Instruction Manual and Experiment Guide for the PASCO scientific Model OS-9246B, OS-9247A, OS-9250, OS-9251 and OS-9254B

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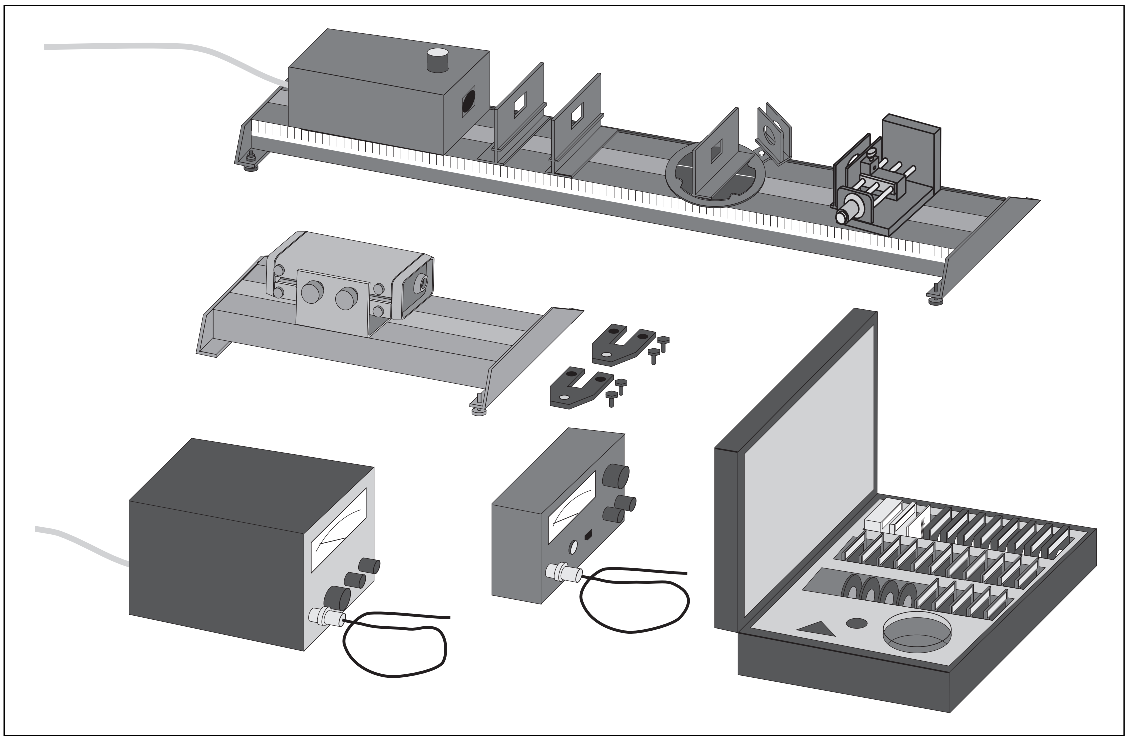
ADVANCED OPTICS SYSTEM



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Introduction

This manual includes operating instructions, specifications, and experiments for the five PASCO Optics systems listed in Table 1. These systems comprise PASCO's "advanced" optics systems (as opposed to our OS-8500 Introductory Optics System, a less sophisticated system which is not described in this manual).

In reality, the five PASCO Optics systems described in this manual are really a single system, available in five different packages. The Complete Optics System (OS-9254A) includes all of the instruments and components available, and enables you to perform all of the experiments described in the *Experiments* section. Each of the other systems includes some subset of the instruments and components included in the Complete System, and can be used to perform some of the experiments.

The components of the five optics systems are completely interchangeable, so if you purchase any combination of systems, you can mix and match components. Moreover, if you decide to upgrade your system, all the components are available separately, so there is no need to purchase duplicate equipment. Information on all instruments and components is provided in the equipment section of this manual.

➤ **NOTE:** The PASCO OS-8500 Introductory Optics System (not described in this manual) is not compatible with any of the systems, instruments, or components described in this manual.

The Experiments Guide section of the PASCO Optics System manual is intended to give the student an outline of the range of optics experiments which can be performed with the PASCO system. The experiments have been written to help the student master any idiosyncracies in the system in order to use the apparatus with maximum efficiency and minimum error. Hopefully the student will gain sufficient technique to design and perform his or her own optics experiments with the PASCO Optics System.

In order to insure success with the various experiments, the student should first read the Equipment Instructions in the first portion of the manual. Also, the light patterns and images will be much easier to see and measure if the ambient room light is kept down to a minimum.

Often an experiment can be performed with either the incadescent light source or the laser. Before using the laser in these cases, the student should read the equipment description as well as Experiment 5 which cover the unique properties of the laser. The most important point to remember is that the laser is not a toy. Do Not Look Directly Into The Laser Or Its Mirror Reflection.

Table 1: Optics Systems and Experiments

System	Catalog Number	Experiments[1]
The Complete Optics System[2]	OS-9254B	All
The Advanced Optics System		
with laser	OS-9246A	All
without laser	OS-9250	1-4
The Intermediate Optics System		
with laser	OS-9247A	1-10
without laser	OS-9251	1-4

[1]These experiments include only those that are fully described in the Experiment section on this manual. With the wide variety of components included in the Complete Optics System, many other experiments are possible.

[2]The Complete Optics System includes the PASCO Interferometer, which is not mentioned in this manual. However, a separate manual is included with the Interferometer.

Equipment

Table 2 lists the equipment included in each of the PASCO optics systems. For example, the Advanced System contains five of the OS-9107 Component Holders, while the Diffraction System contains only one. Major components are identified in Figure 1 on the following page. Minor components, such as lenses, mirrors, filters, etc., are labeled, so there should be no confusion in identifying them.

Information on setting up and using the various instruments and components is provided on the following pages.

➤ **NOTES:**

① The Complete Optics System is not listed in Table 2, because its components are identical to those of the Advanced Optics System. The difference between the two systems is that the Complete System includes the PASCO Interferometer, which comes with its own manual.

② If you purchased a system without the laser (OS-9250 or OS-9251), the included components are as listed in the table, but you will not have the following:

- 0.5 mW Helium Neon Laser (SE-9367)
- Laser Alignment Bench (OS-9172)

Table 2: Component List

Catalog No.	Complete	Advanced	Intermediate	Description	Catalog No.	Complete	Advanced	Intermediate	Description
OS-8020	1	1		High Sensitivity Photometer	OS-9120	1	1	1	Diffuser
OS-9152B			1	Student Photometer	OS-9121	1	1	1	Crossed Arrow Target
SE-9367	1	1	1	0.5 mW HeNe Laser	OS-9165	1	1	1	Slits and Patterns (16 sets on 4 slides)
OS-9256A	1			Interferometer Accessory	OS-9126	1	1	1	Opaque Points and Fresnel Zone Plates
OS-9172	1	1	1	Laser Alignment Bench	OS-9127	1	1	1	5276 line/cm Diffraction Grating
OS-9102B	1	1	1	Incandescent Light Source	OS-9128	1	1	1	Glass Plate
OS-9103	1	1	1	Optics Bench	OS-9129	1	1	1	Acrylic Plate
OS-9104B	1	1	1	Linear Translator	OS-9130	1	1	1	Prism (90°)
OS-9106A	1	1	1	Angular Translator/Component Carrier	OS-9131	1	1	1	-22 mm F.L. Lens
OS-9107	5	5	4	Component Carrier	OS-9132	1	1	1	18 mm F.L. Lens
OS-9108	1	1		Glass Dispersion Tank	OS-9133	1	1	1	48 mm F.L. Lens
OS-9109	3	3	3	Calibrated Polarizer	OS-9134	1	1	1	127 mm F.L. Lens
OS-9110	1	1	1	Calibrated 140 nm Retarder	OS-9135	1	1	1	252 mm F.L. Lens
OS-9111	1	1		Red Spectral Filter	OS-9136	1	1	1	Flat Front Surface Mirror
OS-9112	1	1		Yellow Spectral Filter	OS-9137	1	1	1	Concave Front Surface Mirror
OS-9113	1	1		Green Spectral Filter	OS-9138	1	1	1	Viewing Screen with Metric Scale
OS-9114	1	1		Blue Spectral Filter	OS-9139	1	1	1	Aperture Mask
OS-9115	1	1	1	Hologram	OS-9140	1	1	1	Fitted Case for Optical Components
OS-9116	1	1	1	Photometer Apertures	012-01511	1	1	1	Optics System Manual
OS-9117	1	1	1	Variable Diaphragm	OS-8514	1	1	1	Laser Adapter Bracket
OS-9118	1	1	1	Light Source Apertures (0.5, 0.75)	OS-9255A	1			Precision Interferometer
OS-9119	1	1	1	Light Source Apertures (1.0, 2.0)					

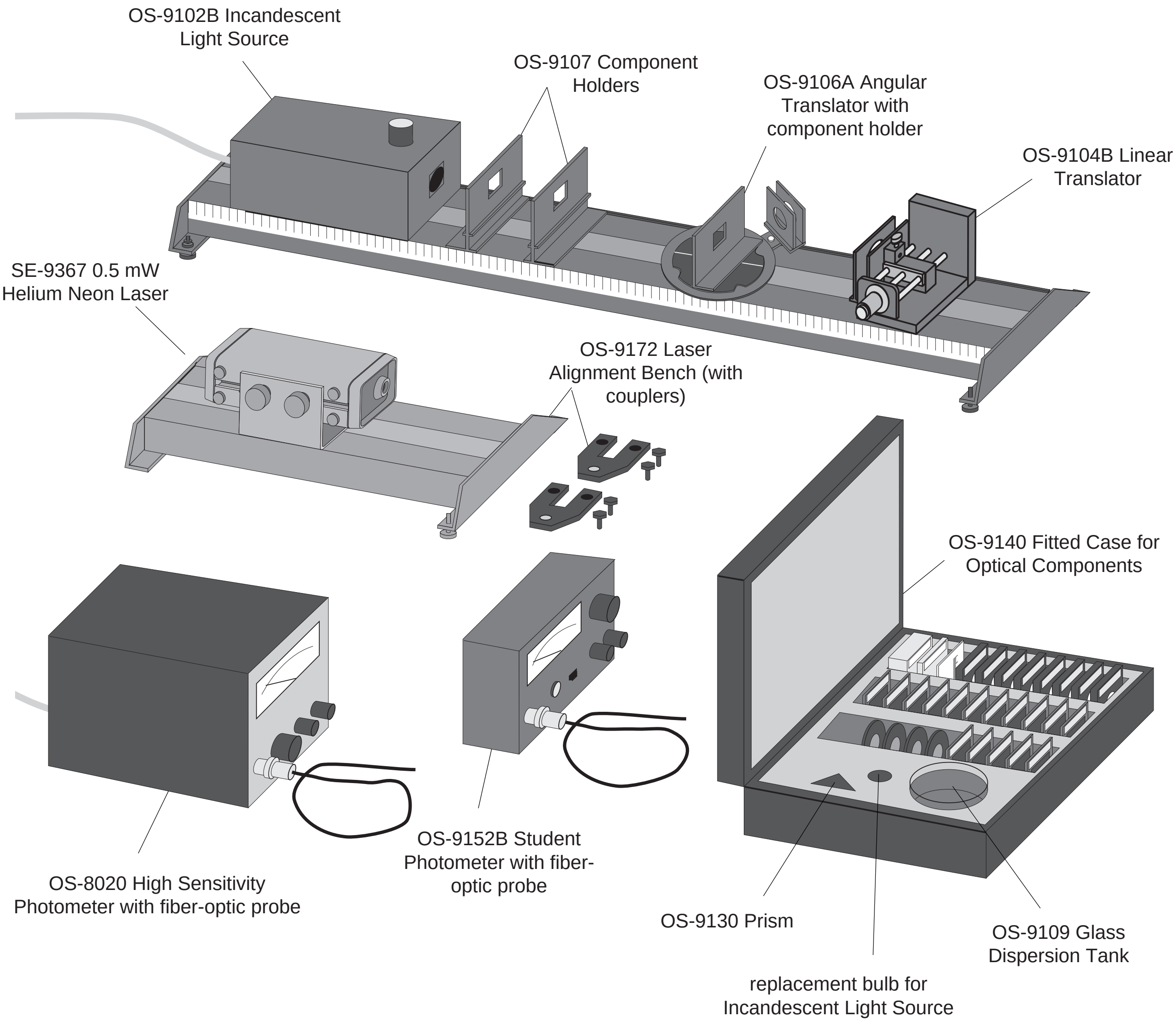


Figure 1: Advanced Optics Equipment

The Optics Bench

The optics bench (see Figure 2) provides a straight, rigid surface for aligning optics experiments. For best results, the bench should be placed on a reasonably flat and level surface, and the leveling screws should be adjusted so the bench rests evenly on all four screws. Once the bench is leveled, tighten the locknuts so there is no slipping.

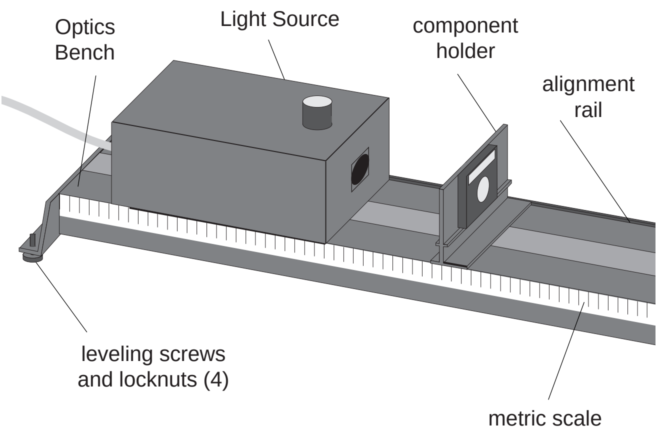


Figure 2: Using the Optics Bench

The incandescent light source and the component holders attach magnetically to the bench as shown. For proper alignment, the edge of the light source and component holders should be mounted flush to the alignment rail, which is the raised edge that runs along one side of the bench. This will ensure that the optical axis of the light source and component holders are coincident, which makes it easier to align optical components.

Your optics bench is guaranteed straight to within 0.25 mm over its full one meter length, and, under normal use, will retain its straightness. However the optics bench will bow slightly if heavily loaded. For example, a one kg mass placed in the center of the bench will produce a deflection of approximately 0.07 mm.

> ➤ **NOTE:** Avoid scratching or otherwise abusing the surface of the magnetic pads on the top of the optics bench. If they get dirty, use only soapy water or rubbing alcohol for cleaning. Other solvents may dissolve the magnetic surfaces.

The Incandescent Light Source

The incandescent light source (see Figure 3) provides 15 candlepower of light with the frequency spectrum shown in Figure 4. The built-in power supply of the light source is regulated, so there's minimal variation in the intensity of the light. This is essential for obtaining accurate data in experiments where a photometer is being used to measure light intensities.

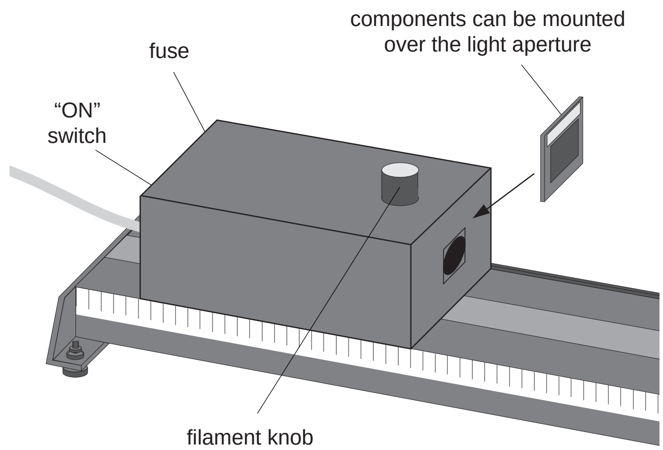


Figure 3: Using the Incandescent Light Source

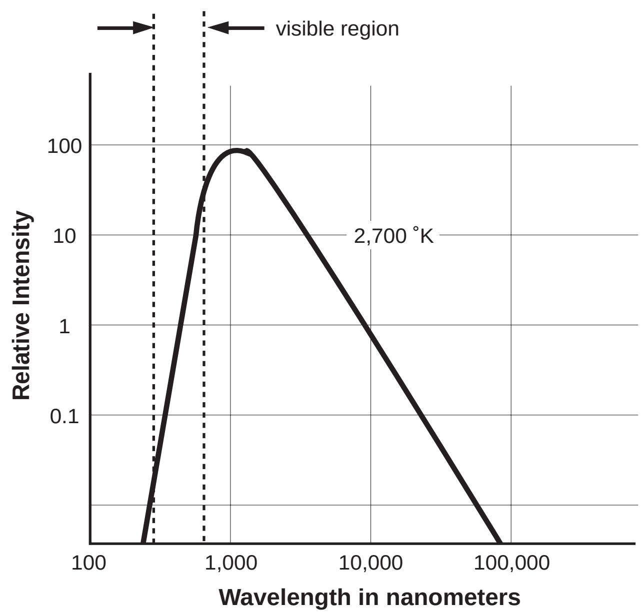


Figure 4: Frequency Spectrum for the Incandescent Light Source

> ➤ **NOTE:** The distance from the front panel of the light source to the light bulb filament is approximately 22 mm.

To turn on the light source, connect the power cord to a grounded receptacle of the appropriate line voltage (120 VAC, 60 Hz, unless otherwise specified), and flip the switch on the rear panel to ON. If at any time the light fails to come on, chances are that the fuse is blown or the light bulb is burnt out. See the Maintenance section for replacement instructions.

The Filament knob on the top of the light source adjusts the position of the light bulb filament transverse to the optical axis of the bench. The filament moves in the same direction as the knob is turned. Components can be mounted onto the magnetic pad on the front panel of the light source, over the light aperture. The crossed-arrow target, for example, is often mounted in this way as an object for lens experiments.

➤ **CAUTION:** When used continuously, the light source becomes hot to the touch. Since it requires no warm-up time, we recommend it be turned on only when setting up or actually performing an experiment.

Specifications for the Incandescent Light Source (Model OS-9102B)

Output: Approximately 15 candlepower

Filament temperature: 2700 °K

Bulb: #93, operated at 12 VDC, 1.0 A; bulb life approximately 700 hours

Regulation: Maximum intensity variation of 2% for a 10% change in line voltage.

Input Power: 105-125 VAC 60 Hz (or 210-240 VAC, 50 Hz if specified when ordered)

Fuse 0.5 A, Slo-Blo (0.25 A for 220 VAC model)

The Helium Neon Laser

The helium neon laser is a 0.5 mW, TEM_{00} mode laser, providing randomly polarized light at a wavelength of 632.8 nm. The built-in power supply is regulated so the output has minimum ripple and the intensity is stable to within ±2.5%. A 15 minute warm up is required to reach full power, but the power on start-up is greater than 0.35 mW. If you'd like more technical specifications, and a detailed explanation of laser operation, see the instruction manual that's included with the laser.

➤ **CAUTION:** This is a relatively safe, low power laser. Nevertheless, we strongly recommend the following precautions:

- Never look into the laser beam, either directly, or as it is reflected from a mirror.
- Set up experiments so the laser is either above or below eye level (for both sitting and standing people).

To Setup the Laser using the Laser Alignment Bench:

The laser is most conveniently aligned using the laser alignment bench, which can be joined to the optics bench using the bench couplers. The procedure is as follows:

① Place the optics bench and the laser alignment bench end to end, as in Figure 5. Notice that only one end of the laser alignment bench has holes for

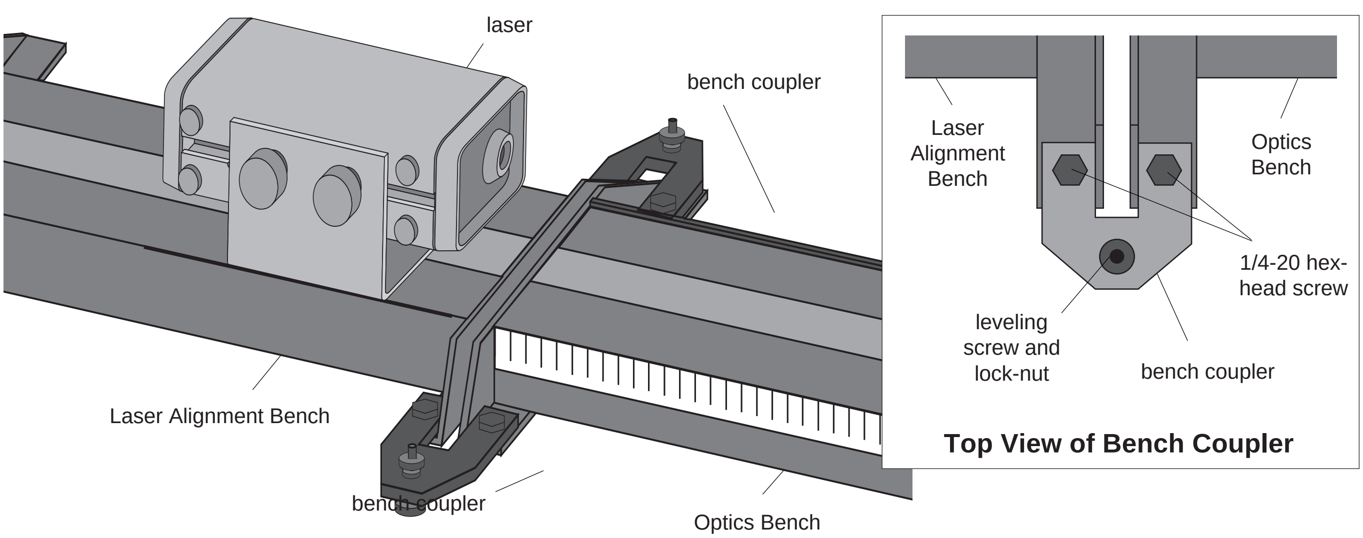


Figure 5: Connecting the Laser Alignment Bench

two leveling screws. That is the end that joins to the optics bench.

② Remove the four leveling screws on the adjoining ends of the two benches.

③ Use the 1/4-20, hex-head screws that are included with the bench couplers to attach the couplers to the legs of the benches, as shown. Do not yet tighten the screws.

④ Insert one of the leveling screws, rubber foot down, through the threaded hole in each coupler.

⑤ By adjusting all five leveling screws (one on the laser alignment bench, two on the optics bench, and two on the bench couplers), align the two benches so they are in a straight line. Use a meter stick or a long straight edge on top of the benches to check vertical alignment, and on the side of the bench to check horizontal alignment.

⑥ When the benches are aligned, tighten the locknuts on all the leveling screws, and also tighten the four hex-head screws. After tightening the screws, re-check the alignment.

To Align the Laser (so the laser beam is coincident with the optical axis of the bench):

① Place a piece of masking tape or tape a piece of paper over the square hole on the front of a component holder, as in Figure 6. Make a small dot on the tape or paper, in the center of the square hole (1-inch from the top of the component shelf, and 1.5-inch from the edge of the component holder).

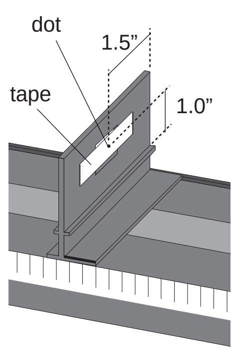


Figure 6: Locating the Optical Axis

② Place the laser on the alignment bench, as in Figure 5. Center the laser on the bench, and make sure it is reasonably parallel with the bench.

③ Place the component holder on the optics bench, about 10 cm from the laser aperture. Make sure that the component holder is flush against the alignment rail of the bench. The dot on the tape now marks the optical axis of the bench.

④ Turn on the laser, and move the aperture end of the laser sideways, as needed, so that the laser beam falls on the dot.

⑤ Move the component holder about 90 cm away from the laser aperture. Again, be sure the edge of the component holder is flush against the alignment rail of the bench.

⑥ Without moving the aperture end of the laser, move the rear end of the laser as needed to recenter the laser beam on the dot. (You may also need to adjust the leveling screws on the laser alignment bench in order to center the laser beam vertically on the dot.)

⑦ Repeat steps 3 through 6 until the laser beam is aligned with the dot for both positions of the component holder.

The Component Holders

Each optics system includes several of the standard component holders, that attach magnetically to the optics bench, as in Figure 7. Components mount magnetically onto either side of the component holders. For proper alignment of the components along the optical axis of the bench:

① Mount the component holder flush against the alignment rail of the bench, as in Figure 7.

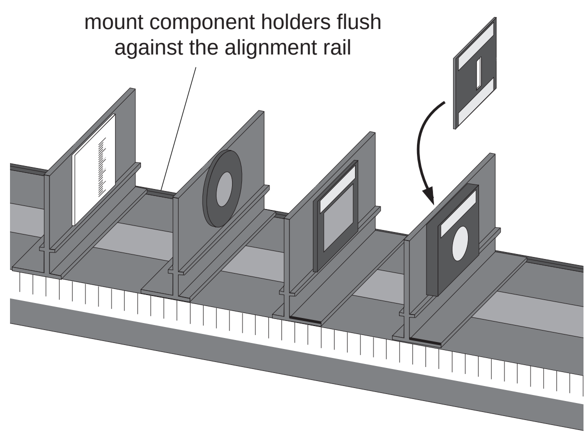


Figure 7: Using the Component Holders

② Mount the component flush against the component ledge, as in Figure 8.

③ Center the component horizontally on the holder.

Each component holder has two white indicator lines that help when making measurements. The line on the side of the holder, near the base, marks the position of the center of the holder against the metric scale of the optics bench. The line on the component ledge marks the angle of rotation for polarizers and for the retarder.

➤ **IMPORTANT:** The indicator line on the side of the base marks the center of the holder, not the optical surface of a component that is mounted on the holder (see Figure 8). For accurate measurements of component positions, Table 3 provides offset values for the various components.

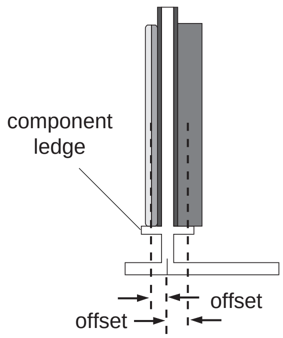


Figure 8: Measuring Component Position

Table 3: Component Offset Values

Component	Offset (mm)
Slide mounted components (filters, crossed-arrow target slits, apertures, etc.)	4.5
Lenses	6.5
Front surface mirror, plane	8.0
Front surface mirror, concave	8.0 (avg)
Variable diaphragm	10.0
Viewing Screen	4.5
Polarizers, retarder	4.5

The Angular Translator

The angular translator is used in most experiments in which reflected, refracted, or scattered light is analyzed. The component that will deflect the light is placed in the center of the rotating table, either directly on the table, or mounted on the angular translator component holder, as shown in Figure 9. The rotating table is then set to various angles, and the angle of incidence is read on the degree plate.

The analyzer arm is rotated to intercept the deflected light. The analyzer arm has built-in component holders for mounting a viewing screen, polarizers, filters, etc. It also has a hole for attaching the fiber-optic probe of a PASCO photometer.

➤ **IMPORTANT:** when attaching the probe, tighten the thumbscrew VERY GENTLY to protect the probe.

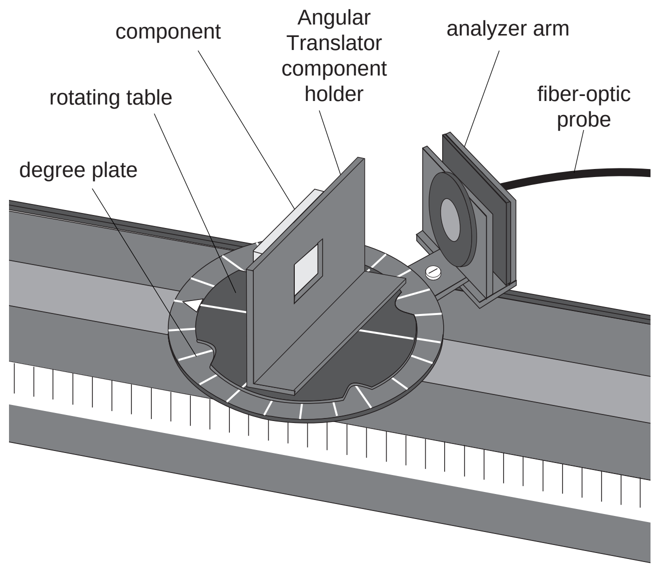


Figure 9: Using the Angular Translator

Tips on Using the Angular Translator

① Mount the rectangular base of the translator flush against the alignment rail of the optics bench.

② Align the degree plate so that the zero degree mark is aligned with the optical axis of the bench. To do this, lift the rotating table off of the degree plate (it's attached magnetically), loosen the exposed screw, align the degree plate, and retighten the screw.

③ When attaching the fiber-optic probe, push the probe all the way into the hole, so the tip of the probe is just at the surface of the rear component holder. You can then place the photometer apertures slide on the rear component holder to clearly define the area of interest.

④ If you are mounting a polarizer (or a retarder) on the analyzer arm, mount it on the front component holder. It has a line that indicates the angle of polarization.

⑤ Use the Angular translator component holder only on the angular translator. It will not hold components at the proper height if used directly on the optics bench.

The Linear Translator

The linear translator (Figure 10) is used to position the fiber-optic probe of a PASCO photometer transverse to the optical axis of the optics bench. It will resolve the position of the probe to within 0.1 mm and can be

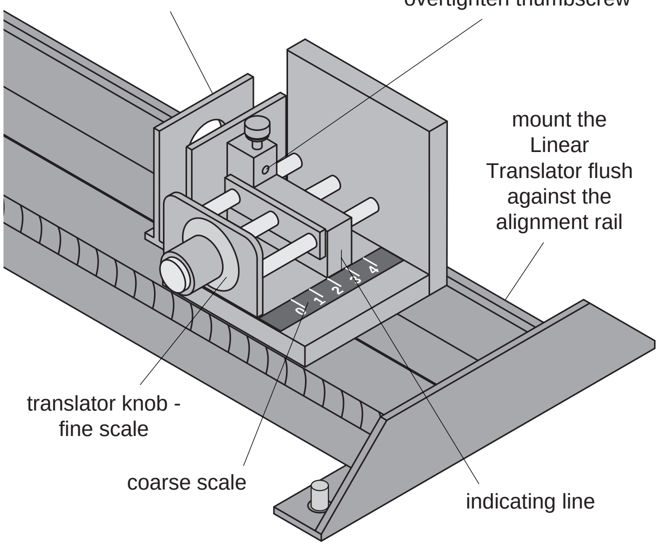


Figure 10: Using the Linear Translator

mounted so that the probe movement is either horizontal or vertical.

Up to three analyzing components, such as filters, polarizers, apertures, etc., can be mounted on the built-in component holders. Polarizers and retarders are best mounted on the front holder, since it has an indicating line for measuring polarization angle. Photometer apertures should be mounted on the rear holder, so they are as close as possible to the tip of the fiber-optic probe.

To use the translator, place the fiber-optic probe in the hole in the rear of the translator. Push it all the way into the hole, so that the surface of the probe is flush with the surface of the rear component holder. Then the photometer apertures slide can be placed on the rear holder to clearly define the area of interest. Important: when securing the probe in the hole, tighten the thumbscrew VERY GENTLY to protect the probe.

Mount the translator on the optics bench, and turn the translator knob to move the probe. Read the probe position to the nearest millimeter using the coarse scale in the rear of the translator. Then read the position to the nearest 0.01 mm using the fine scale on the translator knob.

The Photometers

Depending on which PASCO optics system you're using, you have one of two Photometers: the PI-8020 High Sensitivity Photometer or the OS-9152B Student Photometer (see Figure 11). Both these instruments:

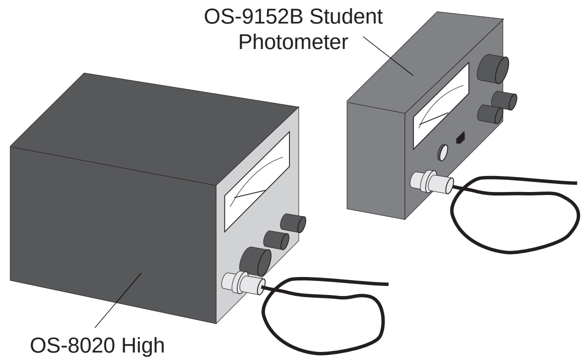


Figure 11: The Photometers

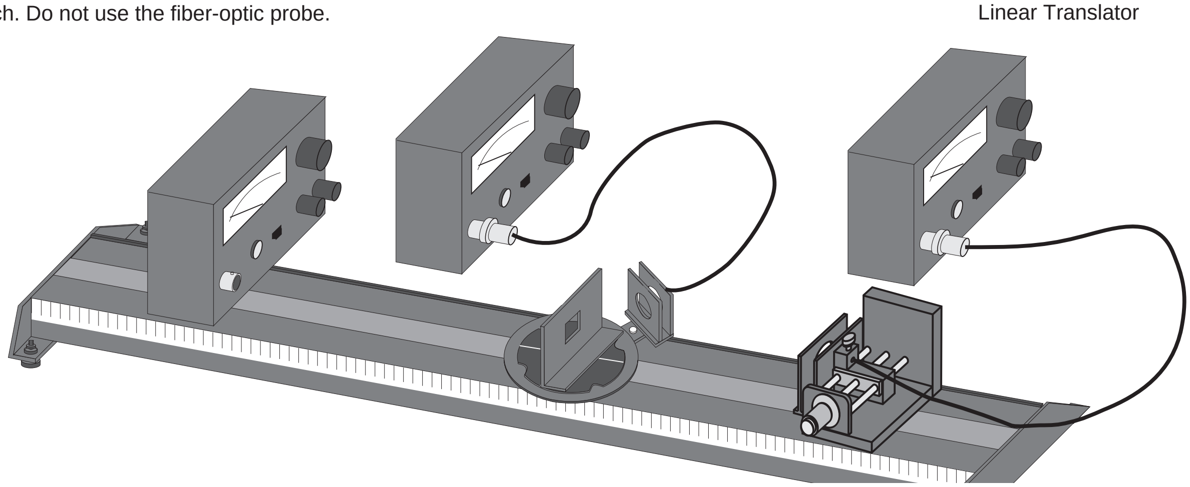


Figure 12: Setting Up the Photometers

- measure relative intensities of incident light.
- include a 70 cm long, fiber optic probe that allows the measurement of light intensities with a spatial resolution of approximately 1 mm. (The linear and angular translators are used to accurately position the probe.)
- use a selenium photovoltaic cell as the light sensor
- provide a recorder output that is proportional to the measured light intensity
- have a variable sensitivity control that allows a full scale reading at any light intensity within the range of the instrument.

The key differences between the two photometers are:

- The OS-8020 High Sensitivity Photometer has a broader choice of intensity ranges (0.1 - 1,000 lux), an illuminated scale, and a built-in power supply.
- The OS-9152B Student Photometer has a narrower choice of intensity ranges (1 - 300 lux), and is powered by a 9 V battery.

Setting Up the Photometers

The photometers can be used with or without the fiber-optic probe, as shown in Figure 12 (the figure shows only the Student Photometer, but both photometers are used in the same way).

When used without the probe, the light must fall directly onto the Light Probe Input connector. In most experiments in which the probe is not used, the photometer is positioned so that the connector is aligned with the optical axis of the bench.

When used with the probe, the intensity of the incident light can be sampled over very small areas (1 mm^2), providing accurate measurements of intensity versus position. To use the probe, connect the probe to the Light Probe Input connector. Then connect the free end of the probe to the probe receptacle in either the linear or angular translator. The probe can now be positioned very accurately to measure intensity versus angle (in a reflection or refraction experiment, for example) or intensity versus vertical or lateral position (in a diffraction experiment, for example).

➤ **IMPORTANT:** To prolong the life and efficiency of the fiber-optic probe:

① Do not bend the probe to a radius of less than 2 inches at any given point (do not coil tighter than a 4” circle).

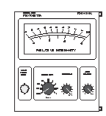
② Do not bend the probe within three inches of either end.

③ Take care not to scratch or mar the end of the probe. If the probe end becomes scratched or dirty, you can either clean it by lightly grinding the end on a fine grinding stone, or you can just cut off the tip of the probe with a razor blade. If you do, be sure that the cut is square.

Making Measurements with the Photometers

For the most part, the operation of the two photometers is the same. In the following description, instructions that apply to only one of the photometers are marked with the appropriate icon. If there is no icon, the instructions apply to both instruments.

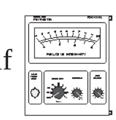
① Zero the Meter Mechanically



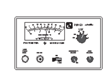
- Before plugging in the OS-8020 Photometer, use a small screwdriver to adjust the Mechanical Zero screw (directly under the meter face) so that the meter reads zero.

- Before turning on the OS-9152B Photometer, use a small screwdriver to adjust the Mechanical Zero screw (directly under the meter face) so that the meter reads zero.

② Connect the Power/Battery Check



- Plug the power cord into a standard 117 VAC, 60 Hz power outlet (or 220 VAC if so designated).



- Set the power switch to the "Batt. Test" position. The meter needle should be deflected to the right of the "Replace Batt." line. If it isn't, then replace the battery (Note: The photometer is shipped with a battery, but it must be installed. To install or replace a battery, see the Maintenance section at the end of the manual.)

③ Zero the Meter Electronically:

- Cover the Light Probe Input connector so that no light reaches the sensor. A good technique is to place a rubber cork tightly over the input connector. A finger over the connector will not shut out the light effectively enough. (Note: a finger over the input connector *will* shut out the light effectively enough for the less sensitive Student Photometer.)

- With the input connector covered, set the sensitivity Range switch to the most sensitive range, and turn the Zero Adjust knob until the meter reads zero. The instrument is now zeroed on all ranges. Now turn the sensitivity Range switch to the highest range.

④ Measuring Relative Intensities

> ➤ **IMPORTANT:** The photometer reading is proportional to the energy of the light that falls on its photovoltaic cell, which is in turn proportional to the intensity of the incident light and to the area of the cell that is illuminated. Therefore, for accurate and consistent results, the incident light should fall directly onto the Light Probe Input connector or fiber-optic probe, with a zero degree angle of incidence.

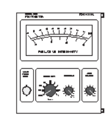
When using the photometers, intensity measurements are always made relative to some established reference value. If you were measuring the intensity of light after it passes through a polarizer, for example, you would first measure the intensity of light for a particular orientation of the polarizer (usually, but not necessarily, the orientation producing a maximum intensity of light). When measuring this reference intensity, you would adjust the photometer sensitivity so that the meter read 10 (full scale). You could then measure the intensity for different orientations of the polarizer. These subsequent measurements would be recorded as a percentage of the original measurement. For example, if the meter read 6.5, you would record the intensity as 65% of the reference value.

In general, to use the photometer to measure relative intensities:

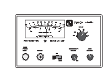
- Arrange the photometer to measure your reference intensity, usually the maximum intensity of light that you expect to measure.
- Turn the sensitivity Range switch clockwise until the photometer reads off scale.
- turn the sensitivity adjust knob counterclockwise until the meter reads exactly 10 (full scale).
- now - without touching the photometer controls - arrange the photometer to measure the other intensities you wish to measure. Read the intensities as a percentage of the original measurement.

> ➤ **NOTE:** After measuring your reference intensity, you can still use the sensitivity Range switch to change the range of the measurement. Just take into account the effect on the reading, as you would for any measuring instrument. For example, if the sensitivity Range switch were set to 100 when the reference source was measured, and then switched to 30, you would use the 0 - 3 scale and read your value as 0 - 30%. In a similar manner, if the sensitivity Range switch were turned to the 300 setting, you would use the 0 - 3 scale, and read your value as 0 - 300%.

⑤ Output Jacks



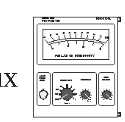
- A pair of output jacks are located on the back panel of the photometer. These jacks provide a voltage that is proportional to the meter reading. The voltage for a full scale meter reading is 140 mV - 10 V @ 1 mA, depending on the range selection. The recorder output voltage is independent of the setting of the Variable sensitivity knob.



- A miniature phone jack is located on the front panel of the Model OS-9152B Photometer. This will provide approximate 1.5 V at 1 mA for a full scale meter reading. Important: The recorder output voltage is independent of the setting of the Variable sensitivity knob.

Specifications

For the OS-8020 only:

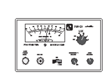


Sensitivity: approximately 0.1 to 1,000 Lux full scale in 1x and 3x ranges.

Meter: 8 cm scale length with 0 - 10 and 0 - 3 graduations.

Output: 140 mV at 1 mA. Banana jack connections on rear panel.

For the OS-9152B only:



Sensitivity: approximately 1 to 300 Lux full scale in 1x and 3x ranges.

Meter: 5 cm scale length with 0 - 10 and 0 - 3 graduations.

Output: 1.5 V at 1 mA. Miniature microphone connector.

Battery: One Burgess 2U6 or Eveready 216 9 volt battery. Approximately 100 hours life.

For both photometers:

Sensitivity: The sensitivity Adjust knob permits any input within the dynamic range of the instrument to be used to provide a full scale reading. When photometer sensitivity is varied using the Range switch, measurements are proportional to the range setting, but only if the sensitivity Adjust knob remains unmoved between measurements.

