

Introduction

The emission and absorption of light was an early subject for investigation by German physicist Max Planck. As Planck attempted to formulate a theory to explain the spectral distribution of emitted light based on a classical wave model, he ran into considerable difficulty. Classical theory (Rayleigh-Jeans Law) predicted that the amount of light emitted from a black body would increase dramatically as the wavelength decreased, whereas experiment showed that it approached zero. This discrepancy became known as the ultraviolet catastrophe.

Experimental data for the radiation of light by a hot, glowing body showed that the maximum intensity of emitted light also departed dramatically from the classically predicted values (Wien's Law). In order to reconcile theory with laboratory results, Planck was forced to develop a new model for light called the quantum model. In this model, light is emitted in small, discrete bundles or quanta.

The relationship between the classical and quantum theories for the emission of light can be investigated using the PASCO scientific h/e Apparatus. Using the Apparatus in combination with the PASCO Mercury Vapor Light Source (Model OS-9286) allows an accurate determination of the h/e ratio and thus a determination of h , Planck's constant.

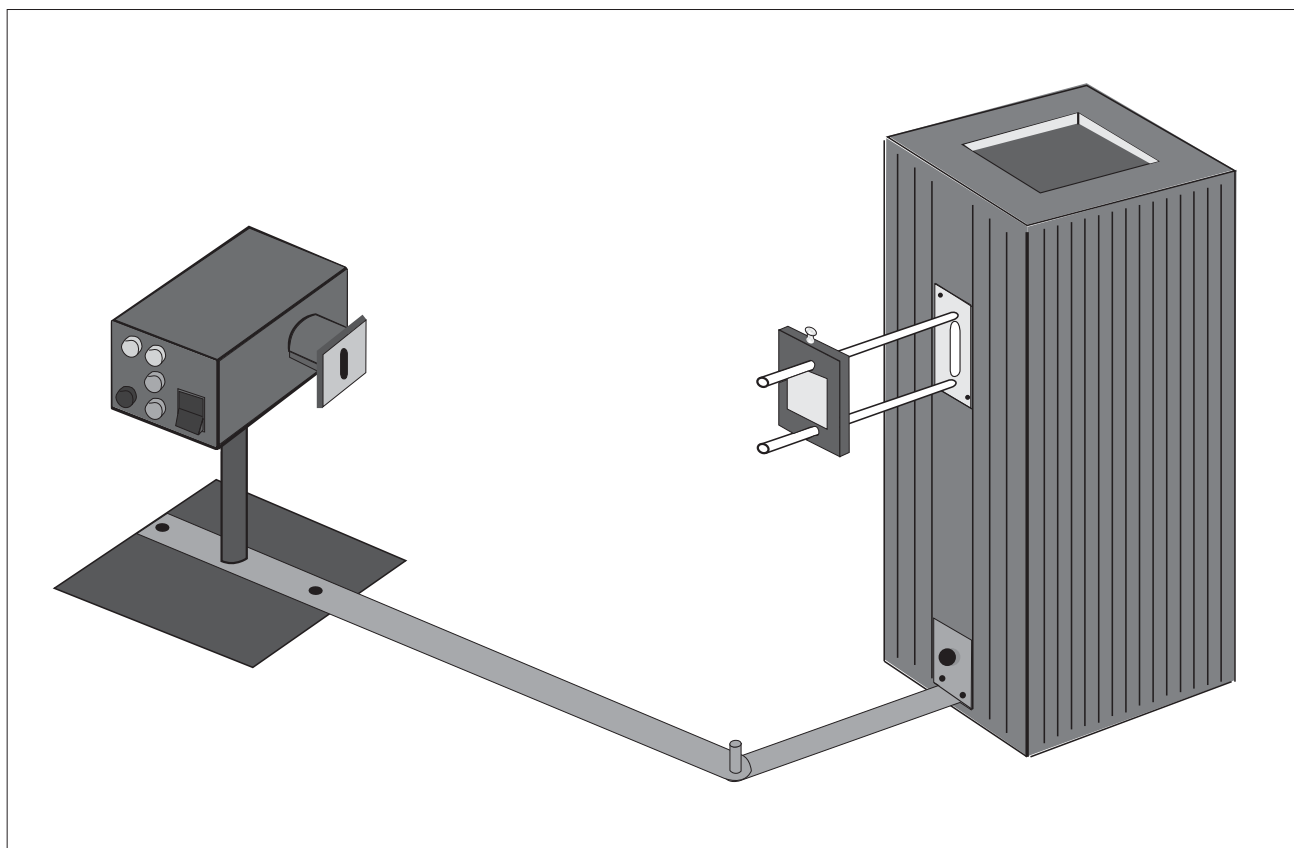


Figure 1. The h/e Apparatus Shown With the Accessory Kit and Mercury Vapor Light Source

Background Theory

Planck's Quantum Theory

By the late 1800's many physicists thought they had explained all the main principles of the universe and discovered all the natural laws. But as scientists continued working, inconsistencies that couldn't easily be explained began showing up in some areas of study.

In 1901 Planck published his law of radiation. In it he stated that an oscillator, or any similar physical system, has a discrete set of possible energy values or levels; energies between these values never occur.

Planck went on to state that the emission and absorption of radiation is associated with transitions or jumps between two energy levels. The energy lost or gained by the oscillator is emitted or absorbed as a quantum of radiant energy, the magnitude of which is expressed by the equation:

$$E = h \nu$$

where E equals the radiant energy, ν is the frequency of the radiation, and h is a fundamental constant of nature. The constant, h , became known as Planck's constant.

Planck's constant was found to have significance beyond relating the frequency and energy of light, and became a cornerstone of the quantum mechanical view of the subatomic world. In 1918, Planck was awarded a Nobel prize for introducing the quantum theory of light.

