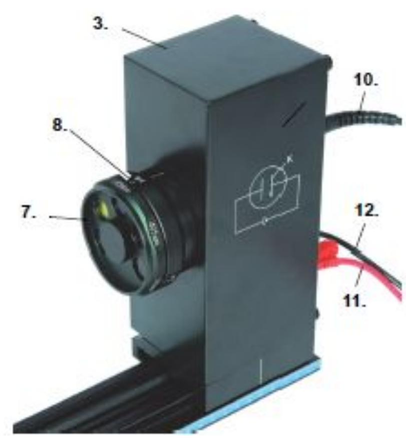
Photoelectric Effect Apparatus

Model No. SE-6609

Equipment List

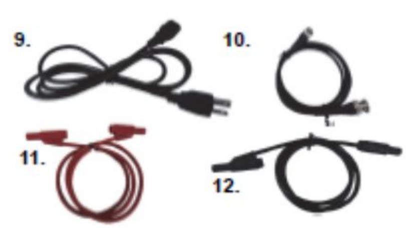


Included Equipment
1. Mercury Light Source Enclosure
2. Track, 60 cm
3. Photodiode Enclosure
4. Mercury Light Source Power Supply
5. DC Current Amplifier
6. Tunable DC (Constant Voltage) Power Supply



Optical Filters, Apertures, and Caps
7. Filter Wheel (365, 405, 436, 546, 577 nm)
8. Aperture Dial (2 mm, 4 mm, 8 mm diameter)
Photodiode Enclosure Cap (not shown)
Mercury Light Source Enclosure Cap (not shown)

Cables and Cords
9. Power Cord (3) (110 V version shown)
10. BNC Connecting Cable, Photodiode Enclosure
11. Connecting Cable, Red
12. Connecting Cable, Black



Safety Information

Warning: *To avoid possible electric shock or personal injury, follow these guidelines:*
• Do not clean the equipments with a wet rag.
• Before use, verify that the apparatus is not damaged.
• Do not defeat power cord safety ground feature.
• Plug in to a grounded (earth) outlet.
• Do not use product in any manner not specified by the manufacturer.
• Do not install substitute parts or perform any unauthorized modification to the product.
• Line and Current Protection Fuses: For continued protection against fire, replace the line fuse and the current-protection fuse only with fuses of the specified type and rating.
• Main Power and Test Input Disconnect: Unplug instrument from wall outlet, remove power cord, and remove all probes from all terminals before servicing. Only qualified, service-trained personnel should remove the cover from the instrument.
• Do not use the equipment if it is damaged. Before you use the equipment, inspect the case. Pay particular attention to the insulation surrounding the connectors.
• Do not use the equipment if it operates abnormally. Protection may be impaired. When in doubt, have the equipment serviced.
• Do not operate the equipment where explosive gas, vapor, or dust is present. Don't use it under wet condition.
• Do not apply more than the rated voltage, as marked on the apparatus, between terminals or between any terminal and earth ground.
• When servicing the equipment, use only specified replacement parts.
• Use caution when working with voltage above 30 V AC RMS, 42 V peak, or 60 V DC. Such voltages pose a shock hazard.
• To avoid electric shock, do not touch any naked conductor with hand or skin.
• Adhere to local and national safety codes. Individual protective equipment must be used to prevent shock and arc blast injury where hazardous live conductors are exposed.
• Remaining endangerment: When an input terminal is connected to dangerous live potential it is to be noted that this potential can occur at all other terminals!

Electrical Symbols

∼ Alternating Current
⎓ Direct Current
⚠ Caution, risk of danger, refer to the operating manual before use.
Caution, possibility of electric shock
⏚ Earth (ground) Terminal
Protective Conductor Terminal
Chassis Ground
CE Conforms to European Union directives.
WEEE, waste electric and electronic equipment
Fuse
| On (Power)
◯ Off (Power)
In position of a bi-stable push control
Out position of a bi-stable push control

Warning: *To avoid permanent injury to your vision never look directly into the light source in this photoelectric experiment without adequate eye protection.*