Spectral Response - Typical selenium cell response (see Figure 13).

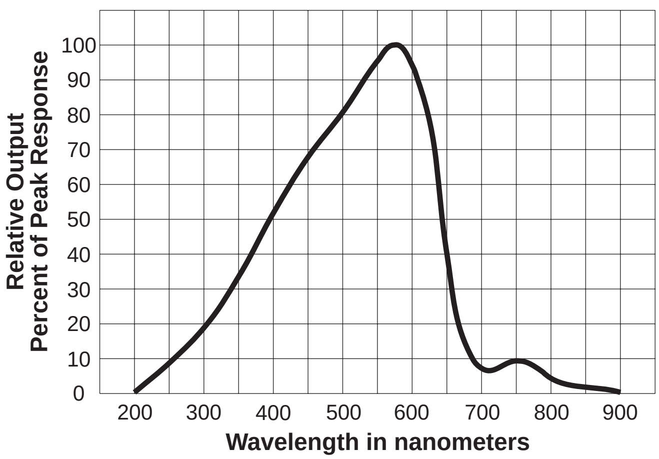


Figure 13: Spectral Response of the Photometers

Controls: Sensitivity Range, Sensitivity Adjust, Zero Adjust

About Absolute Intensity Measurements: The PASCO photometers are most effectively used for making relative light measurements only. However, accurate absolute measurements in units of lux can be made, subject to the following considerations.

- The selenium cell in the PASCO photometers does not have a corrected photo-optic response. The instrument is calibrated to a 2700°K tungsten filament lamp, such as is used in the OS-9102A Incandescent Light Source, and will indicate the correct intensity only for that source. If other light sources are used, absolute intensity measurements will be approximate only. (Accurate relative intensity measurements can be made with any light source.)
- Intensity readings are dependent on the total light energy striking the selenium cell, as well as on the spectrum of that light. Therefore, for accurate absolute measurements, the light must be incident on the full area of the selenium cell. This means that the light must fall with normal incidence directly into the Light Probe Input Connector. The light beam must be broad enough to cover the full area of the connector, and the intensity of the light must be uniform over the full area that strikes the connector.
- The fiber-optic probe restricts both the area and the intensity of the light that reaches the selenium cell. Therefore, when using the fiber-optic probe, only relative measurements can be accurately made.

Components

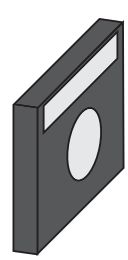
The following section provides information and specifications on all of the optical components included in the OS-9254A Complete Optics System, which includes all the components available from PASCO scientific. For a list of the components that are included in each PASCO optics system, see Table 2 in the *Equipment* section of the manual.

➤ **NOTE:** All the components in the PASCO optics systems have been constructed to stand up under normal laboratory use. The holders are strong and the components, where possible, are recessed for protection. However, care should be taken to avoid touching or scratching the optical surfaces of all components.

When cleaning components:

- Use a very soft cloth, or better yet, use lens tissue, for the optical surfaces.
- Use only alcohol or mild, soapy water as a cleaning agent. Other solvents may attack the plastic holders.

Lenses and Mirrors



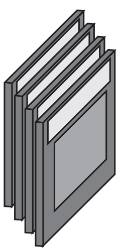
All lenses are made of glass. The mirrors are made of front-surface, aluminum-coated glass. Lenses and mirrors are mounted in 50 x 50 mm acrylic holders, and are recessed to protect the optical surface. The type of component and its focal length (if it has one) is printed on the label on each holder.

The available lenses and mirrors are listed in Table 4.

Table 4: Available Lenses and Mirrors

Catalog Number	Focal Length	Type
Lenses:		
OS-9131	-22 mm	Concave
OS-9132	18 mm	Convex
OS-9133	48 mm	Convex
OS-9134	127 mm	Convex
OS-9135	252 mm	Convex
Mirrors:		
OS-9136	N/A	Flat
OS-9137	25 mm	Concave

Spectral Filters (four slides)



Four spectral filters are listed in Table 5.

Table 5: Available Spectral Filters

Catalog Number	Color
OS-9111	Red
OS-9112	Yellow
OS-9113	Green
OS-9114	Blue

The spectrophotometric absorption curves for the filters are shown in Figure 14.

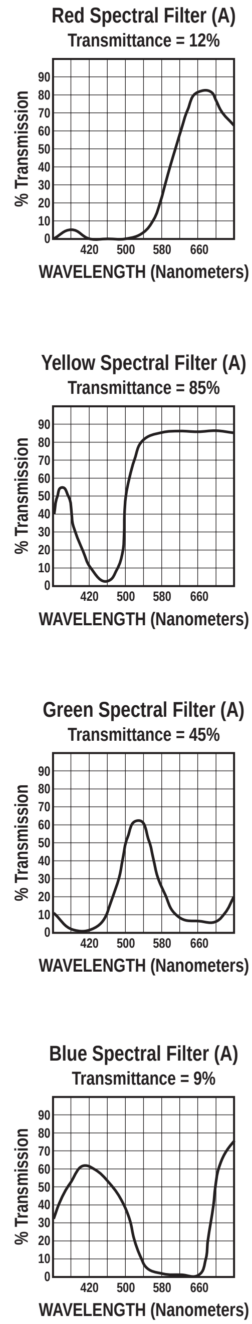
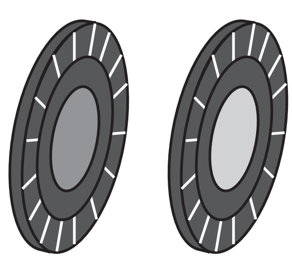


Figure 14: Spectrophotometeric Absorbtion Curves for PASCO Colored Filters

Polarizer, 140 nm Retarder



The polarizers and the retarder are mounted in round acrylic holders with degree scales. The shoulder on the back of the holder fits into the rectangular hole of the component holders, and the components are easily turned to vary the angle of polarization or the retarding axis. The indicator line on the ledge of the component holder indicates the angle.

The polarizing and retarding materials are mounted in the holders with the polarizing and retarding axes parallel (±2°) to a line passing between the 0° and 180° graduations on the degree scale.

The polarizing material is Polaroid Type HN-32. It is a neutral color linear polarizer having a total luminous transmittance of 32%, and an extinction transmittance of about 0.005%. The transmittance spectrum for this material is shown in Figure 15.

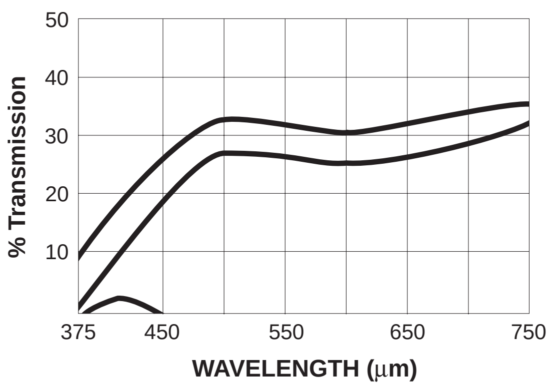


Figure 15: Polar Transmittance Spectrum

The retardance of the retarder may be increased by varying the angle of incidence. Figure 16 shows the increase of retardance as a function of the incident angle. A good method for varying the angle is to mount the retarder in the special component carrier of the angular translator. By rotating the translator table, the angle of incidence can be accurately varied.

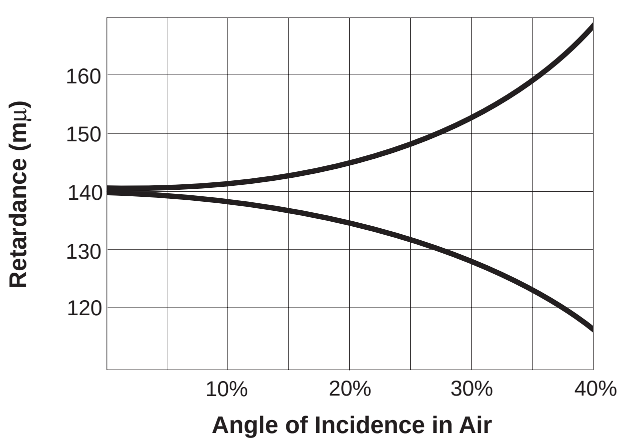
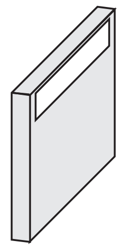


Figure 16: Retardance Versus Angle of Incidence

> ➤ **CAUTION:** The surfaces of the polarizers and retarder are very easily scratched, and should be touched as little as possible. (The surfaces are cellulose acetate butyrate.)

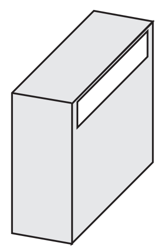
Glass Plate



Size: 50 x 50 x 6 mm

Refractive Index: 1.518 (at 588.9 nm)

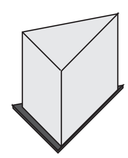
Acrylic Plate



Size: 50 x 50 x 19 mm

Refractive Index: 1.48 - 1.50

Prism



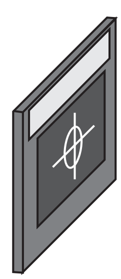
Angles: 90°, 45°, 45°

Refractive Index: 1.5

Material: BK-7 Glass

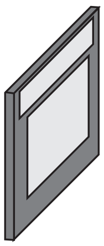
> ➤ **NOTE:** the magnetic pads are strong enough to hold the prism with the steel base in a vertical position.

Crossed-Arrow Target



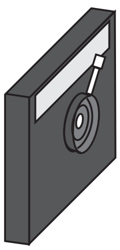
The crossed-arrow target is a useful object for object/image experiments. The fine lines on the horizontal arrow are a millimeter scale, which, when used in conjunction with the millimeter scale on the viewing screen, provides a convenient measure of magnification. The sharp edges and symmetrical shape are helpful for observing and analyzing spherical and chromatic aberration.

Diffuser



The diffuser scatters light for experiments in which a relatively uniform illumination is required. The diffuser material is a thin sheet of acetate with a matte finish.

Variable Diaphragm

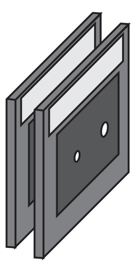


Aperture limits: 1.25 - 10.0 mm

Number of leaves: 10

To vary the aperture, push the handle up or down.

Light Source Apertures (two slides—OS-9118, OS-9119)

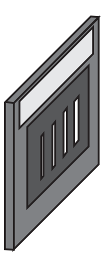


Aperture widths: 0.5, 0.75 mm (OS-9118)

1.0, 2.0 mm (OS-9119)

Use the light source apertures to collimate the light coming from the incandescent light source. You can place the slide on a component holder, or directly over the aperture of the light source.

Photometer Apertures



Aperture Widths: 0.1, 0.2, 0.5, and 1.0 mm

The photometer apertures can be used to vary the resolution of the fiber optic probe of the photometer. For accurate resolution, the tip of the optic probe must be flush against the aperture. This is most easily accomplished using the linear or angular translator as follows (see Figure 17).

① Place the aperture slide on the rear-most holder of the linear or angular translator (the holder closest to the hole for the fiber-optic probe).

② Before inserting the probe, look through the hole and position the aperture slide so the desired aperture is centered in the hole.

③ Insert the fiber-optic probe into the hole so that the tip is flush against the aperture.

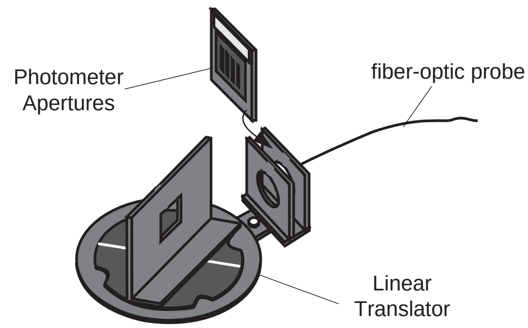
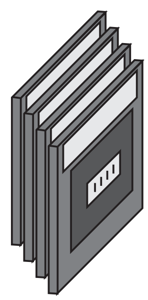


Figure 17: Using the Photometer Apertures

Interference and Diffraction Apertures (4 slides—OS-9165A, B, C, and D)



Slide 1 (OS-9165A): Four single slit apertures of different widths

Slide 2 (OS-9165B): Four double slit apertures of different widths and slit spacing

Slide 3 (OS-9165C): Four multiple slit apertures (2 - 5 slits), constant slit width and slit spacing

Slide 4 (OS-9165D): Two circular apertures and two aperture arrays

Material: 0.005 mm electroformed nickel

Tolerances: ±0.005 mm

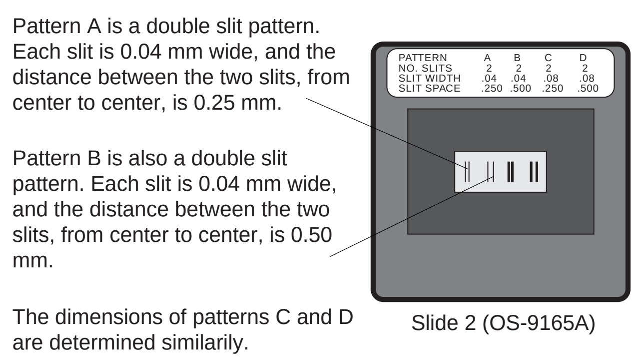


Figure 18: Slit Dimensions

This collection of 4 slides contains 16 slit and aperture patterns appropriate for interference and diffraction experiments. These aperture patterns can be illuminated using either the incandescent light source or the laser. However, if you wish to project the diffraction patterns onto the viewing screen, the laser should be used.

Each slide is labeled with the dimensions of its four patterns. On each slide, the aperture patterns are labeled from A - D, with A corresponding to the left-most pattern, and D corresponding to the right-most pattern.

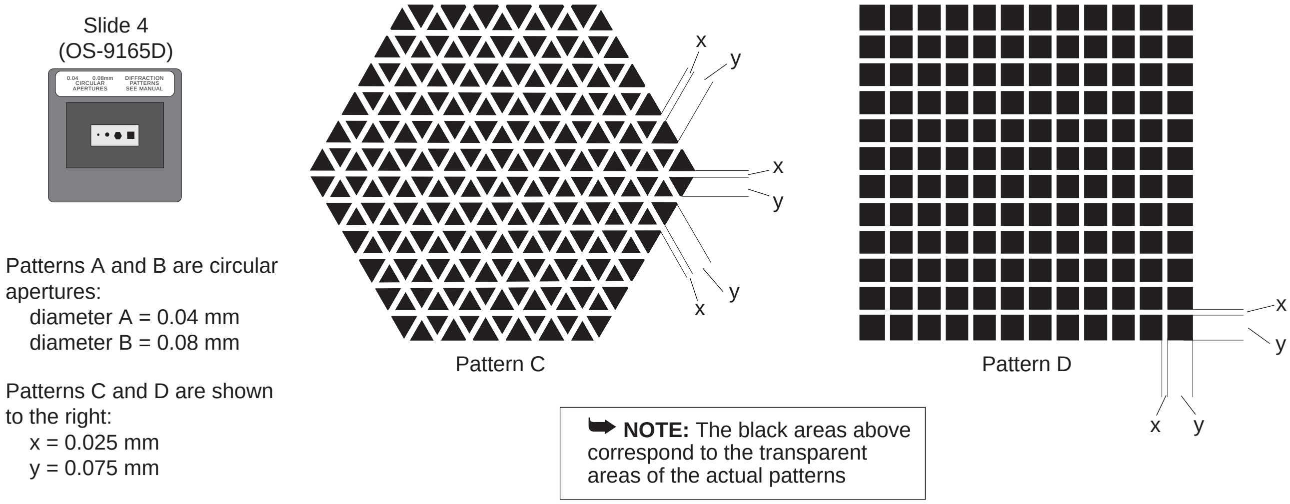


Figure 19: Circular Apertures and Aperture Arrays

Slides 1 - 3 are for single, double, and multiple slit diffraction. See Figure 18 for an explanation of the slit dimensions. Note: Slit Space, the spacing between slits, is measured from the center of one slit to the center of the adjacent slit.

Slide 4 is for diffraction from circular apertures and aperture arrays. The diameter of the circular apertures, patterns A and B, are indicated on the slide (0.04 and 0.08 mm, respectively). The dimensions for the aperture arrays are shown in Figure 19.

> ➤ **NOTE:** When using these slides, it's important that the light illuminate only one aperture pattern at a time. You can use the Aperture Mask (OS-9139) for this purpose, as shown in Figure 20. Just place the slide with the diffraction aperture on one side of a component holder and the aperture mask on the other.

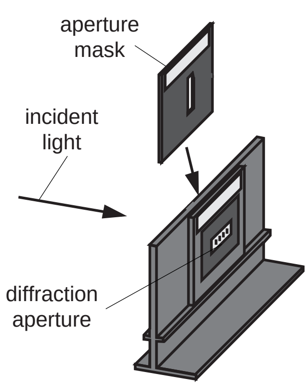
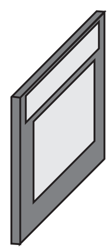


Figure 20: Using the Aperture Mask

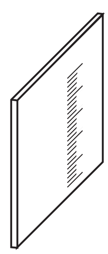
Diffraction Grating



Type: Transmission, plastic replica diffraction grating

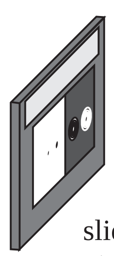
Ruling: 6000 lines per centimeter

Viewing Screen with Metric Scale



40 mm scale on 45 x 45 mm white screen

Opaque Points and Fresnel Zone Plates



Opaque Points: Circular shape, with diameters of 0.25, 0.50, and 1.0 mm.

Tolerances: ±0.05 mm

Fresnel Zone Plates: Figure 21 shows the radii of the zones. The two zone plates on the slide are complementary; the opaque zone of one is the transparent zone of the other. So the radii of the zones are the same for both plates.

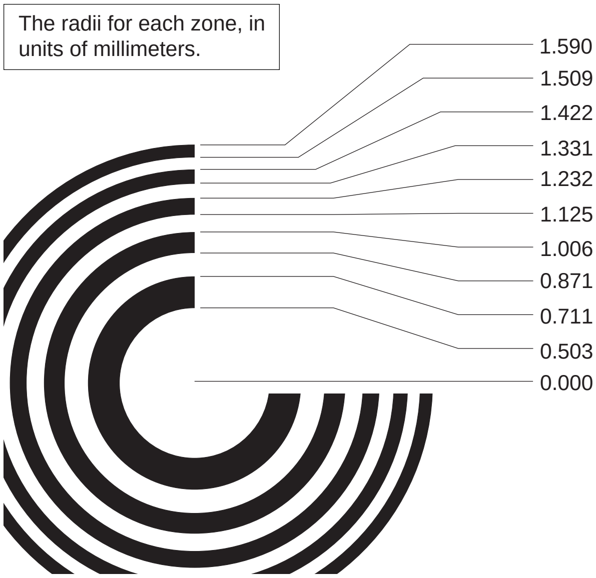
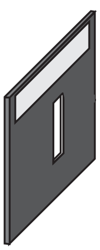


Figure 21: Freznel Zone Radii

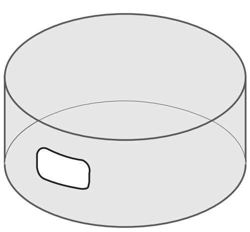
Aperture Mask

Aperture Size: 5 x 18 mm



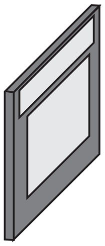
The aperture mask is most frequently used with a set of slits or apertures to insure that light is incident on only one set of slits or one aperture. Place the slit or aperture on a component holder, and place the aperture mask on the other side of the same holder (see Figure 20).

Glass Dispersion Tank



The dispersion tank is 90 mm in diameter, 50 mm in depth, and is made of Pyrex. It is used to hold a solution for experiments in light scattering.

Hologram

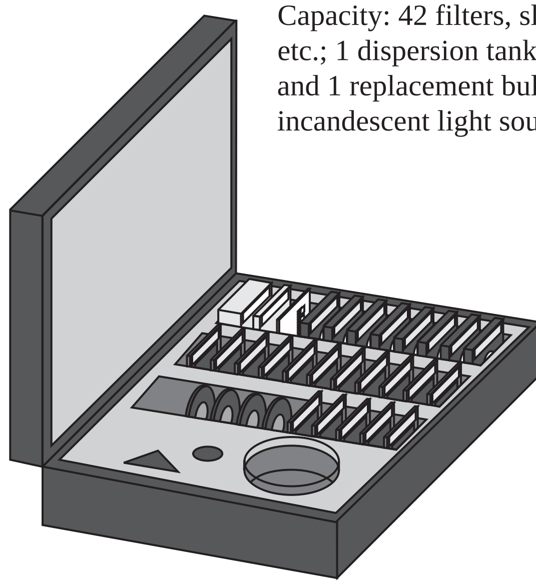


Transmission type hologram

Picture: Chessman

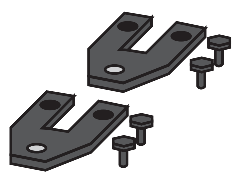
See Experiment 13 for instructions on viewing the hologram.

Fitted Case for Optical Components



Capacity: 42 filters, slits, lenses, etc.; 1 dispersion tank; 1 prism; and 1 replacement bulb for the incandescent light source.

Optical Bench Couplers



The optical bench couplers are used to connect and align two or more PASCO optics benches, and also to connect and align the laser alignment bench with the optics bench. For instructions on using the couplers, see the procedure for setting up the Laser Alignment Bench in the *Using the Equipment* section, earlier in the manual.

Adapting non-PASCO Components

Using Adhesive Backed Steel Foil

Adhesive backed steel foil is available in assorted sizes (OS-9148). It is easily cut and can be attached to non-PASCO components so that they will mount magnetically onto the PASCO component holders.

To use the adhesive backed steel foil:

> ➤ **IMPORTANT:** When using the adhesive backed steel, note that the adhesive on the back of the foil is strong and permanent. Position the foil correctly the first time; there's no second chance.

① Cut the foil to the proper size with an ordinary pair of scissors. If the scissors produce a burr in the foil, cut in such a manner that the burr is toward the adhesive (paper covered) side of the foil.

② Before removing the protective paper backing, bend the foil very slightly so that the paper-covered side is slightly concave. This will prevent the edges of the foil from peeling away once the foil is mounted.

③ Remove the protective paper, align the foil over its proper position, and press down.

Experiments with the Advanced Optics Systems

This manual includes detailed instructions for 13 experiments that can be performed with the various PASCO optics systems. Of course, considering the variety of the components, it isn't possible to present all the possible experiments. A more complete list of possible experiments is provided in Table 6.

Table 6: Systems and Experiments

Complete System

Advanced System

Intermediate System

1. **Reflection:**
   - angle of incidence = angle of reflection
   - reflection from media interfaces (air, mirror, glass, acrylic)
   - reflection, transmission, and absorption coefficients.
2. **Refraction:**
   - Snell's Law
   - indices of refraction (air, mirror, glass, acrylic)
   - critical angle
   - prisms: (dispersion, angle of minimum deviation).
3. **Thin-lens Optics:**
   - focal points
   - image formation and magnification
   - spherical aberration, coma, and astigmatism, depth of field, Foucault knife test.
4. **Interference from Multiple Reflections.**
5. **Polarization I:**
   - dichroic polarizers
   - Brewster's angle.
6. **Wave Nature of Light:**
   - Young's experiment
   - spatial coherence.
7. **Diffraction:**
   - from single and multiple slits
   - airy disk
   - resolution limit of lenses
   - Fresnel zone plates
   - diffraction gratings (transmission and reflection types).
8. **The Laser:**
   - laser theory
   - laser beam characteristics
   - spatial filtering
   - beam spreader.
9. **Polarization II:**
   - retardation plates
   - by scattering
   - circular polarization
10. **Holography (transmission type).**

(end of Intermediate System)

11. **Optical Activity.**
12. **Scattering:**
    - Rayleigh
    - diffraction.

(end of Advanced System)

13. **Interferometry:**
    - Michelson
    - Fabry-Perot
    - Twyman-Green
    - indices of refraction in gases.

Experiment 1: Reflection

EQUIPMENT NEEDED

– Incandescent Light Source (OS-9102B)
– Optics Bench (OS-9103)
– Angular Translator (OS-9106A)
– Component Carrier (OS-9107)
– Glass Plate (OS-9128)
– Acrylic Plate (OS-9129)
– Flat Front Surface Mirror (OS-9136)
– Viewing Screen with Metric Scale (OS-9138)
– Aperture Mask (OS-9139)
– Photometer with optic probe (optional)
– 0.5mW Laser (optional)

Purpose

Light is a series of electromagnetic waves, and, according to laws of propagation of such waves, they theoretically should be reflected to a certain degree at the interface between two mediums (such as sir and glass) which have sufficiently different characteristics. Everyday we observe light reflected from silvered surfaces such as mirrors, from the surface of water, and from ordinary window glass. The purpose of this experiment is to find out if light “obeys” any specific laws during reflection.

Theory

Although light behaves as a wave, if the dimensions used in an experiment are sufficiently large, we can neglect diffraction and interference effects. Hence, in this experiment we represent the propagation of light as a series of rays which follow straight lines (in optically homogeneous mediums). All the results from ordinary geometry can then be used to aid our investigation.

Procedure

Part I: Angles Of Incidence And Reflection

① Position the incandescent light source on the left end of the optical bench, and place the angular translator about 25 cm. From the end of the light source housing. Make sure the 0° marks lie on a line parallel to the bench. Finally adjust the rotating table so that the scored line run perpendicular and parallel to the bench.

② Attach the aperture mask to the standard component carrier and place it between the light source and angular translator so that the mask is ***d*** centimeters from the center of the translator. The distance ***d*** (about 6.5 cm) is the measured distance from the center of the angular translator to the first analyzer holder on the movable are (see Figure 1.1).

③ Center the viewing screen of the special component carrier designed for use with the angular translator, and place the assembly on the rotating table of the translator so that the front surface of the viewing screen coincides with the scored line on the table which runs perpendicular to the optical bench.

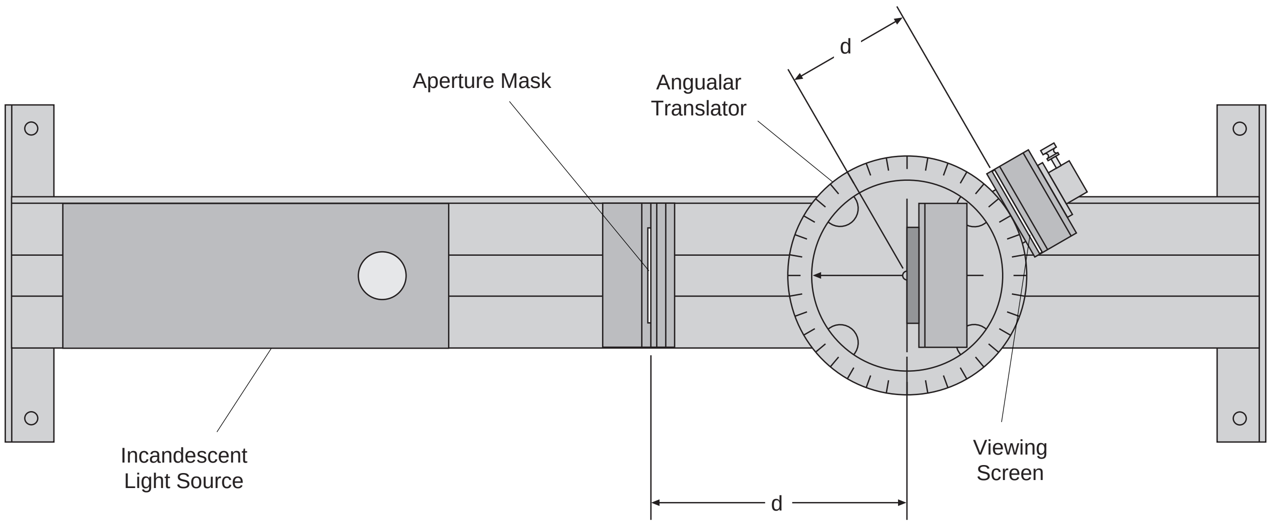


Figure 1.1: Experiment Setup

④ Now switch on the light and adjust the aperture mask's position (don't move the component carrier), until the entire image is on the viewing screen. With the aid of the millimeter scale marked on the screen, center the image horizontally. Turn the screen 90° and center the image vertically.

⑤ Now replace the viewing screen with the flat surface mirror such that the mirror surface coincides with the perpendicularly scored line. Move the viewing screen to the first analyzer holder on the movable are.

⑥ Rotate the table a set number of degrees (for example, 30°), and then move the arm until the reflected image is centered horizontally on the viewing screen. Record the angle which the arm marks with the mirror. Repeat for various settings of the rotating table. What is the relation between the angle of incidence and the angle of reflection? (Angle of incidence is the angle the incident ray makes with the normal to the reflecting surface; similarly for the angle of reflection.)

⑦ Rotate the viewing screen and measure the vertical position of the reflected image. Now measure the vertical position of the aperture mask. With this data determine what spatial relationship exists between an incident ray of light, the reflected ray, and the normal to the mirror at the point of reflection. (e.g. Do they lie in the same plane?).

Part II: Reflections From Glass And Acrylic

① Replace the flat mirror in Part I with the glass plate, taking care that the front surface of the glass coincides with the scored line.

② Rotate the table until the glass plate rests at a convenient angle with the optical bench.

③ Move the arm until the reflected image is visible on the viewing screen. How many images of the rectangular aperture are there? Why?

④ The brightest image (the one on the left) is the reflection from the front surface of the glass. Center this image on the screen and record the angle which the translator arm makes with the glass plate. Repeat the procedure with the rotating table set at several different angles. What is the relation between the angle of incidence and angle of reflection?

⑤ Measure the height of the middle of the reflected image. As in Part I, determine whether the incident ray, reflected ray, and normal to the glass at the point of reflection are all in the same plane.

⑥ Replace the glass plate with the acrylic plate and repeat 1-4. Does the law asserting equality between the angles of incidence and reflection seem to vary with the material used as the reflecting surface?

Optional

① Secure the fiber optic probe in the hole behind the analyzer holders, and use the photometer to detect the relative intensities of reflected and transmitted light for varying angles of the glass plate. Graph your results. Ambient room light must be kept low when using the photometer.

② The entire experiment can be performed very nicely using the laser instead of the incandescent source. The aperture mask is not needed with the laser. Take care to adjust the laser beam as in the equipment instructions so that the beam is parallel to the bench. With the laser, you should be able to see three or four multiple reflections from the glass plate.

Notes:

Experiment 2: Refraction

EQUIPMENT NEEDED

– Incandescent Light Source (OS-9102B)
– Optics Bench (OS-9103)
– Angular Translator (OS-9106A)
– Component Carrier (OS-9107)
– Glass Plate (OS-9128)
– Acrylic Plate (OS-9129)
– Flat Front Surface Mirror (OS-9136)
– Viewing Screen with Metric Scale (OS-9138)
– Aperture Mask (OS-9139)
– Photometer with optic probe (optional)
– 0.5mW Laser (optional)

The velocity of light in free space is very close to 3 x 10^{10} cm/sec., and moreover, the velocity is the same for all wave lengths. The situation is different in most material substances. With few exceptions, the velocity of light in material substances is less than the velocity in free space. Not only is the velocity less, it varies with the wavelength of the light passing through the medium.

If light travels through two mediums with different velocities, the wave nature of the light causes its direction to be altered as it passes from one medium to the other. This phenomenon is referred to as refraction. We can define the index of refraction (***n***) of a material to be the ratio of the velocity of light in free space (***c***) to its velocity in the given material (***v***). Since the velocity (***v***) varies with wavelength, we must specify the corresponding wavelength when referring to an index of refraction.

The purpose of this experiment is to determine the relation between the direction of the incident ray, the direction of the refracted ray, and the index of refraction. The index of refraction for glass (for example) only varies by less the 2% throughout the visible spectrum. Therefore using the incandescent light source in the experiment doesn't introduce much error. With the laser we can theoretically gain much more accuracy.

Procedure

Part I: Index Of Refraction

① Take a square piece of paper about 5 centimeters on a side, and carefully draw a millimeter scale across the middle (you can trace the scale printed on the viewing screen.)

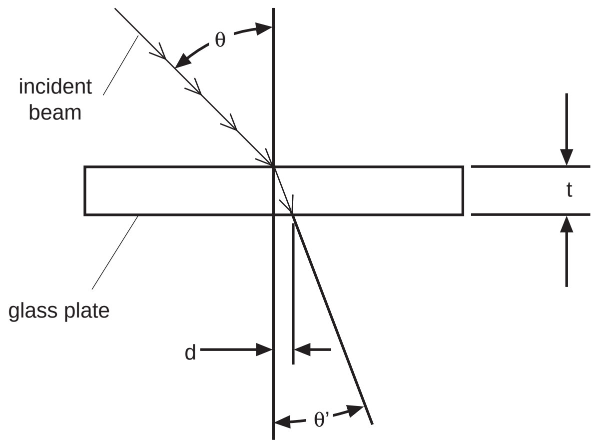
② Using the same equipment setup as in Experiment 1, put the paper between the glass plate and the special component carrier on paper between the glass plate and the special component carrier on the angular translator. The magnetic surface will hold the glass plate and paper in place. The millimeter scale should run horizontally.

③ Adjust the position of the special component carrier until the back surface of the glass plate coincides with the perpendicularly scored line on the table.

④ With the glass plate sitting perpendicular to the bench, adjust the position of the aperture mask so that one vertical edge of the image on the paper lines up with the scored line on the table which is parallel to the bench. If the glass does not alter the light's path, the vertical edge which was centered should remain centered although the translator's table is rotated.

⑤ Rotate the table and record what happens to the previously centered edge. Is the incident ray refracted toward or away form the normal to the glass? Figure 2.1 shows how to calculate the index of refraction given the angle of rotation and the edge displacement of the image.

➤ **NOTE:** Using this method, a small error is introduced since we are not certain that the light very near to the image's edge was exactly perpendicular to the glass plate in the beginning (Why?). Hence the measured value of θ (as in the figure) is not accurate. The methods under Part II give more accurate results.



n' = *index of glass*

n = *index of air* (≈1)

$$\tan \theta' = \frac{d}{t}$$

$$n' = \frac{n \sin\theta}{\sin\theta'} = \frac{\sin\theta}{\sin\theta'}$$

Figure 2.1: Calculating the Index of Refraction

⑥ Replace the glass plate with the acrylic plate and determine the index of refraction for acrylic.

Part II: Alternate Methods

① Remove the paper from between the glass plate and component carrier. With the glass place perpendicular to the bench, put the viewing screen directly behind the plate and adjust the aperture mask to center the image on the screen. Rotate the table to a convenient angle. Light is refracted toward the normal when passing from air to glass. Is the same true when light propagates from glass to air? By observing the position of the image on the viewing screen, you can see that the refraction must be away from the normal at a glass-air interface. (See Figure 2.2)

② The ray passing out of the glass is parallel to, but displaced from the incident ray. By measuring the displacement of both vertical edges of the image, and averaging we can closely estimate the displacement of a ray in the middle of the image. Such a ray was perpendicular to the glass plate before it was rotated.

③ Let ***d*** be the displacement of the image, θ' the angle of incidence (i.e. between refracted ray and normal), and ***t*** the thickness of the glass plate. Then compute θ' from the formula,

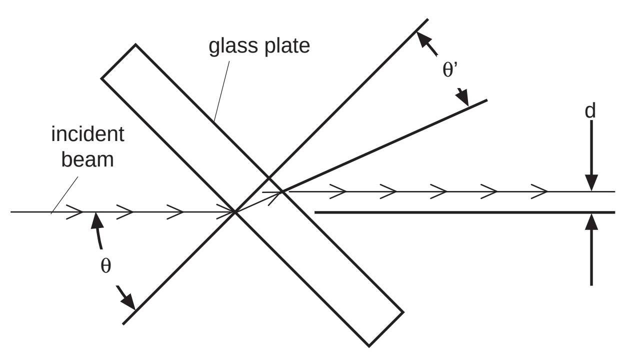


Figure 2.2

$$(\cos\theta)\,(\tan\theta') = (\sin\theta) - \frac{d}{t}$$

④ Taking the index of refraction of air (***n***) to be 1.0, verify that

$$n' = \frac{n \sin\theta}{\sin\theta'}$$

is a constant for various θ. In fact, this is Snell's law where ***n'*** is the index of refraction of the material used.

⑤ Another method of calculating the refractive index is to observe the reflected images. There should be at least two reflected images from the plate. Measure the distance between them (i.e. between their centers). Then if ***d*** is the distance separating then, ***t*** is the plate thickness, θ is angle of incidence, and θ' is angle of refraction, we have,

$$\tan\theta' = \frac{d}{2t\cos\theta}$$

⑥ Repeat both methods with the acrylic plate.

As an option, a laser can be used in all three methods to calculate the index of refraction. No aperture is then needed.

Part III: Critical Angles And Deviation

① Remove the special component carrier from the translator table and replace it with the 90° - 45°-45° prism.

② With the scored lines running perpendicular and parallel to the bench, position the prism so that one of the small faces is centered on the table and coincides with the perpendicularly scored line. (See Figure 2.3).

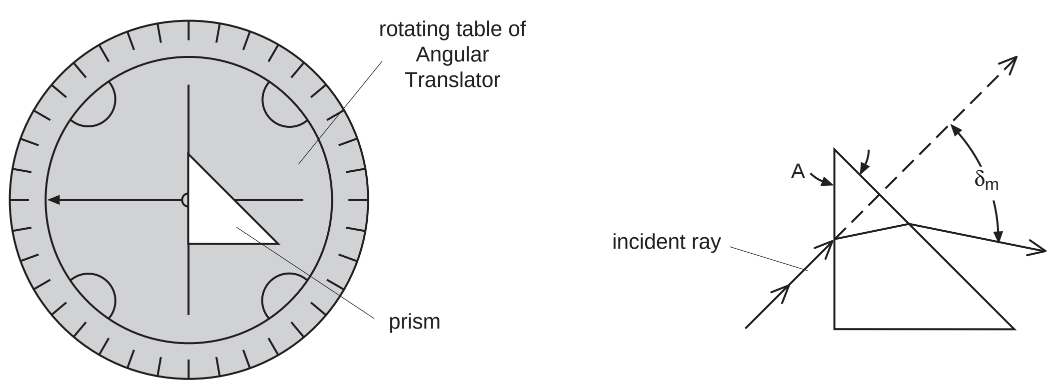


Figure 2.3: Experiment Setup

③ Check the position of the aperture mask so that the center of the light beam travels directly over the center of the table and parallel to the bench.

④ Move the arm until the refracted beam is imaged on the viewing screen.

⑤ Now rotate the table and watch the movement of the image (move the arm if necessary). Although the prism is continually rotated in the same direction, note that the image moves in one direction, and then begins moving in the other direction. The point where the image reverses direction coincides with the angle of minimum deviation. That is, at that particular angle of incidence, the light beam is deviated least from its original path.

⑥ Knowing the angle corresponding to minimum deviation (see Figure 2.3), calculate the index of refraction of the prism material from:

➤ **NOTE:** The edges of the image are colored. Why? This phenomenon is called dispersion.

⑦ Rotate the table until the refracted beam is parallel to the large surface (slanted surface) of the prism. In this position no light propagates through the slanted surface; all the light is internally reflected. (See Figure 2.4)

⑧ Knowing the angle of incidence (θ) at which this occurs we can calculate the angle of incidence (θ') of the light in the prism as it reaches the slanted surface. The angle θ' is called the critical angle.

⑨ The 90° - 45°- 45° prism is designed so that any light normal to the slanted surface is totally internally reflected. Position the prism to observe this phenomenon.

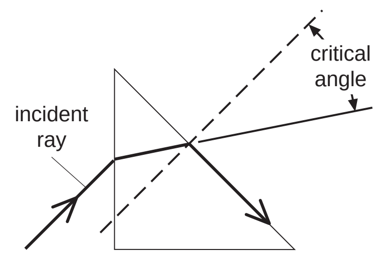


Figure 2.4

Optional

Collimate the incandescent beam with the 48mm and 18mm lenses. Then adjust the prism for maximum deviation. By placing spectral filters over the light source, note how the prism refracts the various colors.

Experiment 3: Lenses

EQUIPMENT NEEDED

– Incandescent Light Source (OS-9102B)
– Optics Bench (OS-9103)
– Component Carrier (4) (OS-9107)
– Variable Diaphragm (OS-9117)
– Crossed Arrow Target (OS-9121)
– -22 mm. F.L. Lens (OS-9131)
– 18 mm. F.L. Lens (OS-9132)
– 48 mm. F.L. Lens (OS-9133)
– 127 mm. F.L. Lens (OS-9134)
– 252 mm. F.L. Lens (OS-9135)
– Aperture mask (OS-9139)
– 0.5mW Laser (optional)
– angular translator/component carrier (optional)
– 25mm F.L. concave front surface mirror (opt.)