The Photoelectric Effect

In photoelectric emission, light strikes a material, causing electrons to be emitted. The classical wave model predicted that as the intensity of incident light was increased, the amplitude and thus the energy of the wave would increase. This would then cause more energetic photoelectrons to be emitted. The new quantum model, however, predicted that higher frequency light would produce higher energy photoelectrons, independent of intensity, while increased intensity would only increase the number of electrons emitted (or photoelectric current). In the early 1900s several investigators found that the kinetic energy of the photoelectrons was dependent on the wavelength, or frequency, and independent of intensity, while the magnitude of the photoelectric current, or number of electrons was dependent on the intensity as predicted by the quantum model. Einstein applied Planck's theory and explained the photoelectric effect in terms of the quantum model using his famous equation for which he received the Nobel prize in 1921:

$$E = h \nu = KE_{\max} + W_0$$

where $KE_{\max}$ is the maximum kinetic energy of the emitted photoelectrons, and W_0 is the energy needed to remove them from the surface of the material (the work function). E is the energy supplied by the quantum of light known as a photon.

The h/e Experiment

A light photon with energy $h\nu$ is incident upon an electron in the cathode of a vacuum tube. The electron uses a minimum W_0 of its energy to escape the cathode, leaving it with a maximum energy of $KE_{\max}$ in the form of kinetic energy. Normally the emitted electrons reach the anode of the tube, and can be measured as a photoelectric current. However, by applying a reverse potential V between the anode and the cathode, the photoelectric current can be stopped. $KE_{\max}$ can be determined by measuring the minimum reverse potential needed to stop the photoelectrons and reduce the photoelectric current to zero.* Relating kinetic energy to stopping potential gives the equation:

$$KE_{\max} = eV$$

Therefore, using Einstein's equation,

$$h \nu = eV + W_0$$

When solved for V , the equation becomes:

$$V = (h/e) \nu - (W_0/e)$$

If we plot V vs ν for different frequencies of light, the graph will look like Figure 2. The V intercept is equal to $-W_0/e$ and the slope is h/e . Coupling our experimental determination of the ratio h/e with the accepted value for e , 1.602×10^{-19} coulombs, we can determine Planck's constant, h .

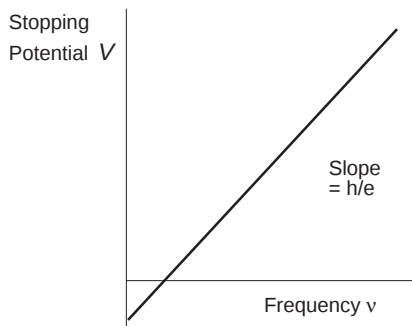


Figure 2. The graph of V vs. ν

***NOTE:** In experiments with the PASCO h/e Apparatus the stopping potential is measured directly, rather than by monitoring the photoelectric current. See the *Theory of Operation* in the Technical Information section of the manual for details.

Equipment and Setup

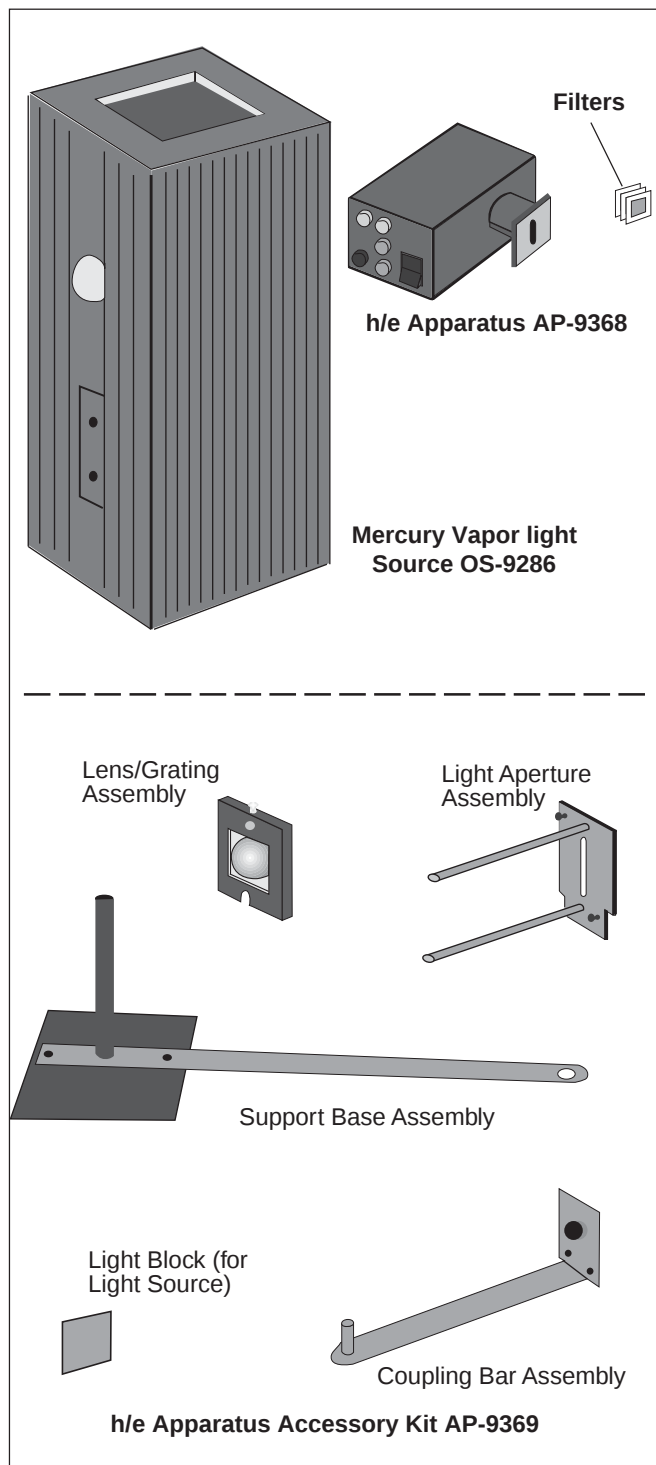


Figure 3. h/e Equipment Identification

* These items may be purchased separately from PASCO scientific, or together as an AP-9370 h/e System.