ADDITIONAL EQUIPMENT

Tunable DC (Constant Voltage) Power Supply

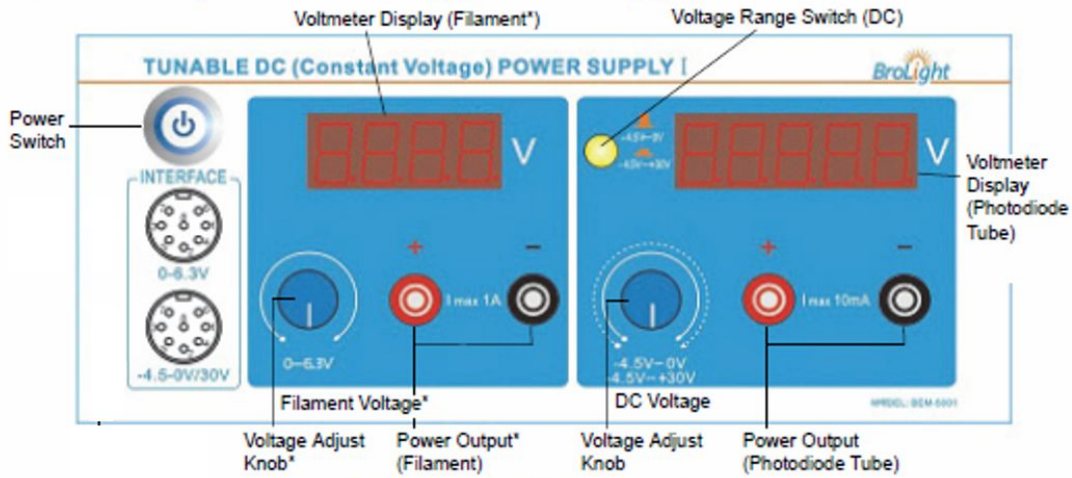


Figure: Tunable DC (Constant Voltage) Power Supply

The **Power Supply** provides potential to the photodiode tube, which is shown on one of the Voltmeter Displays are used to record manually the voltage present that is creating an electric field that influences electrons released from the cathode by the impinging light. The Power Supply has two outputs: the DC Voltage with two ranges, -4.5V to 0V and -4.5V to 30V and the Filament Voltage (0 – 6.3V) that is not used in this experiment.

• **Power Switch:** Turns the power to the Power Supply ON or OFF.

• **Voltmeter Displays:** One display shows the potential across the photodiode tube and the other display shows filament voltage (not used in this experiment).

• V**oltage Range Switch (DC):** Sets the DC voltage range as -4.5V to +30V for plotting current-voltage characteristics and -4.5V to 0 V for measuring the stopping potential.

• **Voltage Adjust Knobs:** One knob adjusts the potential across the photodiode tube for both DC voltage ranges, and the other knob adjusts the potential for the filament (not used in this experiment).

• **Power Output Ports:** One set of ports is for power output to the photodiode tube and the other set is for filament voltage (not used in this experiment).

ADDITIONAL EQUIPMENT

DC Current Amplifier

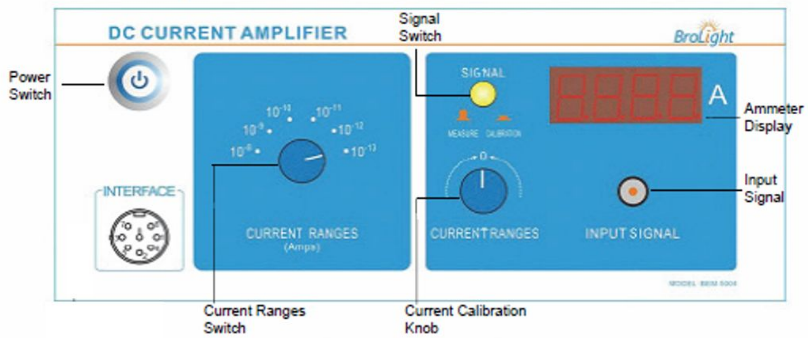


Figure: DC Current Amplifier

The **DC Current Amplifier** is an extremely sensitive instrument that can measure very small quantities of current of electric current generated by such events as the photoelectric effect.

- **Power Switch:** Turns the power to the Current Amplifier ON or OFF.
- **Current Range Switch:** Sets the range for the instrument's current amplifier (10^{-8} to 10^{-13} A).
- **Signal Switch:** Sets the signal for the photodiode tube to CALIBRATION (button IN) or MEASURE (button OUT).
- **Current Calibration Knob:** Adjusts the current through the instrument to zero.
- **Ammeter Display:** Shows the photocurrent through the photodiode tube.
- **Input Signal:** BNC input port for the photodiode tube signal.