Purpose

A lens is merely an optical system which includes two or more refracting surfaces. From the geometry of light rays, it turns out that spherical refracting surfaces are most interesting and most practical. We define the first focal point of a lens to be the point F_1 such that if a point source of light is placed at F_1, all rays will be parallel after passing through the lens. Similarly, the second focal point F_2 is the common point which parallel light rays pass through after passing through the lens. In the case of a lens which is relatively thin compared to the distance from one surface to F_1 or F_2 the first and second focal lengths are the respective distances from F_1 and F_2 to the center of the lens. If the refractive index of the materials on either side of the lens is the same (e.g. if the lens is in air), the first and second focal lengths are equal to a common value (f).

Theory

If in a thin double convex lens, we take the radius of curvature (R_1, R_2) to be positive for both surfaces, we can derive the equation (n is the refractive index of the lens material),

$$\frac{1}{f} = (n - 1)\left(\frac{R_1 + R_2}{R_1 R_2}\right)$$

In a lens system the image of an object often appears to be larger than the object itself; this is referred to as magnification. If s is the distance from the object to the lens, and s' the distance from the lens to the image, then the magnification m is calculated by;

$$m = \frac{s'}{s}$$

Moreover if $d = s - f$ (i.e. distance from the object to the closest focal point) and $d' = s' - f$, then;

$$m = \frac{f}{d} = \frac{d'}{f}$$

In this experiment we wish to verify these theoretical results and to investigate the distortion (called aberration) that spherical lenses introduce into images.

Procedure

Part I: First Local Length

① Position the incandescent light source at the left end of the optical bench.

② Attach a double convex lens to one component carrier and the viewing screen to another.

③ Position the lens and screen at the extreme right end of the bench so that the lens is between the light source and the screen. The further the lens is from the light the more parallel are the rays entering the lens.

④ Adjust the position of the screen until the image is as thin as possible. Then the distance between the middle of the lens and the screen is an approximation of the first focal length. Enumerate all the possible errors. Find the focal length of the other double convex lens. (The focal lengths of the plano-convex lenses are so large compared to the length of the optical bench that the incident light rays are not parallel enough to measure the focal length with any accuracy. We will use another method outlined below).

⑤ Attach the plano-concave lens to one side of a component carrier and attach the aperture mask to the other side. Position the assembly about 40 cm from the light source.

⑥ Place the screen behind the lens and notice that as you move the screen further from the lens, the image expands.

⑦ Measure the image width and corresponding distance from the lens to the screen for two different screen positions. Using simple geometry, calculate where the rays diverged by the lens would theoretically converge in a point in front of the lens. This is an approximation of the focal length.

Part II: Second Focal Length

① Attach a double convex or plano convex lens to a component carrier.

② The light source is a line filament, so if we consider only lateral dimensions the source is essentially a point source. The equipment instructions give the distance from the filament to the front surface of the light source (approximately 21 mm.).

③ Adjust the lens position so that the image on the screen is the same width no matter where the screen is placed (i.e. the emergent rays are parallel). The distance from the lens to filament is the second focal length. Compare to the first focal length.

④ You cannot use the above method to measure the focal lengths of the 18mm. F.L. convex lens of the -22 mm. F.L. plano-concave lens. These lenses cannot be positioned sufficiently close to the filament. Thus, as an alternative, place the 48 mm F.L. double convex lens between the light and the lens to be measured. The focal point of the first lens now becomes the point source for the second.

Part III: Improved Method

① From the formulas in the introduction to this experiment, if the magnification is 1.0, then ***s=s'***, ***d=d'***, and ***f=d***. Hence, at such a lens position, ***s+s' = 4f***.

② Place a double convex lens or a plano-convex lens between the crossed-arrow target and the screen. (All components on separate carriers.)

③ Adjust the position of the lens and screen until the image is in focus and is the same size as the original object. (The target has a millimeter scale on it.) At the final position, the distance from target to screen is four times the focal length.

④ With the focal length, use the formula in the introduction to compute the radius of curvature for the lenses (Assume $R_1 = R_2$ for the double convex lenses; the radius of curvature of a plane is infinite.) Also verify Gauss' formula;

$$\left(\frac{1}{S}\right) + \left(\frac{1}{S'}\right) = \left(\frac{1}{f}\right)$$

Part IV: Magnification

① Position a double convex lens or plano-convex lens between the crossed-arrow target and screen.

② Adjust the position of the lens until the image is focused.

③ Measure the distance from the target to the lens and from the screen to the lens. Calculate the theoretical magnification. (Use both equations).

④ Measure the actual magnification by measuring the distance between the scale markings on the image. Compare with theoretical results.

⑤ Repeat using several combinations of lenses.

You can now assemble a beam spreader for the laser.

⑥ Attach the 18 mm. F.L. double convex lens to the face of the laser.

⑦ Attach the 48 mm. F.L. double convex lens to a component carrier and position the assembly so that the focal points of both lenses coincide. The beam should now have a larger cross-section but should still be parallel.

Part V: Aberrations

Spherical Aberration

A spherical surface lens does not form a point image of a point object originally positioned on the lens axis. Instead the image is a line segment collinear with the lens axis. Thus there is no exact screen position where the image is “ in focus”. Conversely, the point object can be moved slightly along the axis and still appear to be in focus. The amount of movement which maintains a given image sharpness is called the depth of field.

① Position the 18 mm. F.L. double convex lens in front of the incandescent light source (about 30 cm. away). Attach a sharp razor blade to a component carrier, and position the assembly to the right of the 18 mm. lens. Adjust the assembly position until the razor blade is in the focal plane of the lens. The lens image on the razor blade should be a small dot.

② Carefully adjust the razor blade on the carrier until the sharp edge cuts across the center of the focused dot. Place the viewing screen to the right of the razor blade and examine the image. It should resemble one of the patterns in Figure 3.1. Move the razor blade assembly slightly forward or backward and observe the pattern changes. (Note that the patterns only approximate Figure 3.1, since razor edges are not usually optically perfect.) This technique is the Foucault knife test for lenses. Convince yourself that the patterns are due to spherical aberrations. Try using the 48 mm. F.L. lens.

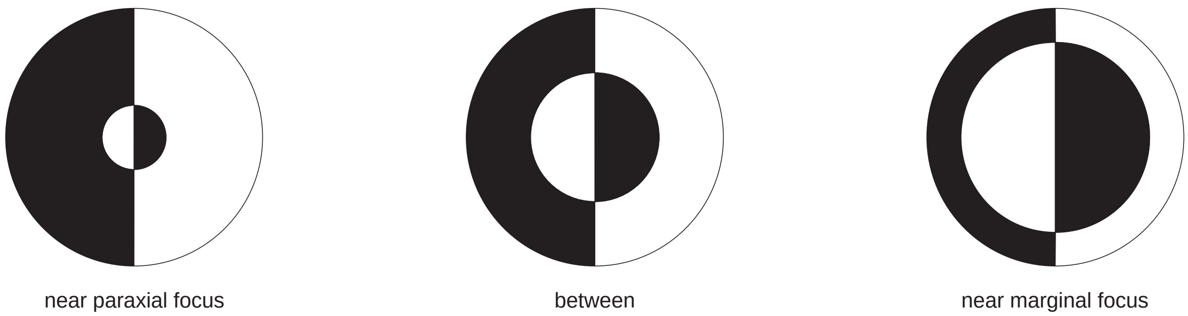


Figure 3.1

③ Place the variable diaphragm just in front of the test lens. By varying the opening, notice that the patterns degenerate. A smaller aperture gives a more unique focal point. If you place the crossed-arrow target between the light source and the variable diaphragm, you can observe that the point where the image is in focus becomes more distinct as the aperture closes. Thus, depth of field varies inversely with aperture size. This phenomenon is familiar to all photographers.

Coma

A point off the lens axis of a spherical surface lens is imaged in three dimensions. The tendency of a lens to spread the image of a point over a plane perpendicular to the lens axis is referred to as coma.

① Place the 48 mm. F.L. lens to the right of the light source and position the 18 mm F.L. lens about 5 cm to the left of the first lens.

② Place the viewing screen on the far right and adjust the position of all components until a small sharp dot is focused on the screen.

③ Now carefully move the 18mm. lens (component carrier and all) perpendicular to the bench and watch the image. The point will change into a small comet-like shape. This effect is due to coma.

Astigmatism

This form of distortion arises from the same aberration as coma. However, astigmatism refers to the tendency of the lens to image an off-axis point in a dimension parallel to the lens axis.

① To observe astigmatism, use the Coma setup as described above.

② While the 18 mm lens is off center, move the screen forward or backward and observe that the image that the image gradually changes from an ellipse to a distorted circle (circle of least confusion) to an ellipse perpendicular to the first one.

Optional

① Using the concave mirror on the angular translator, investigate focal points and magnification of the mirror.

② The laser works just as well as the incandescent source in the above experiments. However, laser “noise” may make some images difficult to detect properly.

Notes:

Experiment 4: The Wave Nature Of Light

EQUIPMENT NEEDED

– Incandescent Light Source (OS-9102B)
– Optics Bench (OS-9103)
– Component Carrier (3) (OS-9107)
– Photometer Apertures (OS-9116)
– Diffuser (OS-9120)
– Electroformed Diffraction Slits (OS-9165B)
– photometer with optic probe (optional)
– linear translator (optional)

Purpose

Around 1800, the English scientist Thomas Young designed and performed an experiment which produced seemingly unexplainable phenomena. At least it was unexplainable in terms of the early “corpuscular” theory of light. Young observed the image of light passing through first one slit, then two slits closely spaced and parallel to one another. He used filtered light from a mercury arc to insure that he had nearly monochromatic light. The first slit insured that light striking the double slit further on had a definite phase relationship among various points on the wave front (i.e. coherence). The image that Young observed was a series of light and dark areas which did not represent a plain geometrical image of double slits. Furthermore, a point on the screen which was illuminated when one of the double slits was covered became dark when both slits were uncovered. A “corpuscular” theory (i.e. light = series of particles) cannot adequately explain this phenomenon.

We can reperform Young’s experiment and in fact eliminate the first slit. If we place the double slits far enough from the light source, the first single slit becomes unnecessary. This shows that there is a definite phase relationship between points on the wave front which pass through the double slits. In other words, in a small angle, light from an incandescent source is spatially coherent.

Procedure

① Position the light source at the left end of the optical bench.

② Attach the diffuser, double-slits, and photometer apertures to three separate component carriers.

③ Position the double-slits about 20 cm from the light source. Place the photometer apertures between the light source and double slits.

④ Pick a sufficiently large single slit on the photometer aperture slide and adjust the position of this slit until one set of double slits is fully illuminated.

⑤ Position the diffuser behind the double slits and adjust its distance from the slits until there is a sharp geometrical image of the two slits. (View the image from the side of the diffuser which faces away from the light source.)

⑥ Move the diffuser slowly away form the slits until the sharp geometrical image becomes an interference pattern with several maxima and minima.

⑦ Adjust the single slit (i.e. one of the photometer apertures) until only one of the double slits is illuminated. Observe the image (it is not a clear image, but rather a diffraction pattern).

⑧ Now illuminate both slits and observe the image. Notice that some points previously illuminated are now dark.

⑨ Move the double slits and diffuser to the far right of the bench and observe that the single slit is no longer necessary. (However, you still need some sort of edge to cover one of the double slits in order to examine the two different patterns. It is convenient to attach the aperture mask to the same component carrier as the double slits. Adjust the mask's position to allow one or two slits to be illuminated.)

Optional

① Attach the photometer's fiber optic probe to the linear translator and use the translator to scan the images. Place a small aperture such as the light source apertures in front of the probe on the rear surface of the analyzer holder. Adjust the aperture so that light incident on it enters the probe. Using the aperture minimizes effects due to ambient light. Plot intensity versus position for both one slit uncovered and two slits uncovered.

② Measure the intensity of the bright middle band (I_{max}) and then measure the intensity at the middle of the first shaded bands on either side (I_{min}). Calculate the Michelson visibility coefficient (V) from:

$$V = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

This coefficient gives a measure of the coherence of the incident light. The value 1.00 indicates nearly perfect coherence.

Experiment 5: The Laser

EQUIPMENT NEEDED

– Photometer (PI-8020 or OS-9152B)
– 0.5mW Laser (SE-9367)
– Optics Bench (OS-9103)
– Linear Translator (OS-9104A)
– Component Carrier (5) (OS-9107)
– Variable Diaphragm (OS-9117)
– Electroformed Diffraction Slits (OS-9165B)
– -22 mm. F.L. lens (OS-9131)
– 18 mm. F.L. lens (OS-9132)
– 48 mm. F.L. lens (OS-9133)
– Viewing screen with metric scale (OS-9138)
– Aperture mask (OS-9139)

Purpose

This experiment is designed to familiarize the student with the basic characteristics of laser light. The laser is based on the phenomenon of stimulated emision. If an electron of a given atom is in an excited state (i.e. higher energy level than normal), and if a photon of proper frequency interacts with this electron, the electron is triggered into deexciting itself by emitting a photon. Moreover, the original photon continues on its way unchanged. This process continues in a chain reaction causing a "photon cascade". When the cascade is sufficiently intense, it bursts through the partially reflecting mirrors of the laser cavity. This burst of light is almost perfectly coherent since the photons are all in phase. We can test the coherence in a manner similar to Experiment 4. Moreover, since the photons have the same frequency, the light is nearly monochromatic.

➤ **NOTE:** Due to the design of the lasing cavity, the laser beam is collimated (i.e. waves are "parallel"). Thus there is little loss of energy flux (i.e. $\frac{energy}{cm^2}$) due to divergence of the light beam. The .5 mW he-Ne gas laser produces about 1/4 the energy flux of the sun. Although this energy level seems to be way below that which causes permanent eye damage, in order to insure safety, never look directly into the laser beam or its mirror reflection.

➤ **NOTE:** Allow the laser 1-1/2 hours to warm up before using it in any experiment requiring measurement of beam intensities. Otherwise the expansion of the glass laser tube causes the mirrors to move and hence the beam intensity varies radically.

Procedure

Part I: Beam Characteristics

① Position the laser on the optical bench and align the beam following the procedure in the equipment instructions. The beam should then be parallel to the bench.

➤**NOTE:** It is safe to view the laser beam's image on the viewing screen, since the laser light reaching your eye is only a small fraction of the original beam. The rest of the beam has been diffused or absorbed by the screen.

② In a darkened room observe the color of the beam. There should be an intense red spot (from light emitted by neon) and perhaps some incoherent blue or green light (from light emitted by the helium).

③ Write on a white sheet with various colored marking pens. Attach the -22 mm. F.L. lens to the front of the laser and view the colored writing as it is illuminated by the diverging laser light. (Keep the room dark.) Explain you observation.

④ With the beam still passing through the lens, observe the image on the screen. The irregularities in the image are due to impurities in the gas mixture and to imperfection in the laser tube.

⑤ Remove the lens. Observe the size of the beam's image at various distances from the laser (up to, say, 10 meters away). You can make accurate measurements with the photometer and calculate the divergence of the beam. To do this, we arbitrarily define the diameter of the beam as follows. If ***I*** is the intensity at the center of the beam at any given position, the diameter is the maximum distance between points of intensity,

$$\left(\frac{1}{2}\right) I$$

Since the beam is so intense, the photometer's shutter must be nearly closed in order to keep the readings on scale. (Observe also how ***I*** changes with the distance from the laser.)

Part II: Coherence

① Following the same procedure as in Experiment 4 (except that the single slit is not needed), note the interference pattern.

② Use the photometer to make the measurements necessary to calculate the Michelson visibility coefficient (see Experiment 4).

➤ **NOTE:** The laser beam also has a temporal coherence (i.e. the wave stays in a given phase for a length of time) which can be measured with an interferometer.

Part III: Beam Spreader

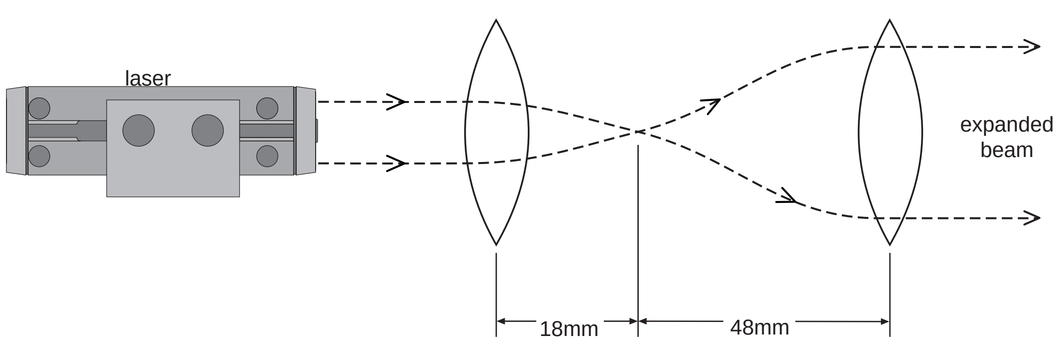


Figure 5.1: Experiment Setup

① Attach the 18 mm F.L. lens and 48 mm F.L. lens to component carriers and position them as in Figure 5.1. The 18 mm F.L. lens on the front of the laser.)

② Adjust the position of the 48 mm F.L. lens until the emerging beam is again collimated. Check the collimation by observing the image size at various position along the bench. If the beam is collimated, the image should remain fairly constant. This enlarged collimated beam makes some experiments much easier to perform.

Part IV: Spatial Filtering

Imperfections in the laser optics introduce unwanted “noise” into the beam. Some of the noise can be removed with the following procedure.

① Set up the beam spreader as in Part III.

② Attach the variable diaphragm to a component carrier and adjust the aperture to as small as possible. (The smaller light source apertures can also be used.)

③ Position the aperture assembly between the two lenses so that the focal point of the first lens falls at the center of the aperture.

④ The emerging beam will be much cleaner and gives sharper interference and diffraction patterns.

Questions

① When the beam is incident on a piece of paper, why does the image appears “grainy”? (See Experiment 6.)

Notes:

Experiment 6: Interference From Multiple Reflections

EQUIPMENT NEEDED

– 0.5mW Laser (SE-9367)
– Optics Bench (OS-9103)
– Component Carrier (5) (OS-9107)
– Glass Plate (OS-9128)
– Acrylic Plate (OS-9129)
– 18 mm. F.L. Lens (OS-9132)
– 48 mm. F.L. Lens (OS-9133)
– Viewing Screen with Metric Scale (OS-9138)

Purpose

The patterns of light observed in Young's experiment (Experiment 4) are partially due to a wave phenomenon called interference. When two light waves are coincident and in phase, they re-enforce each other resulting in a wave of grater amplitude (i.e. brighter) than either. If the two waves are coincident and 180° out of phase, they cancel each other. Of course there are various degrees of re-enforcement or cancellation between total re-enforcement (called constructive interference) and total cancellation (called destructive interference).

The interference from two slits was dealt with qualitatively in Experiment 4 and will be dealt with quantitatively in Experiment 7. Therefore, in the present experiment, we will consider another case of interference; that is, interference from multiple reflections.

Procedure

① Set up the laser. Position the lens to form a beam spreader.

② Attach the screen and glass plate to component carriers and position them as shown in Figure 6.1.

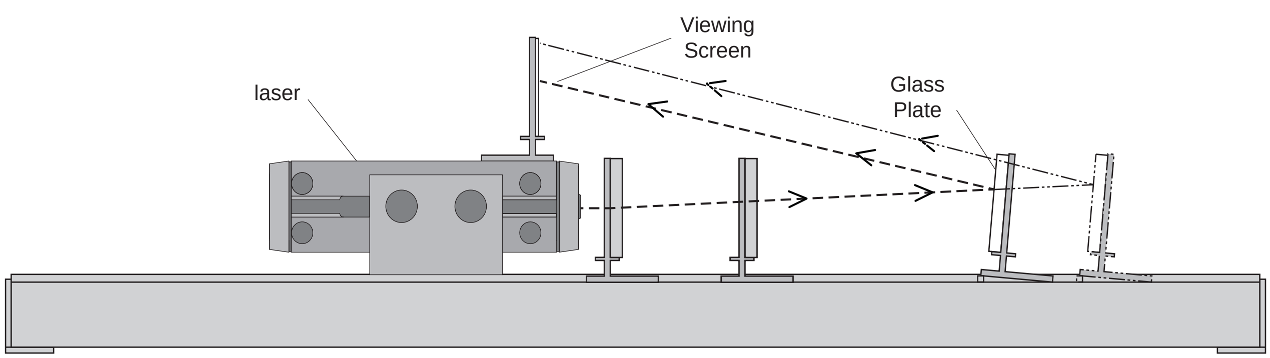


Figure 6.1: Experiment Setup

③ Use a small plate of some sort to prop the glass plate at a small angle. Adjust the angle until the image is seen on the screen above the laser.

④ Note the interference pattern. The irregularity of the pattern is due to deviations in the flatness of the glass plate. Move the plate on the carrier and observe the fringe changes.

⑤ Move the second lens of the beam spreader until the emerging beam diverges slightly. Observe the interference fringes.

⑥ Move the glass plate further down the bench so that its angle of inclination is reduced. Note the fringes. Can you explain the change of pattern, if any?

⑦ Repeat the procedure using the acrylic plate instead of the glass one. Account for the differences in the interference pattern.

Experiment 7: Diffraction By Slits

EQUIPMENT NEEDED

– Photometer (PI-8020 or OS-9152B)
– 0.5mW Laser (SE-9367)
– Optics Bench (OS-9103)
– Linear Translator (OS-9104A)
– Component Carrier (3) (OS-9107)
– Photometer Apertures (OS-9116)
– Aperture Mask (OS-9139)
– Electroformed Diffraction Slits (OS-9165A)
– Electroformed Diffraction Slits (OS-9165B)
– Electroformed Diffraction Slits (OS-9165C)
– Electroformed Diffraction Slits (OS-9165D)
– 48 mm. F. L. Lens (OS-9133)
– Viewing Screen with Metric Scale (OS-9138)

Purpose

When light passes near the edge of an opaque object and then onto a screen, there appears to be some illumination in the area of the geometrical shadow. In other words, light fails to travel in straight lines when passing sharp edges. This phenomenon is called diffraction and occurs because of the wave nature of light.

There are basically two categories of diffraction effects. The first is Fraunhofer diffraction, which refers to diffraction produced when both the light source and screen are an infinite distance from the given obstacle. Fresnel diffraction is the second type and refers to diffraction produced when either the source or screen or both are at finite distances from the obstacle. We can observe Fraunhofer diffraction experimentally by using a collimated light source and placing the viewing screen at the focal plane of a double convex lens located behind the obstacle.

Theory

Since light does not travel in straight lines near a sharp edge, there are many different path lengths from the obstacle to the screen. If there is sufficient difference in path length, two waves reaching the same point on the screen may be 180° out of phase resulting in destructive interference. On the other hand, constructive interference may also occur. The complete explanation of patterns observed in Young’s experiment depends on both interference and diffraction effects.

If we use the incandescent source in studying diffraction, we still get interference patterns (see Experiment 4), but, since interference patterns depend on the wavelength of the light and since white light contains light of various wavelengths, the patterns are not sharp. The coherence and monochromaticity of laser light make it ideal for this experiment.

Procedure

① Position the laser at the left end of the bench and align the beam as in the equipment instructions.

② Attach the slide of single slits on a component carrier and position the assembly midway down the bench.

③ attach the viewing screen to a component carrier and position it at the right end of the bench.

④ Adjust the slit position until the laser beam is incident on the full width of the slit.

⑤ Observe the diffraction pattern on the screen. Adjust the screen position if necessary to obtain image clarity. This is an example of Fresnel diffraction.

⑥ With the slits attached to the side of the component carrier facing the laser, attach the 48 mm. F.L. lens to the other side.

⑦ Move the screen to the focal plane of the lens (i.e. 48mm. from the center of the lens) and observe the diffraction pattern. This is an example of fraunhofer diffraction.

⑧ Now replace the screen with the linear translator (with fiber optic probe attached). Check that the unobstructed laser beam is at the proper level to be incident on the photometer probe (adjust if necessary). With the photometer shutter closed, adjust the translator so that the beam strikes the center of the probe. Now place the photometer aperture slide on the rear surface of the translator's analyzer holder so that the 0.1 mm. slit crosses the center of the beam. With this set up, only light incident on the small slit will be read by the photometer.

⑨ Form another diffraction pattern and slowly scan the pattern with the translator. Plot intensity versus position. Verify that relative intensity falls off as;

$$(\sin \frac{\theta}{\theta})^2$$

(See a standard text for theoretical derivation.) (If the laser has not warmed up for at least 1-12 hours, there may be fluctuations in the beam intensity due to the expanding glass laser tube.)

⑩ Form the diffraction pattern of multiple slits and slits of varying sizes and separation. (If the images are too small, magnify them with a system of lenses.)

⑪ Spread the beam of the laser and illuminate the special patterns on slide OS-9125. Observe the diffraction pattern (Fraunhofer and Fresnel). Attempt to deduce the dimensions of the original aperture arrangement.

Experiment 8: Diffraction At Circular Edges

EQUIPMENT NEEDED

– Photometer (PI-8020 or OS-9152B)
– 0.5mW Laser (SE-9367)
– Optics Bench (OS-9103)
– Linear Translator (OS-9104A)
– Component Carrier (OS-9107)
– Photometer Apertures (OS-9116)
– Viewing Screen with Metric Scale (OS-9138)
– Light Source Apertures (OS-9118)
– Light Source Apertures (OS-9119)
– Opaque Points and Fresnel Zone Plates (OS-9126)
– -22 mm. F. L. lens (OS-9131)
– 18 mm. F.L. lens (OS-9132)
– 48 mm. F. L. lens (OS-9233)

Purpose

Diffraction in all cases is due to the same property of light. However, in certain circumstances, the pattern is easily predicted with mathematical methods. Such is the case with the circular apertures. Airy was the first (1835) to calculate the diffraction pattern of a circular aperture, and hence the bright disk in the center of the pattern is referred to as the “Airy” disk.

A circular lens also tends to diffract the incident light waves. This is due to the fact that the incident wave travels through more glass at the center of the lens than at the edges. The resultant bending of light forms diffraction patterns with an Airy disk. The smallest size of such a disk represents the resolution limit of the lens. That is, the lens cannot distinguish between two points which are closer together than the diameter of the smallest Airy disk.

Theory

Fresnel studied diffraction by considering the intensity at a given point due to approaching spherical wave fronts. He divided the wave front into annular sections such that the distance from the given point to the edge of the first disk is one-half wave length greater than form the point to the center of the disk. Similarly for the distance from the point to the edge of the second disk, as compared to the distance to the edge of the first disk. By blocking out alternate zones, we have in effect a lens. The diffraction effect focuses incident light at the given point. This sort of lens is the familiar Fresnel zone plate, and its design depends on the wavelength of the incident light, as well as the desired focal point.

Procedure

Part I: Airy Disk

① Position the laser on the bench and align the beam.

② Attach the smallest light source apertures to a component carrier and position it a few centimeters in front of the laser so that the beam is incident on the entire aperture.

③ Put the screen on a component carrier and place the assembly about 40 cm. from the circular aperture. Observe the pattern.

④ Try various sizes of apertures and then use the linear translator and photometer to scan the pattern (see Experiment 7). Compare your results with the theory.

Part II: Lens Diffraction

① Attach the -22 mm. F.L. lens on the front of the laser.

② Place the 48 mm. F.L. lens on a carrier positioned such that the diverging beam completely covers the lens. This will be the “test” lens.

③ The diverging lens tends to place a point source 22 mm. to the left of the lens (i.e., somewhere inside the laser). Calculate where the 48 mm. lens should image such a point (use Gauss’s formula,

$$\frac{1}{s} + \frac{1}{s'} = \frac{1}{f}$$

Set the screen at the image point and observe the Airy disk.

④ If the pattern is too small, try magnifying it with the 18mm. lens.

Optional

⑤ Place a variable aperture in front of the test lens and note that the Airy disk increases with smaller lens openings.

Part III: Fresnel Zone Plates

① Put the zone plate on a carrier positioned in front of the laser. You probably will have to assemble a beam spreader (see Experiment 5) to insure that the beam covers the zone plate.

② The zone plates in the system are designed with a focal length of about 40 cm. Place the screen at the focal point and observe the bright central dot.

③ Scan the pattern with translator and photometer and compare the intensity of the central dot with the intensity of the unobstructed beam. In order to compare intensities, cover the fiber optic probe with a light source aperture which is at least as small (if possible) as the central dot in the Fresnel pattern. Then use the same aperture when scanning the unobstructed beam.

④ Try the “opposite” zone plate, as well as the plane opaque points. Scan all the patterns for intensity distributions.

Experiment 9: Determining The Wavelength Of Light

EQUIPMENT NEEDED

– 0.5mW Laser (SE-9367)
– Optics Bench (OS-9103)
– Component Carrier (2) (OS-9107)
– 6000 line/cm. diffraction grating (OS-9127)
– 48 mm. F.L. Lens (OS-9122)
– Viewing Screen with Metric Scale (OS-9138)
– steel machinist's scale (about 1/64" markings)

Purpose

A plane diffraction grating is a series of many thousands of slits placed close together. In a transmission grating, light passes through the slits and is diffracted causing interference. The slits are so narrow and so numerous that the interference is rather sharp with well-spaced fringes. By measuring these fringe separation, we can calculate the wavelength of the diffracted light.

Theory

Referring to Figure 9.1, if ***f*** is the focal length of a lens placed behind the grating, and if we approximate the size of very small angles, the distance ***x*** from the lens axis to the mth maximum on the screen is given by:

$$x = \frac{(\lambda fm)}{d}$$

where λ is the wavelength of light and ***d*** is the slit separation (distance between midpoints of two adjacent slits).

A rather nice experiment can be performed using a common machinist scale as a reflection grating. Light is reflected from between scale markings, but not from the markings themselves. The interference pattern exhibits well defined fringes if the scale markings are sufficiently close together. Again we can calculate the wavelength of light from the measured fringe separations.

If we approximate the cosine function, we find that if ***d*** is the separation of adjacent markings on the ruler, and if x_n is the distance from the ruler's plane to the nth maximum (see Figure 9.2), then

$$\lambda = d\frac{(x_n^2 - x_o^2)}{2nL^2}$$

where ***L*** is the distance from the screed to the midpoint of the beam's incidence on the ruler and x_0 is the position of the directly reflected beam.

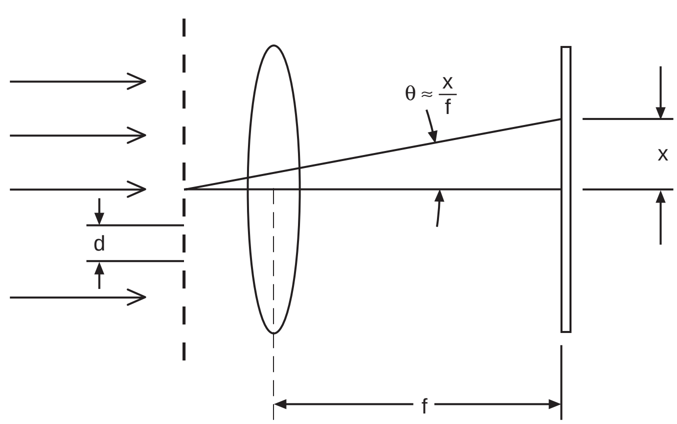


Figure 9.1

Procedure

Part I: Diffraction Grating Method

① Set up the laser. Place the diffraction grating and 48 mm. lens on opposite sides of the same component carrier.

② Position the grating so that it faces the laser and place the screen in the focal plane of the 48 mm. lens.

③ With the beam passing through the grating and lens, you should be able to see the central maximum and the first order maximum on either side. Measure the separation and calculate the wavelength. (You may improve your accuracy slightly by using the linear translator and photometer to measure the distance between fringes).

④ Try using the incandescent light source in place of the laser. For a sharper image, collimate the light beam first; (just placing the 18 mm. F.L. lens on the front of the incandescent source is sufficient). Cover the source with each of the color (spectral) filters in turn and observe the corresponding image.

Part II: Machinist's Scale Method

① Set up the laser and attach the machinist's scale to a component carrier as in Figure 9.2.

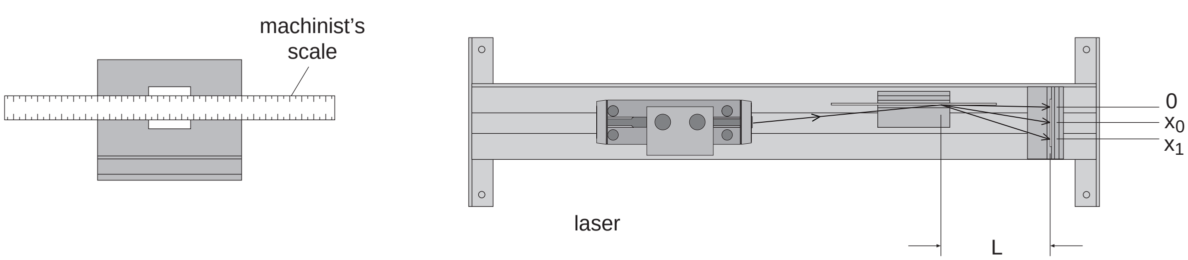


Figure 9.2: Experiment Setup

② Set the scale assembly on the bench so that the machinist's scale is parallel to the center of the bench but displaced slightly from the center line. Place the viewing screen at the right end of the bench.

③ Now adjust the laser alignment so that the beam just grazes the scale (see Figure 9.2).

④ Adjust the scale's position on the carrier so that the beam grazes the scale on the scale markings.

⑤ Observe the diffraction pattern (it may be necessary to pull the screen off the bench to see several orders of maxima).

⑥ Make the necessary measurements and compute the wavelength of the laser.

Experiment 10: Polarization

EQUIPMENT NEEDED

– Photometer (PI-8020 or OS-9152B)
– 0.5mW Laser (SE-9367)
– Incandescent Light Source (OS-9102B)
– Optics Bench (OS-9103)
– Angular Translator (OS-9106A)
– Component Carrier (3) (OS-9107)
– Calibrated Polarizer (3) (OS-9109)
– Calibrated 140 nm Retarder (OS-9110)
– Acrylic Plate (OS-9129)
– Prism (90°) (OS-9130)
– Flat Front Surface Mirror (OS-9136)
– Viewing Screen with Metric Scale (OS-9138)
– Aperture Mask (OS-9139)

Purpose

Diffraction and interference effects occur with any type of wave. However, since light is a transverse electromagnetic wave, it exhibits one property not common to all waves. This unique property is polarization. As a light wave travels through a medium, the electric and magnetic fields oscillate in a plane perpendicular to the direction of travel. If all light waves from a given source are such that their electric field vectors are parallel, the light is said to be linearly polarized.

Some crystalline substances which exhibit a property called dichroism are useful in producing polarized light. A dichroic substance tends to absorb light to varying degrees depending on the polarization form of the incident beam. With proper engineering, the light transmitted through such a substance is linearly polarized. Using PASCO polarizers, the transmitted light is linearly polarized with the electric vector parallel to the 0° -180° axis of the polarizer. Other crystals exhibit a property called bifringence or double refractions. With proper orientation of the crystal, an incident light wave normal to the crystal face is split into two beams, one of which is delayed by a fraction of a wavelength. By carefully choosing orientation and thickness of bifringent crystals, we can devise a retardation plate.

The PASCO retardation plate causes one wave to lag behind the other by 140 nm (that is, 1/4 wavelength if the light's wavelength is 560 nm) . If a polarizer and 1/4 wave retardation plate are sandwiched together with polarized (either left- or right-handed).

Another way of producing linearly polarized light is by reflection. Electromagnetic wave theory predicts that light is reflected to a greater or lesser degree depending on its form of polarization relative to the surface of the reflecting medium. Hence, as Sir David Brewster discovered in 1812, there is a predictable angle of incidence at which light reflected from a medium is totally linearly polarized.

Procedure

Part I: Dichroic Polarizers

① Set up the laser. Place a polarizer on a carrier and let the laser beam pass through it.

② Rotate the polarizer and observe varying intensities of the image. Is the laser light polarized? Using the photometer, check beam intensity versus time.

➤ **NOTE:** The laser beam's polarized components vary slightly with temperature. For accurate results, carefully monitor the changes. There are no such variations if the incandescent light source is used.

③ Attach a second polarizer to the special component carrier of the angular translator and place it on the rotating table so that it is perpendicular to the bench. (The angular translator is used here only so that we can attach the fiber optic probe to the arm and use the photometer later.)

④ Adjust the first polarizer so that the 0° -180° axis is vertical.

⑤ Place the screen on the movable arm and adjust the arm position until the beam strikes the screen.

⑥ Observe the image intensity as you rotate the second polarizer.

⑦ remove the screen and attach the photometer's fiber optic probe. Again rotate the polarizer and record intensity of the transmitted beam for various angles. Verify that if I_m is the maximum intensity of transmitted light, then

$$I = I_m \cos^2\theta \text{ } (\textit{Malus' law})$$

where I is the intensity of the transmitted beam and θ is the angle which the second polarizer's axis (0° -180° line) makes with the first polarizer's axis.

⑧ Adjust both polarizers so that their polarizing axes are perpendicular to each other. Observe that no light is transmitted onto the screen.

⑨ Now insert a third polarizer (mounted on a carrier) between the original two in such a way that the polarizing axis of the third makes an angle of 45° with the axis of the first polarizer. Is any light transmitted now? Why?

Part II: Circularly Polarized Light

① On one component carrier attach both a polarizer and the retardation plate such that the 0° - 180° axis of the retarder makes a 45° angle with that of the polarizer.

② Place the assembly on the bench with the polarizer facing the laser.

③ Use the viewing screen and a second polarizer to determine if the beam transmitted through the polarizer-retarder combination is polarized or not.

④ Now put the flat surface mirror to the right of the polarizer-retarder assembly and reflect the beam back through the assembly. Note the image intensity on the laser's face (the mirror must be set at a slight angle so you can see the image on the laser's face). Rotate the retarder and note the image intensity.

➤ **NOTE:** Circularly polarized light can be either left - or right-handed in orientation (depending on the relative orientation of retarder and polarizer axes). However, an assembly which circularly polarizes light into one form will not transmit circularly polarized light of the other form. In the above experiment, the mirror changes the form of the circularly polarized light. Hence, the reflected beam is not transmitted.

➤ **CAUTION:** The retarder is not exactly a 1/4 wave plate for the laser light.)

⑤ The retarder's effect can be varied by changing the angle of the incident beam. Set up the apparatus to investigate this variation.

Part III: Brewster's Angle

① Leave the first polarizer in front of the laser and adjust the 0° -180° axis so that it is horizontal.

② Attach the glass coincides with one of the scored lines.

③ Put the viewing screen on the movable arm and adjust both the rotating table and the arm until the reflected image is on the screen.

④ Continue rotating the table until the image intensity is a minimum. Note the incidence angle for such a minimum. This is the Brewster angle.

⑤ At the angle of minimum reflection, remove the first polarizer and attach it on the first holder on the movable arm. Move the screen to the second holder.

⑥ Verify that all light being reflected is linearly polarized. In what plane is it polarized?

⑦ check to see if the transmitted light is polarized.

⑧ Use the photometer to plot the degree of polarization of both reflected and transmitted beams for various angles of incidence.

⑨ Repeat the procedure using the acrylic plate.

⑩ Repeat the procedure using the incandescent source instead of the laser. Room light must be very low in order to see the images clearly.

Notes:

Experiment 11: Optical Activity

EQUIPMENT NEEDED

– Photometer (PI-8020 or OS-9152B)
– 0.5mW Laser (SE-9367)
– Optics Bench (OS-9103)
– Angular Translator (OS-9106A)
– Component Carrier (OS-9107)
– Glass Dispersion Tank (OS-9108)
– Calibrated Polarizer (HN-32) (2) (OS-9109)
– Photometer Apertures (OS-9116)

Purpose

A linearly polarized light wave may be considered to be the resultant wave upon superimposing two circularly polarized waves — one right-handed and one left-handed. Some crystals and some solutions tend to split linearly polarized light into these two circularly polarized components. As the two wave components travel through the substance, one lags behind the other. Since the two waves are still coincident, when they emerge the resultant wave is again linearly polarized. However, because of the retardation of one component, the emerging light is linearly polarized in a different direction.

If the direction of polarization is rotated to the right (relative to looking in the direction which the light is travelling), the substance is said to be dextrorotatory. Substances which rotate the polarization to the left are called laevorotary. Solutions of cane sugar are dextrorotatory due to the asymmetry of the sugar molecule.

Procedure

① Fill the glass dispersion tank with a cane sugar and water solution (by weight: 15%-20% sugar).

② Place the filled tank on the rotating table of the angular translator which should be positioned on the bench.

③ Position the laser at the left of the bench and put a polarizer (on a carrier) between the laser and tank.