Equipment Required:

- Digital voltmeter (SE-9589)
- h/e Apparatus, (AP-9368*)
- h/e Apparatus Accessory Kit, (AP-9369*)
- Mercury Vapor Light Source, (OS- 9286*)

Installing the Batteries

The h/e Apparatus requires two 9-volt batteries (supplied but not installed). The battery compartment is accessed by loosening the thumbscrew on the rear end panel, and removing the cover plate.

► **NOTE:** The h/e Apparatus can also be powered using a ± 9 V dual power supply. Just remove the batteries and connect +9 V to the "+6 V MIN" battery test terminal and -9 V to the "-6 V MIN" battery test terminal.

Battery Voltage Check

Although the h/e Apparatus draws only a small amount of current and batteries normally last a long time, it's a good idea to check the output voltage before each use. Battery test points are located on the side panel of the Apparatus near the ON/OFF switch. Batteries functioning below the recommended minimum operating level of 6 volts may cause erroneous results in your experiments.

To check the batteries, use a voltmeter to measure between the OUTPUT ground terminal and each BATTERY TEST terminal (-6V MIN and +6V MIN). If either battery tests below its minimum rating, it should be replaced before running experiments.

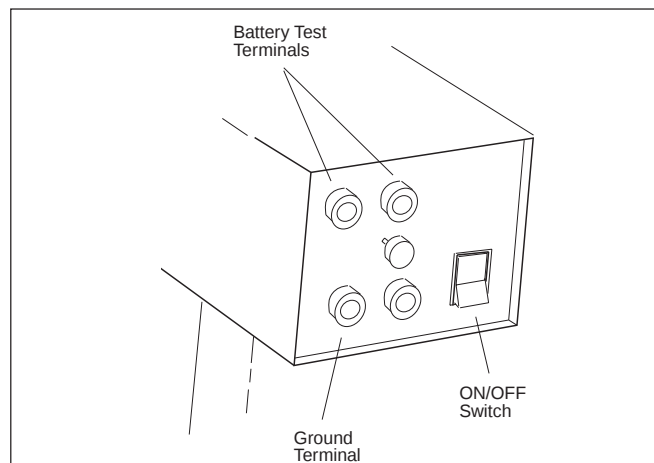


Figure 4. Battery Test Points

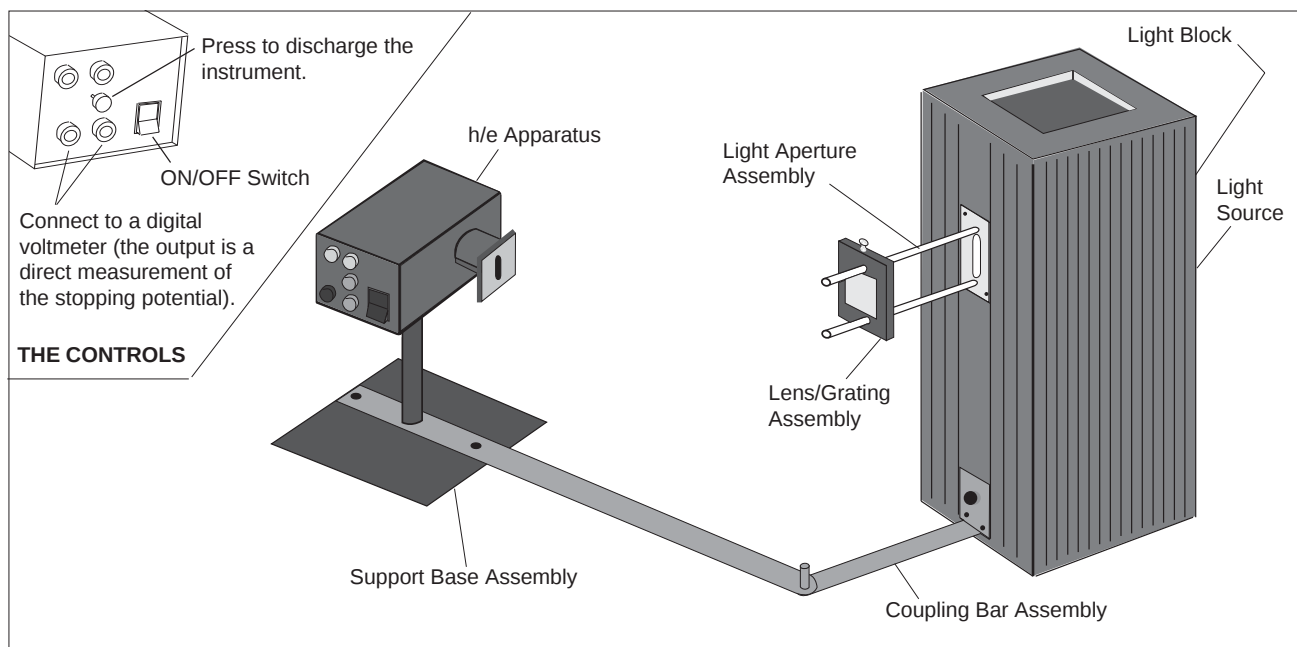


Figure 5. Equipment Setup Using a Mercury Vapor Light Source and the h/e Apparatus

Equipment Setup

The standard setup for h/e experiments is shown in Figure 5. Details for setting up the apparatus are described below.

1. The Light Source design allows simultaneous connection of two Light Aperture assemblies: one on the front and one on the back. If you are using only one Light Aperture and h/e Apparatus, install the Light Block (supplied with the Accessory Kit) in the mounting groove closest to the body of the housing on the back of the Light Source (see Figure 6).
2. Slide the Light Aperture Assembly into the center mounting groove on the front of the Light Source. Secure it in place by finger-tightening the two thumbscrews against the front of the Light Source housing.
3. The Lens/Grating Assembly mounts on the support bars of the Light Aperture Assembly (Figure 7). Loosen the thumbscrew, slip it over the bars, and finger-tighten the thumbscrew to hold it securely.