PHOTOELECTRIC EXPERIMENT 1
INSTRUCTIONS

INVESTIGATION OF THE RELATIONSHIP
BETWEEN
LIGHT FREQUENCY (*f*) AND STOPPING VOLTAGE (V_o)
(2 mm Aperture Setting)

Read and set up the PASCO apparatus as indicated on pages 1-3

GENERAL INSTRUCTIONS: In this experiment we detect but do not measure the photocurrent. We measure the smallest stopping potential directly as a function of incident light frequency. The wavelengths and corresponding frequencies used correspond to the spectral lines of the mercury vapor light source, and are separated by passing the light through a diffraction grating. The wavelengths and frequencies used are tabulated and associated with the lowest stopping voltage required to obtain zero current . These values are taken as the given quantities to be used in your calculations and analysis.

Your lab instructor will assist you in collecting the first data point where a small stopping voltage succeeds in just preventing the current generated by the light on the photodiode located in the photodiode enclosure. Your team will then increase the frequency of the light striking the diode and measure the smallest stopping voltage that reduces the current from the diode exposed to the selected light frequency (color) to zero amperes.

Note that you must discharge the system by pressing the PUSH TO ZERO button before each new measurement.

CAUTION: THE MERCURY VAPOR LAMP IS ENCLOSED IN A METAL HOUSING WITH A SMALL APERTURE. DO NOT LOOK DIRECTLY INTO THE APERTURE.

1.Turn on the PHOTOELECTRIC MERCURY LIGHT SOURCE 30 minutes prior to collecting data.
2. Turn on the Tunable DC Power Supply and the DC Current Amplifier.
3. Select the 2 mm Aperture Dial Setting on the Photodiode Enclosure
4. Calibrate the DC Current Amplifier by pushing the SIGNAL switch to the inmost position
    a) Set the CURRENT RANGES switch knob on the DC Current Amplifier to 10^{-8} A
    b) Turn the CURRENT RANGES calibration knob until the Ammeter display reads zero (multiple zero's are normally visible)
    c) Set the CURRENT RANGES switch knob on the DC Current Amplifier to 10^{-9} A
    d) Turn the CURRENT RANGES calibration knob until the Ammeter display reads zero (multiple zero's are normally visible)
    e) Set the CURRENT RANGES switch knob on the DC Current Amplifier to 10^{-10} A
    f) Turn the CURRENT RANGES calibration knob until the Ammeter display reads zero (multiple zero's are normally visible)
    g) Set the CURRENT RANGES switch knob on the DC Current Amplifier to 10^{-11} A

h) Turn the CURRENT RANGES calibration knob until the Ammeter display reads zero (multiple zero's are normally visible)
i) Set the CURRENT RANGES switch knob on the DC Current Amplifier to 10^{-12} A
j) Turn the CURRENT RANGES calibration knob until the Ammeter display reads zero (as close to zero as possible...it is projected that this calibration will be sufficient for usable data in this experiment)

NOTE: In this experiment, use only the five first-order spectral lines of Hg. Omit measurements with the second-order lines. The first color will be selected and the technique for determining stopping voltage will be demonstrated by the instructor. All subsequent colors will be of a higher frequency and the stopping voltage will be determined and recorded by your team.

5. Set the Voltage Range switch on the Tunable DC Power Supply to -4.5 - 0 V position. Turn the rightmost Voltage Adjust Knob until the rightmost Voltmeter Display is 0 V.
6. Select a wavelength using the color wheel mounted on the Diode Light Enclosure. The wavelength indicated by the filter will be used to determine the selected frequency.
7. Press the SIGNAL switch on the DC Current Amplifier so that the button (switch) is out away from the housing. The reading of the Ammeter Display fn the DC Current Amplifier is the current generated by the impinging light on the photodiode. Select the CURRENT RANGE that provides a readable current on the DC CURRENT Amplifier Ammeter Display.
8. Vary the Voltage Range switch on the Tunable DC Power Supply increasingly more negative (from the initial value of 0 V) until the reading of the Ammeter Display of the DC Current Amplifier is 0. When the current on the Ammeter Display is as close to "0" Amperes as possible record the value in the Voltmeter Display on the Tunable DC Power Supply. This is the "Stopping Voltage" (or the voltage required to just stop the flow of all electrons off the photodiode due to the light.
9. Record the light frequency and associated magnitude of the topping voltage.
   (the magnitude of the voltage means that the negative sign can be dropped)

Perform 4-10 with 4 additional different colors (frequencies of light). Five values of stopping voltages for five different colors is sufficient for this analysis.

ANALYSIS:

1. Plot the magnitude of stopping voltage (vertical axis) as a function of the frequency of the light striking the diode (horizontal axis).