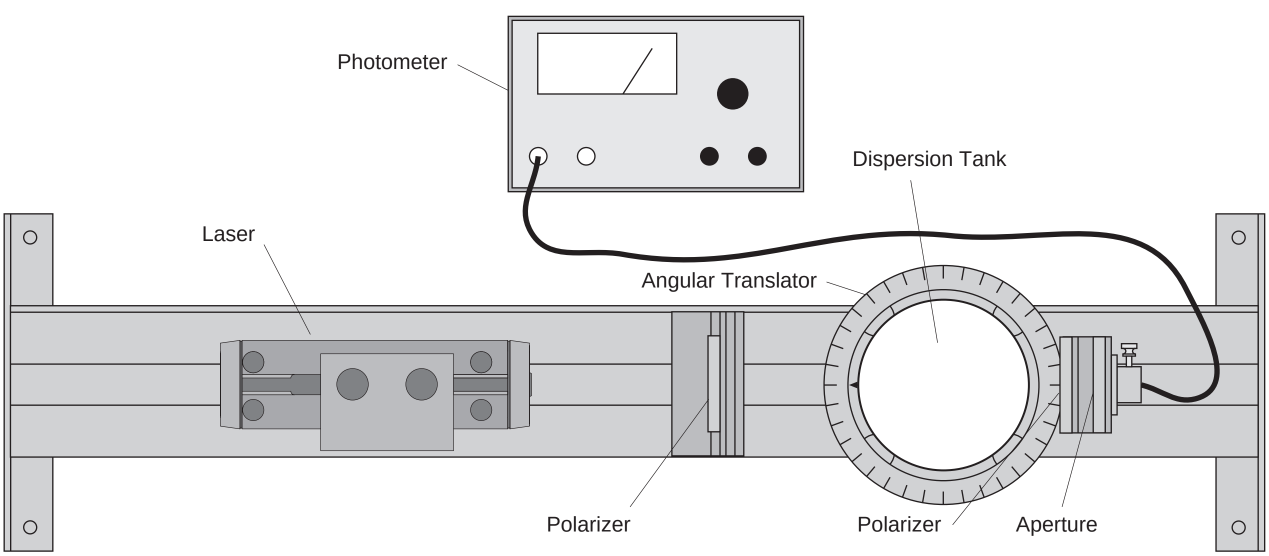


Figure 11.1: Experiment Setup

④ Attach a second polarizer to the front surface of the analyzer holder on the moveable arm of the angular translator. Put a photometer aperture on the rear surface of the analyzer holder. (See Figure 11.1)

⑤ With the fiber optic probe attached behind the photometer aperture, use the potometer to measure the transmitted beam's intensity as the second polarizer is rotated.

⑥ From the intensity results, determine the direction of polarization of the transmitted beam. Compare to the original polarization direction.

⑦ Repeat the procedure for differing concentration is sufficiently high to considerably rotate the polarization direction. However, the photometer gives much more useful and quantitative results.)

➤ **NOTE:** The Photometer is not necessary if very rough results are sufficient and if the sugar concentration is sufficiently high to considerably rotate the polarization direction. However, the Photometer gives much more useful and quantitative results.

Experiment 12: Scattering

EQUIPMENT NEEDED

– Photometer (PI-8020 or OS-9152B)
– Incandescent Light Source (OS-9102B)
– Optics Bench (OS-9103)
– Angular Translator (OS-9106A)
– Component Carrier (2) (OS-9107)
– Glass Dispersion Tank (OS-9108)
– Calibrated Polarizer (HN-32) (OS-9109)
– 48 mm. F. L. Lens (OS-9133)
– Red Spectral Filter (OS-9111)
– Yellow Spectral filter (OS-9112)
– Green Spectral filter (OS-9113)
– Blue Spectral filter (OS-9114)
– Photometer Apertures (OS-9116)
– 18 mm. F.L. Lens (OS-9132)

Purpose

Why is the sky blue (without smog)? And why is light from the sky linearly polarized (check with a polarizer)? Both observations are due mostly to a light phenomenon referred to as scattering. There are two basic types of scattering — Rayleigh scattering and diffraction (or Mei) scattering. If the particles causing scattering are small compared with the wavelength of the incident light, then Rayleigh scattering is more predominate. As particle size increases, the light is diffracted to a greater degree. Of course, the transparency of the particles greatly affects the results in either case.

Rayleigh scattering is the main factor in accounting for a blue sky. When a light wave form the sun strikes a molecule in the atmosphere (see Figure 12.1), the oscillating electric field sets the charged particles in the molecule oscillating. This oscillation can be separated into two components: one along the X axis and one along the Y axis. These two components of oscillation act as miniature antennas which radiate perpendicular to the direction of oscillation. Hence, light is scattered in the XY plane Figure 12.1 shows the component breakdown of one wave which is linearly polarized.

The oscillation of the molecule is a forced oscillation, and hence the amplitude increases as the frequency of the incident light gets closer to the resonant frequency of the molecule. The frequencies of visible light are generally less than resonant frequencies of molecules in the atmosphere, yet the higher the higher the frequency (i.e., near blue light), the higher the amplitude of the scattered light. Thus, blue light is scattered more than red light.

During the day, the light which reflects off other particles of the atmosphere is mostly blue scattered light. Direct sunlight minus the blue light which is scattered appears yellow or red.

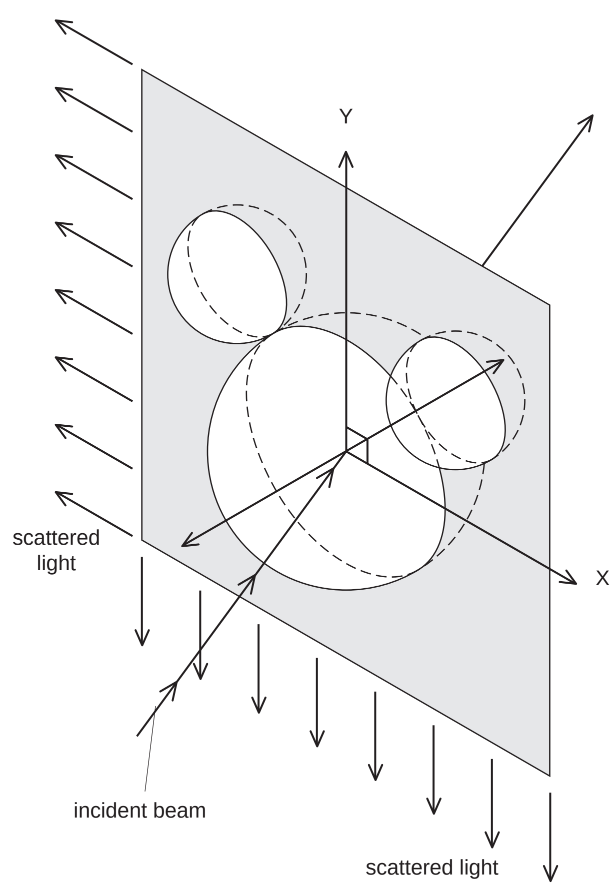


Figure 12.1: Scattering

Toward evening sunlight travels through more atmosphere and, hence, loses more blue light from scattering. When the resulting light reflects off a cloud, the observer sees reddish-colored light. Thus, sunsets often appear to have a red hue.

In this experiment we will use a milk solution and examine the scattered light from milk globules. There will be a combination of Rayleigh and diffraction scattering (see a standard text for theoretical predictions). Using a concentrated silver nitrate solution, we can observe the effect of decreasing particle size.

Procedure

① Place the incandescent light source and angular translator on the optical bench.

② Attach the aperture mask to a component carrier and position it between the light source and translator.

③ Fill the dispersion tank with water and mix in a few cubic centimeters of milk to make the solution just slightly cloudy.

④ Place the filled tank on the rotating table of the angular translator.

⑤ Adjust the aperture mask and tank position so that the incident beam is perpendicular to the tank's surface.

⑥ With the fiber optic probe in position and the photometer aperture on the rear surface of the analyzer holder, use the photometer to measure light intensity at several points around the tank. (Room light must be very low.)

⑦ Now place one of the color (spectral) filters (transmission curves in the equipment instructions) on the front of the light source over the beam. Again measure intensities at various points around the tank. Plot intensity versus angle. Repeat for each filter. Which light is scattered more? (In interpreting your results, remember that the mild globules also cause diffraction effects.)

⑧ Repeat the procedure for a concentrated solution of silver nitrate in water.

Optional

⑨ Replace the incandescent source with the laser and observe scattering at that particular wavelength.

Experiment 13: Holography

EQUIPMENT NEEDED

– 0.5mW Laser (SE-9367)
– Optics Bench (OS-9103)
– Component Carrier (OS-9107)
– Hologram (OS-9115)
– -22 mm. F.L. Lens (OS-9131)
– incandescent light source (optional)
– Red Spectral filter (optional)
– Green Spectral filter (optional)
– Blue Spectral filter (optional)
– 18 mm. F.L. lens (optional)
– 48 mm. F.L. lens (optional)

Purpose

Holography is a method of lensless photography which allows one to record and later reproduce three-dimensional images. In ordinary photography, only the light intensities are recorded on film. No information concerning phase relations is saved. However, in holography a reference beam interferes with the reflected beams from an object. A film plate records the corresponding interference pattern. After developing, the film at this grating, the first order diffracted waves are exact replicas of the original reflected beams from the object.

Because of the high coherence and monochromaticity of laser light, using lasers in preparing and reproducing a hologram increases the quality of the reproduced image. In the following demonstration, we will examine some of the properties of a transmission hologram.

Procedure

① Position the laser at the left of the optical bench and align the beam.

② Attach the -22 mm. F.L. lens to the front of the laser

③ Attach the hologram to a component carrier and position on the hologram.

④ Now look through the hologram towards the laser with your eyes off the central axis of the beam so that you don’t look directly into the laser beam. Focus on a point several centimeters behind the hologram and observe the images. Move your head from side to side to observe the parallax effects and hence verify that the image is three-dimensional. (See Figure 13.1)

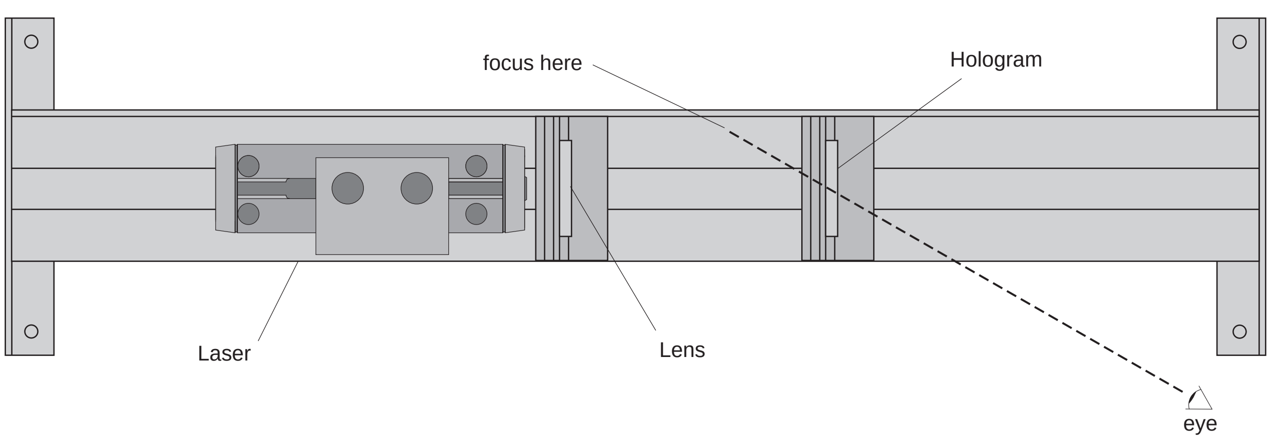


Figure 13.1: Experiment Setup

⑤ Now cover half of the hologram with the aperture mask or similar opaque object. Again, look at the image. Is the entire image still visible? This is one striking property which photography does not exhibit.

Optional

⑥ Use the incandescent light source instead of the laser. Try both with and without collimating the beam.

⑦ Observe the image. Why the colors?

⑧ Place each of the color (spectral) filters in turn over the light source. Observe the image.

Technical Support

Feed-Back

If you have any comments about this product or this manual please let us know. If you have any suggestions on alternate experiments or find a problem in the manual please tell us. PASCO appreciates any customer feed-back. Your input helps us evaluate and improve our product.

To Reach PASCO

For Technical Support call us at 1-800-772-8700 (toll-free within the U.S.) or (916) 786-3800.

Contacting Technical Support

Before you call the PASCO Technical Support staff it would be helpful to prepare the following information:

• If your problem is computer/software related, note:

Title and Revision Date of software.

Type of Computer (Make, Model, Speed).

Type of external Cables/Peripherals.

• If your problem is with the PASCO apparatus, note:

Title and Model number (usually listed on the label).

Approximate age of apparatus.

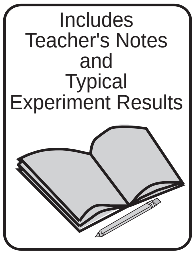
A detailed description of the problem/sequence of events. (In case you can't call PASCO right away, you won't lose valuable data.)

If possible, have the apparatus within reach when calling. This makes descriptions of individual parts much easier.

• If your problem relates to the instruction manual, note:

Part number and Revision (listed by month and year on the front cover).

Have the manual at hand to discuss your questions.



Instruction Manual and Experiment Guide for the PASCO scientific Models OS-9255A thru OS-9258A

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PRECISION INTERFEROMETER

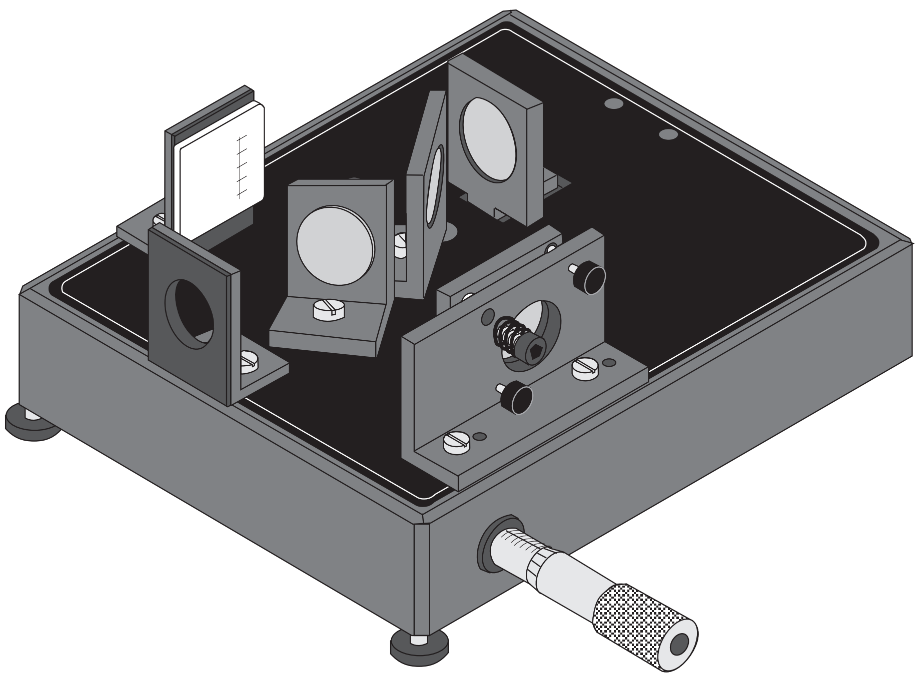

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Table of Contents

Copyright, Warranty, and Equipment Return

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1. The packing carton must be strong enough for the item shipped.
2. Make certain there are at least two inches of packing material between any point on the apparatus and the inside walls of the carton.
3. Make certain that the packing material cannot shift in the box or become compressed, allowing the instrument come in contact with the packing carton.

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Introduction

The OS-9255A Precision Interferometer provides both a theoretical and a practical introduction to interferometry. Precise measurements can be made in three modes:

Michelson

The Michelson Interferometer is historically important, and also provides a simple interferometric configuration for introducing basic principles. Students can measure the wavelength of light and the indices of refraction of air and other substances.

Twyman-Green

The Twyman-Green Interferometer is an important contemporary tool for testing optical components. It has made it possible to create optical systems that are accurate to within a fraction of a wavelength.

> ➤ **NOTE:** The PASCO Precision Interferometer is not designed for actual component testing in the Twyman-Green mode. It is intended only to provide a simple introduction to this important application of interferometry.

Fabry-Perot

The Fabry-Perot Interferometer is also an important contemporary tool, used most often for high resolution spectrometry. The fringes are sharper, thinner, and more widely spaced than the Michelson fringes, so small differences in wavelength can be accurately resolved. The Fabry-Perot interferometer is also important in laser theory, as it provides the resonant cavity in which light amplification takes place.

Switching between these three modes of operation and aligning components is relatively simple, since all mirrors mount to the base in fixed positions, using captive panel screws. Lenses, viewing screens, and other components mount magnetically to the base using the included component holders.

Measurements are precise in all three modes of operation. A 5 kg machined aluminum base provides a stable surface for experiments and measurements. All mirrors are flat to 1/4 wavelength, and the built-in micrometer resolves mirror movement to within one micron.

Equipment

The OS-9255A Precision Interferometer includes the following equipment:

- 5 kg Base with built-in micrometer
- Adjustable Mirror
- Movable Mirror
- Beam Splitter
- Compensator Plate
- (2) Component Holder
- Viewing Screen
- Lens, 18 mm Focal Length
- Diffuser
- Fitted Storage Case

Additional Equipment Required –

- Laser (OS-9171)
- Laser Bench (OS-9172)

➤ **NOTE:** The preceding equipment includes everything needed for basic Michelson interferometry. You can produce clear fringes and make precise measurements of the wavelength of your source. However, to perform the experiments in this manual, you will need additional components, such as the OS-9256A Interferometer Accessories or a comparable set of your own components.The Precision Interferometer is available as a complete system. Please refer to your current PASCO catalog for details.

Additional Equipment Recommended –

The OS-9256A Interferometer Accessories includes:

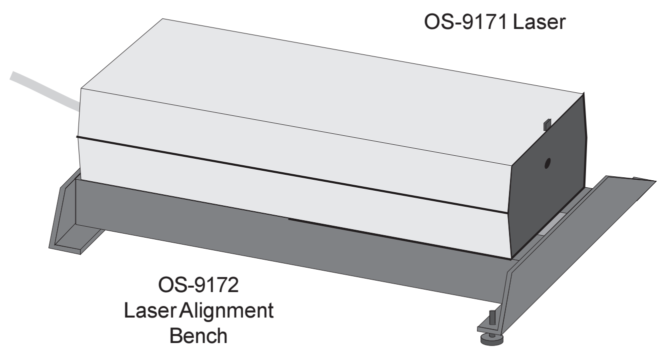
- Rotating Pointer
- Vacuum Cell
- Component Holder
- Lens, 18 mm Focal Length
- Lens, 48 mm Focal Length
- Glass Plate
- (2) Polarizer
- Vacuum Pump with Gauge

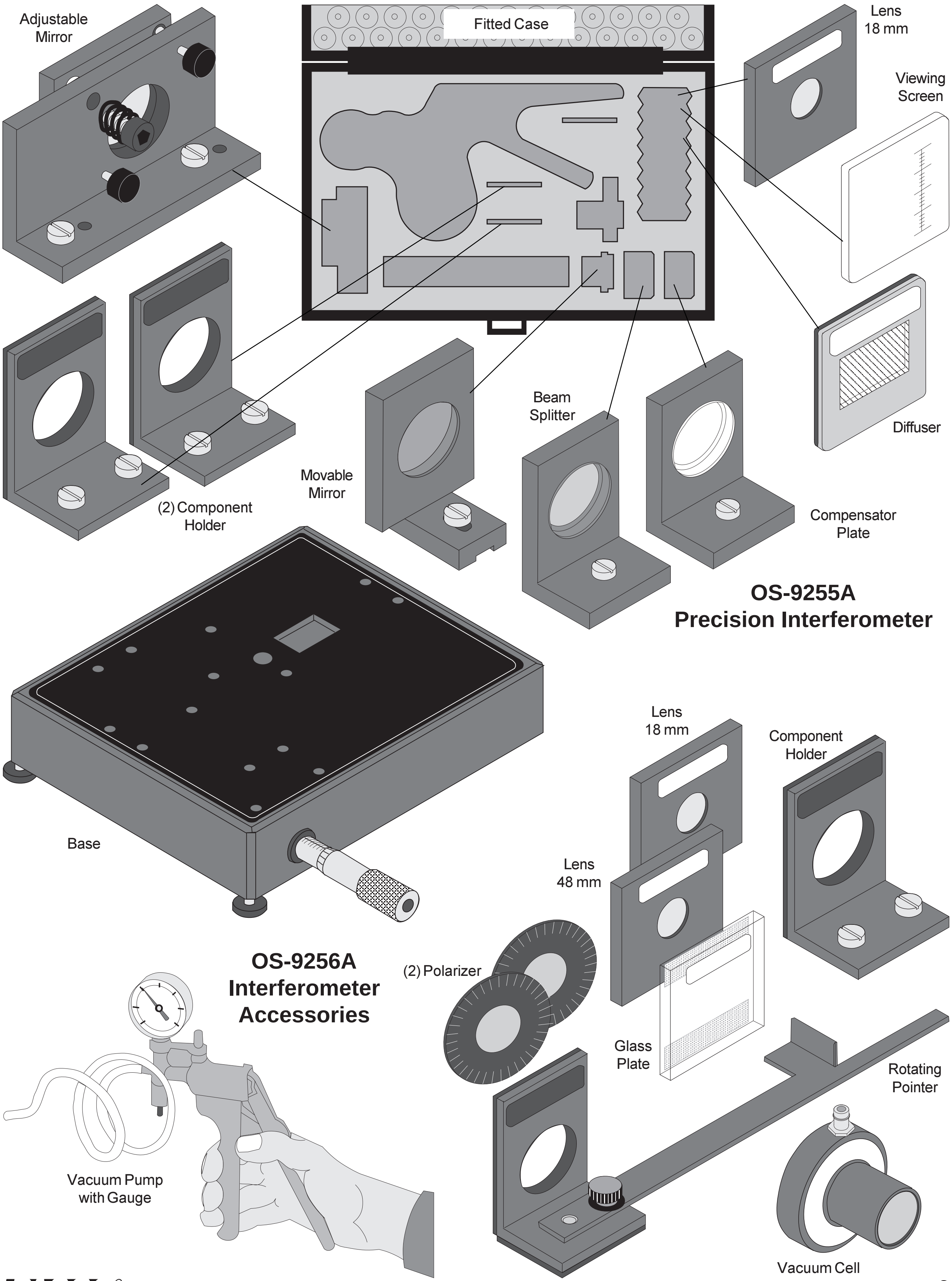
➤ **NOTE:** The OS-9255A Fitted Case also provides storage for these accessory components.

About Your Light Source

We strongly recommend a laser for most introductory applications. A spectral light source can be used (see the Appendix), but that really comprises an experiment in and of itself for beginning students. A laser source is easy to use and produces bright, sharp fringes.

The OS-9171 Laser and OS-9172 Laser Alignment Bench are available from PASCO. However, any low power laser that operates in the visible range will work well. If you want to demonstrate the importance of polarization in interferometry, a non-polarized laser should be used. For easy alignment, the beam should be approximately 4 cm above the level of the bench top.




Adjustable Mirror
Fitted Case
Lens 18 mm
Viewing Screen
Diffuser
Beam Splitter
Movable Mirror
(2) Component Holder
Compensator Plate
OS-9255A
Precision Interferometer
Base
Lens 18 mm
Component Holder
Lens 48 mm
OS-9256A
Interferometer Accessories
(2) Polarizer
Glass Plate
Rotating Pointer
Vacuum Pump with Gauge
Vacuum Cell

Theory of Operation

Interference Theory

A beam of light can be modeled as a wave of oscillating electric and magnetic fields. When two or more beams of light meet in space, these fields add according to the principle of superposition. That is, at each point in space, the electric and magnetic fields are determined as the vector sum of the fields of the separate beams.

If each beam of light originates from a separate source, there is generally no fixed relationship between the electromagnetic oscillations in the beams. At any instant in time there will be points in space where the fields add to produce a maximum field strength. However, the oscillations of visible light are far faster than the human eye can apprehend. Since there is no fixed relationship between the oscillations, a point at which there is a maximum at one instant may have a minimum at the next instant. The human eye averages these results and perceives a uniform intensity of light.

If the beams of light originate from the same source, there is generally some degree of correlation between the frequency and phase of the oscillations. At one point in space the light from the beams may be continually in phase. In this case, the combined field will always be a maximum and a bright spot will be seen. At another point the light from the beams may be continually out of phase and a minima, or dark spot, will be seen.

Thomas Young was one of the first to design a method for producing such an interference pattern. He allowed a single, narrow beam of light to fall on two narrow, closely spaced slits. Opposite the slits he placed a viewing screen. Where the light from the two slits struck the screen, a regular pattern of dark and bright bands appeared. When first performed, Young's experiment offered important evidence for the wave nature of light.

Young's slits can be used as a simple interferometer. If the spacing between the slits is known, the spacing of the maxima and minima can be used to determine the wavelength of the light. Conversely, if the wavelength of the light is known, the spacing of the slits could be determined from the interference patterns.

The Michelson Interferometer

In 1881, 78 years after Young introduced his two-slit experiment, A.A. Michelson designed and built an interferometer using a similar principle. Originally Michelson designed his interferometer as a means to test for the existence of the ether, a hypothesized medium in which light propagated. Due in part to his efforts, the ether is no longer considered a viable hypothesis. But beyond this, Michelson's interferometer has become a widely used instrument for measuring the wavelength of light, for using the wavelength of a known light source to measure extremely small distances, and for investigating optical media.

Figure 1 shows a diagram of a Michelson interferometer. The beam of light from the laser strikes the beam-splitter, which reflects 50% of the incident light and transmits the other 50%. The incident beam is therefore split into two beams; one beam is transmitted toward the movable mirror (M_1), the other is reflected toward the fixed mirror (M_2). Both mirrors reflect the light directly back toward the beam-splitter. Half the light from M_1 is reflected from the beam-splitter to the viewing screen and half the light from M_2 is transmitted through the beam-splitter to the viewing screen.

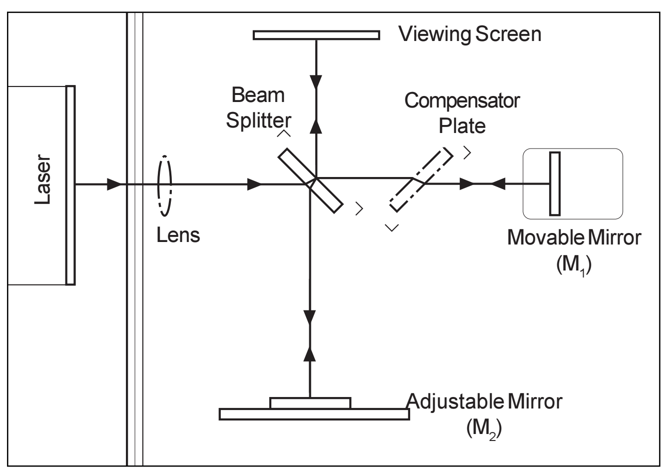


Figure 1. Michelson Interferometer

In this way the original beam of light is split, and portions of the resulting beams are brought back together. Since the beams are from the same source, their phases are highly correlated. When a lens is placed between the laser source and the beam-splitter, the light ray spreads out, and an interference pattern of dark and bright rings, or fringes, is seen on the viewing screen (Figure 2).

Figure 2. Fringes

Since the two interfering beams of light were split from the same initial beam, they were initially in phase. Their relative phase when they meet at any point on the viewing screen, therefore, depends on the difference in the length of their optical paths in reaching that point.

By moving M_1, the path length of one of the beams can be varied. Since the beam traverses the path between M_1 and the beam-splitter twice, moving M_1 1/4 wavelength nearer the beam-splitter will reduce the optical path of that beam by 1/2 wavelength. The interference pattern will change; the radii of the maxima will be reduced so they now occupy the position of the former minima. If M_1 is moved an additional 1/4 wavelength closer to the beam-splitter, the radii of the maxima will again be reduced so maxima and minima trade positions, but this new arrangement will be indistinguishable from the original pattern.

By slowly moving the mirror a measured distance $\mathbf{d_m}$, and counting **m**, the number of times the fringe pattern is restored to its original state, the wavelength of the light (λ) can be calculated as:

$$\lambda = \frac{2d_m}{m}$$

If the wavelength of the light is known, the same procedure can be used to measure $\mathbf{d_m}$.

➤ **NOTE: Using the Compensator**

In Figure 1, notice that one beam passes through the glass of the beam-splitter only once, while the other beam passes through it three times. If a highly coherent and monochromatic light source is used, such as a laser, this is no problem. With other light sources this is a problem.

The difference in the effective path length of the separated beams is increased, thereby decreasing the coherence of the beams at the viewing screen. This will obscure the interference pattern.

A compensator is identical to the beam-splitter, but without the reflective coating. By inserting it in the beam path, as shown in Figure 1, both beams pass through the same thickness of glass, eliminating this problem.

The Twyman-Green Interferometer

The Twyman-Green Interferometer is a variation of the Michelson Interferometer that is used to test optical components. A lens can be tested by placing it in the beam path, so that only one of the interfering beams passes through the test lens (see Figure 3). Any irregularities in the lens can be detected in the resulting interference pattern. In particular, spherical aberration, coma, and astigmatism show up as specific variations in the fringe pattern.

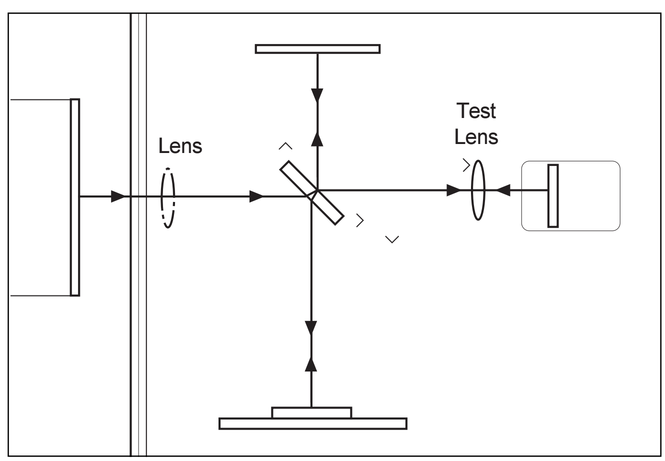


Figure 3. Twyman-Green Interferometer

The Fabry-Perot Interferometer

In the Fabry-Perot Interferometer, two partial mirrors are aligned parallel to one another, forming a reflective cavity. Figure 4 shows two rays of light entering such a cavity and reflecting back and forth inside. At each reflection, part of the beam is transmitted, splitting each incident ray into a series of rays. Since the transmitted rays are all split from a single incident ray, they have a constant phase relationship (assuming a sufficiently coherent light source is used).

The phase relationship between the transmitted rays depends on the angle at which each ray enters the cavity and on the distance between the two mirrors. The result is a circular fringe pattern, similar to the Michelson pattern, but with fringes that are thinner, brighter, and more widely spaced. The sharpness of the Fabry-Perot fringes makes it a valuable tool in high-resolution spectrometry.

As with the Michelson Interferometer, as the movable mirror is moved toward or away from the fixed mirror, the fringe pattern shifts. When the mirror movement is equal to 1/2 of the wavelength of the light source, the new fringe pattern is identical to the original.

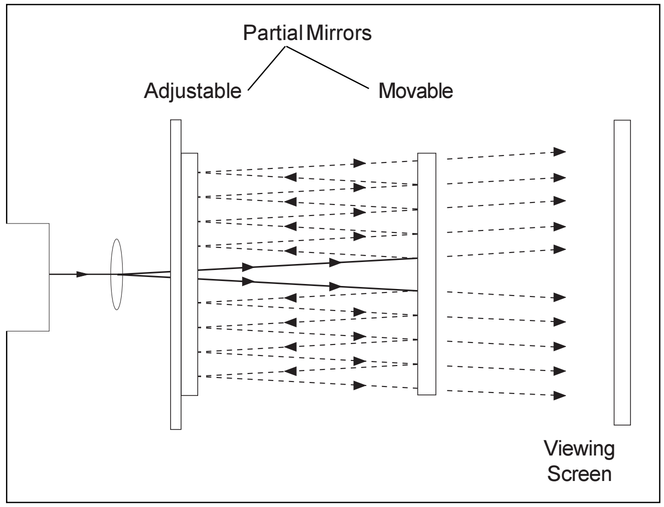


Figure 4. Fabry-Perot Interferometer

Setup and Operation

Laser Alignment

- If you are using a PASCO Laser and Laser Alignment Bench, the setup and alignment procedure is as follows.
- If you are using a different laser, the alignment procedure is similar. Adjust your laser so that the beam is approximately 4 cm above the table top. Then align the beam as in steps 4 and 5, below.
- If you are using a spectral light source instead of a laser, see *Suggestions for Additional Experiments*, near the end of the manual.

To set up and align your PASCO Laser:

1. Set the interferometer base on a lab table with the micrometer knob pointing toward you.
2. Position the laser alignment bench to the left of the base approximately perpendicular to the interferometer base and place the laser on the bench.
3. Secure the movable mirror in the recessed hole in the interferometer base.
4. Turn the laser on. Using the leveling screws on the laser bench, adjust its height until the laser beam is approximately parallel with the top of the interferometer base and strikes the movable mirror in the center. (To check that the beam is parallel with the base, place a piece of paper in the beam path, with the edge of the paper flush against the base. Mark the height of the beam on the paper. Using the piece of paper, check that the beam height is the same at both ends of the bench.)
5. Adjust the X-Y position of the laser until the beam is reflected from the movable mirror right back into the laser aperture. This is most easily done by gently sliding the rear end of the laser transverse to the axis of the alignment bench, as shown in Figure 5.

You are now ready to set up the interferometer in any of its three modes of operation.

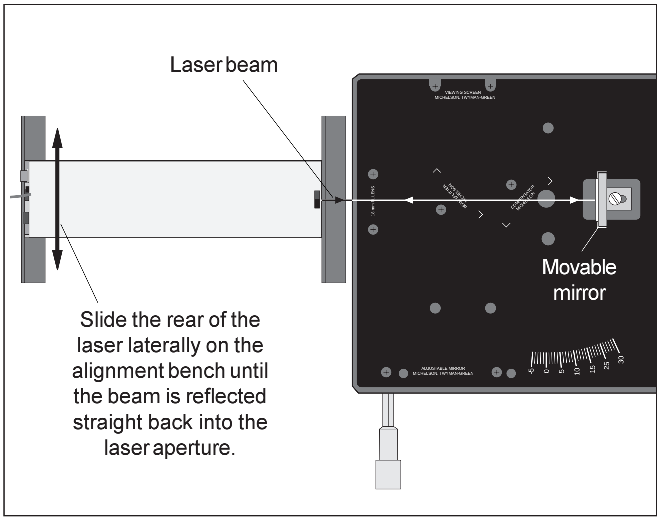


Figure 5. Aligning the Laser

> ➤ **NOTE:**
> For ease of installation the placement of the individual components in the various modes is indicated on the label.

Michelson Mode

1. Align the laser and interferometer base as previously described. The laser beam should be approximately parallel with the top of the base, should strike the center of the movable mirror, and should be reflected directly back into the laser aperture.
2. Mount the adjustable mirror on the interferometer base. Position one component holder in front of the laser. Place the other component holder opposite the adjustable mirror and attach the viewing screen to its magnetic backing. See Figure 6.
3. Position the beam-splitter at a 45 degree angle to the laser beam, within the crop marks, so that the beam is reflected to the fixed mirror. Adjust the angle of the beam-splitter as needed so that the reflected beam hits the fixed mirror near its center.
4. There should now be two sets of bright dots on the viewing screen; one set comes from the fixed mirror and the other comes from the movable mirror. Each set of dots should include a bright dot with two or more dots of lesser brightness (due to multiple reflections). Adjust the angle of the beam-splitter again until the two sets of dots are as close together as possible, then tighten the thumbscrew to secure the beam-splitter.

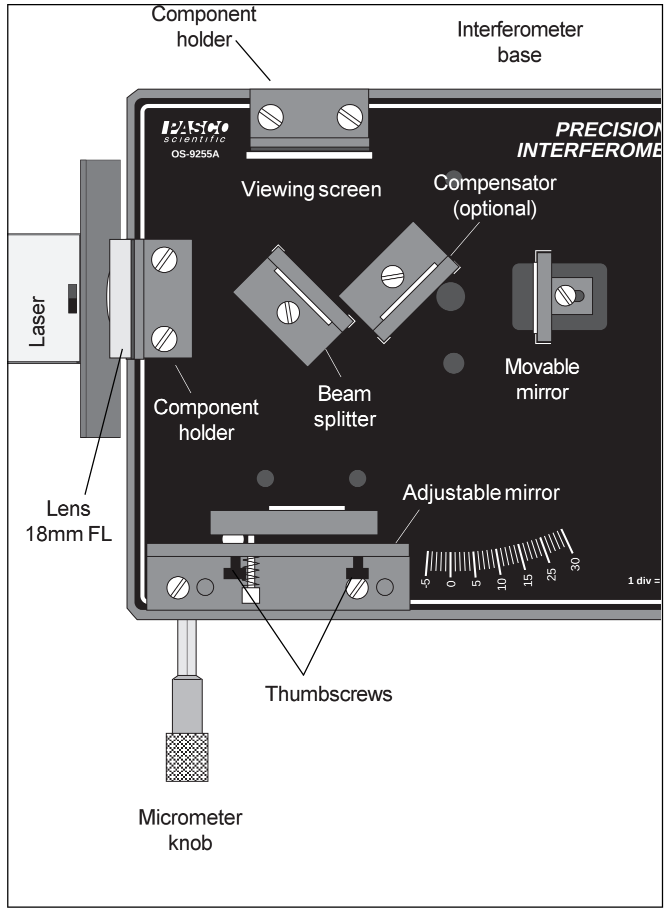


Figure 6. Michelson Mode Setup

5. Using the thumbscrews on the back of the adjustable mirror, adjust the mirror's tilt until the two sets of dots on the viewing screen coincide.
6. The compensator is not needed for producing interference fringes when using a laser light source. However, if you wish to use the compensator, it mounts perpendicular to the beam-splitter, as shown.
7. Attach the 18 mm FL lens to the magnetic backing of the component holder in front of the laser, as shown, and adjust its position until the diverging beam is centered on the beam-splitter. You should now see circular fringes on the viewing screen. If not, carefully adjust the tilt of the adjustable mirror until the fringes appear.
8. If you have trouble obtaining fringes, see *Trouble-Shooting* at the end of this section.

Twyman-Green Mode

1. Set up the interferometer in the Michelson mode, as described above.
2. Remove the pointer from the rotational componet holder. (It is recommended to store the pointer, washer and thumbscrew in the storage case.) Place the component holder between the beam-splitter and the movable mirror (see Figure 7). It attaches magnetically. Mount a second 18 mm FL lens (L_2) on its magnetic backing and position it .
3. Remove the original lens (L_1) from in front of the laser.

   Observe the two sets of dots on the viewing screen—one set from the movable mirror and one set from the adjustable mirror. Adjust the position of L_2 until both sets of dots are the same size.
4. Adjust the tilt of the adjustable mirror until the two sets of dots coincide.
5. Replace lens L_1 in front of the laser. Move the viewing screen so it's at least 12 inches from the edge of the interferometer base. Fringes should appear in the bright disk of the viewing screen. Fine adjustments of L_1 may be necessary to find the fringes. A piece of white paper or cardboard can be used in place of the viewing screen. A 48 mm FL convex lens may also be used to magnify the projected image of the fringes.

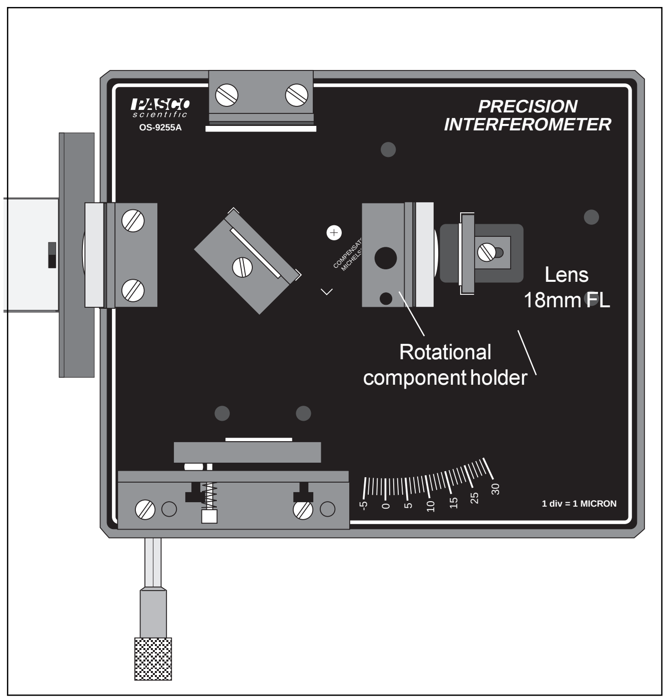


Figure 7. Twyman-Green Mode Setup

Fabry-Perot Mode

1. Align the laser and interferometer base as described in *Laser Alignment* at the beginning of this section. The laser beam should be approximately parallel with the top of the base, should strike the center of the movable mirror, and should be reflected directly back into the laser aperture.
2. Mount the adjustable mirror where indicated on the interferometer base and one component holder in front of the movable mirror. See Figure 8.
3. Place the other component holder behind the movable mirror and attach the viewing screen to its magnetic backing. You should see several images of the laser beam on the viewing screen.
4. Using the thumbscrews, adjust the tilt of the adjustable mirror until there is only one bright dot on the screen.
5. Now mount the 18 mm FL lens on the front component holder. A clear sharp interference pattern should be visible on the viewing screen. If you use light with two component wavelengths, instead of a laser, two sets of fringes can be distinguished on the viewing screen.