► **NOTE:** The grating is blazed to produce the brightest spectrum on one side only. During your experiment, you may need to turn the Lens/Grating Assembly around in order to have the brightest spectrum on a convenient side of your lab table.

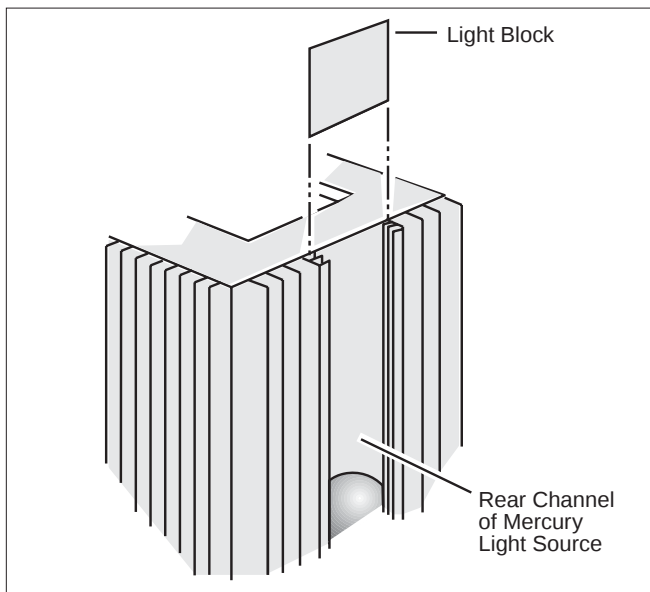


Figure 6. Installing the Light Block

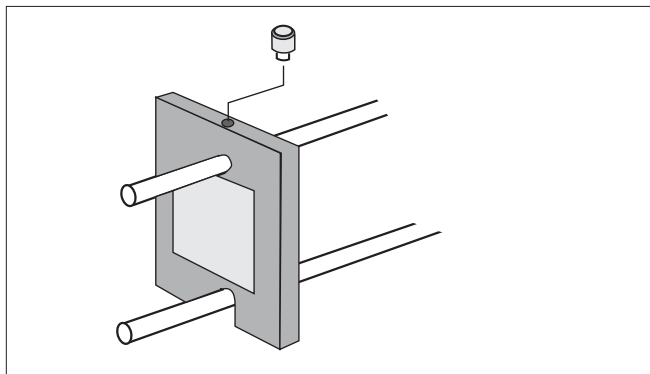


Figure 7. Lens/Grating Mounting Detail

4. Turn on the Light Source and allow it to warm up for five minutes. Check the alignment of the Light Source and the Aperture by looking at the light shining on the back of the Lens/Grating assembly. If necessary, adjust the back plate of the Light Aperture Assembly by loosening the two retaining screws (Figure 8) and sliding the aperture plate left or right until the light shines directly on the center of the Lens/Grating Assembly.

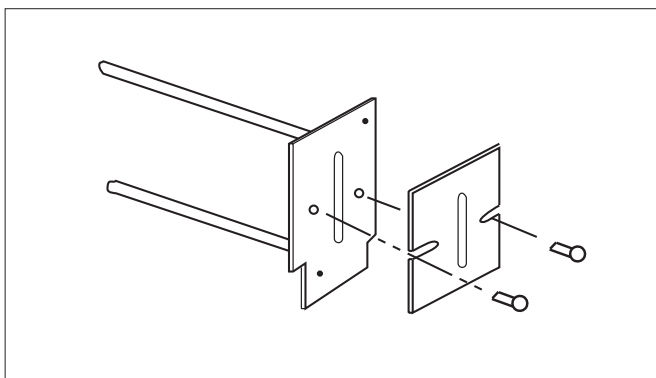


Figure 8. Light Aperture Adjustment

5. Insert the Coupling Bar assembly into the lower mounting groove of the Light Source (Figure 5). Secure in place by tightening the thumbscrew against the front of the Light Source housing.
6. Remove the screw from the end of the Support Base rod. Insert the screw through the hole in the Support Base plate and attach the rod to the Support Base plate by tightening the screw (use Phillips drive screwdriver).
7. Place the h/e Apparatus onto the Support Base Assembly.
8. Place the Support Base assembly over the pin on the end of the Coupling Bar assembly.
9. Connect a digital voltmeter (DVM) to the OUTPUT terminals of the h/e Apparatus. Select the 2V or 20V range on the meter.
10. Set the h/e Apparatus directly in front of the Mercury Vapor Light Source. By sliding the Lens/Grating assembly back and forth on its support rods, focus the light onto the white reflective mask of the h/e Apparatus (Figure 9).

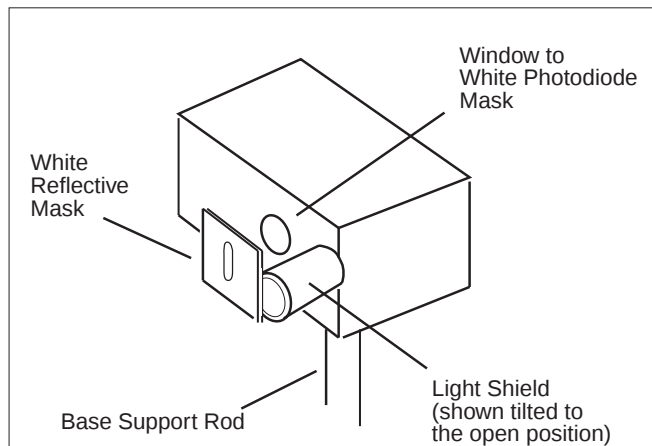


Figure 9. h/e Light Shield

11. Roll the light shield of the Apparatus out of the way to reveal the white photodiode mask inside the Apparatus. Rotate the h/e Apparatus until the image of the aperture is centered on the window in the photodiode mask. Then tighten the thumbscrew on the base support rod to hold the Apparatus in place.
12. As in step 9, slide the Lens/Grating assembly back and forth on its support rods, until you achieve the sharpest possible image of the aperture on the window in the photodiode mask. Tighten the thumbscrew on the Lens/Grating assembly and replace the light shield.
13. Turn the power switch ON. Rotate the h/e Apparatus about the pin of the Coupling Bar Assembly until one of the colored maxima in the first order shines directly on the slot in the white reflective mask. Rotate the h/e Apparatus on its support base so that the same spectral maxima that falls on the opening in the White Reflective Mask also falls on the window in the photodiode mask.