2. Based on the plot in #1 what is the relationship between the magnitude of the stopping voltage and the frequency of the light striking the photodiode?

3. What is the mathematical expression that relates the magnitude of the stopping voltage to the frequency of the light?

4. What does the horizontal axis intercept represent according to Einstein's quanta model for light?

5. What does the vertical axis intercept represent according to Einstein's quanta model for light?

6. What does the slope of the mathematical expression generated from the data collected represent? [NOTE; This slope was observed to be exactly the same for all materials struck by a light that freed electrons from the surface.]

7. Combine data from different teams into a single table and compare results. How are they different? How are they the same?

8. Which model of light could most easily and consistently explain all of this observed behavior? Compare how light imagined as a particle, light imagined as a wave and light imagined as a quanta would explain the relationship depicted by the magnitude of stopping voltage as a function of light frequency.

PHOTOELECTRIC EXPERIMENT 2
INSTRUCTIONS

INVESTIGATION OF THE RELATIONSHIP BETWEEN LIGHT FREQUENCY (*f*) AND STOPPING VOLTAGE (V_o) (4 mm Aperture Setting)

Read and set up the PASCO apparatus as indicated on pages 1-3

GENERAL INSTRUCTIONS: In this experiment we detect but do not measure the photocurrent. We measure the smallest stopping potential directly as a function of incident light frequency. The wavelengths and corresponding frequencies used correspond to the spectral lines of the mercury vapor light source, and are separated by passing the light through a diffraction grating. The wavelengths and frequencies used are tabulated and associated with the lowest stopping voltage required to obtain zero current . These values are taken as the given quantities to be used in your calculations and analysis.

Your lab instructor will assist you in collecting the first data point where a small stopping voltage succeeds in just preventing the current generated by the light on the photodiode located in the photodiode enclosure. Your team will then increase the frequency of the light striking the diode and measure the smallest stopping voltage that reduces the current from the diode exposed to the selected light frequency (color) to zero amperes.

Note that you must discharge the system by pressing the PUSH TO ZERO button before each new measurement.

CAUTION: THE MERCURY VAPOR LAMP IS ENCLOSED IN A METAL HOUSING WITH A SMALL APERTURE. DO NOT LOOK DIRECTLY INTO THE APERTURE.

1.Turn on the PHOTOELECTRIC MERCURY LIGHT SOURCE 30 minutes prior to collecting data.
2. Turn on the Tunable DC Power Supply and the DC Current Amplifier.
3. Select the 4 mm Aperture Dial Setting on the Photodiode Enclosure
4. Calibrate the DC Current Amplifier by pushing the SIGNAL switch to the inmost position
   a) Set the CURRENT RANGES switch knob on the DC Current Amplifier to 10^{-8} A
   b) Turn the CURRENT RANGES calibration knob until the Ammeter display reads zero (multiple zero's are normally visible)
   c) Set the CURRENT RANGES switch knob on the DC Current Amplifier to 10^{-9} A
   d) Turn the CURRENT RANGES calibration knob until the Ammeter display reads zero (multiple zero's are normally visible)
   e) Set the CURRENT RANGES switch knob on the DC Current Amplifier to 10^{-10} A
   f) Turn the CURRENT RANGES calibration knob until the Ammeter display reads zero (multiple zero's are normally visible)
   g) Set the CURRENT RANGES switch knob on the DC Current Amplifier to 10^{-11} A

h) Turn the CURRENT RANGES calibration knob until the Ammeter display reads zero (multiple zero's are normally visible)
i) Set the CURRENT RANGES switch knob on the DC Current Amplifier to 10^{-12} A
j) Turn the CURRENT RANGES calibration knob until the Ammeter display reads zero (as close to zero as possible...it is projected that this calibration will be sufficient for usable data in this experiment)

NOTE: In this experiment, use only the five first-order spectral lines of Hg. Omit measurements with the second-order lines. The first color will be selected and the technique for determining stopping voltage will be demonstrated by the instructor. All subsequent colors will be of a higher frequency and the stopping voltage will be determined and recorded by your team.