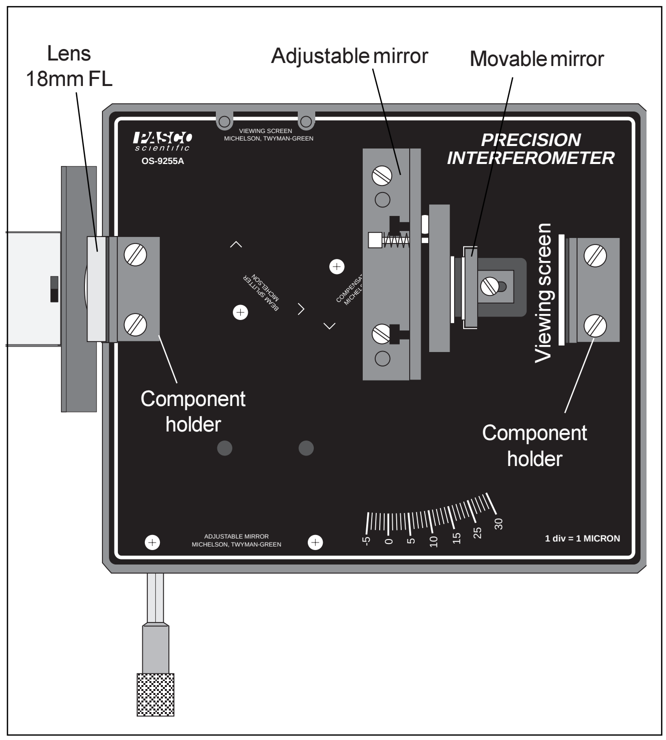


Figure 8. Fabry-Perot Mode Setup

Tips on Using the Interferometer

Accurate Fringe-Counting

The following techniques can help you make accurate measurements.

1. It's not necessary that your interference pattern be perfectly symmetrical or sharp. As long as you can clearly distinguish the maxima and minima, you can make accurate measurements.

2. It's easy to lose track when counting fringes. The following technique can help.

   Center the interference pattern on the viewing screen using the thumbscrews on the back of the fixed mirror. Select a reference line on the millimeter scale and line it up with the boundary between a maxima and a minima (see Figure 9). Move the micrometer dial until the boundary between the next maximum and minimum reaches the same position as the original boundary. (The fringe pattern should look the same as in the original position.) One fringe has gone by.

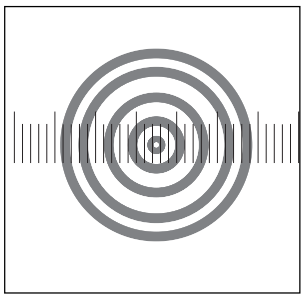


Figure 9. Counting Fringes

3. When turning the micrometer dial to count fringes, always turn it one complete revolution before you start counting, then continue turning it in the same direction while counting. This will almost entirely eliminate errors due to backlash in the micrometer movement.

   Backlash is a slight slippage that always occurs when you reverse the direction of motion in a mechanical instrument. (Turning the micrometer dial clockwise moves the movable mirror toward the right. Turning the dial counter-clockwise moves the mirror toward the left.) The PASCO micrometer is designed to minimize backlash. However, by using the technique described above, you can practically eliminate all effects of backlash in your measurements.

4. Always take several readings and average them for greater accuracy.

5. The slip ring at the base of the micrometer knob adjusts the tension in the dial. Before making a measurement, be sure the tension is adjusted to give you the best possible control over the mirror movement.

Calibrating the Micrometer

For even more accurate measurements of the mirror movement, you can use a laser to calibrate the micrometer. To do this, set up the interferometer in Michelson or Fabry-Perot mode. Turn the micrometer knob as you count off at least 20 fringes. Carefully note the change in the micrometer reading, and record this value as d'. The actual mirror movement, d, is equal to $N\lambda/2$, where λ is the known wavelength of the light (0.6328 µm for a standard helium-neon laser) and N is the number of fringes that were counted. In future measurements, multiply your micrometer readings by d/d' for a more accurate measurement.

➤ **NOTE:** You can also adjust the micrometer calibration mechanically. The process is not difficult, but for most accurate results, the above procedure is still recommended. See the *Maintenance* section at the end of the manual for the mechanical calibration procedure.

Demonstrations

The PASCO interferometer is not designed for large demonstrations. However, for small demonstrations, you can use the 48 mm focal length lens (included in the Interferometer Accessories) to magnify the fringe pattern and project it onto a wall or screen. It is helpful to have a powerful laser for large projections.

Using the Diffuser

It's sometimes more convenient to view the interference pattern through the diffuser rather than on the viewing screen. Just place the diffuser where you would normally place the viewing screen, and look through it toward the interferometer.

Sources of Experimental Error

Backlash— Although PASCO's carefully designed mirror movement reduces backlash considerably, every mechanical system is susceptible to backlash. However, the effects of backlash can be practically eliminated by using proper technique when counting fringes (see item 3 under Accurate Fringe-Counting, on the previous page).

Mirror Travel— The amount of mirror movement per dial turn of the micrometer is constant to within 1.5%. Most of this error occurs at the extreme ends of the mirror's total possible movement. For very accurate measurements, see *Calibrating the Micrometer*, above, and remember that the mirrors are flat to within 1/4 wavelength across their surface.

Troubleshooting

If you have trouble producing a clear set of interference fringes, consider the following possible sources of difficulty:

1. **Warm up your Laser—** Many lasers vary in intensity and/or polarization as they warm up. To eliminate any possible fringe or intensity variations, allow the laser to warm up prior to setting up an experiment. (The PASCO laser should warm up in about 1 hour.)
2. **Check your Mirrors—** The beam-splitter and movable mirror are carefully mounted in their brackets to remain perpendicular to the interferometer base when set up. If the brackets are bent slightly out of alignment, the resulting fringe patterns will be distorted somewhat. If they are significantly out of alignment, it may be impossible to obtain fringes.
3. **Background Fringes—** Reflections from the front and back surfaces of the mirrors and beam-splitter often cause minor interference patterns in the background of the main fringe pattern. These background patterns normally do not move when the mirror is moved, and have no impact on measurements made using the main interference pattern.
4. **Convection Currents—** If the fringe pattern appears to wave or vibrate, check for air currents. Even a slight breeze can effect the fringes.
5. **Vibration—** Under normal conditions, the interferometer base and mirror mounts are stable enough to provide a vibration free setup. However, if the experiment table is vibrating sufficiently, it will effect the interference pattern.

➤ **IMPORTANT:** If the movable mirror doesn't move when you turn the micrometer dial, see *Micrometer Spacer Replacement* in the *Maintenance* section at the end of this manual.

Component Specifications

Interferometer Mirrors— 3.175 cm in diameter; 0.635 ± 0.012 cm thick; flat to 1/4 wavelength on both sides; coated on one side for 80% reflectance and 20% transmission.

Beam-Splitter— 3.175 cm in diameter; 0.635 ± 0.012 cm thick; flat to 1/4 wavelength on both sides; coated on one side for 50% reflectance and 50% transmission.

Compensator— Identical to the beam-splitter, but uncoated.

Movable Mirror— movement is controlled by the micrometer that is built-into the interferometer base; turning the dial clockwise moves the mirror toward the right (looking from the micrometer side); 25 microns per micrometer dial revolution (±1% near center of movement); movement through full distance of travel is linear to within 1.5%.

➤ **IMPORTANT:** Avoid touching all mirror surfaces. Minute scratches and dirt can impair the clarity of interference images. See the *Maintenance* section at the end of this manual for cleaning instructions.

Experiment 1: Introduction to Interferometry

EQUIPMENT NEEDED:

– Basic Interferometer (OS-9255A)
– Laser (OS-9171)
– Laser Alignment Bench (OS-9172)
– Interferometer Accessories (OS-9256A)
Component Holder, (2) Calibrated Polarizers

Introduction

In general, an interferometer can be used in two ways. If the characteristics of the light source are accurately known (wavelength, polarization, intensity), changes in the beam path can be introduced and the effects on the interference pattern can be analyzed. Experiments 2 and 3 are examples of this procedure. On the other hand, by introducing specific changes in the beam path, information can be obtained about the light source that is being used.

In this experiment, you'll use the interferometer to measure the wavelength of your light source. If you have a pair of polarizers, you can also investigate the polarization of your source.

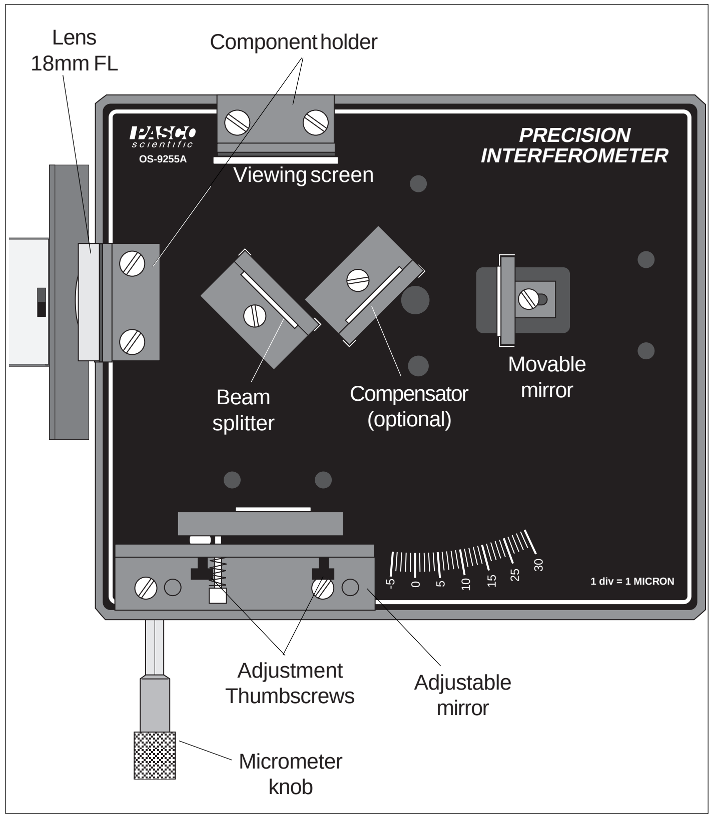


Figure 1.1. Michelson Mode Setup

Procedure

Part I: Wavelength

1. Align the laser and interferometer in the Michelson mode, so an interference pattern is clearly visible on your viewing screen. See *Setup and Operation* for instructions.
2. Adjust the micrometer knob to a medium reading (approximately 50 µm). In this position, the relationship between the micrometer reading and the mirror movement is most nearly linear.
3. Turn the micrometer knob one full turn counterclockwise. Continue turning counterclockwise until the zero on the knob is aligned with the index mark. Record the micrometer reading.

> ➤ **NOTE:** When you reverse the direction in which you turn the micrometer knob, there is a small amount of give before the mirror begins to move. This is called mechanical backlash, and is present in all mechanical systems involving reversals in direction of movement. By beginning with a full counterclockwise turn, and then turning only counterclockwise when counting fringes, you can eliminate errors due to backlash.

4. Adjust the position of the viewing screen so that one of the marks on the millimeter scale is aligned with one of the fringes in your interference pattern. You will find it easier to count the fringes if the reference mark is one or two fringes out from the center of the pattern.
5. Rotate the micrometer knob slowly counterclockwise. Count the fringes as they pass your reference mark. Continue until some predetermined number of fringes have passed your mark (count *at least* 20 fringes). As you finish your count, the fringes should be in the same position with respect to your reference mark as they were when you started to count. Record the final reading of the micrometer dial.

6. Record $\mathbf{d_m}$, the distance that the movable mirror moved toward the beam-splitter according to your readings of the micrometer knob. Remember, each small division on the micrometer knob corresponds to one µm (10^{-6} meters) of mirror movement.
7. Record **N,** the number of fringe transitions that you counted.
8. Repeat steps 3 through 7 several times, recording your results each time.
9. Go on to part two. If you have time afterward, try setting up the interferometer in Fabry-Perot mode and repeating steps 3 through 8.

Part II : Polarization (using the Calibrated Polarizer, part of OS-9256A Interferometer Accessories)

1. Place a polarizer between the laser and the beam-splitter. Try several polarization angles. How does this effect the brightness and clarity of the fringe pattern?
2. Remove that polarizer and place a polarizer in front of the fixed or movable mirror. Try several polarization angles. How does this effect the fringe pattern?
3. Now try two polarizers, one in front of the fixed mirror, and one in front of the movable mirror. First rotate one polarizer, then the other. Again, note the effects.

Analysis

Part I

1. For each trial, calculate the wavelength of the light ($\lambda = 2\mathbf{d_m}/\mathbf{N}$), then average your results. If you tried the Fabry-Perot mode also, calculate the wavelength independently for that data. The same formula applies.

Part II

1. From your observations in step 1 of the procedure, can you determine the polarization characteristics of your light source? Does it vary with time?
2. Do your observations from step 2 give you any more information about the polarization of your source?
3. From your observations in step 3, do cross-polarized beams interfere?

Questions

1. In the calculation to determine the value of λ based on the micrometer movement, why was $\mathbf{d_m}$ multiplied by two?
2. Why move the mirror through many fringe transitions instead of just one? Why take several measurements and average the results?
3. If you tried the Fabry-Perot mode, was your measured λ the same? If not, can you speculate about possible reasons for the difference? Do you have more confidence in one value as opposed to the other?
4. If the wavelength of your light source is accurately known, compare your results with the known value. If there is a difference, to what do you attribute it?
5. When measuring mirror movement using the micrometer dial on the interferometer, what factors limit the accuracy of your measurement?
6. When measuring mirror movement by counting fringes using a light source of known wavelength, what factors might limit the accuracy of your measurement?
7. What role does polarization play in producing an interference pattern?

Experiment 2: The Index of Refraction of Air

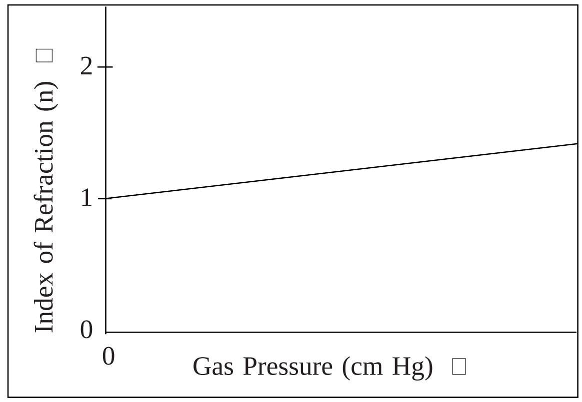


Figure 2.1. Index of Refraction versus Gas Pressure

EQUIPMENT NEEDED:

– Basic Interferometer (OS-9255A)
– Laser (OS-9171)
– Laser Alignment Bench (OS-9172)
– Interferometer Accessories (OS-9256A)
  Rotational pointer, Vacuum cell, Vacuum pump

Introduction

In the Michelson interferometer, the characteristics of the fringe pattern depend on the phase relationships between the two interfering beams. There are two ways to change the phase relationships. One way is to change the distance traveled by one or both beams (by moving the movable mirror, for example). Another way is to change the medium through which one or both of the beams pass. Either method will influence the interference pattern. In this experiment you will use the second method to measure the index of refraction for air.

For light of a specific frequency, the wavelength λ varies according to the formula:

$$\lambda = \lambda_o/\mathbf{n};$$

where λ_o is the wavelength of the light in a vacuum, and n is the index of refraction for the material in which the light is propagating. For reasonably low pressures, the index of refraction for a gas varies linearly with the gas pressure. Of course for a vacuum, where the pressure is zero, the index of refraction is exactly 1. A graph of index of refraction versus pressure for a gas is shown in Figure 2.1. By experimentally determining the slope, the index of refraction of air can be determined at various pressures.

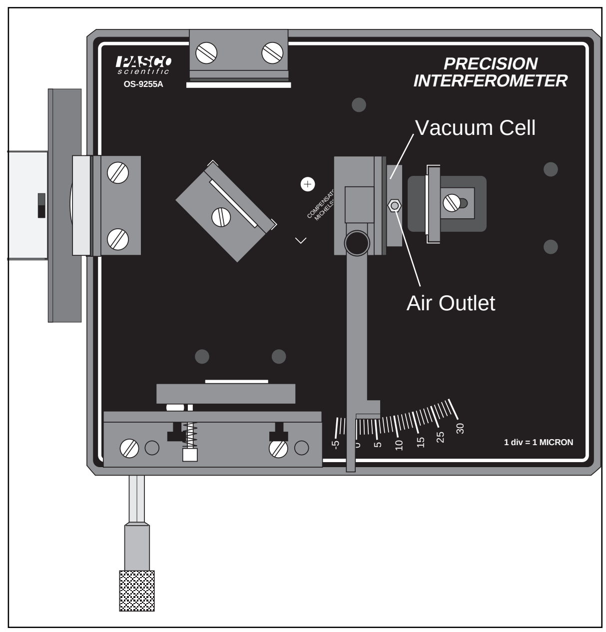


Figure 2.2. Equipment Setup

Procedure

1. Align the laser and interferometer in the Michelson mode. See *Setup and Operation*.
2. Place the rotational pointer between the movable mirror and the beam-splitter (see Figure 2.2). Attach the vacuum cell to its magnetic backing and push the air hose of the vacuum pump over the air outlet hole of the cell. Adjust the alignment of the fixed mirror as needed so the center of the interference pattern is clearly visible on the viewing screen. (The fringe pattern will be somewhat distorted by irregularities in the glass end-plates of the vacuum cell. This is not a problem.)
3. For accurate measurements, the end-plates of the vacuum cell must be perpendicular to the laser beam. Rotate the cell and observe the fringes. Based on your observations, how can you be sure that the vacuum cell is properly aligned?

4. Be sure that the air in the vacuum cell is at atmospheric pressure. If you are using the OS-8502 Hand-Held Vacuum Pump, this is accomplished by flipping the vacuum release toggle switch.

5. Record $\mathbf{P_i}$, the initial reading on the vacuum pump gauge. Slowly pump out the air in the vacuum cell. As you do this, count **N**, the number of fringe transitions that occur. When you're done, record **N** and also $\mathbf{P_f}$, the final reading on the vacuum gauge. (Some people prefer to begin with the vacuum cell evacuated, then count fringes as they let the air slowly out. Use whichever method is easier for you.)

➤ **NOTE:** Most vacuum gauges measure pressure with respect to atmospheric pressure (i.e., 34 cm Hg means that the pressure is 34 cm Hg below atmospheric pressure, which is ~ 76 cm Hg). The actual pressure inside the cell is:

$$\mathbf{P}_{\text{absolute}} = \mathbf{P}_{\text{atmospheric}} - \mathbf{P}_{\text{gauge}}$$

Analyzing Your Data

As the laser beam passes back and forth between the beam-splitter and the movable mirror, it passes twice through the vacuum cell. Outside the cell the optical path lengths of the two interferometer beams do not change throughout the experiment. Inside the cell, however, the wavelength of the light gets longer as the pressure is reduced.

Suppose that originally the cell length, **d**, was 10 wavelengths long (of course, it's much longer). As you pump out the cell, the wavelength increases until, at some point, the cell is only 9-1/2 wavelengths long. Since the laser beam passes twice through the cell, the light now goes through one less oscillation within the cell. This has the same effect on the interference pattern as when the movable mirror is moved toward the beam-splitter by 1/2 wavelength. A single fringe transition will have occurred.

Originally there are $\mathbf{N_i} = 2\mathbf{d}/\lambda_i$ wavelengths of light within the cell (counting both passes of the laser beam). At the final pressure there are $\mathbf{N_f} = 2\mathbf{d}/\lambda_f$ wavelengths within the cell. The difference between these values, $\mathbf{N_i} - \mathbf{N_f}$, is just **N**, the number of fringes you counted as you evacuated the cell. Therefore: $\mathbf{N} = 2\mathbf{d}/\lambda_i - 2\mathbf{d}/\lambda_f$.

However, $\lambda_i = \lambda_0/\mathbf{n_i}$ and $\lambda_f = \lambda_0/\mathbf{n_f}$; where $\mathbf{n_i}$ and $\mathbf{n_f}$ are the initial and final values for the index of refraction of the air inside the cell. Therefore $\mathbf{N} = 2\mathbf{d}(\mathbf{n_i} - \mathbf{n_f})/\lambda_0$; so that $\mathbf{n_i} - \mathbf{n_f} = \mathbf{N}\lambda_0/2\text{d}$. The slope of the n vs pressure graph is therefore:

$$\frac{n_i - n_f}{P_i - P_f} = \frac{N\lambda_0}{2d(P_i - P_f)}$$

where $\mathbf{P_i}$ = the initial air pressure; $\mathbf{P_f}$ = the final air pressure; $\mathbf{n_i}$ = the index of refraction of air at pressure $\mathbf{P_i}$; $\mathbf{n_f}$ = the index of refraction of air at pressure $\mathbf{P_f}$; **N** = the number of fringe transitions counted during evacuation; λ_0 = the wavelength of the laser light in vacuum (see your instructor);
d = the length of the vacuum cell (3.0 cm).

1. Calculate the slope of the n vs pressure graph for air.

2. On a separate piece of paper, draw the n vs pressure graph.

Questions

1. From your graph, what is $\mathbf{n_{atm}}$, the index of refraction for air at a pressure of 1 atmosphere (76 cm Hg).

2. In this experiment, a linear relationship between pressure and index of refraction was assumed. How might you test that assumption?

3. The index of refraction for a gas depends on temperature as well as pressure. Describe an experiment that would determine the temperature dependence of the index of refraction for air.

Experiment 3: The Index of Refraction of Glass

EQUIPMENT NEEDED:

– Basic Interferometer (OS-9255A)
– Laser (OS-9171)
– Laser Alignment Bench (OS-9172)
– Interferometer Accessories
 Rotating Table, Glass Plate

Introduction

In Experiment 2, the index of refraction of air was measured by slowly varying the density of air along a fixed length of one beam path in the Michelson Interferometer. That method obviously won't work with a solid substance, such as glass. Therefore, in order to measure the index of refraction of glass, it's necessary to slowly vary the length of glass through which the interferometer beam passes. This experiment introduces a technique for making such a measurement.

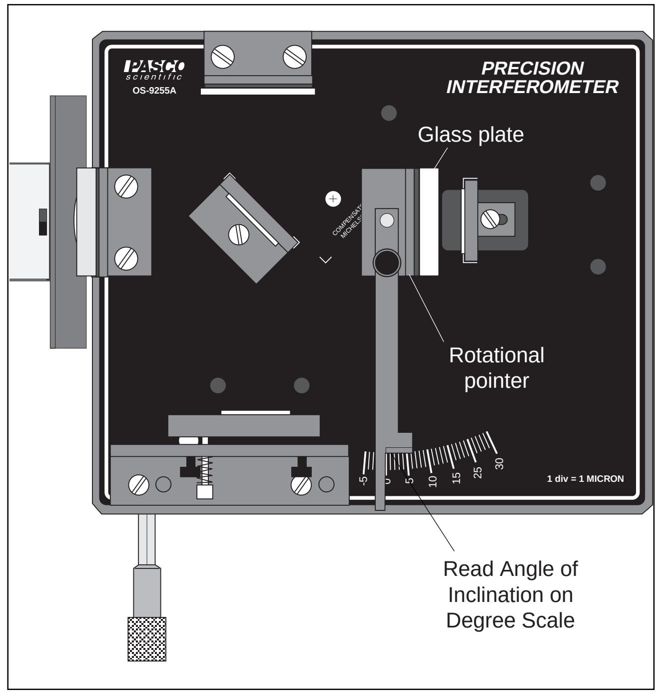


Figure 3.1. Equipment Setup

Procedure

1. Align the laser and interferometer in the Michelson mode. See *Setup and Operation*.
2. Place the rotating table between the beam-splitter and movable mirror, perpendicular to the optical path.

➤ **NOTE:** if the movable mirror is too far forward, the rotating table won't fit. You may need to loosen the thumbscrew and slide the mirror farther back.

3. Mount the glass plate on the magnetic backing of the rotational pointer.
4. Position the pointer so that its "0" edge on the Vernier scale is lined up with the zero on the degree scale on the interferometer base.
5. Remove the lens from in front of the laser. Hold the viewing screen between the glass plate and the movable mirror. If there is one bright dot and some secondary dots on the viewing screen, adjust the angle of the rotating table until there is one bright dot. Then realign the pointer scale. The plate should now be perpendicular to the optical path.
6. Replace the viewing screen and the lens and make any minor adjustments that are necessary to get a clear set of fringes on the viewing screen.
7. Slowly rotate the table by moving the lever arm. Count the number of fringe transitions that occur as you rotate the table from 0 degrees to an angle θ (at least 10 degrees).

Data Analysis

In principle, the method for calculating the index of refraction is relatively simple. The light passes through a greater length of glass as the plate is rotated. The general steps for measuring the index of refraction in such a case is as follows:

1. Determine the change in the path length of the light beam as the glass plate is rotated. Determine how much of the change in path length is through glass, $\mathbf{d_g}(\theta)$, and how much is through air, $\mathbf{d_a}(\theta)$.
2. Relate the change in path length to your measured fringe transitions with the following equation:

$$\frac{2n_a d_a(\theta) + 2n_g d_g(\theta)}{\lambda_0}$$

where $\mathbf{n_a}$ = the index of refraction of air (see Experiment 2), $\mathbf{n_g}$ = the index of refraction of the glass plate (as yet unknown), λ_0 = the wavelength of your light source in vacuum, and **N** = the number of fringe transitions that you counted.

Carrying out this analysis for the glass plate is rather complicated, so we'll leave you with the equation shown below for calculating the index of refraction based on your measurements. Nevertheless, we encourage you to attempt the analysis for yourself. It will greatly increase your understanding of the measurement and also of the complications inherent in the analysis.

$$\frac{(2t - N\lambda_0)(1 - \cos\theta)}{2t(1 - \cos\theta) - N\lambda_0}$$

where **t** = the thickness of the glass plate.

➤ **NOTE:** Our thanks to Prof. Ernest Henninger, DePauw University, for providing this equation from *Light Principles and Measurements,* by Monk, McGraw-Hill, 1937.

Suggestions for Additional Experiments

Twyman-Green—

Twyman-Green operation gives students a quick, qualitative look at how interferometry can be used to test optical components. See *Twyman-Green Mode* in the *Setup and Operation* section of the manual.

Any distortion of the circular fringe pattern is due to spherical aberration from the test lens. Turn the lens until it sits at various angles to the optical path and watch the fringe pattern change. Distortion here is due partially to astigmatism from the lens.

Spectral Light Fringes—

Although interferometry is easiest with a laser light source, measurements can be made successfully using any monochromatic source of sufficient brightness. However, if a laser is not used, it is generally not possible to project the interference fringes onto a screen. Instead, the fringes are viewed by looking into the beam-splitter (or into the movable mirror in Fabry-Perot mode).

If you use a spectral light source with spectral lines at several different frequencies, it may be necessary to use a filter that blocks all but one of the spectral wavelengths.

Michelson Mode:

> ➤ **NOTE:**
> One difficulty when using a non-laser light source in Michelson mode is that the coherence length of the light is far less with a non-laser source. Because of this, the compensator should be used. It mounts magnetically on the back of the beam-splitter (the side opposite the thumbscrew).
>
> It's also important that the optical paths of the two interfering beams should be nearly equal. To ensure that this is the case, set up the interferometer with a laser (if you have one) and adjust the movable mirror position until the fewest possible fringes appear on the screen. (Theoretically, when the beam paths are exactly equal, one big maximum should appear that occupies the whole screen. But this is usually not possible to achieve in practice due to optical imperfections.) Then remove the viewing screen and replace the laser with the spectral light source. If fringes aren't visible when looking into the beam-splitter, proceed as follows:

a. Tape two thin pieces of wire or thread to the surface of the diffuser to form cross-hairs.

b. Place the diffuser between the light source and the beam-splitter.

c. Adjust the angle of the beam-splitter so that, when looking into the beam-splitter, you can see two images of the cross-hairs.

d. Adjust the tilt of the fixed mirror until the cross-hairs are superimposed. You should be able to see the fringe pattern.

Fabry-Perot mode:

a. Tape two thin pieces of wire or thread to the surface of the diffuser to form cross-hairs.

b. Set up the equipment in Fabry-Perot mode, and place the diffuser between the light source and the fixed mirror.

c. Look into the movable mirror from behind. Adjust the tilt of the fixed mirror until the cross-hairs are superimposed. You should be able to see the fringe pattern.

White Light Fringes—

With careful alignment, the interferometer will produce fringes from multi-chromatic or even white light . The procedure is the same as for any non-laser source, as described above. However, since it is harder to get a visible interference pattern, it is strongly recommended that you first set up the interferometer using a laser. Then substitute your white light source.

Use a Photometer—

Use a photometer, such as PASCO Model OS-9152B, to scan the fringe patterns. You can compare the intensity distributions in the Michelson and Fabry-Perot modes. Or use it to more accurately determine polarization effects. Or just use it as an aid in counting fringes.

Heat Distribution in Air—

With the interferometer in Michelson mode, strike a match and bring it close to one of the optical paths. Note the distortions in the fringe pattern. For a more quantitative approach, you could construct an air tight cell, and heat the contents to observe the effects of heat on the index of refraction of air.

➤ **IMPORTANT**— The Vacuum Cell is not designed to be heated.

Index of Refraction for Gases—

Measure the indices of refraction for various gases. Caution: The PASCO Vacuum Chamber is NOT designed to hold positive pressures. You will need to provide your own gas chamber.

Fabry-Perot Spectroscopy—

The Fabry-Perot mode is customarily used as a high-resolution spectrometer. Very close spectral lines, as in magnetic splitting, can be resolved much more accurately than with any but the highest quality diffraction gratings.

Maintenance

Micrometer Calibration

The micrometer is calibrated before it is shipped. However, if recalibration becomes necessary, use the following procedure:

1. Turn the interferometer over, and remove the bottom cover.
2. Loosen the two screws shown in Figure A1. Slide the bearing surface toward the pivot to increase mirror movement per turn of the micrometer dial. Slide the bearing surface away from the pivot to decrease mirror movement per dial turn. Tighten the screws and replace the bottom cover.

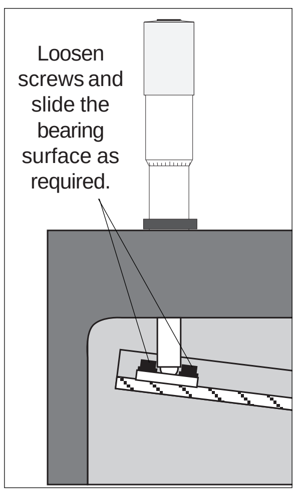


Figure A1. Calibration

Testing your calibration is most easily performed using a laser light source of known wavelength, as in Experiment 1.

Micrometer Spacer Replacement

In order to provide extremely fine, backlash-free control of the movable mirror, the mechanical linkage between the micrometer and the movable mirror is maintained under a state of spring-loaded compression. This compression also holds part of the linkage (a spacer) in place. Under normal use, the spacer will never fall out of position. However, a sudden jolt can jar the spacer and the spring loose. In this case, the micrometer will no longer work, and you'll hear the parts rolling around inside.

To replace the spacer:

1. Turn the interferometer over, and remove the bottom cover.
2. Position the spacer between the two ball bearings, as shown in Figure A2. Release the lever, and check that the spacer is snugly in place.
3. Replace the bottom panel.

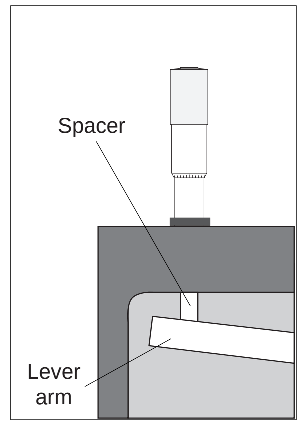


Figure A2. Spacer Replacement

Mirror Care

The mirror and beam-splitter surfaces are precision ground and coated. Dirt or scratches will distort the fringe pattern, so handle all optical surfaces with care. Clean the surfaces occasionally with lens tissue.

Vacuum Cell

Clean the glass windows on the vacuum chamber occasionally with lens tissue.

Storage

Rotate the Micrometer Knob fully IN before storing the Interferometer.

Replacement Parts

Component	Part No.
Interferometer Base	003-05137
Adjustable Mirror	003-03957
Beam-Splitter	003-03956
Movable Mirror	003-03955
Component Holder	003-05161
Compensator	003-03958
Interferometer Manual	012-05187
Vacuum Pump	OS-8502

Component	Part No.
Vacuum Cell	003-05162
Rotational Pointer	003-05160
Fitted Case	650-05178
Viewing Screen	003-05119
Diffuser	003-03941
Polarizer	003-04924
Glass Plate	003-04034
Lens, 18mm FL	003-03814
Lens, 48mm FL	003-03806

Teacher's Guide

Experiment 1: Introduction to Interferometry

Part I – General

	Dm	wavelength
Michelson	1.60×10^{-5}	640.0×10^{-9}
	1.60×10^{-5}	640.0×10^{-9}
	1.60×10^{-5}	640.0×10^{-9}
Fabry-Perot	1.60×10^{-5}	640.0×10^{-9}
	1.50×10^{-5}	600.0×10^{-9}
	1.55×10^{-5}	620.0×10^{-9}
	average:	$630.0 \times 10^{-9} \pm 16.7 \times 10^{-9}$
	actual:	632.8×10^{-9}
	% diff.	0.44%

Part II – General

1. The pattern became somewhat dimmer, due to absorbtion by the polarizer; but other than that, there was no variation when we polarized the light coming into the interferometer.
2. Adding a polarizer in front of the movable mirror had little effect. The contrast of the interference pattern reduced, and the pattern rotated when the polarizer was rotated.
3. There was no pattern unless the two polarizers were in the same orientation.

Reference to – Analysis (Part II)

1. The laser we used was unpolarized, and does not seem to change polarization with time.
2. No, there was no change. This would support our hypothesis that the laser used was unpolarized.
3. Cross-polarized beams do <u>not</u> interfere.

Answers to – Questions

1. The change in path length is twice the movement of the mirror.
2. Measuring only many fringes, many times, decreases the chance of random error affecting our results.
3. They were roughly the same. The Fabry-Perot measurement could instill more confidence, because the fringes are sharper and easier to count.
4. The difference is probably due to our uncertainty in measurement.
5. Limiting factors are play in the system and uncertainty in our micrometer position.
6. Losing count of fringes, and inexact positioning of the fringes relative to our reference mark.
7. In order to interfere, the two light beams must have the same polarization.

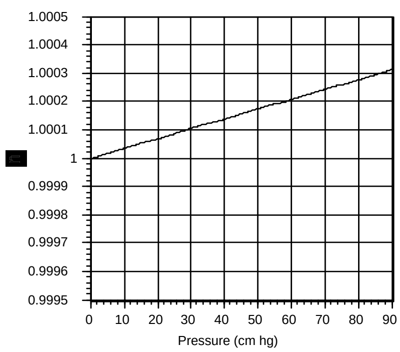
Experiment 2: The Index of Refraction of Air

Reference to – Procedure

1. The chamber will be properly aligned when the reflections off the front and back end-plates are aligned with each other and with the main interference pattern. (This alignment may actually cause a secondary interference pattern, but it will be very faint and will not affect your measurements.)

2. It seems easiest to apply the vacuum first, then count the fringes as the vacuum was released.

   The average slope, starting at a guage reading of 60, was 3.462×10^{-6}.



Answers to – Questions

1. Extrapolating from our slope and the known index of refraction of vacuum,

   $n_{atm} = 1.000263$.

2. Measure the index of refraction at various pressures, and see if it increases linearly. (It does.)

3. Answers will vary; but they should include some way of heating the air on one arm of the interferometer without heating the air on the other arm or the interferometer itself.

Experiment 3: The Index of Refraction of Glass

Reference to – Procedure

1. The glass plate must be absolutely perpendicular to the laser for accurate measurement of the index of refraction. When the plate is perpendicular, there will be a faint secondary fringe pattern (Fabry-Perot interference between the front and back surfaces of the plate) visible in the center of the view screen.
2. It is important to measure as large an angle as possible, and measure the angle as carefully as possible.

Reference to – Analysis

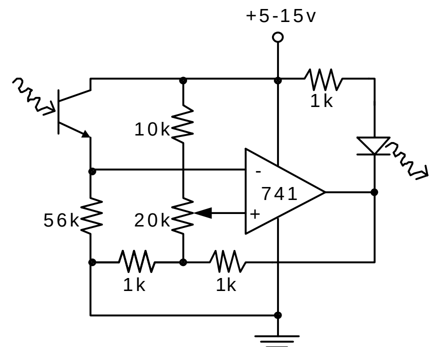
1. The actual equation, which is derived in *Optics of the Electromagnetic Spectrum,* by C.L. Andrews (Prentice-Hall, 1960) is

$$n_g = \frac{(2t - N\lambda_0)(1 - \cos\theta) + \left(\frac{N^2\lambda_0^{\ 2}}{4t}\right)}{2t(1 - \cos\theta) - N\lambda_0}$$

The second term is negligible for visible wavelengths, and may be ignored.

Notes – General

It is often difficult to count large numbers of fringes due to eyestrain. If you find this to be the case, you may want to make a circuit such as this:



The phototransistor should be mounted in a plate of sheet steel, which can then be held in the magnetic viewscreen holder. Mask the transistor with a piece of electrical tape with a pinhole at the center. Adjust the sensitivity of the circuit with the 20k potentiometer so that the flashes of the LED can be counted instead of the actual fringes.

This circuit may also be used in conjunction with the PASCO Series 6500 computer interface so that the fringes can be counted by computer, if desired.

Technical Support

Feedback

If you have any comments about the product or manual, please let us know. If you have any suggestions on alternate experiments or find a problem in the manual, please tell us. PASCO appreciates any customer feedback. Your input helps us evaluate and improve our product.

To Reach PASCO

For technical support, call us at 1-800-772-8700 (toll-free within the U.S.) or (916) 786-3800.

fax: (916) 786-3292

e-mail: techsupp@pasco.com

web: www.pasco.com

Contacting Technical Support

Before you call the PASCO Technical Support staff, it would be helpful to prepare the following information:

➤ If your problem is with the PASCO apparatus, note:

- Title and model number (usually listed on the label);
- Approximate age of apparatus;
- A detailed description of the problem/sequence of events (in case you can't call PASCO right away, you won't lose valuable data);
- If possible, have the apparatus within reach when calling to facilitate description of individual parts.

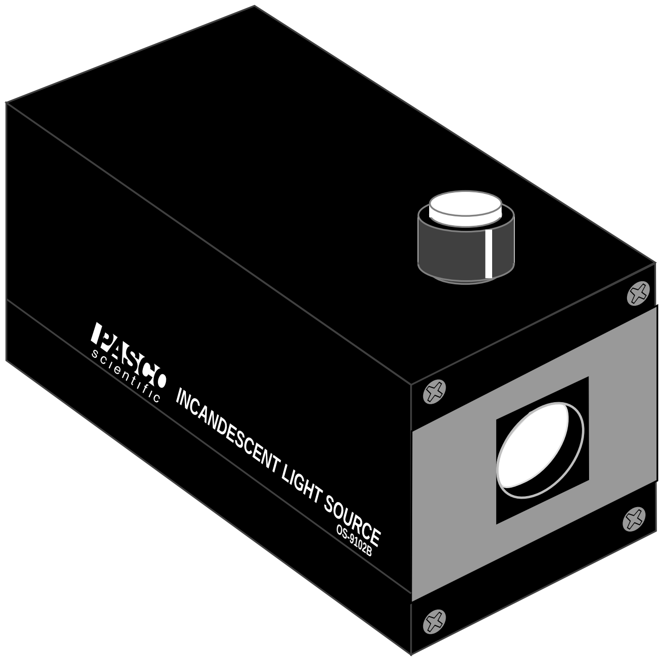
➤ If your problem relates to the instruction manual, note:

- Part number and revision (listed by month and year on the front cover);
- Have the manual at hand to discuss your questions.

012-05399A
12/93
$2.00

Instruction Manual for the PASCO scientific Model OS-9102B

INCANDESCENT LIGHT SOURCE



Introduction

With an output of approximately 15 candle power, this incandescent light source is bright and produces sufficient intensity in the visible spectrum for performance of such demanding experiments as Young’s coherence. Its regulated power supply ensures a well-regulated output to within 2% (for a 10% line voltage variation), which is necessary for accurate measurements of relative intensity. Filament position is adjustable and the power supply fuse is protected.

The light source mounts magnetically to the PASCO optical bench, and has a magnetic panel around the output aperture for attaching such accessories as lenses, slits and filters.

Operating Instructions

1. Place the light source on the optical bench with its steel pads on the bottom touching the magnetic strips on the bench, and its back edge pressed up against the alignment rail of the optical bench. To minimize bending of the optical bench, it is advisable to place the light source near one end of the bench.
2. Connect the light source to a grounded receptacle of the appropriate output voltage. The input requirements of your unit are listed on the product serial label.
3. When necessary, adjust the large knob on top of the light source to align the bulb filament along the optical axis of the optical bench. The bulb filament will move in the same direction that the knob is turned.
4. Mount filters, apertures, variable diaphragms etc. on the magnetic surface of the front panel.