► **NOTE:** The white reflective mask on the h/e apparatus is made of a special fluorescent material. This allows you to see the ultraviolet line as a blue line, and it also makes the violet line appear more blue. You can see the actual colors of the light if you hold a piece of white non-fluorescent material in front of the mask. (The palm of your hand works in a pinch, although it fluoresces enough that the UV line will still be visible.)

When making measurements it is important that only one color falls on the photodiode window. There must be no overlap from adjacent spectral maxima.

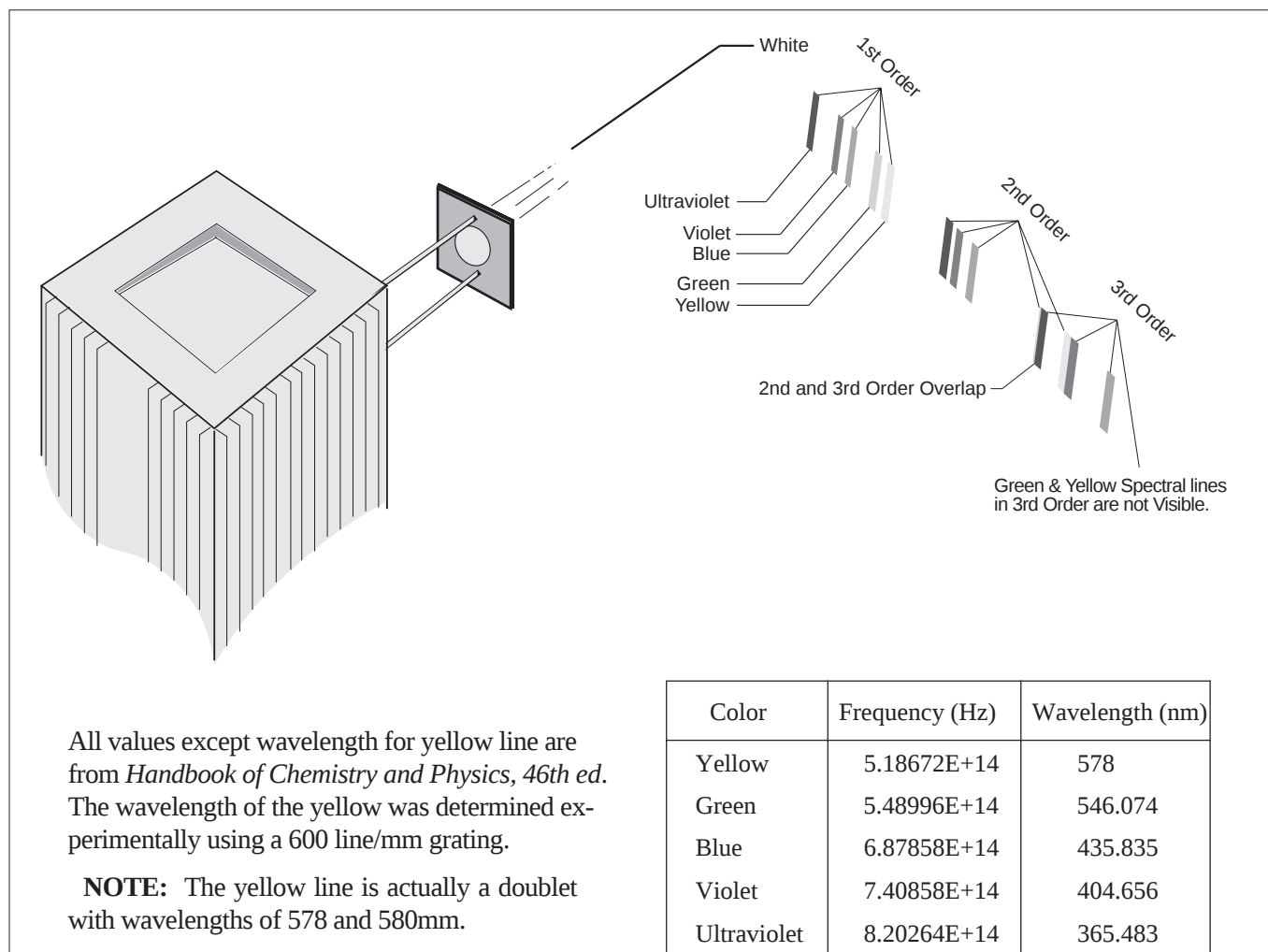


Figure 10. The Three Orders of Light Gradients

14. Press the “PUSH TO ZERO” button on the side panel of the h/e Apparatus to discharge any accumulated potential in the unit's electronics. This will assure the Apparatus records only the potential of the light you are measuring. Note that the output voltage will drift with the absence of light on the photodiode.
15. Read the output voltage on your digital voltmeter. It is a direct measurement of the stopping potential for the photoelectrons. (See *Theory of Operation* in the Technical Information section of the manual for an explanation of the measurement.)

► **NOTE:** For some apparatus, the stopping potential will temporarily read high and then drop down to the actual stopping potential voltage.

Using the Filters

The (AP-9368) h/e Apparatus includes three filters: one Green and one Yellow, plus a Variable Transmission Filter. The filter frames have magnetic strips and mount to the outside of the White Reflective Mask of the h/e Apparatus.

Use the green and yellow filters when you're using the green and yellow spectral lines. These filters limit higher frequencies of light from entering the h/e Apparatus. This prevents ambient room light from interfering with the lower energy yellow and green light and masking the true results. It also blocks the higher frequency ultraviolet light from the higher order spectra which may overlap with lower orders of yellow and green.