5. Set the Voltage Range switch on the Tunable DC Power Supply to -4.5 - 0 V position. Turn the rightmost Voltage Adjust Knob until the rightmost Voltmeter Display is 0 V.
6. Select a wavelength using the color wheel mounted on the Diode Light Enclosure. The wavelength indicated by the filter will be used to determine the selected frequency.
7. Press the SIGNAL switch on the DC Current Amplifier so that the button (switch) is out away from the housing. The reading of the Ammeter Display fn the DC Current Amplifier is the current generated by the impinging light on the photodiode. Select the CURRENT RANGE that provides a readable current on the DC CURRENT Amplifier Ammeter Display.
8. Vary the Voltage Range switch on the Tunable DC Power Supply increasingly more negative (from the initial value of 0 V) until the reading of the Ammeter Display of the DC Current Amplifier is 0. When the current on the Ammeter Display is as close to "0" Amperes as possible record the value in the Voltmeter Display on the Tunable DC Power Supply. This is the "Stopping Voltage" (or the voltage required to just stop the flow of all electrons off the photodiode due to the light.
9. Record the light frequency and associated magnitude of the topping voltage.
(the magnitude of the voltage means that the negative sign can be dropped)

Perform 4-10 with 4 additional different colors (frequencies of light). Five values of stopping voltages for five different colors is sufficient for this analysis.

ANALYSIS:

1. Plot the magnitude of stopping voltage (vertical axis) as a function of the frequency of the light striking the diode (horizontal axis).

2. Based on the plot in #1 what is the relationship between the magnitude of the stopping voltage and the frequency of the light striking the photodiode?

3. What is the mathematical expression that relates the magnitude of the stopping voltage to the frequency of the light?

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6. What does the slope of the mathematical expression generated from the data collected represent? [NOTE; This slope was observed to be exactly the same for all materials struck by a light that freed electrons from the surface.]

7. Combine data from different teams into a single table and compare results. How are they different? How are they the same?

8. Which model of light could most easily and consistently explain all of this observed behavior? Compare how light imagined as a particle, light imagined as a wave and light imagined as a quanta would explain the relationship depicted by the magnitude of stopping voltage as a function of light frequency.

PHOTOELECTRIC EXPERIMENT 3
INSTRUCTIONS

INVESTIGATION OF THE RELATIONSHIP BETWEEN LIGHT FREQUENCY (*f*) AND STOPPING VOLTAGE (V_o)
(8 mm Aperture Setting)

Read and set up the PASCO apparatus as indicated on pages 1-3

GENERAL INSTRUCTIONS: In this experiment we detect but do not measure the photocurrent. We measure the smallest stopping potential directly as a function of incident light frequency. The wavelengths and corresponding frequencies used correspond to the spectral lines of the mercury vapor light source, and are separated by passing the light through a diffraction grating. The wavelengths and frequencies used are tabulated and associated with the lowest stopping voltage required to obtain zero current . These values are taken as the given quantities to be used in your calculations and analysis.

Your lab instructor will assist you in collecting the first data point where a small stopping voltage succeeds in just preventing the current generated by the light on the photodiode located in the photodiode enclosure. Your team will then increase the frequency of the light striking the diode and measure the smallest stopping voltage that reduces the current from the diode exposed to the selected light frequency (color) to zero amperes.

Note that you must discharge the system by pressing the PUSH TO ZERO button before each new measurement.

CAUTION: THE MERCURY VAPOR LAMP IS ENCLOSED IN A METAL HOUSING WITH A SMALL APERTURE. DO NOT LOOK DIRECTLY INTO THE APERTURE.

1.Turn on the PHOTOELECTRIC MERCURY LIGHT SOURCE 30 minutes prior to collecting data.
2. Turn on the Tunable DC Power Supply and the DC Current Amplifier.
3. Select the 8 mm Aperture Dial Setting on the Photodiode Enclosure
4. Calibrate the DC Current Amplifier by pushing the SIGNAL switch to the inmost position
   a) Set the CURRENT RANGES switch knob on the DC Current Amplifier to 10^{-8} A
   b) Turn the CURRENT RANGES calibration knob until the Ammeter display reads zero (multiple zero's are normally visible)
   c) Set the CURRENT RANGES switch knob on the DC Current Amplifier to 10^{-9} A
   d) Turn the CURRENT RANGES calibration knob until the Ammeter display reads zero (multiple zero's are normally visible)
   e) Set the CURRENT RANGES switch knob on the DC Current Amplifier to 10^{-10} A
   f) Turn the CURRENT RANGES calibration knob until the Ammeter display reads zero (multiple zero's are normally visible)
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h) Turn the CURRENT RANGES calibration knob until the Ammeter display reads zero (multiple zero's are normally visible)
i) Set the CURRENT RANGES switch knob on the DC Current Amplifier to 10^{-12} A
j) Turn the CURRENT RANGES calibration knob until the Ammeter display reads zero (as close to zero as possible...it is projected that this calibration will be sufficient for usable data in this experiment)