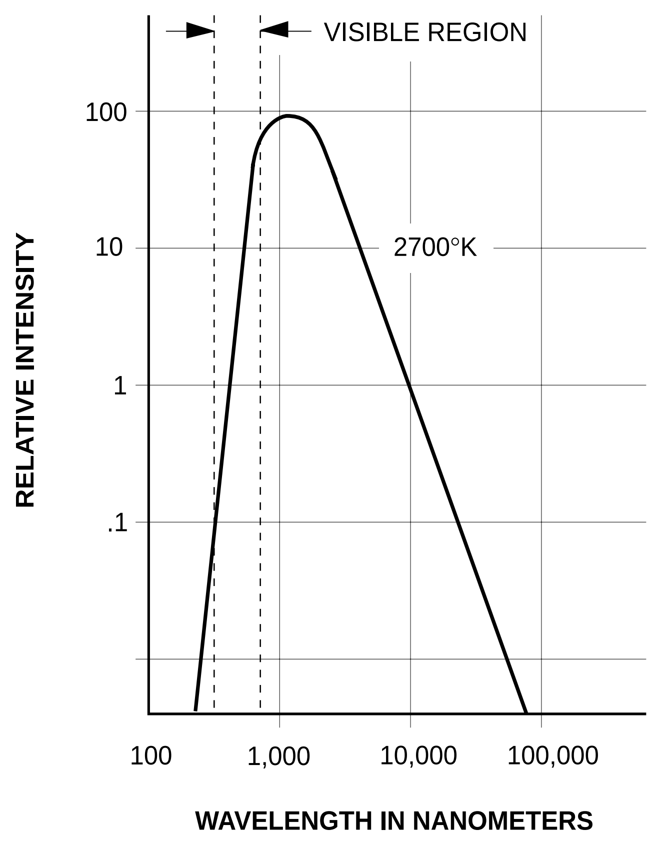


Figure 1 Spectral Output

10101 Foothills Blvd. • Roseville, CA 95747-7100
Phone (916) 786-3800 • FAX (916) 786-8905 • www.pasco.com

CAUTION

RISK OF ELECTRIC SHOCK
DO NOT OPEN

CAUTION:

TO PREVENT THE RISK OF ELECTRIC SHOCK, DO NOT REMOVE BACK COVER. NO USER-SERVICEABLE PARTS INSIDE. REFER SERVICING TO QUALIFIED SERVICE PERSONNEL.

The lightning flash with arrowhead, within an equilateral triangle, is intended to alert the user of the presence of uninsulated "dangerous voltage" within the product's enclosure that may be of sufficient magnitude to constitute a risk of electric shock to persons.

The exclamation point within an equilateral triangle is intended to alert the user of the presence of important operating and maintenance (servicing) instructions in the literature accompanying the appliance.

Troubleshooting

If the bulb fails to light: The most common cause for this situation is a burned-out bulb. Remove the bulb (Instructions are given in the next section.) and check to see if the filament is broken.

> **Note:** A filament may appear broken to the unaided eye. Therefore, it is recommended that in case of doubt, check filament continuity with an ohmmeter.

If the filament is in good condition, remove the fuse from the back panel and check if the fuse is blown. A defective fuse should be replaced only with a fuse of equal value.
Should the replacement fuse also blow, it is highly probable that a malfunction has developed in the power supply.

DO NOT ATTEMPT TO OPERATE THE LIGHT SOURCE WITH A HIGHER RATED FUSE!

If the product is under warranty, or repairs by PASCO scientific are desired please refer to the Equipment Return section in this manual. If you desire to perform repairs, necessary technical data is provided.

> **Caution**
>
> The lamp and power supply generate considerable heat, and after continuous operation the light source housing will become hot to the touch.
>
> It is recommended, therefore, that you turn on the light source only when setting up and for the duration of the experiment.

Replacement of bulbs

1. Turn light source switch to OFF and disconnect the power cord.
2. Remove the four screws from the front panel (the panel with the 22mm diameter hole in its center).

> **Caution:**
>
> 1. Removing the back panel will expose the operator to the components operating at 115VAC. Therefore, only experienced technicians should remove the panel.
>
> 2. Always disconnect the power cord from the input power source before removing the panel.

3. Gently push the bulb back against the socket, turn the bulb counter-clockwise, and remove the bulb. (The bulb has a standard “twist to lock” type bayonet socket.)
4. A new #93 bulb is inserted by reversing the operation in step 3.

> Note: When replacing the front panel, make certain that the bottom edge of the panel does not hang below the bottom surface (with the steel pads) of the light source. If the bottom edge does hang below, it will hinder the steel pads from making proper contact with the optical bench.

Replacement Parts

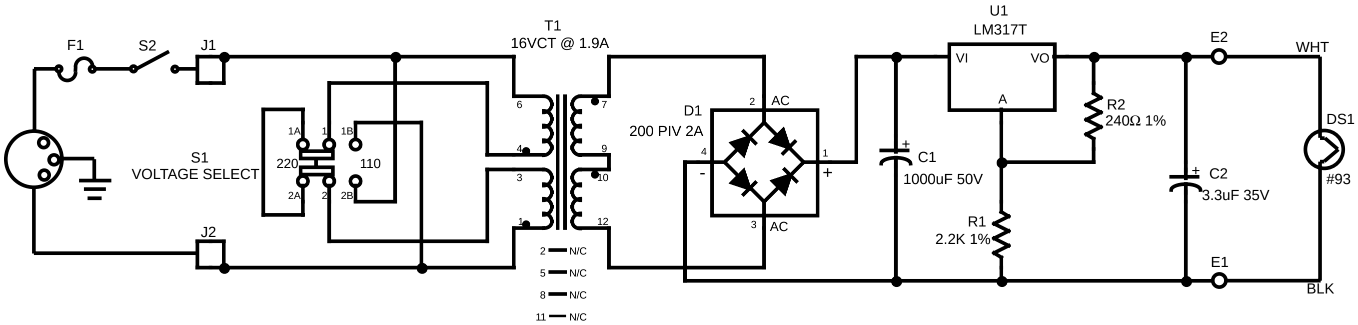
DS1

The preferred replacement is a #93 bulb available as PASCO Model OS-9177 (Package of five), or from most automotive stores.

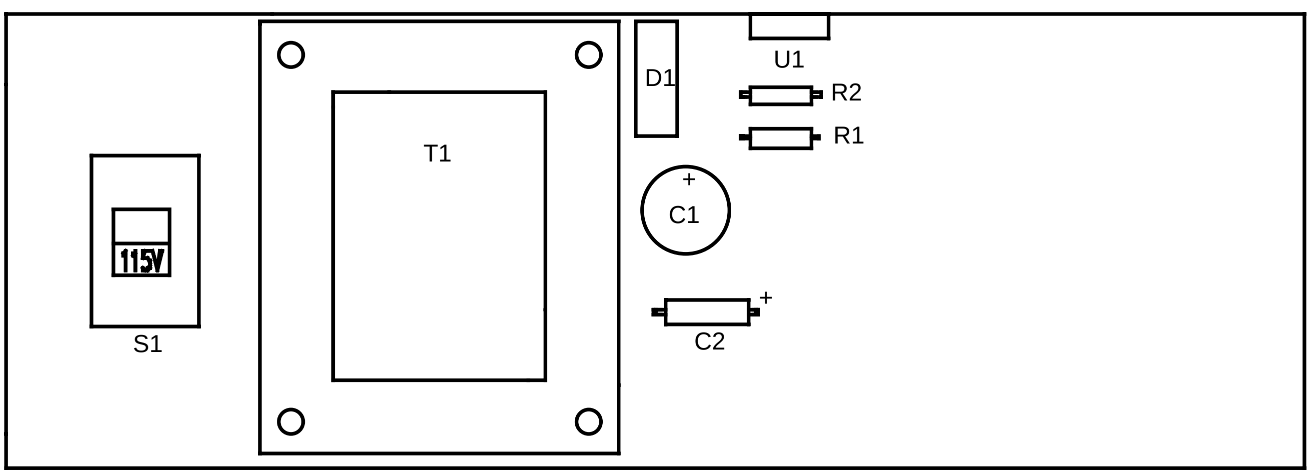
A #1003 bulb will also function adequately in the OS-9102A Light Source.

If neither of these bulbs can be obtained, any single contact, bayonet based bulb with an operating voltage of 12.8VDC and a current rating between .8 and 1.1A may be used. Bulbs with current ratings higher than 1.1A may damage the power supply.

	PASCO #	DESCRIPTION
U1:	430-085	IC-LM317T POSITIVE V REG
D1:	410-010	BRIDGE-BR82L 200PIV 2A
T1:	322-039	XFMR,POWER 115/230-16VCT 2A
C1:	222-023	CAP, ELECT-1000µF 50V RL
C2:	220-005	CAP, TANT-3.3µF, 35V, 10%
F1:	530-018	FUSE,5X20 250V 0.5A (115VAC)
	530-032	FUSE,5X20 250V 0.25A (230VAC)
S2:	511-025	SWITCH RSCA711-VB-B-9-V



SCHEMATIC OS-9102B



COMPONENT LAYOUT

Specifications

Output: Approximately 15 candle power
For spectral output see Figure 1.

Filament temperature: 2700°K

Bulb: #93 operated at 12VDC, 1A, lifespan approximately 700 hours

Regulation: Maximum light output change of 2% for a 10 % change of input voltage

Distance from filament to front panel light opening: approximately 22mm

Input: 90-110VAC, 60Hz or
100-125VAC, 60Hz,
200-250VAC, 50Hz,
220-270VAC, 50Hz.

Fuse: 5X20mm 0.5A, Slo-Blo (115VAC)
5X20mm 0.25A, Slo-Blo (230VAC)

Limited Warranty

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③ Make certain that the packing material cannot shift in the box or become compressed, allowing the instrument come in contact with the packing carton.

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012-01521D
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**Instruction Sheet
for the PASCO
Model OS-8020**

High Sensitivity Photometer

Introduction

The PASCO Model OS-8020 High Sensitivity Photometer measures relative intensities of incident light from approximately 0.1 - 1,000 lux. Its features include:

- Fiber-Optic Probe— The 70 cm long probe lets you measure intensity with 1 mm spatial resolution. You can, for example, scan a diffraction pattern for accurate intensity versus position measurements. (PASCO carries linear and angular translators than can be used to accurately position the probe.)
- Variable Sensitivity— Provides a full scale reading at any light intensity within the range of the instrument.
- Recorder Output—The recorder output is proportional to the measured light intensity. Use it to drive external meters, strip chart recorders, etc.

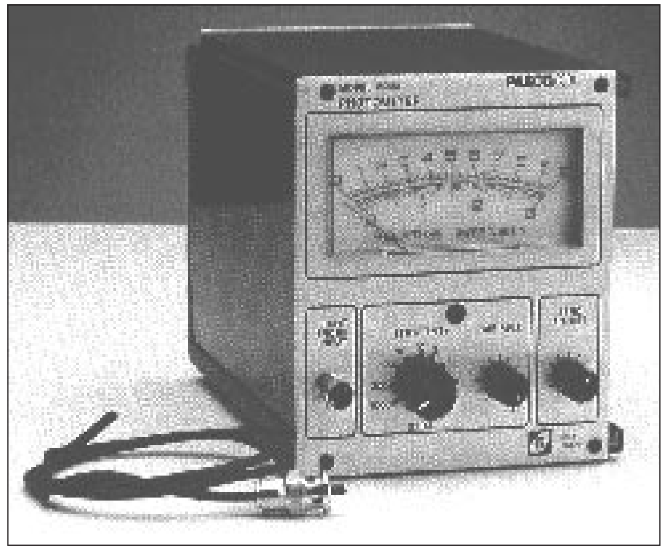
Additional Equipment Recommended:

The following items are available separately, or as components in a complete PASCO optics system. They are not required for using the photometer, but the Translators ensure accurate placement of the fiber optic probe. Both the Linear and the Angular Translator are designed to mount on the PASCO Optics Bench.

- Angular Translator, PASCO Model OS-9106
- Linear Translator, PASCO Model OS-9104
- Optics Bench, PASCO Model OS-9103

Setup Procedure

The photometer can be used with or without the fiber-optic probe. When used without the probe, the light must fall directly onto the Light Probe Input connector. When used with the probe, the intensity of the incident light can be sampled over very small areas (1 mm ^{2}), providing accurate measurements of intensity versus position. However, measurements without the probe are more sensitive, since the probe restricts the area and intensity of the incident light.



OS-8020 High Sensitivity Photometer with Fiber-Optic Probe

To use the probe, connect the probe to the Light Probe Input connector. Then position the free end of the probe so that the incident light falls directly onto its surface, normal to the plane of the tip.

➤ **IMPORTANT:** To prolong the life and efficiency of the fiber-optic probe:

① Do not bend the probe to a radius of less than 2 inches at any given point (do not coil tighter than a 4” circle).

② Do not bend the probe within three inches of either end.

③ Take care not to scratch or mar the tip of the probe. If the tip becomes scratched or dirty, clean it by light grinding with a fine grinding stone, or just cut off the tip with a razor blade (be sure that the cut is square).

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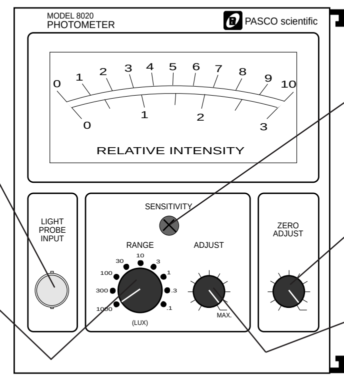
LIGHT PROBE INPUT— CONNECT THE FIBER-OPTIC PROBE OR, FOR GREATER SENSITIVITY, LET THE LIGHT SHINE DIRECTLY INTO THE CONNECTOR.

SENSITIVITY RANGE— SELECT THE LOWEST RANGE SUCH THAT YOUR REFERENCE INTENSITY (THE HIGHEST INTENSITY EXPECTED IN YOUR EXPERIMENT) CAUSES SLIGHTLY MORE THAN A FULL SCALE DEFLECTION.



MECHANICAL ZERO— WHEN ZEROING MECHANICALLY, POWER SHOULD BE OFF.

ZERO ADJUST, ELECTRONIC— WHEN ZEROING ELECTRONICALLY, COVER THE LIGHT PROBE INPUT CONNECTOR TIGHTLY.

SENSITIVITY ADJUST— AFTER SETTING THE SENSITIVITY RANGE, ADJUST SO THAT YOUR REFERENCE INTENSITY PRODUCES A FULL SCALE DEFLECTION.

Photometer Controls

Operation

① **Zero the Meter Mechanically:** Before plugging in the photometer, use a small screwdriver to adjust the Mechanical Zero screw (see illustration, above) so that the meter reads zero.

② **Connect the Power:** Plug the power cord into a standard 115 VAC, 60 Hz power outlet (or 220 VAC, 50 Hz if indicated on the back panel of the photometer).

③ **Zero the Meter Electronically:** Cover the Light Probe Input connector so that no light reaches the sensor. A good technique is to place a rubber cork tightly over the input connector. A finger over the connector will not shut out the light effectively enough.

With the input connector covered, set the Sensitivity Range switch to the most sensitive range (.1), and turn the Zero Adjust knob until the meter reads zero. The instrument is now zeroed on all ranges. Now turn the Sensitivity Range switch to the highest range (1000).

④ **Measuring Relative Intensities:** When using the photometer, intensity measurements are always made relative to some established reference value. If you are measuring the intensity of light after it passes through a polarizer, for example, first measure the intensity for a particular orientation of the polarizer (usually, but not necessarily, the orientation producing a maximum intensity of light). Then adjust the Sensitivity Range and Sensitivity Adjust so that the meter reads 10 (full scale). Now measure the intensity for different orientations of the polarizer. These subsequent measurements can be recorded as a percentage of the original measurement. For example, if the meter reads 6.5, record the intensity as 65% of the reference value.

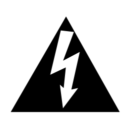
In general, to use the photometer to measure relative intensities:

- Arrange the photometer to measure your reference intensity, usually the maximum intensity of light that you expect to measure.
- Turn the Sensitivity Range switch clockwise to the lowest range for which the photometer reads beyond full scale.
- Turn the Sensitivity Adjust knob counterclockwise until the meter reads exactly 10 (full scale).
- Now—without touching the Sensitivity Adjust knob—arrange the photometer to measure the other intensities you wish to measure. Read the intensities as a percentage of the original measurement.

CAUTION

**RISK OF ELECTRIC SHOCK
DO NOT OPEN**

CAUTION:
TO PREVENT THE RISK OF ELECTRIC SHOCK, DO NOT REMOVE COVER ON UNIT. NO USER SERVICEABLE PARTS INSIDE. REFER SERVICING TO QUALIFIED SERVICE PERSONNEL.



The lightning flash with arrowhead, within an equilateral triangle, is intended to alert the user of the presence of uninsulated "dangerous voltage" within the product's enclosure that may be of sufficient magnitude to constitute a risk of electric shock to persons.

The exclamation point within an equilateral triangle is intended to alert the user of the presence of important operating and maintenance (servicing) instructions in the literature accompanying the appliance.

➢ **NOTES:**

- After measuring your reference intensity, you can still use the Sensitivity Range switch to change the range of the measurement. Just take into account the effect on the reading, as you would for any measuring instrument. For example, if the Sensitivity Range switch were set to 100 when the reference source was measured, and then switched to 30, you would use the 0 - 3 scale and read your value as 0 - 30%.
- The photometer reading is proportional to the energy of the light that falls on its photovoltaic cell, which is in turn proportional to the intensity of the incident light and to the area of the cell that is illuminated. Therefore, for accurate and consistent results, the incident light should fall directly onto the Light Probe Input connector or onto the end of the fiber-optic probe, with a zero degree angle of incidence.

⑤ **Output to a Recorder or External Meter:** A pair of banana plug terminals are located on the back panel of the photometer. These jacks provide a voltage that is proportional to the meter reading. The output for a full scale meter reading is between 140 mV and 10 V at up to 1 mA, depending on the range selection. The recorder output voltage is independent of the setting of the Sensitivity Adjust knob.

Absolute Intensity Measurements

The High Sensitivity Photometer is most effectively used for relative intensity measurements. However, accurate absolute measurements in units of lux can be made, subject to the following considerations.

- The selenium cell in the PASCO photometers does not have a corrected photopic response. The instrument is calibrated to a 2700°K tungsten filament lamp, such as is used in the OS-9102A Incandescent Light Source, and will indicate the correct intensity only for that source. If other light sources are used, absolute intensity measurements will be approximate only. Accurate relative intensity measurements can be made with any light source.
- Intensity readings are dependent on the total light energy striking the selenium cell, as well as on the spectrum of that light. Therefore, for accurate absolute measurements, the light must be incident on the full area of the selenium cell. This means that the light must fall with normal incidence directly into the Light Probe Input Connector. The light beam must be broad enough to cover the full area of the connector, and the intensity of the light must be uniform over the full area that strikes the connector.
- The fiber-optic probe restricts both the area and the intensity of the light that reaches the selenium cell. Therefore, when using the fiber-optic probe, only relative measurements can be accurately made.

Specifications

Sensitivity— approximately 0.1 to 1,000 Lux full scale in 1x and 3x ranges. Using the Sensitivity Adjust knob, any input within the dynamic range of the instrument can be used to provide a full scale reading. When photometer sensitivity is varied using the Range switch, measurements are proportional to the range setting, but only if the Sensitivity Adjust knob remains unmoved between measurements.

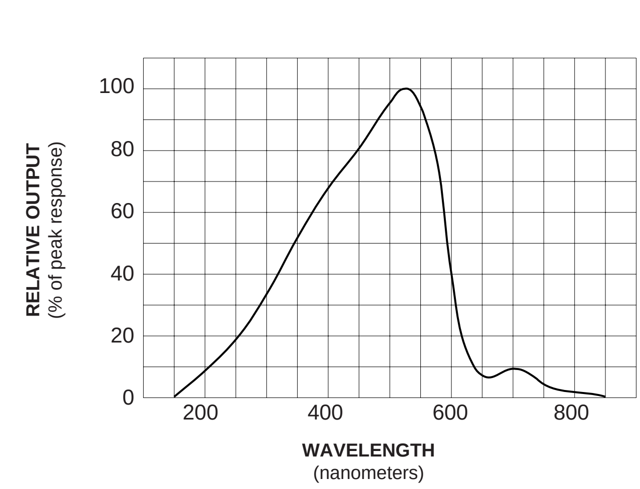
Meter— 8 cm scale length with 0 - 10 and 0 - 3 graduations.

Output— 140 mV at 1 mA. Banana jack connections on rear panel.

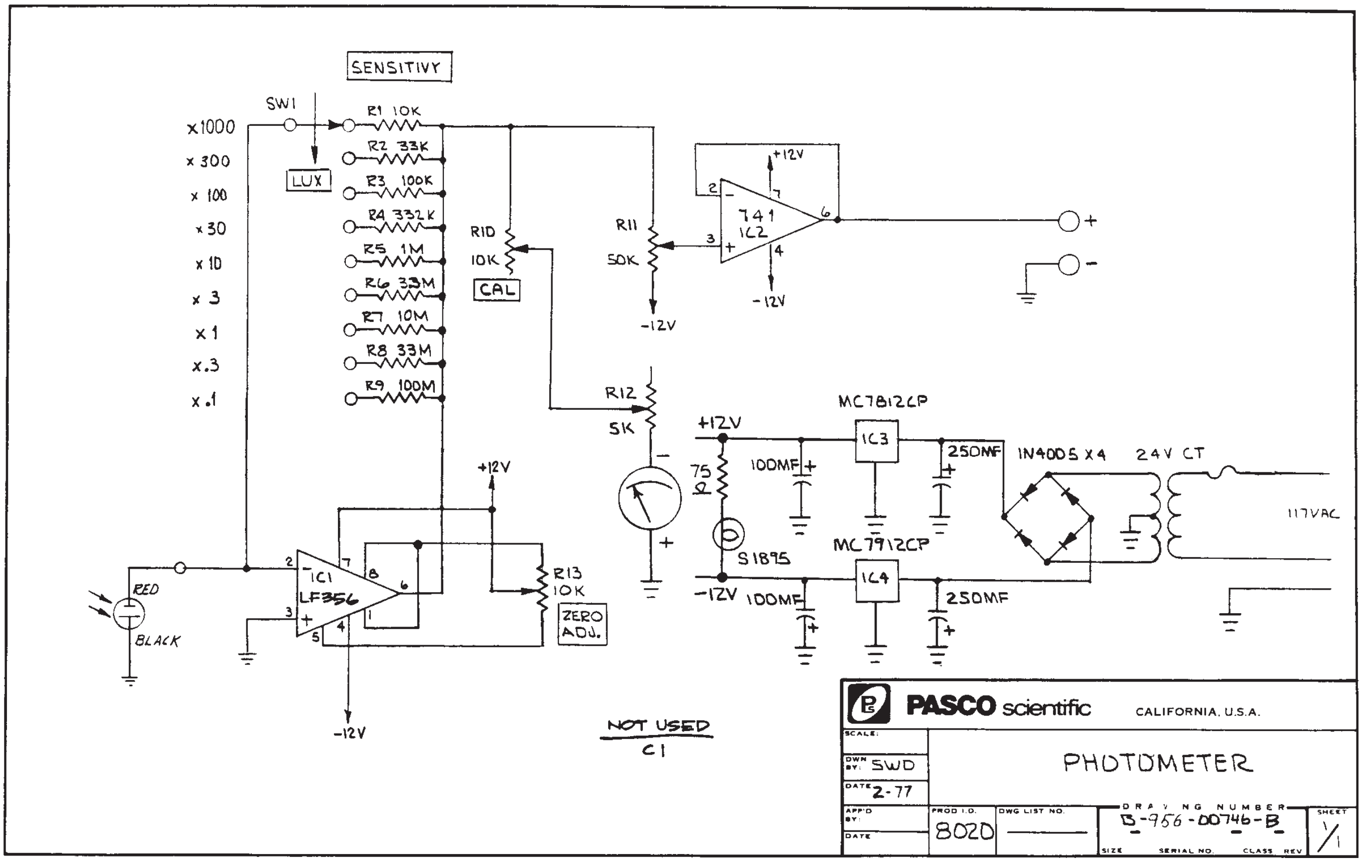
Spectral Response— Typical selenium cell response (see below).

Controls— Sensitivity Range, Sensitivity Adjust, Zero Adjust

Schematic— See the following page.



Spectral Response



SCHEMATIC
OS-8020 High Sensitivity Photometer
(Drawing # B-956-00746-B)

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Includes
Teacher's Notes
and
Typical
Experiment Results

Instruction Manual and Experiment Guide for the PASCO scientific Model TD-8553/8554A/8555

012-04695D

03/99

THERMAL RADIATION SYSTEM

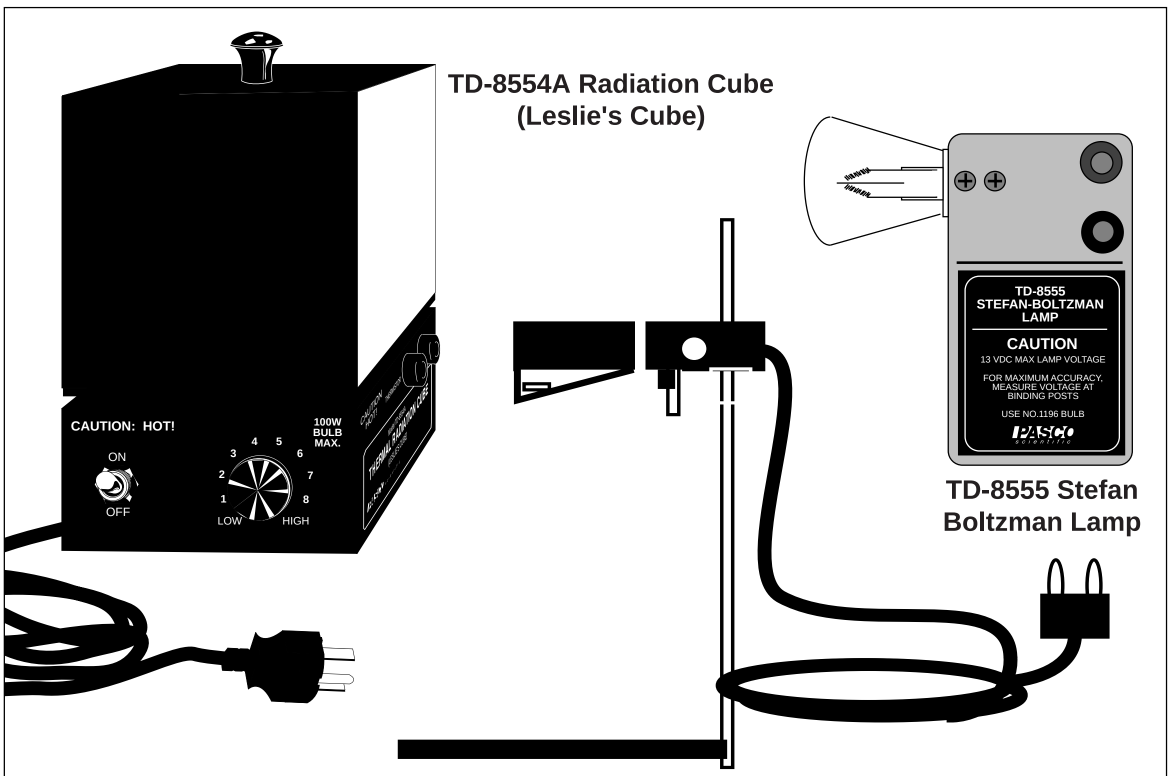

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Table of Contents

Copyright, Warranty, and Equipment Return

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Credits

This manual authored by: Bruce Lee

Teacher's guide written by: Eric Ayres

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Introduction

The PASCO Thermal Radiation System includes three items: the TD-8553 Radiation Sensor, the TD-8554A Radiation Cube (Leslie's Cube), and the TD-8555 Stefan-Boltzmann Lamp. This manual contains operating instructions for each of these items plus instructions and worksheets for the following four experiments:

① Introduction to Thermal Radiation,

② Inverse Square Law,

③ Stefan-Boltzmann Law* (at high temperatures),

④ Stefan-Boltzmann Law* (at low temperatures).

* The Stefan-Boltzmann law states that the radiant energy per unit area is proportional to the fourth power of the temperature of the radiating surface.

In addition to the equipment in the radiation system, several standard laboratory items, such as power supplies and meters are needed for most experiments. Check the experiment section of this manual for information on required equipment.

If you don't have all the items of the radiation system, read through the operating instructions for the equipment you do have, then check the experiment section to determine which of the experiments you can perform. (A radiation sensor is required for all the experiments.)

Radiation Sensor

The PASCO TD-8553 Radiation Sensor (Figure 1) measures the relative intensities of incident thermal radiation. The sensing element, a miniature thermopile, produces a voltage proportional to the intensity of the radiation. The spectral response of the thermopile is essentially flat in the infrared region (from 0.5 to 40 µm), and the voltages produced range from the microvolt range up to around 100 millivolts. (A good millivolt meter is sufficient for all the experiments described in this manual. See the current PASCO catalog for recommended meters.)

The Sensor can be hand held or mounted on its stand for more accurate positioning. A spring-clip shutter is opened and closed by sliding the shutter ring forward or back. During experiments, the shutter should be closed when measurements are not actively being taken. This helps reduce temperature shifts in the thermopile reference junction which can cause the sensor response to drift.

➤ **NOTE:** When opening and closing the shutter, it is possible you may inadvertently change the sensor position. Therefore, for experiments in which the sensor position is critical, such as Experiment 3, two small sheets of opaque insulating foam have been provided. Place this heat shield in front of the sensor when measurements are not actively being taken.

The two posts extending from the front end of the Sensor protect the thermopile and also provide a reference for positioning the sensor a repeatable distance from a radiation source.

Specifications

Temperature Range: -65 to 85 °C.
Maximum Incident Power: 0.1 Watts/cm^2.
Spectral Response: .6 to 30µm.
Signal Output: Linear from 10^{-6} to 10^{-1} Watts/cm^2.

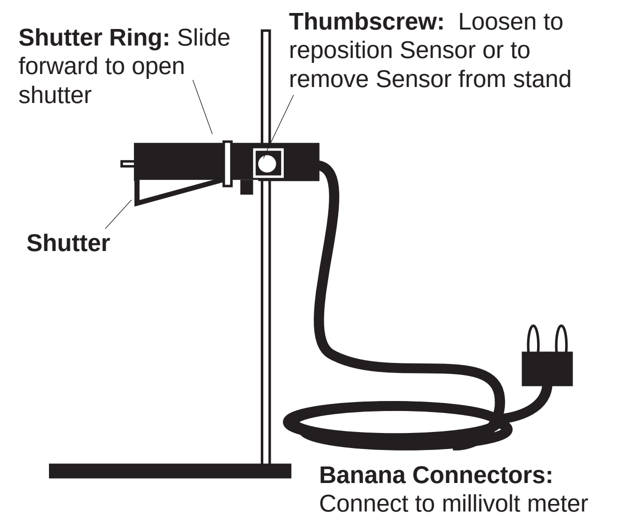


Figure 1 Radiation Sensor

Thermal Radiation Cube (Leslie's Cube)

The TD-8554A Radiation Cube (Figure 2) provides four different radiating surfaces that can be heated from room temperature to approximately 120 °C. The cube is heated by a 100 watt light bulb. Just plug in the power cord, flip the toggle switch to "ON", then turn the knob clockwise to vary the power.

Measure the cube temperature by plugging your ohmmeter into the banana plug connectors labeled THERMISTOR. The thermistor is embedded in one corner of the cube. Measure the resistance, then use Table 1, below, to translate the resistance reading into a temperature measurement. An abbreviated version of this table is printed on the base of the Radiation Cube.

➤ **NOTE:** For best results, a digital ohmmeter should be used. (See the current PASCO catalog for recommended meters.)

➤ **IMPORTANT:** When replacing the light bulb, use a 100-Watt bulb. Bulbs of higher power could damage the cube.

CAUTION: Cube may be HOT!

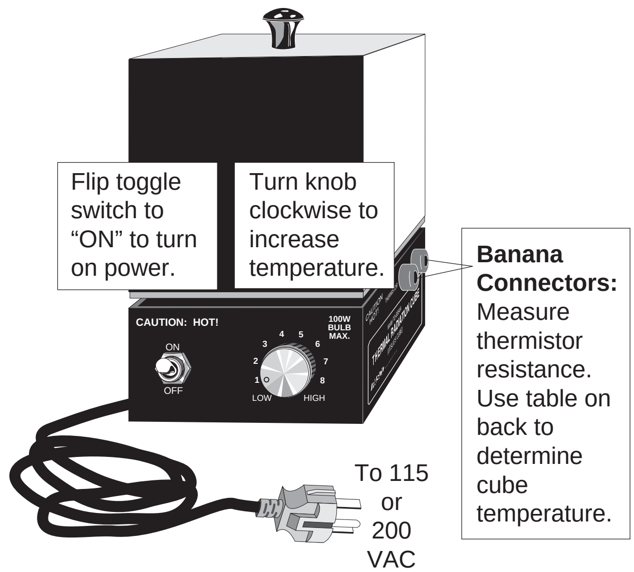


Figure 2 Radiation Cube (Leslie's Cube)

Table 1

Resistance versus Temperature for the Thermal Radiation Cube

Therm. Res. (Ω)	Temp. (°C)	Therm. Res. (Ω)	Temp. (°C)	Therm. Res. (Ω)	Temp. (°C)	Therm. Res. (Ω)	Temp. (°C)	Therm. Res. (Ω)	Temp. (°C)	Therm. Res. (Ω)	Temp. (°C)
207,850	10	66,356	34	24,415	58	10,110	82	4,615.1	106	2,281.0	130
197,560	11	63,480	35	23,483	59	9,767.2	83	4,475.0	107	2,218.3	131
187,840	12	60,743	36	22,590	60	9,437.7	84	4,339.7	108	2,157.6	132
178,650	13	58,138	37	21,736	61	9,120.8	85	4,209.1	109	2,098.7	133
169,950	14	55,658	38	20,919	62	8,816.0	86	4,082.9	110	2,041.7	134
161,730	15	53,297	39	20,136	63	8,522.7	87	3,961.1	111	1,986.4	135
153,950	16	51,048	40	19,386	64	8,240.6	88	3,843.4	112	1,932.8	136
146,580	17	48,905	41	18,668	65	7,969.1	89	3,729.7	113	1,880.9	137
139,610	18	46,863	42	17,980	66	7,707.7	90	3,619.8	114	1,830.5	138
133,000	19	44,917	43	17,321	67	7,456.2	91	3,513.6	115	1,781.7	139
126,740	20	43,062	44	16,689	68	7,214.0	92	3,411.0	116	1,734.3	140
120,810	21	41,292	45	16,083	69	6,980.6	93	3,311.8	117	1,688.4	141
115,190	22	39,605	46	15,502	70	6,755.9	94	3,215.8	118	1,643.9	142
109,850	23	37,995	47	14,945	71	6,539.4	95	3,123.0	119	1,600.6	143
104,800	24	36,458	48	14,410	72	6,330.8	96	3,033.3	120	1,558.7	144
100,000	25	34,991	49	13,897	73	6,129.8	97	2,946.5	121	1,518.0	145
95,447	26	33,591	50	13,405	74	5,936.1	98	2,862.5	122	1,478.6	146
91,126	27	32,253	51	12,932	75	5,749.3	99	2,781.3	123	1,440.2	147
87,022	28	30,976	52	12,479	76	5,569.3	100	2,702.7	124	1,403.0	148
83,124	29	29,756	53	12,043	77	5,395.6	101	2,626.6	125	1,366.9	149
79,422	30	28,590	54	11,625	78	5,228.1	102	2,553.0	126	1,331.9	150
75,903	31	27,475	55	11,223	79	5,066.6	103	2,481.7	127		
72,560	32	26,409	56	10,837	80	4,910.7	104	2,412.6	128		
69,380	33	25,390	57	10,467	81	4,760.3	105	2,345.8	129		

Stefan-Boltzmann Lamp

IMPORTANT: The voltage into the lamp should **NEVER exceed 13 V**. Higher voltages will burn out the filament.

The TD-8555 Stefan-Boltzmann Lamp (Figure 3) is a high temperature source of thermal radiation. The lamp can be used for high temperature investigations of the Stefan-Boltzmann Law. The high temperature simplifies the analysis because the fourth power of the ambient temperature is negligibly small compared to the fourth power of the high temperature of the lamp filament (see Experiments 3 and 4). When properly oriented, the filament also provides a good approximation to a point source of thermal radiation. It therefore works well for investigations into the inverse square law.

By adjusting the power into the lamp (13 Volts max, 2 A min, 3 A max), filament temperatures up to approximately 3,000 °C can be obtained. The filament temperature is determined by carefully measuring the voltage and current into the lamp. The voltage divided by the current gives the resistance of the filament.

Equipment Recommended

AC/DC LV Power Supply (SF-9584) or equivalent capable of 13 V @ 3 A max

$$T = \frac{R - R_{ref}}{\alpha R_{ref}} + T_{ref}$$

For small temperature changes, the temperature of the tungsten filament can be calculated using **a**, the temperature coefficient of resistivity for the filament:

where,
- T = Temperature
- R = Resistance at temperature T
- T_{ref} = Reference temperature (usually room temp.)
- R_{ref} = Resistance at temperature T_{ref}
- α = Temperature coefficient of resistivity for the filament ($\alpha = 4.5 \times 10^{-3}\ K^{-1}$ for tungsten)

For large temperature differences, however, **a** is not constant and the above equation is not accurate.

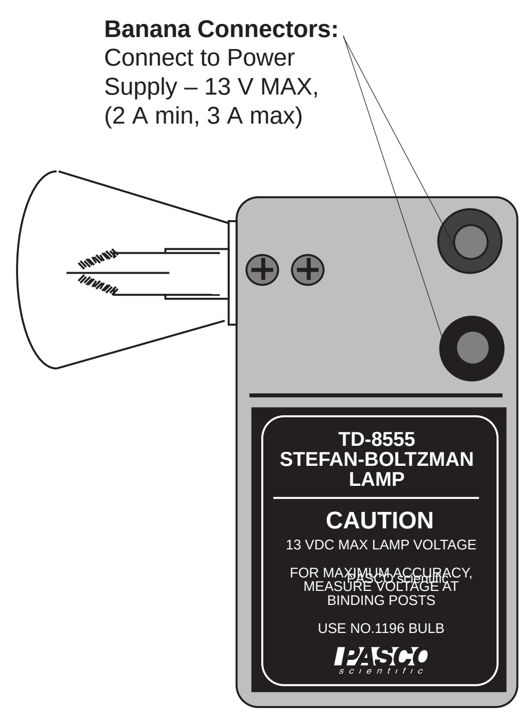


Figure 3 Stefan-Boltzmann Lamp

REPLACEMENT BULB: GE Lamp No. 1196, available at most auto parts stores.
➤ **NOTE:** When replacing the bulb, the leads should be soldered to minimize resistance.

For large temperature differences, therefore, determine the temperature of the tungsten filament as follows:

① Accurately measure the resistance (R_{ref}) of the tungsten filament at room temperature (about 300 °K). Accuracy is important here. A small error in R_{ref} will result in a large error in your result for the filament temperature.