The Variable Transmission Filter consists of computer-generated patterns of dots and lines that vary the intensity (not the frequency) of the incident light. The relative transmission percentages are 100%, 80%, 60%, 40%, and 20%.

Experiment 1: The Wave Model of light vs. the Quantum Model

According to the photon theory of light, the maximum kinetic energy, KE_{max} , of photoelectrons depends only on the frequency of the incident light, and is independent of the intensity. Thus the higher the frequency of the light, the greater its energy.

In contrast, the classical wave model of light predicted that KE_{max} would depend on light intensity. In other words, the brighter the light, the greater its energy.

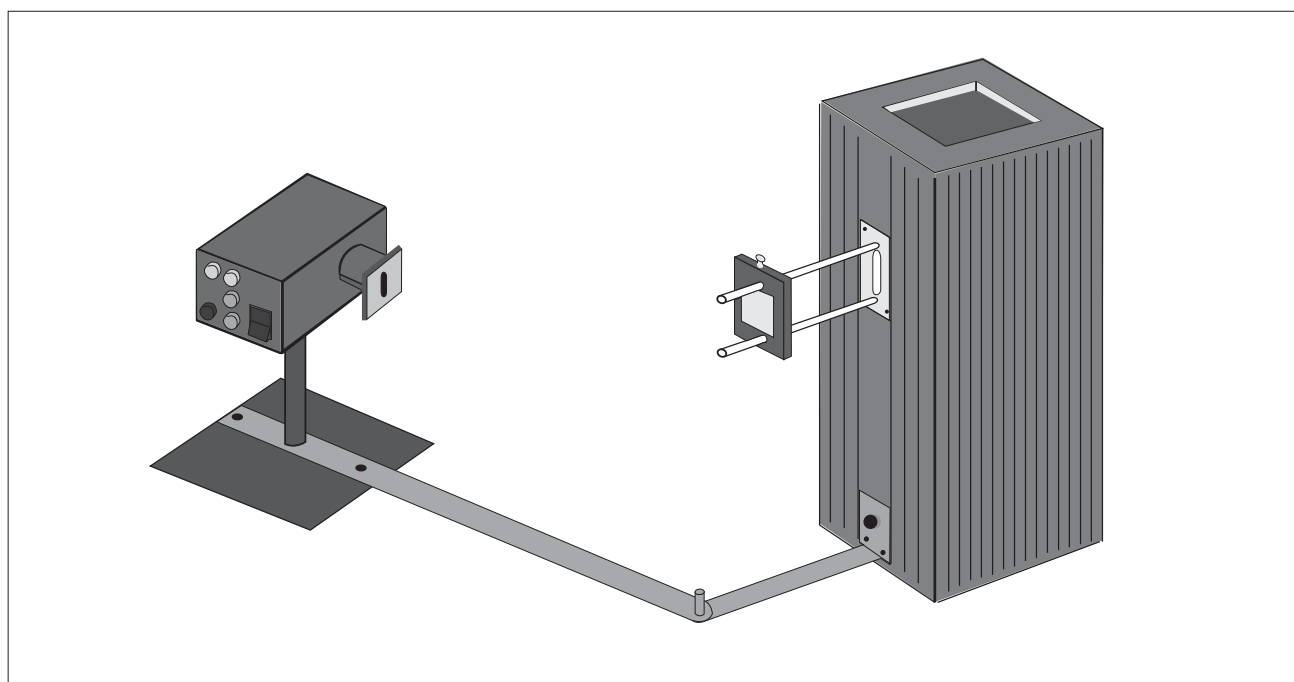
This lab investigates both of these assertions. Part A selects two spectral lines from a mercury light source and investigates the maximum energy of the photoelectrons as a function of the intensity. Part B selects different spectral lines and investigates the maximum energy of the photoelectrons as a function of the frequency of the light.

Setup

Set up the equipment as shown in the diagram below. Focus the light from the Mercury Vapor Light Source onto the slot in the white reflective mask on the h/e Apparatus. Tilt the Light Shield of the Apparatus out of the way to reveal the white photodiode mask inside the Apparatus. Slide the Lens/Grating assembly forward and back on its support rods until you achieve the sharpest image of the aperture centered on the hole in the photodiode mask. Secure the Lens/Grating by tightening the thumbscrew.

Align the system by rotating the h/e Apparatus on its support base so that the same color light that falls on the opening of the light screen falls on the window in the photodiode mask, with no overlap of color from other spectral lines. Return the Light Shield to its closed position.

Check the polarity of the leads from your digital voltmeter (DVM), and connect them to the OUTPUT terminals of the same polarity on the h/e Apparatus.



Experiment 1. Equipment Setup

Procedure

Part A

1. Adjust the h/e Apparatus so that only one of the spectral colors falls upon the opening of the mask of the photodiode. If you select the green or yellow spectral line, place the corresponding colored filter over the White Reflective Mask on the h/e Apparatus
2. Place the Variable Transmission Filter in front of the White Reflective Mask (and over the colored filter, if one is used) so that the light passes through the section marked 100% and reaches the photodiode. Record the DVM voltage reading in the table below.

Press the instrument discharge button, release it, and observe approximately how much time is required to return to the recorded voltage.

3. Move the Variable Transmission Filter so that the next section is directly in front of the incoming light. Record the new DVM reading, and approximate time to recharge after the discharge button has been pressed and released.

Repeat Step 3 until you have tested all five sections of the filter.

Repeat the procedure using a second color from the spectrum.

Color #1 _____ (name)	%Transmission	Stopping Potential	Approx. Charge Time
	100		
	80		
	60		
	40		
	20		
Color #2 _____ (name)	%Transmission	Stopping Potential	Approx. Charge Time
	100		
	80		
	60		
	40		
	20		

Part B

1. You can easily see five colors in the mercury light spectrum. Adjust the h/e Apparatus so that only one of the yellow colored bands falls upon the opening of the mask of the photodiode. Place the yellow colored filter over the White Reflective Mask on the h/e Apparatus.
2. Record the DVM voltage reading (stopping potential) in the table below.
3. Repeat the process for each color in the spectrum. Be sure to use the green filter when measuring the green spectrum.