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5. Set the Voltage Range switch on the Tunable DC Power Supply to -4.5 - 0 V position. Turn the rightmost Voltage Adjust Knob until the rightmost Voltmeter Display is 0 V.
6. Select a wavelength using the color wheel mounted on the Diode Light Enclosure. The wavelength indicated by the filter will be used to determine the selected frequency.
7. Press the SIGNAL switch on the DC Current Amplifier so that the button (switch) is out away from the housing. The reading of the Ammeter Display fn the DC Current Amplifier is the current generated by the impinging light on the photodiode. Select the CURRENT RANGE that provides a readable current on the DC CURRENT Amplifier Ammeter Display.
8. Vary the Voltage Range switch on the Tunable DC Power Supply increasingly more negative (from the initial value of 0 V) until the reading of the Ammeter Display of the DC Current Amplifier is 0. When the current on the Ammeter Display is as close to "0" Amperes as possible record the value in the Voltmeter Display on the Tunable DC Power Supply. This is the "Stopping Voltage" (or the voltage required to just stop the flow of all electrons off the photodiode due to the light.
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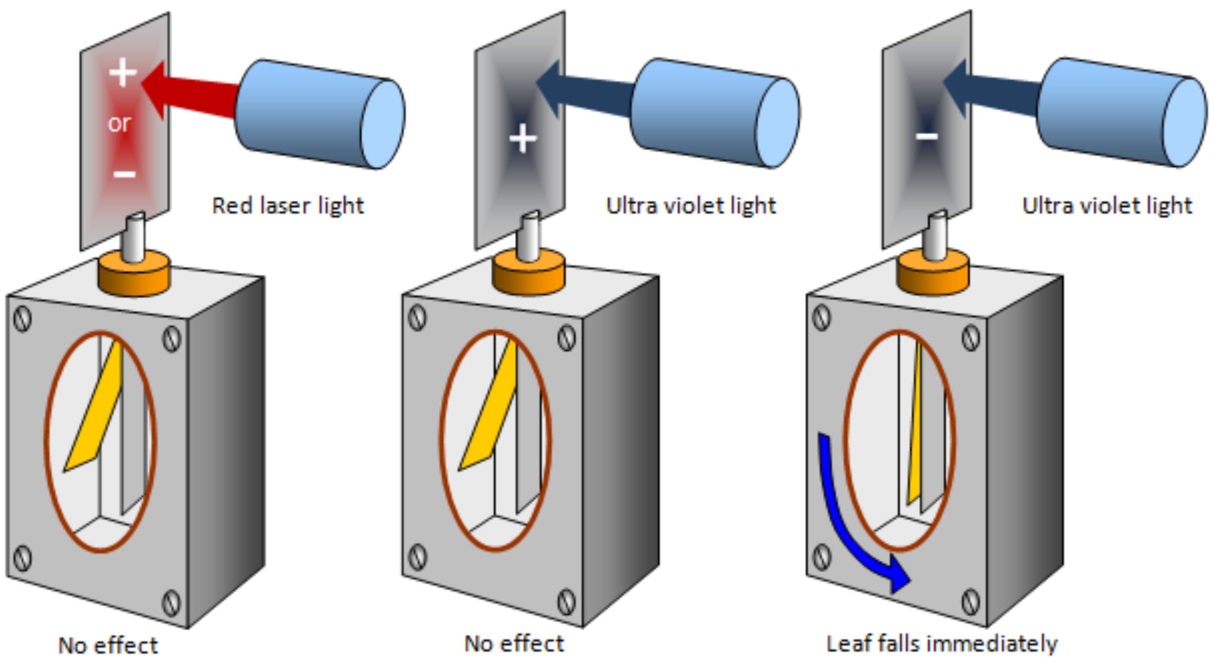
Appendix C
The Photoelectric Effect
Electroscope Experiment

Experiment by Keith Gibbs

The Photoelectric Effect[1]

When is a wave not a wave - when it's a particle!
In 1887 Heinrich Hertz noticed that sparks would jump between two spheres when their surfaces were illuminated by light from another spark. This effect was studied more carefully in the following years by Hallwachs and Lenard. They called the effect photoelectric emission and a very simple experiment can be used to investigate it.