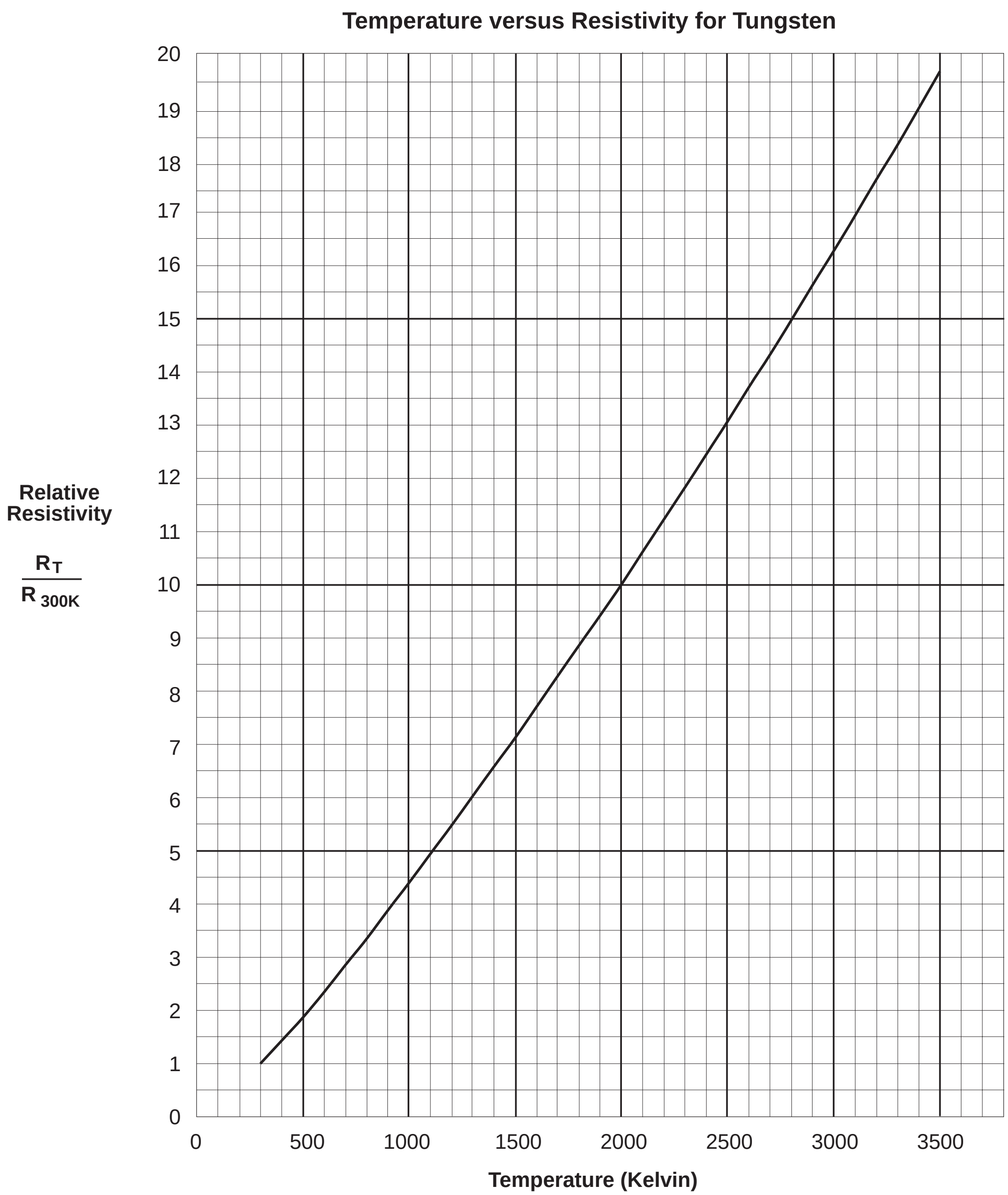
② When the filament is hot, measure the voltage and current into the filament and divide the voltage by the current to measure the resistance (R_T).

③ Divide R_T by R_{ref} to obtain the relative resistance (R_T/R_{ref}).

④ Using your measured value for the relative resistivity of the filament at temperature T, use Table 2 on the following page, or the associated graph, to determine the temperature of the filament.

Table 2 Temperature and Resistivity for Tungsten

R/R_{300K}	Temp °K	Resistivity μΩ cm	R/R_{300K}	Temp °K	Resistivity μΩ cm	R/R_{300K}	Temp °K	Resistivity μΩ cm	R/R_{300K}	Temp °K	Resistivity μΩ cm
1.0	300	5.65	5.48	1200	30.98	10.63	2100	60.06	16.29	3000	92.04
1.43	400	8.06	6.03	1300	34.08	11.24	2200	63.48	16.95	3100	95.76
1.87	500	10.56	6.58	1400	37.19	11.84	2300	66.91	17.62	3200	99.54
2.34	600	13.23	7.14	1500	40.36	12.46	2400	70.39	18.28	3300	103.3
2.85	700	16.09	7.71	1600	43.55	13.08	2500	73.91	18.97	3400	107.2
3.36	800	19.00	8.28	1700	46.78	13.72	2600	77.49	19.66	3500	111.1
3.88	900	21.94	8.86	1800	50.05	14.34	2700	81.04	26.35	3600	115.0
4.41	1000	24.93	9.44	1900	53.35	14.99	2800	84.70			
4.95	1100	27.94	10.03	2000	56.67	15.63	2900	88.33			



Experiment 1: Introduction to Thermal Radiation

EQUIPMENT NEEDED:

— Radiation Sensor, Thermal Radiation Cube
— Millivoltmeter
— Window glass
— Ohmmeter.

➤ **NOTES:**

① If lab time is short, it's helpful to preheat the cube at a setting of 5.0 for 20 minutes before the laboratory period begins. (A very quick method is to preheat the cube at full power for 45 minutes, then use a small fan to reduce the temperature quickly as you lower the power input. Just be sure that equilibrium is attained with the fan off.)

② Part 1 and 2 of this experiment can be performed simultaneously. Make the measurements in Part 2 while waiting for the Radiation Cube to reach thermal equilibrium at each of the settings in Part 1.

③ When using the Radiation Sensor, always shield it from the hot object except for the few seconds it takes to actually make the measurement. This prevents heating of the thermopile which will change the reference temperature and alter the reading.

Radiation Rates from Different Surfaces

Part 1

① Connect the Ohmmeter and Millivoltmeter as shown in Figure 1.1.

② Turn on the Thermal Radiation Cube and set the power switch to "HIGH". Keep an eye on the ohmmeter reading. When it gets down to about 40 kΩ, reset the power switch to 5.0. (If the cube is preheated, just set the switch to 5.0.)

③ When the cube reaches thermal equilibrium—the ohmmeter reading will fluctuate around a relatively fixed value—use the Radiation Sensor to measure the radiation emitted from each of the four surfaces of the cube. Place the Sensor so that the posts on its end are in contact with the cube surface (this ensures that the distance of the measurement is the same for all surfaces). Record your measurements in the appropriate table on the following page. Also measure and record the resistance of the thermistor. Use the table on the base of the cube to determine the corresponding temperature.

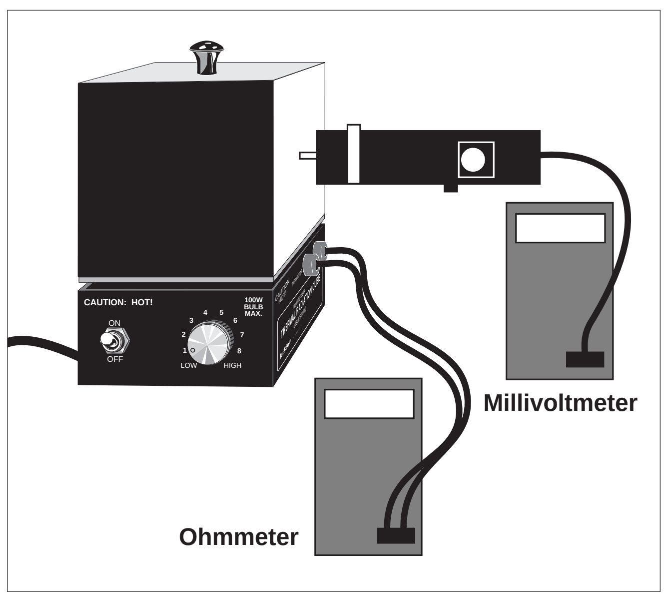


Figure 1.1 Equipment Setup

④ Increase the power switch setting, first to 6.5, then to 8.0, then to "HIGH". At each setting, wait for the cube to reach thermal equilibrium, then repeat the measurements of step 1 and record your results in the appropriate table.

Part 2

Use the Radiation Sensor to examine the relative magnitudes of the radiation emitted from various objects around the room. On a separate sheet of paper, make a table summarizing your observations. Make measurements that will help you to answer the questions listed below.

Absorption and Transmission of Thermal Radiation

① Place the Sensor approximately 5 cm from the black surface of the Radiation Cube and record the reading. Place a piece of window glass between the Sensor and the bulb. Does window glass effectively block thermal radiation?

② Remove the lid from the Radiation Cube (or use the Stefan-Boltzmann Lamp) and repeat the measurements of step 1, but using the bare bulb instead of the black surface. Repeat with other materials.

Radiation Rates from Different Surfaces

Data and Calculations

Power Setting 5.0

Therm. Res. ________ Ω
Temperature ________ °C

Surface	Sensor Reading (mV)
Black	
White	
Polished Aluminum	
Dull Aluminum	

Power Setting 6.5

Therm. Res. ________ Ω
Temperature ________ °C

Surface	Sensor Reading (mV)
Black	
White	
Polished Aluminum	
Dull Aluminum	

Power Setting 8.0

Therm. Res. ________ Ω
Temperature ________ °C

Surface	Sensor Reading (mV)
Black	
White	
Polished Aluminum	
Dull Aluminum	

Power Setting 10.0

Therm. Res. ________ Ω
Temperature ________ °C

Surface	Sensor Reading (mV)
Black	
White	
Polished Aluminum	
Dull Aluminum	

Questions (Part 1)

① List the surfaces of the Radiation Cube in order of the amount of radiation emitted. Is the order independent of temperature?

② It is a general rule that good absorbers of radiation are also good emitters. Are your measurements consistent with this rule? Explain.

Questions (Part 2)

① Do different objects, at approximately the same temperature, emit different amounts of radiation?

② Can you find materials in your room that block thermal radiation? Can you find materials that don't block thermal radiation? (For example, do your clothes effectively block the thermal radiation emitted from your body?)

Absorption and Transmission of Thermal Radiation

Questions

① What do your results suggest about the phenomenon of heat loss through windows?

② What do your results suggest about the Greenhouse Effect?

Notes

Experiment 2: Inverse Square Law

EQUIPMENT NEEDED:

— Radiation Sensor
— Stefan-Boltzmann Lamp, Millivoltmeter
— Power Supply (12 VDC; 3 A), meter stick.

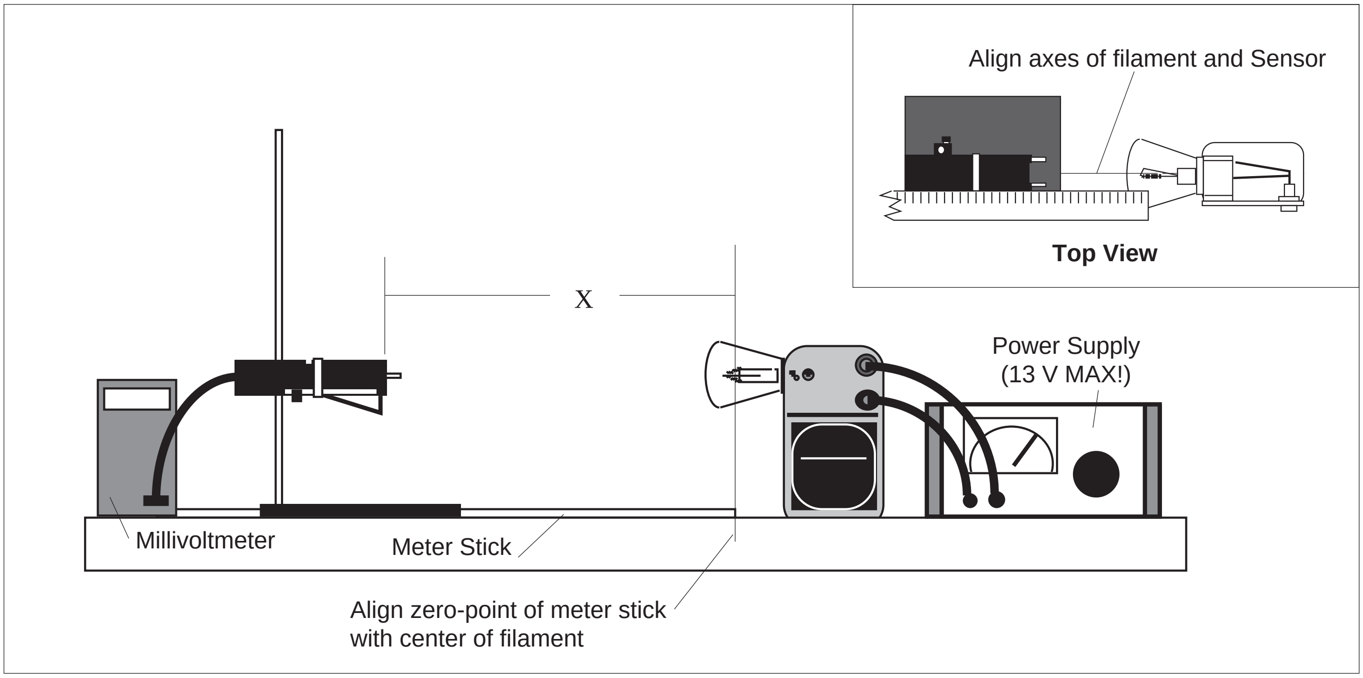


Figure 2.1 Equipment Setup

① Set up the equipment as shown in Figure 2.1.

a. Tape a meter stick to the table.

b. Place the Stefan-Boltzmann Lamp at one end of the meter stick as shown. The zero-point of the meter stick should align with the center of the lamp filament.

c. Adjust the height of the Radiation Sensor so it is at the same level as the filament of the Stefan-Boltzmann Lamp.

d. Align the lamp and sensor so that, as you slide the Sensor along the meter stick, the axis of the lamp aligns as closely as possible with the axis of the Sensor.

e. Connect the Sensor to the millivoltmeter and the lamp to the power supply as indicated in the figure.

② With the lamp OFF, slide the sensor along the meter stick. Record the reading of the millivolt-meter at 10 cm intervals. Record your values in Table 2.1 on the following page. Average these values to determine the ambient level of thermal radiation. You will need to subtract this average ambient value from your measurements with the lamp on, in order to determine the contribution from the lamp alone.

③ Turn on the power supply to illuminate the lamp. Set the voltage to approximately 10 V.

➤ **IMPORTANT:** Do not let the voltage to the lamp exceed 13 V.

④ Adjust the distance between the Sensor and the lamp to each of the settings listed in Table 2.2. At each setting, record the reading on the millivoltmeter.

➤ **IMPORTANT:** Make each reading quickly. Between readings, move the Sensor away from the lamp, or place the reflective heat shield between the lamp and the Sensor, so that the temperature of the Sensor stays relatively constant.

X (cm)	Ambient Radiation Level (mV)
10	
20	
30	
40	
50	
60	
70	
80	
90	
100	
Average Ambient Radiation Level =	

Table 2.1
Ambient Radiation Level

X (cm)	Rad (mV)	$1/X^2$ (cm^{-2})	Rad - Ambient (mV)
2.5			
3.0			
3.5			
4.0			
4.5			
5.0			
6.0			
7.0			
8.0			
9.0			
10.0			
12.0			
14.0			
16.0			
18.0			
20.0			
25.0			
30.0			
35.0			
40.0			
45.0			
50.0			
60.0			
70.0			
80.0			
90.0			
100.0			

Table 2.2
Radiation Level versus Distance

Calculations

① For each value of X, calculate $1/X^2$. Enter your results in Table 2.2.

② Subtract the Average Ambient Radiation Level from each of your Rad measurements in Table 2.2. Enter your results in the table.

③ On a separate sheet of paper, make a graph of Radiation Level versus Distance from Source, using columns one and four from Table 2.2. Let the radiation level be the dependent (y) axis.

④ If your graph from part 3 is not linear, make a graph of Radiation Level versus $1/X^2$, using columns three and four from table 2.2.

Questions

① Which of the two graphs is more linear? Is it linear over the entire range of measurements?

② The inverse square law states that the radiant energy per unit area emitted by a point source of radiation decreases as the square of the distance from the source to the point of detection. Does your data support this assertion?

③ Is the Stefan-Boltzmann Lamp truly a point source of radiation? If not, how might this affect your results? Do you see such an effect in the data you have taken?

Notes

Experiment 3: Stefan-Boltzmann Law (high temperature)

EQUIPMENT NEEDED:

— Radiation Sensor
— Ohmmeter
— Voltmeter (0-12 V)
— Ohmmeter
— Stefan-Boltzmann Lamp
— Ammeter (0-3 A)
— Millivoltmeter
— Thermometer.

Introduction

The Stefan-Boltzmann Law relates R, the power per unit area radiated by an object, to T, the absolute temperature of the object. The equation is:

$$R = \sigma T^4; \quad \left(\sigma = 5.6703 \quad x\ 10^{-8}\ \frac{W}{m^2 K^4}\right)$$

In this experiment, you will make relative measurements of the power per unit area emitted from a hot object, namely the Stefan-Boltzmann Lamp, at various temperatures. From your data you will be able to test whether the radiated power is really proportional to the fourth power of the temperature.

Most of the thermal energy emitted by the lamp comes from the filament of the lamp. The filament temperature can be determined using the procedure given on pages 3 and 4 of this manual.

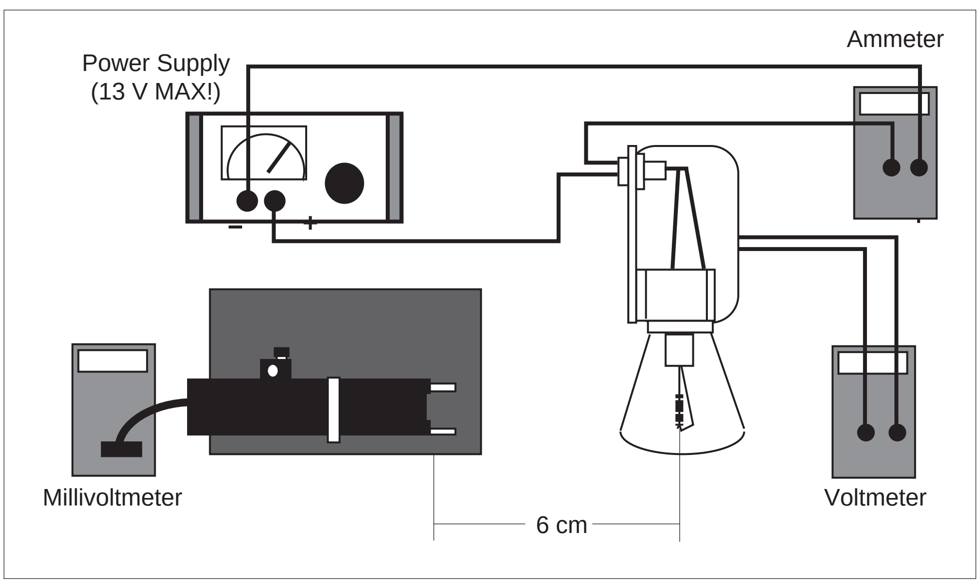


Figure 3.1 Equipment Setup

Procedure

➤ **IMPORTANT:** The voltage into the lamp should NEVER exceed 13 V. Higher voltages will burn out the filament.

① **BEFORE TURNING ON THE LAMP**, measure T_{ref}, the room temperature in degrees Kelvin, (K=°C + 273) and R_{ref}, the resistance of the filament of the Stefan-Boltzmann Lamp at room temperature. Enter your results in the spaces on the following page.

② Set up the equipment as shown in Figure 3.1. The voltmeter should be connected directly to the binding posts of the Stefan-Boltzmann Lamp. The Sensor should be at the same height as the filament, with the front face of the Sensor approximately 6 cm away from the filament. The entrance angle of the thermopile should include no close objects other than the lamp.

③ Turn on the power supply. Set the voltage, V, to each of the settings listed in Table 3.1 on the following page. At each voltage setting, record I, the ammeter reading, and Rad, the reading on the millivoltmeter.

➤ **IMPORTANT:** Make each Sensor reading quickly. Between readings, place both sheets of insulating foam between the lamp and the Sensor, with the silvered surface facing the lamp, so that the temperature of the Sensor stays relatively constant.

Data and Calculations

① Calculate R, the resistance of the filament at each of the voltage settings used (R = V/I). Enter your results in Table 3.1.

② Use the procedure on pages 3 and 4 of this manual to determine T, the temperature of the lamp filament at each voltage setting. Enter your results in the table.

③*Calculate T^4 for each value of T and enter your results in the table.

④*On a separate sheet of paper, construct a graph of Rad versus T^4. Use Rad as your dependent variable (y-axis).

*In place of calculations ① and , some may prefer to perform a power regression on Rad versus T to determine their relationship, or graph on log-log paper and find the slope.

Questions

① What is the relationship between Rad and T? Does this relationship hold over the entire range of measurements?

② The Stefan-Boltzmann Law is perfectly true only for ideal, black body radiation. A black body is any object that absorbs all the radiation that strikes it. Is the filament of the lamp a true black body?

③ What sources of thermal radiation, other than the lamp filament, might have influenced your measurements? What affect would you expect these sources to have on your results?

$\alpha = 4.5 \times 10^{-3}\ K^{-1}$

T_{ref} (room temperature) = _______ K (K = °C + 273)

R_{ref} (filament resistance at T_{ref}) = ________Ω

Table 3.1

Data			Calculations		
V (Volts)	I (Amps)	Rad (mV)	R (Ohms)	T (K)	T^4 (K^4)
1.00					
2.00					
3.00					
4.00					
5.00					
6.00					
7.00					
8.00					
9.00					
10.00					
11.00					
12.00					

Notes

Experiment 4: Stefan-Boltzmann Law (low temperature)

EQUIPMENT NEEDED:

— Radiation Sensor
— Millivoltmeter
— Thermal Radiation Cube
— Ohmmeter.

Introduction

In experiment 3, you investigated the Stefan-Boltzmann Law ($R_{rad} = sT^4$) for the high temperatures attained by an incandescent filament. At those high temperatures (approximately 1,000 to 3,000 K), the ambient temperature is small enough that it can be neglected in the analysis. In this experiment you will investigate the Stefan-Boltzmann relationship at much lower temperatures using the Thermal Radiation Cube. At these lower temperatures, the ambient temperature can not be ignored.

If the detector in the Radiation Sensor were operating at absolute zero temperature, it would produce a voltage directly proportional to the intensity of the radiation that strikes it. However, the detector is not at absolute zero temperature so it is also radiating thermal energy. According to the Stefan-Boltzmann law, it radiates at a rate, $R_{det} = sT_{det}^{4}$. The voltage produced by the sensor is proportional to the radiation striking the detector minus the radiation leaving it. Mathematically, the sensor voltage is proportional to $R_{net} = R_{rad} – R_{det} = s(T^4 - T_{det}^{4})$. As long as you are careful to shield the Radiation Sensor from the Radiation Cube when measurements are not being taken, T_{det} will be very close to room temperature (T_{rm}).

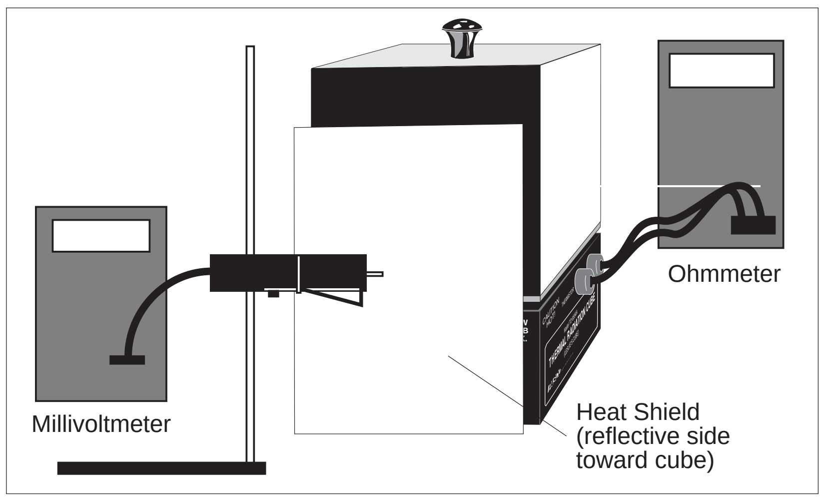


Figure 4.1 Equipment Setup

Procedure

① Set up the equipment as shown in Figure 4.1. The Radiation Sensor should be pointed directly at the center of one of the better radiating surfaces of the cube (the black or white surface). The face of the Sensor should be parallel with the surface of the cube and about 3 to 4 cm away.

② With the Thermal Radiation Cube off, measure R_{rm}, the resistance of the thermistor at room temperature. Enter this data in the space on the following page.

③ Shield the sensor from the cube using the reflecting heat shield, with the reflective side of the shield facing the cube.

④ Turn on the Radiation Cube and set the power switch to 10.

⑤ When the thermistor resistance indicates that the temperature is about 12 C° above room temperature, turn the power down so the temperature is changing slowly. Read and record R, the ohmmeter reading, and Rad, the millivoltmeter reading. The readings should be taken as nearly simultaneously as possible while briefly removing the heat shield. Record these values in Table 4.1.

➤ **IMPORTANT:** Make each reading quickly, removing the heat shield only as long as it takes to make the measurement. Take care that the position of the sensor with respect to the cube is the same for all measurements.

⑥ Replace the heat shield, and turn the cube power to 10. When the temperature has risen an additional 12-15 C°, repeat the measurements of step 5. Repeat this procedure at about 12-15° intervals until the maximum temperature of the cube is reached.

Data and Calculations

Room Temperature: R_{rm} = ________ Ω

T_{rm} = ____ °C = _____ K

Table 4.1

Data			Calculations		
R (ý)	Rad (mV)	T_c (°C)	T_k (K)	T_k^4 (K^4)	$T_k^4 - T_{rm}^4$ (K^4)

① Using the table on the base of the Thermal Radiation Cube, determine T_c, the temperature in degrees Centigrade corresponding to each of your thermistor resistance measurements. For each value of T_c, determine T_k, the corresponding value in degrees Kelvin (K = °C + 273). Enter both sets of values in Table 4.1, above. In the same manner, determine the room temperature, T_{rm}.

② CalculateT_k^4 for each value of T_k and record the values in the table.

③ Calculate $T_k^4 - T_{rm}^4$ for each value of T_k and record your results in the table.

④ On separate sheet of paper, construct a graph of Rad versus $T_k^4 - T_{rm}^4$. Use Rad as the dependent variable (y-axis).

Questions

① What does your graph indicate about the Stefan-Boltzmann law at low temperatures?

② Is your graph a straight line? Discuss any deviations that exist.

Teacher's Guide

Experiment 1: Introduction to Thermal Radiation

Notes on Questions

Part 1

① In order of decreasing emissivity, the surfaces are Black, White, Dull Aluminum, and Polished Aluminum. This order is independent of temperature; and within the temperature range tested, the ratio of emissions between sides is almost constant. The normalized percentages are as follows: (Black is defined as 100%)

Surface	Normalized Emissions	Standard Error
Black	100	
White	96.86	±1.21%
Dull	20.23	±2.17%
Polished	7.38	±1.82%

② Measurements are consistent with the rule. The better reflectors (poorer absorbers) are poor emitters.

Notes on Questions

Part 2

① Yes. All sides of the Leslie's Cube are at the same temperature, but the polished side emits less than 10% as much radiation as the black side.

② Materials that block thermal radiation well include aluminum foil, styrofoam, etc. Materials that do not block radiation as well include air, clothing, etc. All materials will block radiation to some degree, but there are strong differences in how much is blocked.

Notes on Questions

Absorbtion and Transmission of Thermal Radiation

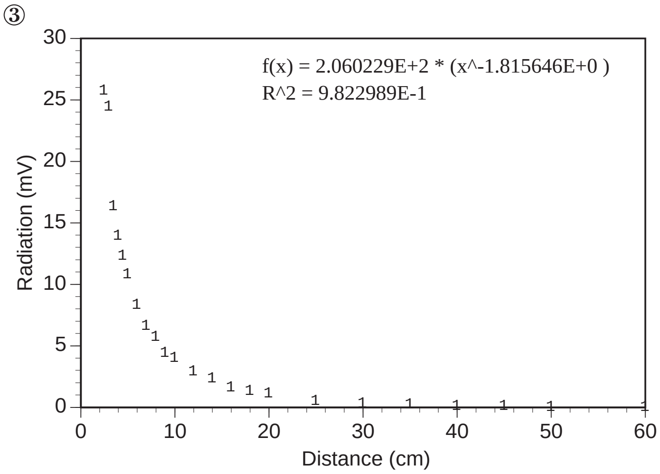
① Heat loss through (closed) windows is primarily conductive. Although the glass tested transmitted some infrared, most was blocked.

② A greenhouse allows light in, but does not allow much heat to escape. This phenomenon is used to grow tropical plants in cold climates.

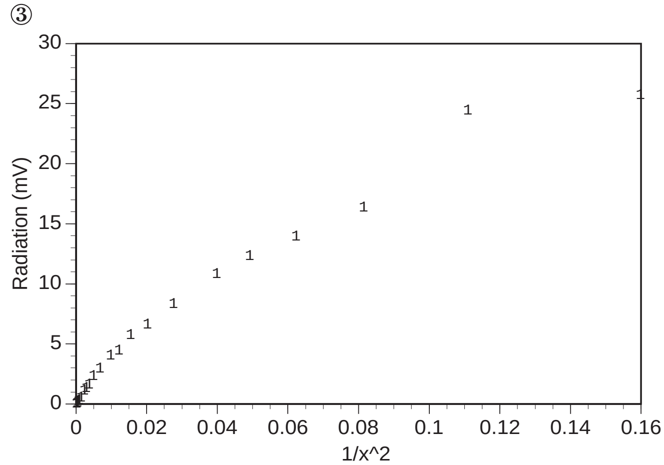
Experiment 2: Inverse Square Law

Calculations

③



③



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Notes on Questions

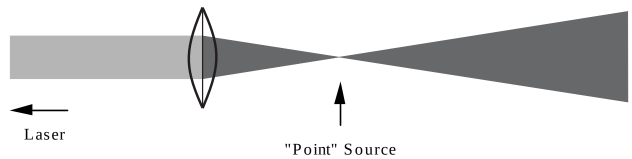
① The graph of Radiation versus $1/x^2$ is more linear, but not over the entire range. There is a distinct falloff in intensity at the nearer distances, due to the non-point characteristics of the lamp. (A graph of Radiation versus $1/x^2$ using only data points from 10cm or more is nearly linear.)

② If we use data from distances that are large compared to the size of the lamp filament—so that the filament is effectively a "point"—then this data supports the hypothesis.

③ The Stefan-Boltzmann Lamp is not truly a point source. If it were not, then there would be a falloff in light level for measurements taken close to the lamp. This falloff can be seen in our data.

Suggestion:

The largest part of the error in this lab is due to the non-point nature of the Stefan-Boltzmann Lamp. You can approximate a much better "point" source with a laser and a converging lens.



For best results, use a short-focal-length lens and make sure that the sensor is always completely within the beam.

Experiment 3: Stefan-Boltzmann Law (at high temperatures)

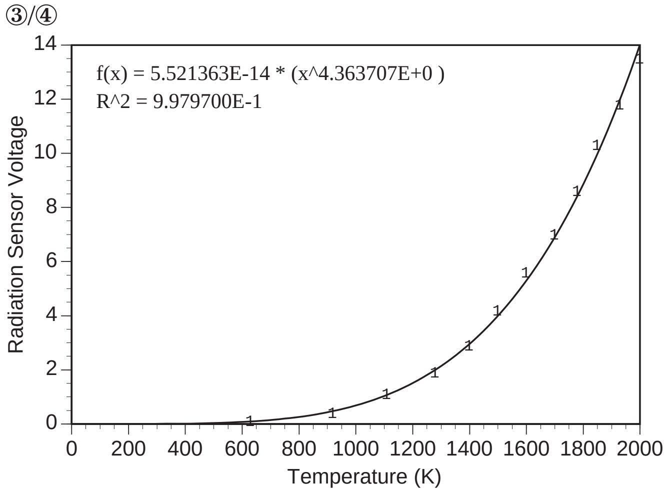
Notes on Procedure

Part 1

③ Between readings, place the insulating material between the lamp and the sensor. For best results use both sheets, with the aluminum sides facing away from each other. Remove the sheets for only enough time to take each measurement.

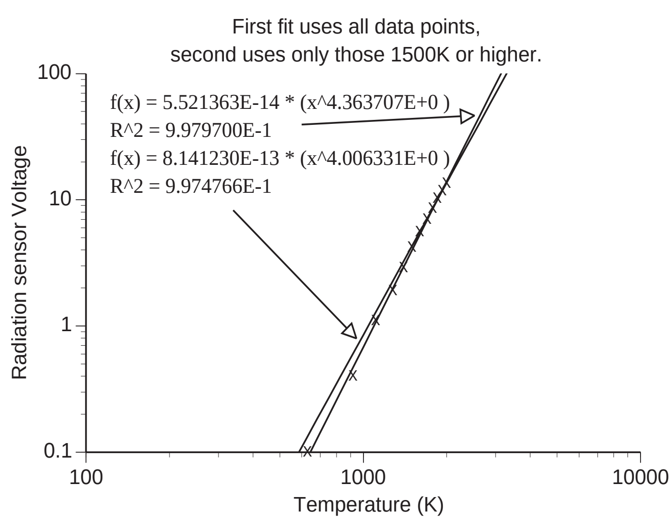
Calculations

③/④



Notes on Questions

① A power regression of our data shows a power of 4.36. However, an analysis of only those points with temperature greater than 1500° shows a power of 4.01. This inaccuracy in the low-temperature points is due to absorbtion of the infrared by the glass lamp bulb. (See experiment 1) This absorbtion is more significant at the lower temperatures, where the infrared makes up a larger percentage of the entire output.



② The lamp filament is not a true black body. If it were, it would be completely and totally black at room temperature. It is a fairly good approximation, though, as long as the temperature is high enough that the emitted light is much greater than the incident light.

③ Any other thermal source in the room would influence the results, including the warm body of the experimenter and the room itself. These introduce some error, but it is small as long as the temperature of the lamp is high compared to the temperature of these other sources.

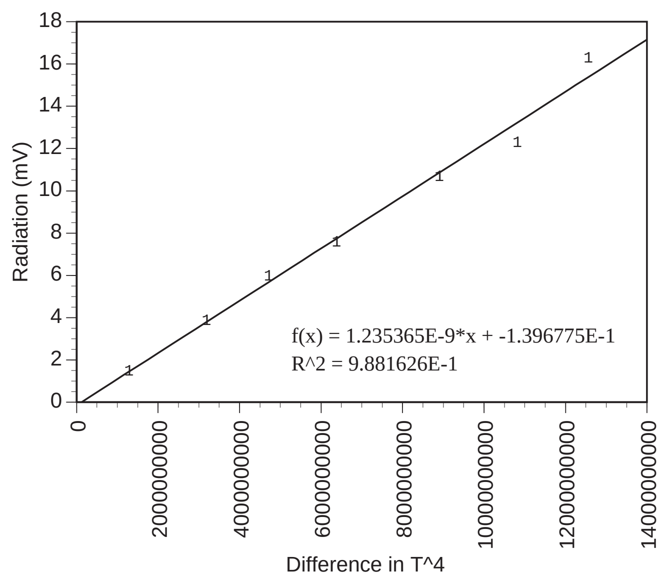
Experiment 4: Stefan-Boltzmann Law (at low temperatures)

Notes on Procedure

③ Make sure that the Thermal Radiation Cube has been off for enough time to be at equilibrium with the room before making this measurement. If the cube has been turned on recently, use another thermometer to make the measurement.

⑤ Use ridiculous precautions with this experiment. It is impossible to have too much insulation between the cube and the sensor between measurements. For our experiments, we use two foam sheets covered with aluminum tape, and an air gap between the sheets. We never removed this heat shield for more than 5 seconds while taking a measurement.

Calculations



Notes on Questions

① The linearity of this graph indicates that the Stefan-Boltzmann equation is correct, even at low temperatures.

② The graph should be straight, with some statistical variations.

Notes

Technical Support

Feed-Back

If you have any comments about this product or this manual please let us know. If you have any suggestions on alternate experiments or find a problem in the manual please tell us. PASCO appreciates any customer feed-back. Your input helps us evaluate and improve our product.

To Reach PASCO

For Technical Support call us at 1-800-772-8700 (toll-free within the U.S.) or (916) 786-3800.

Contacting Technical Support

Before you call the PASCO Technical Support staff it would be helpful to prepare the following information:

• If your problem is computer/software related, note:

Title and Revision Date of software.

Type of Computer (Make, Model, Speed).

Type of external Cables/Peripherals.

• If your problem is with the PASCO apparatus, note:

Title and Model number (usually listed on the label).

Approximate age of apparatus.

A detailed description of the problem/sequence of events. (In case you can't call PASCO right away, you won't lose valuable data.)

If possible, have the apparatus within reach when calling. This makes descriptions of individual parts much easier.

• If your problem relates to the instruction manual, note:

Part number and Revision (listed by month and year on the front cover).

Have the manual at hand to discuss your questions.

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Instruction Sheet for the PASCO Model TD-8555

STEFAN-BOLTZMAN LAMP

Introduction

The Stefan-Boltzmann Lamp is a high temperature source of thermal radiation. It can be used with a radiation detector, such as PASCO's Model TD-8553 Radiation Sensor, to investigate the Stefan-Boltzmann Law:

$$R_{rad} = \sigma T^4;$$

where R_{rad} is the power per unit area radiated by an object, and T is its temperature. This law can also be investigated using a low temperature source such as PASCO's Model TD-8554 Thermal Radiation Cube. However, the high temperature of the Stefan-Boltzmann Lamp simplifies the analysis because the fourth power of the ambient temperature is negligibly small compared to the fourth power of the high temperature of the lamp filament.

When properly oriented, the filament of the Stefan-Boltzmann Lamp provides a good approximation to a point source of thermal radiation. It therefore works well for investigations into the inverse square law.

Measuring the Filament Temperature

By adjusting the power into the lamp (13 Volts Maximum, between 2 and 3 A or approximately 36 Watts), filament temperatures up to approximately 3,000 °C can be obtained. The filament temperature is determined by carefully measuring the voltage and current into the lamp. The voltage divided by the current gives the resistance of the filament.

For small temperature changes, the temperature of the tungsten filament can be calculated using α, the temperature coefficient of resistivity for the filament:

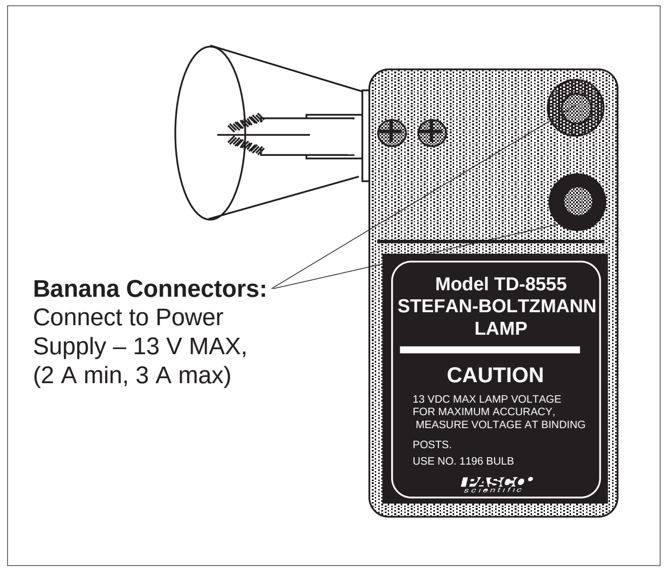
$$T = \frac{R - R_{ref}}{\alpha R_{ref}} + T_{ref}$$

where,

T = Temperature
R = Resistance at temperature T
T_{ref} = Reference temperature (usually room temp.)
R_{ref} = Resistance at temperature T_{ref}
α = Temperature coefficient of resistivity for the filament

Recommended Equipment

AC/DC LV Power Supply SF-9584 or equivalent capable of 13 V @ 3 A max.



For large temperature differences, however, α is not constant and the above equation is not accurate.

For large temperature differences, therefore, determine the temperature of the tungsten filament as follows:

1. Accurately measure the resistance (R_{ref}) of the tungsten filament at room temperature (about 300 °K). Accuracy is important here. A small error in R_{ref} will result in a large error in your result for the filament temperature.
2. When the filament is hot, measure the voltage and current into the filament and divide the voltage by the current to measure the resistance (R_T).
3. Divide R_T by R_{ref} to obtain the relative resistance (R_T/R_{ref}).
4. Using your measured value for the relative resistivity of the filament at temperature T, use Table 2 on the following page, or the associated graph, to determine the temperature of the filament.

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Important: The voltage into the lamp should **NEVER exceed 13 V.** Higher voltages will burn out the filament.

Replacement Bulb: Use GE Lamp No. 1196, available at most auto parts stores. When replacing the bulb, solder the leads to minimize resistance.

Note: Complete instructions for the Stefan-Boltzmann and inverse square law experiments can be found in the Instruction Manual and Experiment Guide for the PASCO scientific Thermal Radiation System (PASCO Part NO. 012-02845).