Analysis

1. Describe the effect that passing different amounts of the same colored light through the Variable Transmission Filter has on the stopping potential and thus the maximum energy of the photoelectrons, as well as the charging time after pressing the discharge button.
2. Describe the effect that different colors of light had on the stopping potential and thus the maximum energy of the photoelectrons.
3. Defend whether this experiment supports a wave or a quantum model of light based on your lab results.

Explain why there is a slight drop in the measured stopping potential as the light intensity is decreased.

► **NOTE:** While the impedance of the zero gain amplifier is very high ($\approx 10^{13} \Omega$), it is not infinite and some charge leaks off. Thus charging the apparatus is analogous to filling a bath tub with different water flow rates while the drain is partly open.

Light Color	Stopping Potential
Yellow	
Green	
Blue	
Violet	
Ultraviolet	

Notes

Experiment 2: The Relationship between Energy, Wavelength, and Frequency

According to the quantum model of light, the energy of light is directly proportional to its frequency. Thus, the higher the frequency, the more energy it has. With careful experimentation, the constant of proportionality, Planck's constant, can be determined.

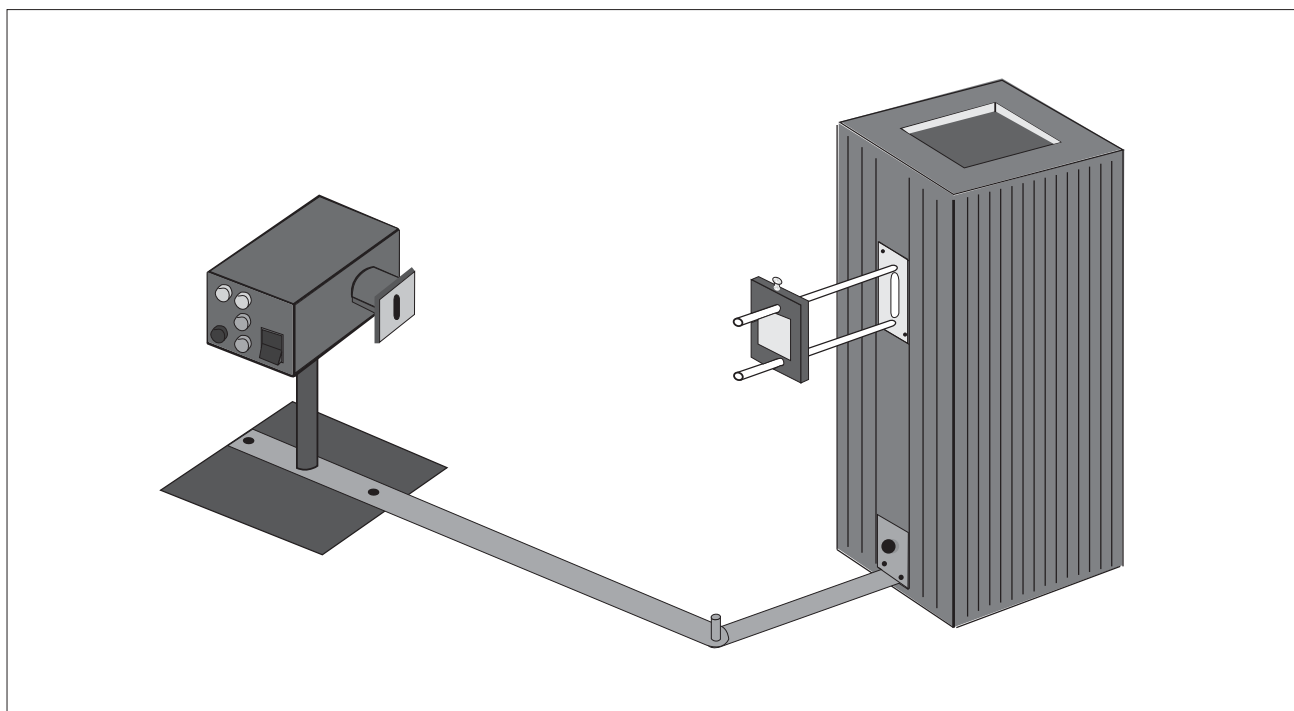
In this lab you will select different spectral lines from mercury and investigate the maximum energy of the photoelectrons as a function of the wavelength and frequency of the light.

Setup

Set up the equipment as shown in the diagram below. Focus the light from the Mercury Vapor Light Source onto the slot in the white reflective mask on the h/e Apparatus. Tilt the Light Shield of the Apparatus out of the way to reveal the white photodiode mask inside the Apparatus. Slide the Lens/Grating assembly forward and back on its support rods until you achieve the sharpest image of the aperture centered on the hole in the photodiode mask. Secure the Lens/Grating by tightening the thumbscrew.

Align the system by rotating the h/e Apparatus on its support base so that the same color light that falls on the opening of the light screen falls on the window in the photodiode mask with no overlap of color from other spectral bands. Return the Light Shield to its closed position.

Check the polarity of the leads from your digital voltmeter (DVM), and connect them to the OUTPUT terminals of the same polarity on the h/e Apparatus.



Experiment 2. Equipment Setup

Procedure

1. You can see five colors in two orders of the mercury light spectrum. Adjust the h/e Apparatus carefully so that only one color from the first order (the brightest order) falls on the opening of the mask of the photodiode.
2. For each color in the first order, measure the stopping potential with the DVM and record that measurement in the table below. Use the yellow and green colored filters on the Reflective Mask of the h/e Apparatus when you measure the yellow and green spectral lines.
3. Move to the second order and repeat the process. Record your results in the table below.

Analysis

Determine the wavelength and frequency of each spectral line. Plot a graph of the stopping potential vs. frequency.