In the diagram shown above a clean zinc plate is fitted to the top of a gold leaf electroscope and then given a positive charge (you can do this either with a charged glass rod or an EHT supply. **DANGER HIGH VOLTAGE**). The next thing is to shine some radiation on it, using an ordinary lamp, a helium-neon laser (giving out intense red light) or an ultra violet light has absolutely no effect. The electroscope stays charged and the leaf stays up.
However if the plate is given a negative charge to start with (using say a charged polythene rod) there is a difference. Using the lamp and even the laser has no effect, but when ultra violet light is shone on the plate the leaf falls immediately, the electroscope has been discharged. (Doing the experiment in a vacuum proves that it is not ions in the air that are causing the discharge.)

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[1] http://www.schoolphysics.co.uk/age16-19/Quantum physics/text/Photoelectric_effect/index.html

No effect can be produced with radiation of longer wavelength (lower frequency and smaller energy) no matter how long the radiation is shone on the plate.

The plate was emitting electrons when the ultra violet radiation fell on it and this explained why the leaf only fell when it had an initial negative charge - when it was positive the electrons were attracted back to the plate.

The researchers found four important facts about the experiment:
(a) no electrons were emitted from the plate if it was positive
(b) the number of electrons emitted per second depended on the intensity of the incident radiation
(c) the energy of the electrons depended on the frequency of the incident radiation
(d) there was a minimum frequency (fo) below which no electrons were emitted no matter how long radiation fell on the surface
This minimum frequency is called the **threshold frequency** for that material. Photons with a lower frequency will never cause electron emission. This can be explained like this.
The free electrons are held in the metal in a "hole" in the electric field, this is called a potential well. Energy has to be supplied to them to enable them to escape from the surface. Think of a person down a hole with very smooth sides. They can only escape if they can jump out of the hole in one go. They cannot get half way up and then have a rest - it's all or nothing!. This is just like the electrons. The deeper the "hole" the more tightly bound are the electrons and the greater energy and therefore greater frequency of radiation is needed to release them.

The quantum theory of Max Planck is needed to explain the photoelectric effect. In trying to explain the variation of energy with wavelength for the radiation emitted by hot objects he came to the conclusion that all radiation is emitted in **quanta** and the energy of one quantum is given by the equation:

$$\text{Quantum Energy} = hf$$

The amount of energy needed to just release a photoelectron is known as the **work function** for the metal. This can also be expressed in terms of the minimum frequency that will cause photoelectric emission.

Work function (W) = hf_o

The table below gives the work function for a number of surfaces - both in joules and in electron volts. The threshold frequency for each surface is also included.

Element	**W (Joules)**	**W (eV)(V)**	**f_o (frequency) (Hz)**	**λ_o (wavelength) (nm)**
Sodium	3.8×10^{-19}	2.40	5.8×10^{14}	520
Caesium	3.0×10^{-19}	1.88	4.5×10^{14}	666
Lithium	3.7×10^{-19}	1.88	5.6×10^{14}	560
Calcium	4.3×10^{-19}	2.69	6.5×10^{14}	462
Magnesium	4.3×10^{-19}	3.69	8.9×10^{14}	337
Silver	7.6×10^{-19}	4.75	11.14×10^{14}	263
Platinum	10.0×10^{-19}	6.75	15.1×10^{14}	199

Another way of looking at it is to think of a fairground coconut shy. A brother and sister are trying to knock the coconuts off their stands. The boy has a large box of table tennis balls which he is throwing at the coconuts, with little effect. No matter how many of the table tennis balls he throws at a coconut it will still stay in place – the table tennis balls represent the "red" quanta. However his sister has a pistol! This represents the violet quanta. A single shot from the pistol will knock off a coconut and it will do it immediately.

As we saw in the previous experiment we could illuminate the zinc plate all day with a high powered laser and the leaf of the electroscope would not fall. However as soon as we shone the ultra violet light on the plate the leaf dropped. This is because the ultra violet light has a high enough frequency and therefore each quantum of ultra violet has sufficient energy. One quantum has enough energy to kick out an electron in one go.

The photoelectric effect is therefore very good evidence for the particulate nature of light.

Appendix D
Computer Simulation of PE Guide

PhET Tips for Teachers Photoelectric Effect

Non-obvious controls:

- Select Show photons in the Options menu to show the light beam as composed of individual photons.
- Select Control photon number instead of intensity in the Options menu to change the Intensity slider to a Number of photons slider.
- Use the camera icon () to take a snapshot of the graphs so that you can compare graphs for different settings.
- You can Pause the sim and then use Step to incrementally analyze.
- If you are doing a lecture demonstration, set your screen resolution to 1024x768 so the simulation will fill the screen and be seen easily.