Determine the slope and y-intercept. Interpret the results in terms of the h/e ratio and the W_o/e ratio. Calculate h and W_o .

In your discussion, report your values and discuss your results with an interpretation based on a quantum model for light.

First Order Color	Wavelength nm	Frequency $\times 10^{14}$ Hz	Stopping Potential volts
Yellow			
Green			
Blue			
Violet			
Ultraviolet			
Second Order Color	Wavelength nm	Frequency $\times 10^{14}$ Hz	Stopping Potential volts
Yellow			
Green			
Blue			
Violet			
Ultraviolet			

Technical Information

Theory of Operation

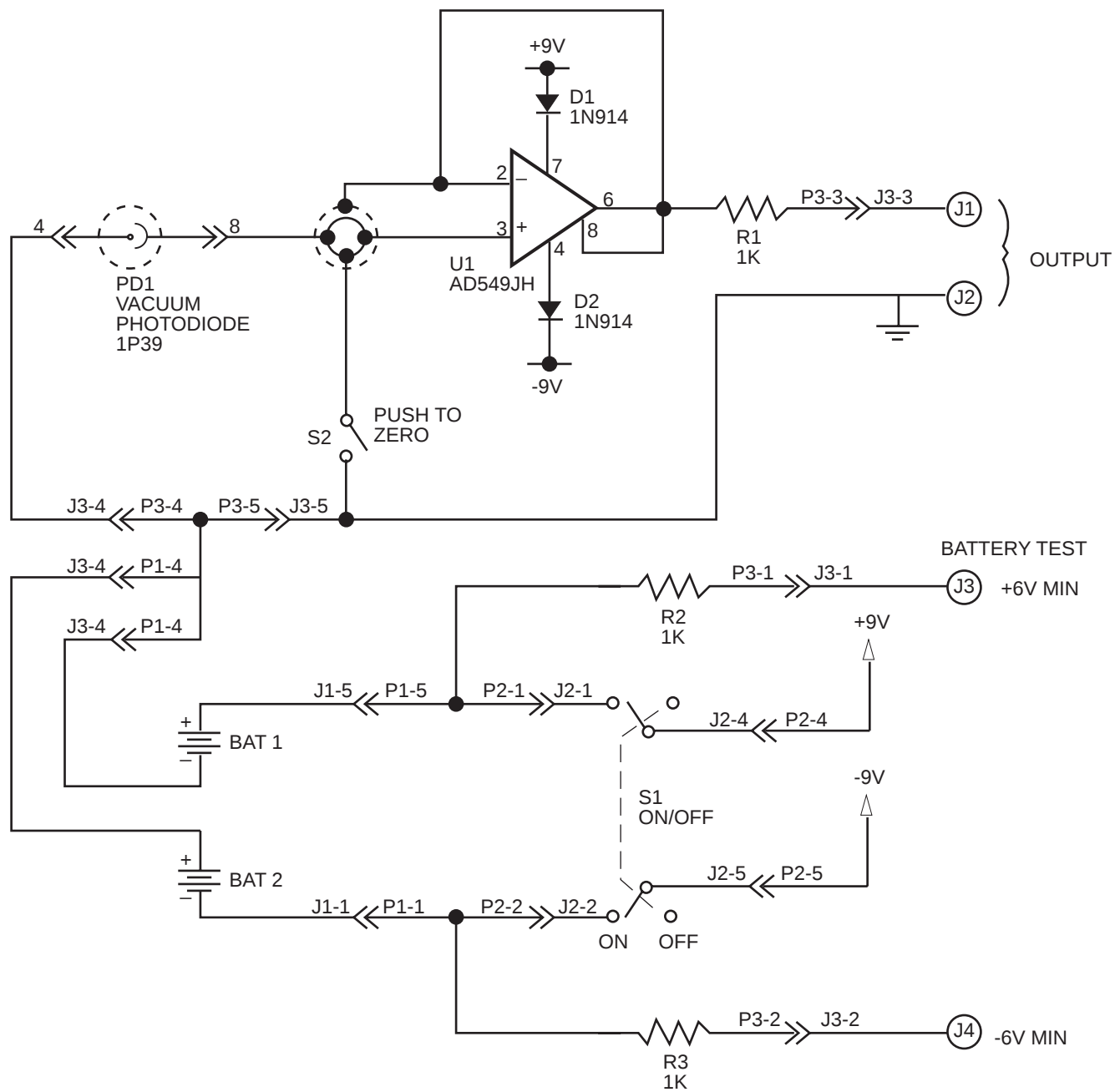
In experiments with the h/e Apparatus, monochromatic light falls on the cathode plate of a vacuum photodiode tube that has a low work function, W_0 . Photoelectrons ejected from the cathode collect on the anode.

The photodiode tube and its associated electronics have a small capacitance which becomes charged by the photoelectric current. When the potential on this capacitance reaches the stopping potential of the photoelectrons, the current decreases to zero, and the anode-to-cathode voltage stabilizes. This final voltage between the anode and cathode is therefore the stopping potential of the photoelectrons.

To let you measure the stopping potential, the anode is connected to a built-in amplifier with an ultrahigh input impedance ($> 10^{13} \Omega$), and the output from this amplifier is connected to the output jacks on the front panel of the apparatus. This high impedance, unity gain ($V_{out}/V_{in} = 1$) amplifier lets you measure the stopping potential with a digital voltmeter.

Due to the ultra high input impedance, once the capacitor has been charged from the photodiode current it takes a long time to discharge this potential through some leakage. Therefore a shorting switch labeled “PUSH TO Zero” enables the user to quickly bleed off the charge. However, the op-amp output will not stay at 0 volts after the switch is released since the op-amp input is floating.

Due to variances in the assembly process, each apparatus has a slightly different capacitance. When the zero switch is released, the internal capacitance along with the user's body capacitance coupled through the switch is enough to make the output voltage jump and/or oscillate. Once photoelectrons charge the anode the input voltage will stabilize.



Schematic Diagram