Important modeling notes / simplifications:

- Electrons are emitted with a range of energies because photons can eject electrons with a range of binding energies. If more of a photon's energy is used to release an electron, the emitted electron will have less kinetic energy. Note that this behavior is different from the simplified model used by some textbooks, in which all electrons are emitted with the same kinetic energy. If you want to use this simplified model, you can check the "show only highest energy electrons" option. This option does not change the graphs because current is still calculated based on all the electrons.
- Not every photon emits an electron, even if the photons have enough energy to emit electrons. If a photon is absorbed by an electron with binding energy greater than the photon energy, the electron will not be released. Photons with higher energies are more likely to release electrons because a greater proportion of the electrons in the metal have binding energy less than the photon energy. Therefore, as you increase the frequency, the number of emitted electrons (and therefore the current) will increase until all photons are emitting electrons. Note that this behavior is different from the simplified model used by many textbooks, in which every photon with frequency greater than the threshold frequency releases an electron, so the current is constant above the threshold frequency.
- In the default setting, since the intensity of light is proportional to the number of photons times the frequency, if you increase the frequency while holding the intensity constant, the number of photons will decrease. Therefore, if

you increase the frequency past the point where all photons are emitting electrons (see previous bullet), the number of emitted electrons (and therefore the current) will start to decrease. Note that this is different from the simplified model used by many textbooks, in which current is constant above the threshold frequency. If you want to be able to change the frequency without changing the number of photons, select “Control photon number instead of intensity” in the Options menu.

- We assume that all electrons are ejected perpendicular to the plate for computational simplicity. In a real experiment, photons are ejected in all directions. Students often ask whether the electrons actually come off at different angles, and are generally willing to accept that this is just a simplification of the simulation.
- We ignore advanced issues such as contact potential, thermionic emission, and reverse current. Insights into student use / thinking:

Written by Sam McKagan, last updated April 14, 2011

- Research[2] shows that students often have difficulty understanding the basic circuit involved in the photoelectric effect. For example, students may think that the voltage rather than the light makes the electrons come off the plate, or attempt to apply V = IR. It is worth spending some time addressing such student difficulties.
- Many students have difficulty understanding the relationship between current and electron speed. Our students often have heated debates about whether increasing the speed of the electrons leads to an increase in current. The simulation is a critical tool in resolving these debates, because students can see upon close inspection that increasing the speed of the electrons does not increase the number arriving per second on the plate, and therefore does not increase the current.
- In interviews, we found that even students with no science background were able to figure out how the photoelectric effect experiment works by playing with this simulation, but they needed further guidance to understand the implications of the experiment for the photon model of light. Suggestions for sim use:

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[2] R. N. Steinberg, G. E. Oberem, and L. C. McDermott, “Development of a computer-based tutorial on the photoelectric effect,” *American Journal of Physics* **64**, 1370 (1996).

- For tips on using PhET sims with your students see: Guidelines for Inquiry Contributions and Using PhET Sims
- The simulations have been used successfully with homework, lectures, in-class activities, or lab activities. Use them for introduction to concepts, learning new concepts, reinforcement of concepts, as visual aids for interactive demonstrations, or with in-class clicker questions. To read more, see Teaching Physics using PhET Simulations
- For activities and lesson plans written by the PhET team and other teachers, see: Teacher Ideas & Activities
- We recommend using a guiding inquiry activity to help students “discover” the model of light that explains the behavior seen in the simulation.
- Give students a table of work functions for different materials, and ask them to use the simulation to determine the mystery metal (marked “?????”).
- You can demonstrate the concept of stopping potential very dramatically by showing that if you set the battery voltage just below the stopping potential, the electrons just make it to the opposite plate and turn around. This often elicits laughter from students the first time they see it.
- Ask students to figure out a way to use the simulation to determine Planck’s constant.
- Ask students how the graph of current vs. voltage would change if the simplification of electrons being ejected only perpendicular to the plate were not made. (It would level off at some positive voltage, rather than at 0 volts, because more of the electrons flying off at sharp angles would be attracted back to the positive plate.)
- For more information about the use of this simulation in a modern physics class, see: S. B. McKagan, W. Handley, K. K. Perkins, and C. E. Wieman, “A Research-Based Curriculum for Teaching the Photoelectric Effect,” American Journal of Physics 77, 87 (2009): http://per.colorado.edu/papers/McKagan_etal/photoelectric.pdf

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S. B. McKagan, W. Handley, K. K. Perkins, and C. E. Wieman, “A Research-Based Curriculum for Teaching the Photoelectric Effect,” *American Journal of Physics* **87**, 77 (2009).