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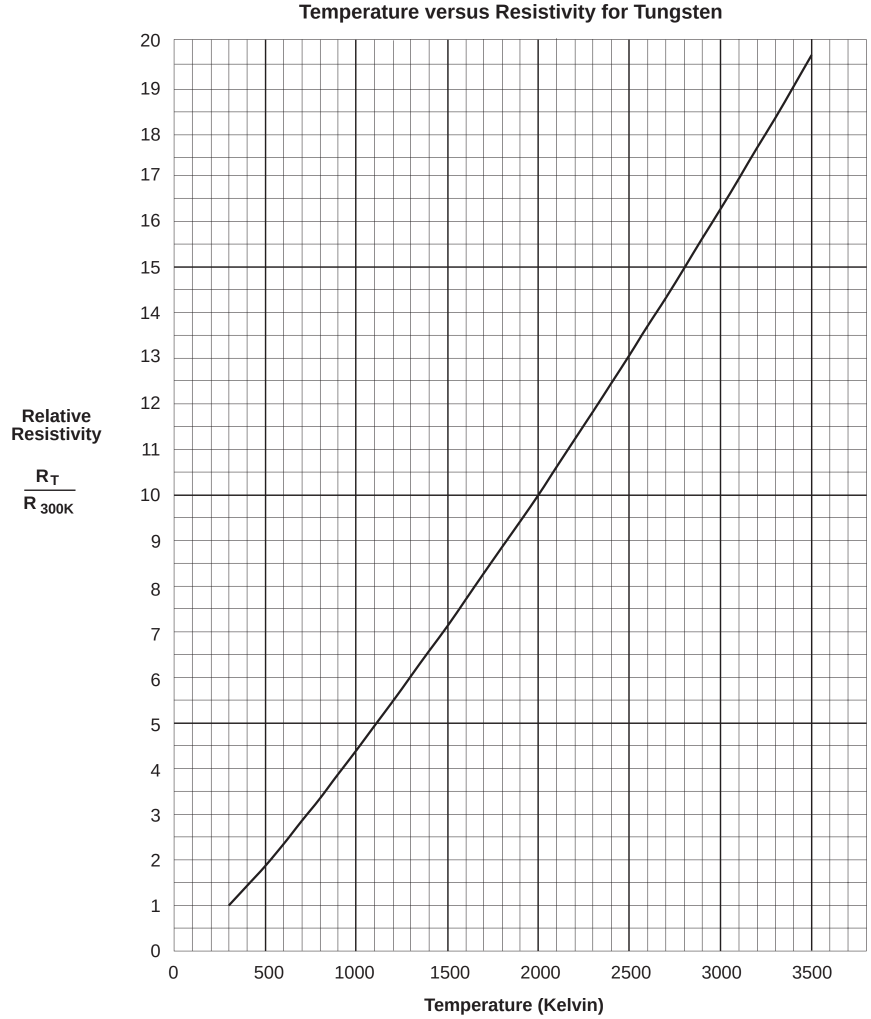
Temperature and Resistivity for Tungsten

R/R_{300K}	Temp °K	Resistivity μΩ cm	R/R_{300K}	Temp °K	Resistivity μΩ cm	R/R_{300K}	Temp °K	Resistivity μΩ cm	R/R_{300K}	Temp °K	Resistivity μΩ cm
1.0	300	5.65	5.48	1200	30.98	10.63	2100	60.06	16.29	3000	92.04
1.43	400	8.06	6.03	1300	34.08	11.24	2200	63.48	16.95	3100	95.76
1.87	500	10.56	6.58	1400	37.19	11.84	2300	66.91	17.62	3200	99.54
2.34	600	13.23	7.14	1500	40.36	12.46	2400	70.39	18.28	3300	103.3
2.85	700	16.09	7.71	1600	43.55	13.08	2500	73.91	18.97	3400	107.2
3.36	800	19.00	8.28	1700	46.78	13.72	2600	77.49	19.66	3500	111.1
3.88	900	21.94	8.86	1800	50.05	14.34	2700	81.04	26.35	3600	115.0
4.41	1000	24.93	9.44	1900	53.35	14.99	2800	84.70			
4.95	1100	27.94	10.03	2000	56.67	15.63	2900	88.33			

Temperature versus Resistivity for Tungsten



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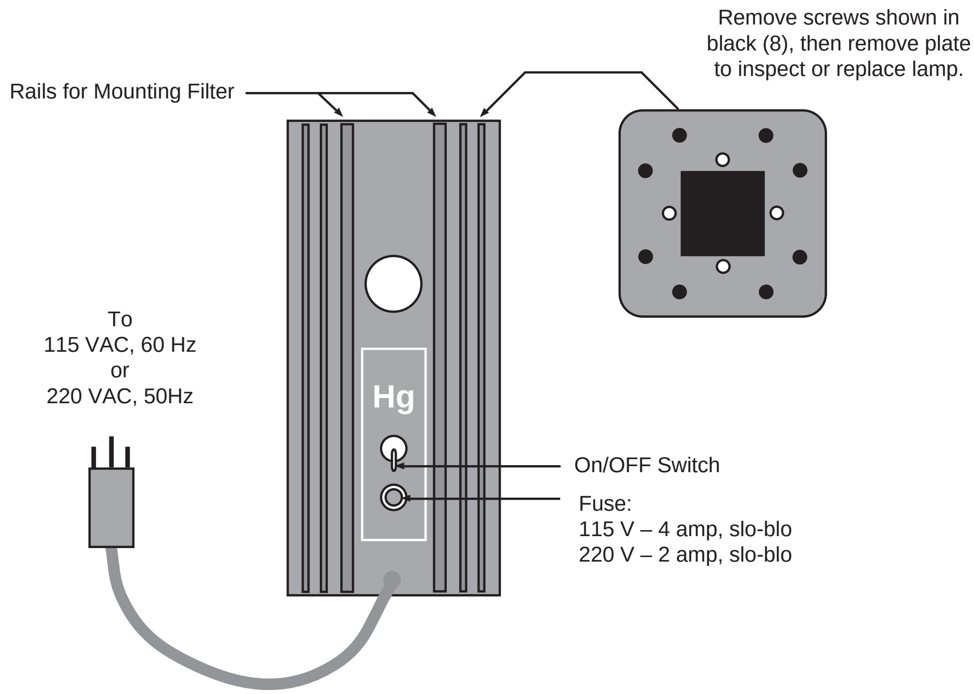
Instruction Sheet for the PASCO Model OS-9286

MERCURY VAPOR LIGHT SOURCE



Introduction

The PASCO scientific Model OS-9286 Mercury Vapor Light Source provides approximately 3,000 lumens of light in the mercury spectrum. The 100 watt light source comes ready to use, with a built-in power supply so the unit can be powered from a standard 115 VAC, 60 Hz outlet (OS-9286-220 is powered from a 220 VAC, 50 Hz outlet). Cooling fins and air vents on the sturdy aluminum case ensure cool, safe operation. In addition, rails on the front and rear of the case can be used for mounting standard 2-inch by 2-inch filters, so that monochromatic light can be obtained.

➤ **NOTE:** For maximum life of the mercury vapor lamp:

① Always operate the light source in its upright position.

② If you are going to use the light source more than once during the day, leave it on. Lamp wear results more from turning the light source on and off than from steady operation.

This instruction sheet edited by: Dave Griffith

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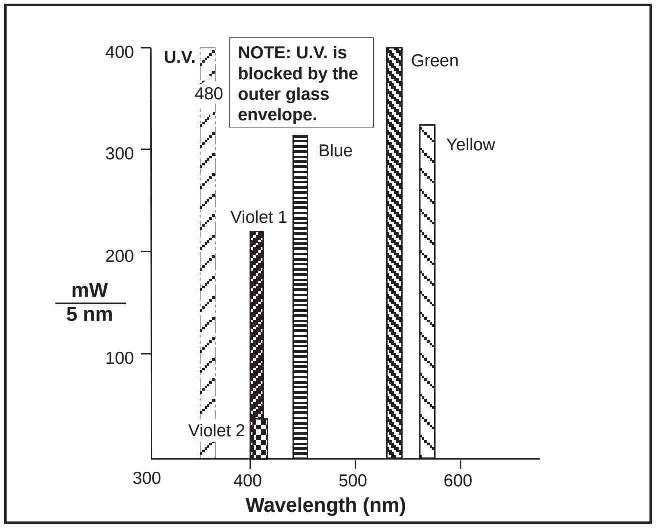


Spectral Power Distribution per 1000 Lumens

Color	Frequency (Hz)	Wavelength (nm)
Yellow	5.18672E+14	578
Green	5.48996E+14	546.074
Blue	6.87858E+14	435.835
Violet	7.40858E+14	404.656
Ultraviolet	8.20264E+14	365.483

Wavelength of the Mercury Spectral Lines

All values except wavelength for yellow line are from *Handbook of Chemistry and Physics, 46th ed*. The wavelength of the yellow was determined experimentally using a 600 line/mm grating.

➤ **NOTE:** The yellow line is actually a doublet with wavelengths of 578 and 580nm.

To Operate the Light Source:

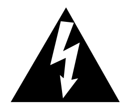
Simply plug it into a standard, grounded, 115 VAC (or 220VAC) outlet; then flip the switch on the front of the light source to ON.

➤ **CAUTION:** The outer glass tube of the mercury vapor lamp blocks harmful ultraviolet radiation produced by the lamp. *If the outer tube is cracked or broken, this radiation can cause severe skin burn and produce eye inflammation.* Regularly inspect the outer tube for cracks, especially if the light source has received a significant jolt. *If the glass bulb is broken, immediately turn lamp off and remove it to avoid possible injury*. Replace Bulb prior to next use.

CAUTION

RISK OF ELECTRIC SHOCK
DO NOT OPEN

CAUTION:
TO PREVENT THE RISK OF ELECTRIC SHOCK, DO NOT REMOVE COVER ON UNIT. NO USER SERVICEABLE PARTS INSIDE. REFER SERVICING TO QUALIFIED SERVICE PERSONNEL.



The lightning flash with arrowhead, within an equilateral triangle, is intended to alert the user of the presence of uninsulated “dangerous voltage” within the product’s enclosure that may be of sufficient magnitude to constitute a risk of electric shock to persons.

The exclamation point within an equilateral triangle is intended to alert the user of the presence of important operating and maintenance (servicing) instructions in the literature accompanying the appliance.

Maintenance

The light source lamp can be expected to provide 24,000+ hours of trouble free operation. However, if the light at any time fails to come on, first check the fuse on the front of the light source case. If the fuse is not blown, you may need to replace the lamp. In rare cases, the problem may be with the ballast. However, ballast replacement should be performed only by experienced personnel. If the fuse is intact and replacing the bulb does not restore operation, we recommend you return the unit to PASCO scientific for repair.

➤ ***CAUTION—HIGH VOLTAGE:*** *Do not open the light source with the unit plugged in.*

To Replace the Mercury Vapor Lamp:

① Unplug the light source. Allow 10 to 15 minutes for the lamp to cool.

② Unscrew the eight screws that attach the top plate of the light source and remove the top plate.

③ Using a glove or several folds of thick cloth to protect your hand, unscrew the lamp. Discard it as you would any broken glass.

④ Replace the lamp and the top plate of the light source.

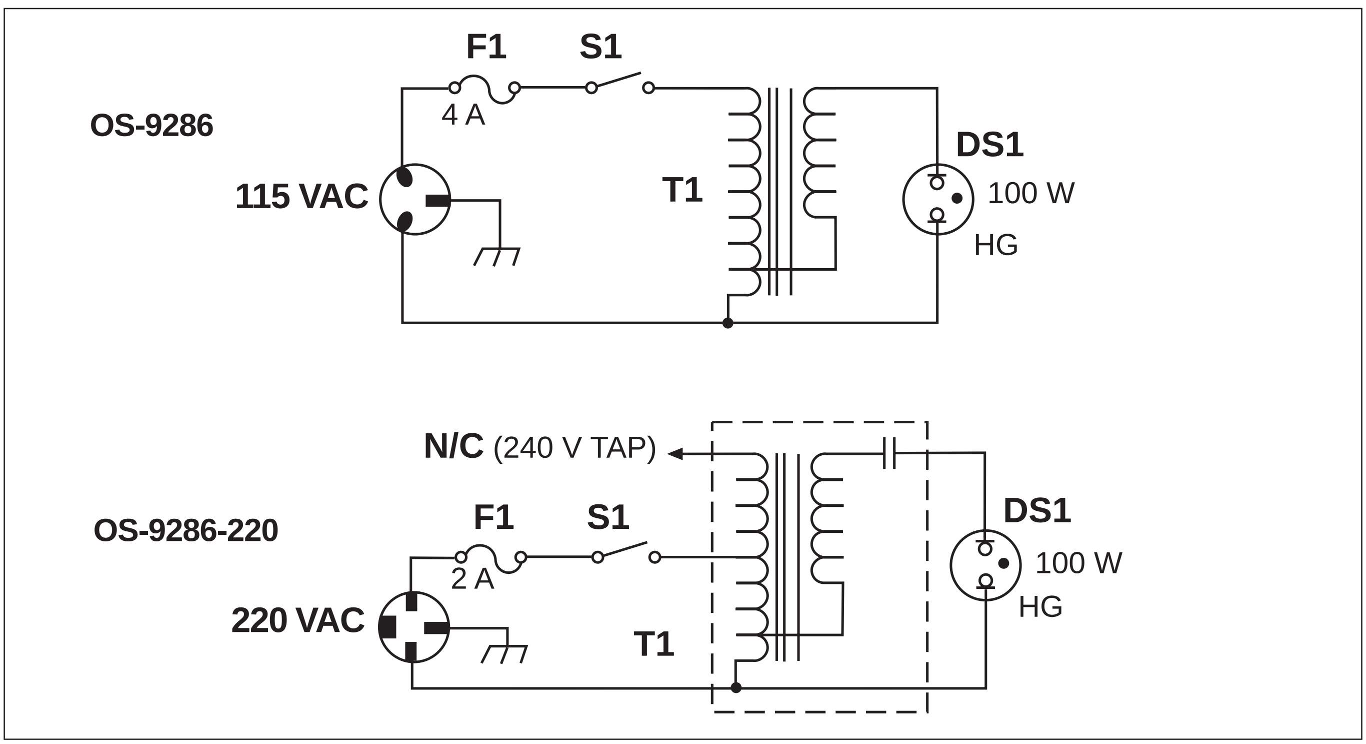
Replacement Parts

Only the following replacement parts should be used:

Description	Pasco #
OS-9286	
Hg Lamp GE HR100A38	526-018
Hg Lamp Ballast	322-019
Fuse (5x20) 4 amp, slo-blo	530-035
OS-9286-220	
Hg Lamp GE HR100A38	526-018
Hg Lamp Ballast	322-028
Fuse (5x20) 2 amp, slo-blo	530-036

Other PASCO Spectral Equipment

PASCO scientific offers a variety of student spectral light sources, and a precision student spectrometer for accurate spectral measurements in the student lab. For more information, check the current PASCO catalog, or call toll-free at 1-800-772-8700. Outside the United States call 1-916-786-3800.



Schematic

Warranty and Equipment Return

Limited Warranty

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Equipment Return

Should this product have to be returned to PASCO scientific, for whatever reason, notify PASCO scientific by letter or phone BEFORE returning the product. Upon notification, the return authorization and shipping instructions will be promptly issued.

➤ **NOTE:**
NO EQUIPMENT WILL BE ACCEPTED FOR RETURN WITHOUT AN AUTHORIZATION.

When returning equipment for repair, the units must be packed properly. Carriers will not accept responsibility for damage caused by improper packing. To be certain the unit will not be damaged in shipment, observe the following rules:

① The carton must be strong enough for the item shipped.

② Make certain there is at least two inches of packing material between any point on the apparatus and the inside walls of the carton.

③ Make certain that the packing material can not shift in the box, or become compressed, thus letting the instrument come in contact with the edge of the box.

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Includes
Teacher's Notes
and
Typical
Experiment Results

Instruction Manual
and Experiment Guide
for the PASCO scientific
Model AP-9368 and AP-9369

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h/e Apparatus

and

h/e Apparatus Accessory Kit

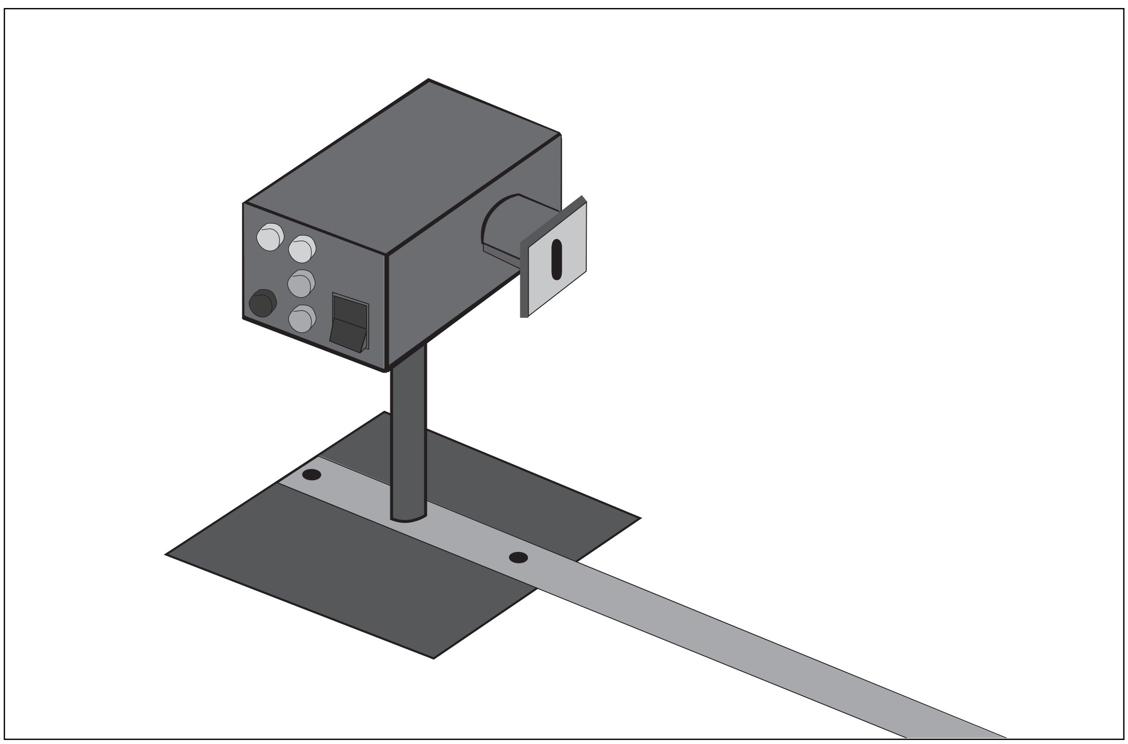

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Table of Contents

Copyright, Warranty, and Equipment Return

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Credits

This manual edited by: Dave Griffith

Teacher's guide written by: Eric Ayar

Equipment Return

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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.

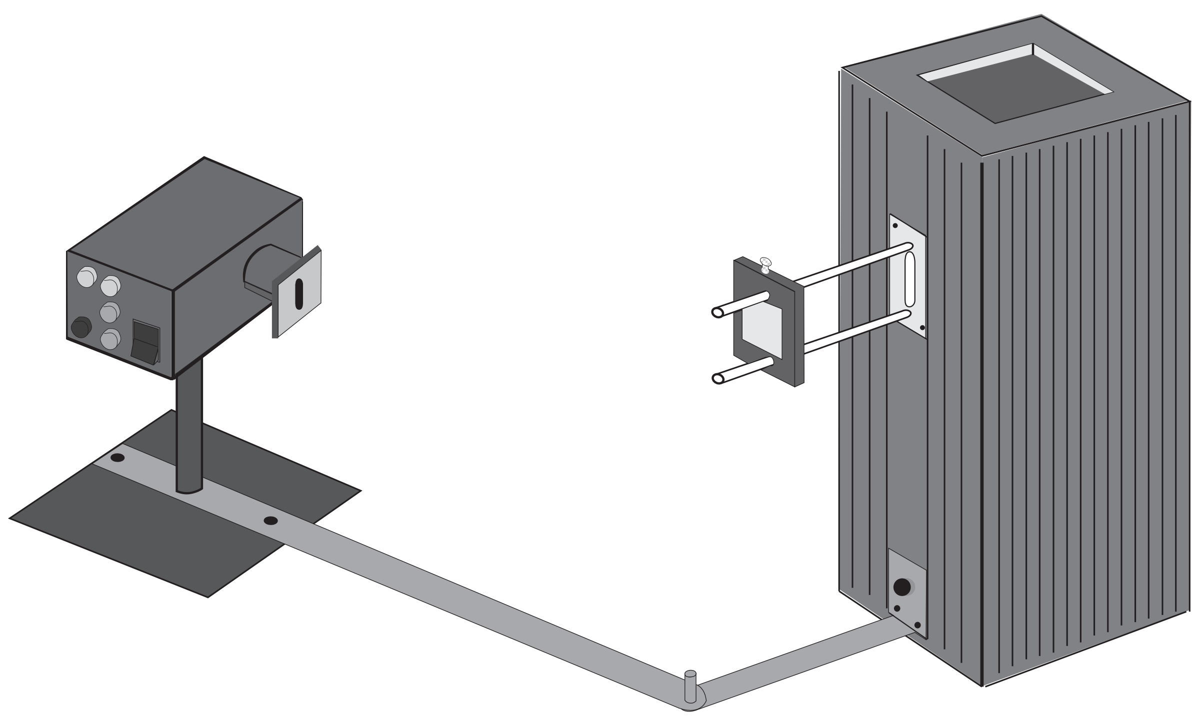


Figure 1. The h/e Apparatus Shown With the Accessory Kit and Mercury Vapor Light Source

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:

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

where KE_{max} is the maximum kinetic energy of the emitted photoelectrons, and W_O 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_O 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:

$$KE_{max} = Ve$$

Therefore, using Einstein's equation,

$$h\nu = Ve + W_O$$

When solved for V, the equation becomes:

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

If we plot V vs ν for different frequencies of light, the graph will look like Figure 2. The V intercept is equal to $-W_O/e$ 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.

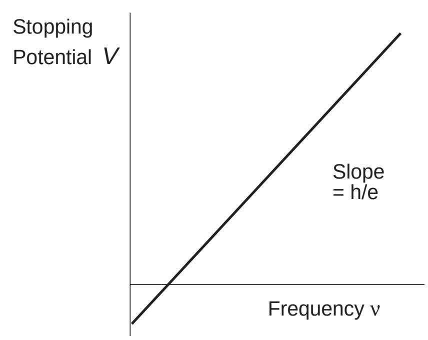


Figure 2. The graph of V vs. ν

***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

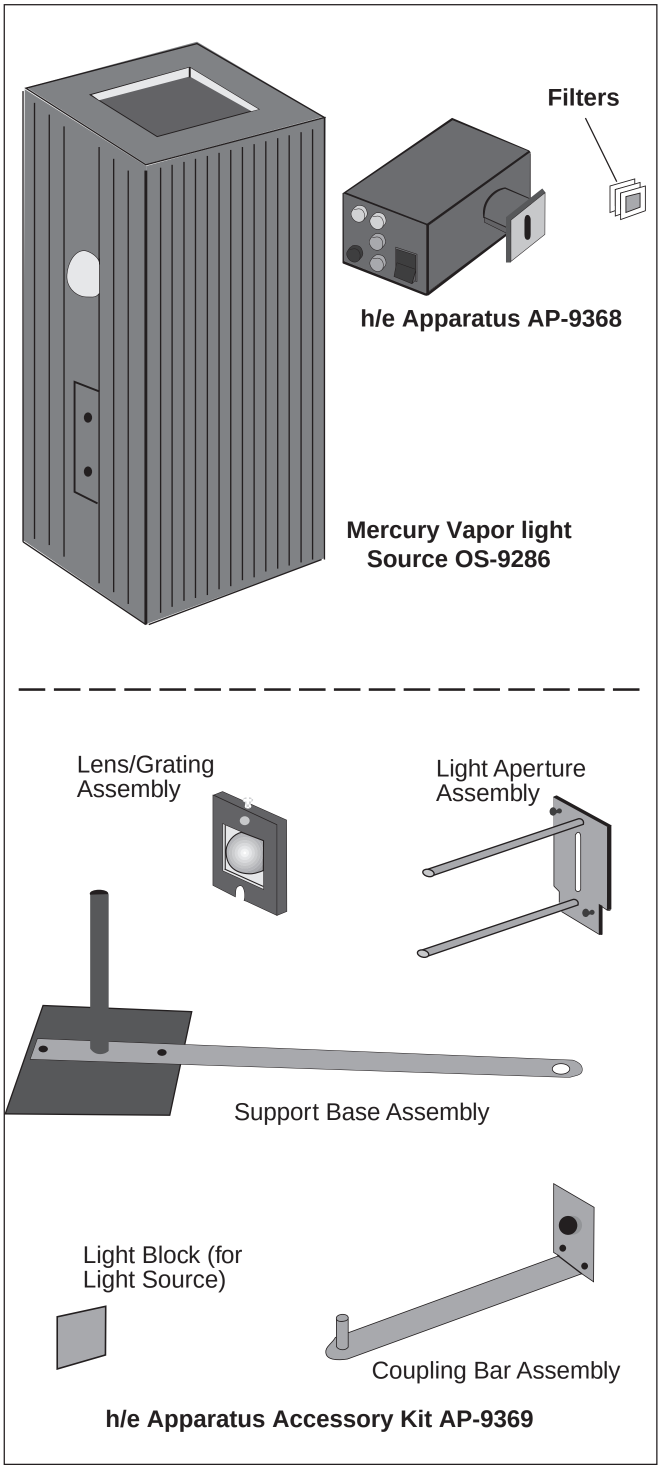


Figure 3. h/e Equipment Identification

* 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.

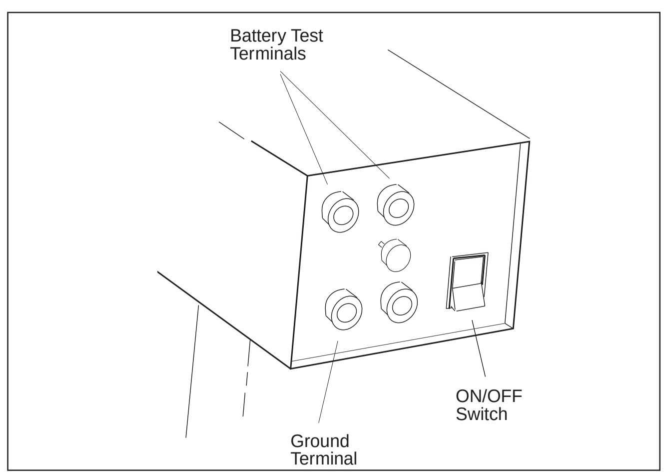


Figure 4. Battery Test Points

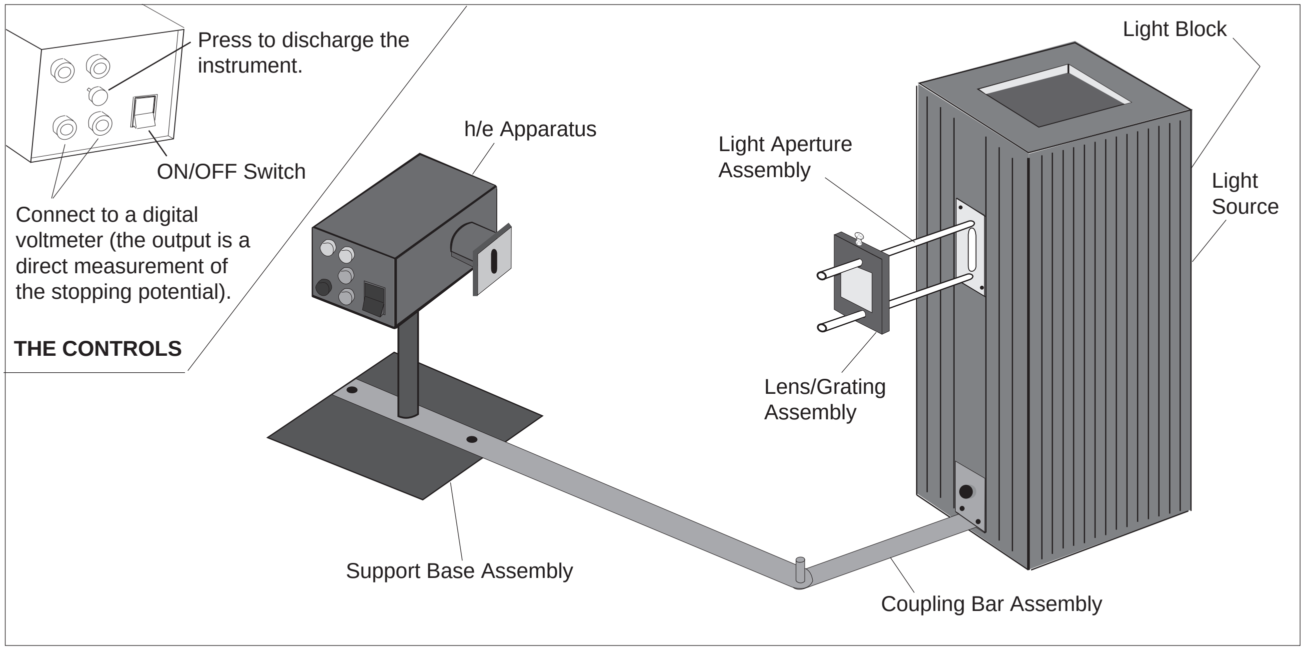


Figure 5. Equipment Setup Using a Mercury Vapor Light Source and the h/e Apparatus

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.

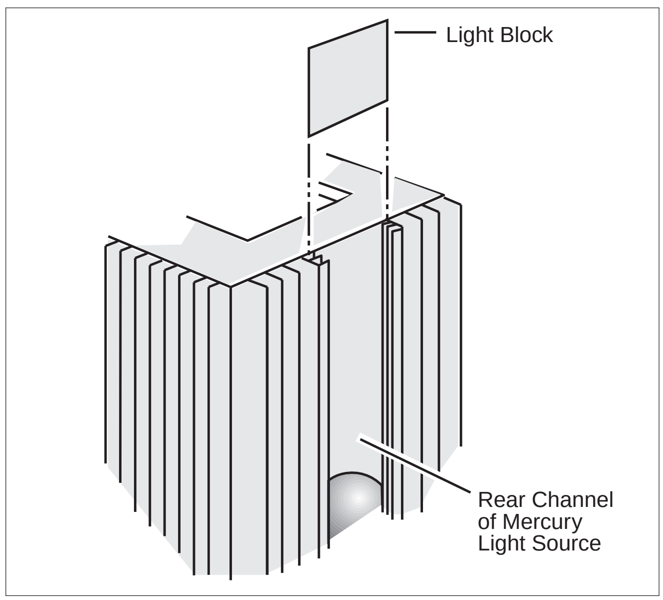


Figure 6. Installing the Light Block

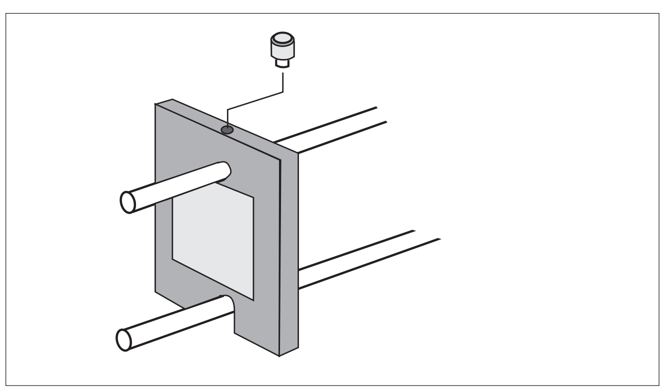


Figure 7. Lens/Grating Mounting Detail

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.

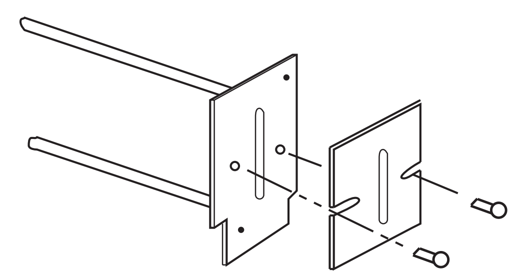


Figure 8. Light Aperture Adjustment

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).

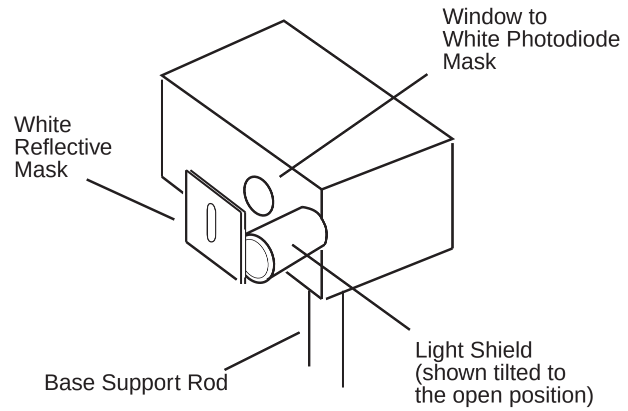
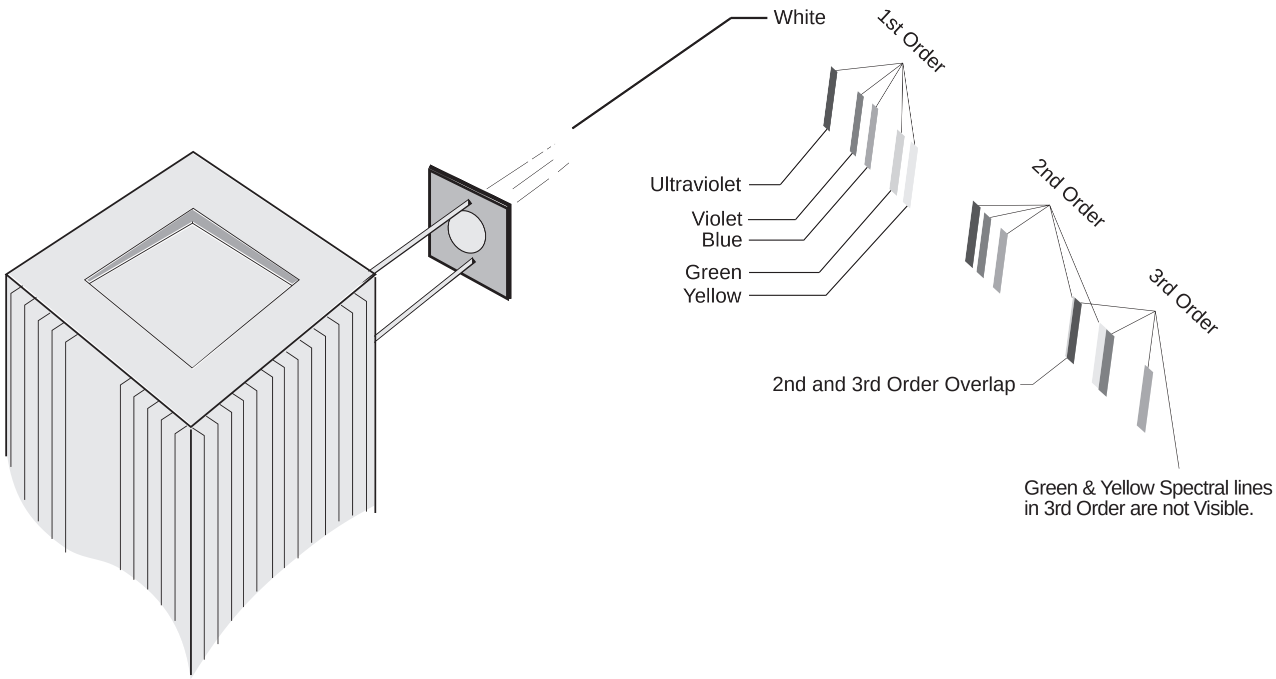


Figure 9. h/e Light Shield

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.



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Color	Frequency (Hz)	Wavelength (nm)
Yellow	5.18672E+14	578
Green	5.48996E+14	546.074
Blue	6.87858E+14	435.835
Violet	7.40858E+14	404.656
Ultraviolet	8.20264E+14	365.483

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.

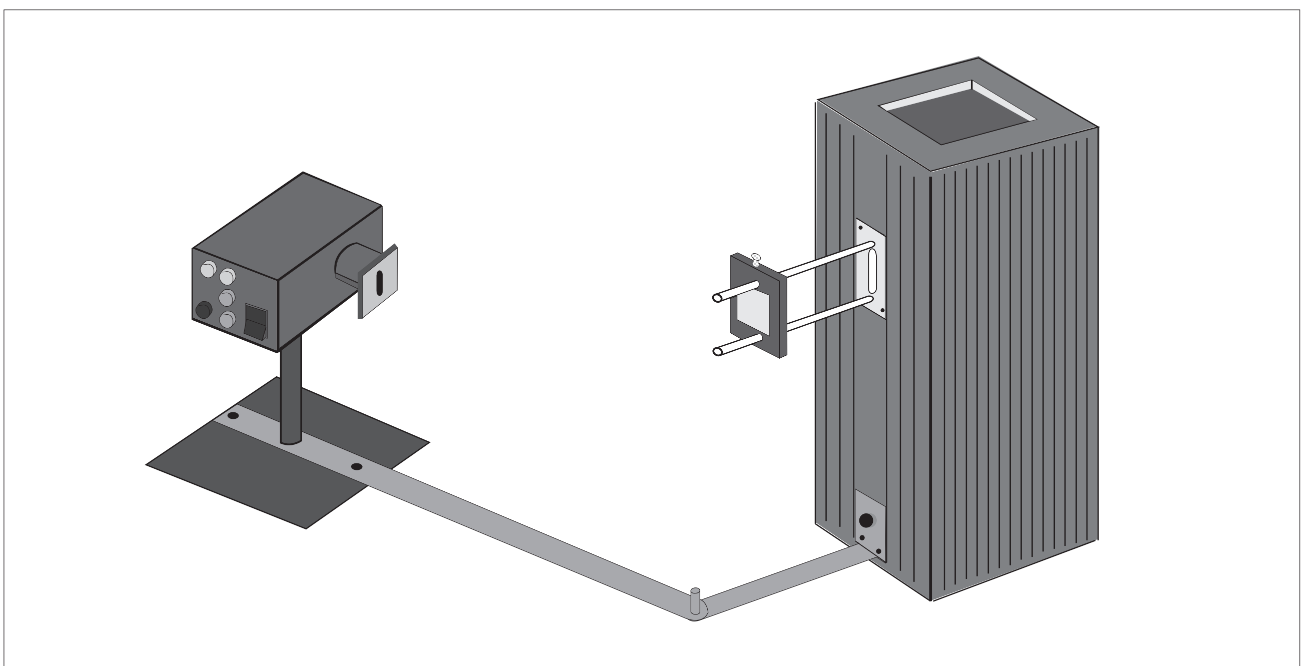
This lab investigates both of these assertions. Part A selects two spectral lines from a mercury light source and investigates the maximum energy of the photoelectrons as a function of the intensity. Part B selects different spectral lines and investigates the maximum energy of the photoelectrons as 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 (♠10^{13} Ω), 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.

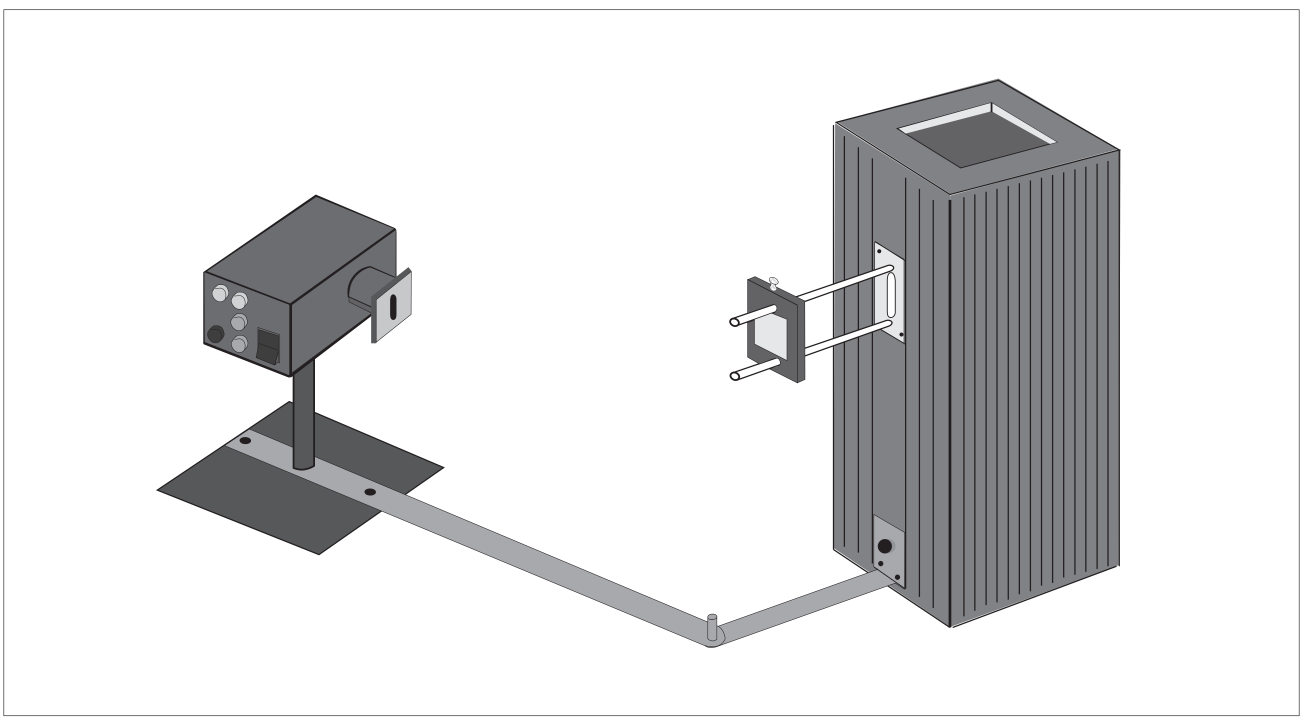
In this lab you will select different spectral lines from mercury and investigate the maximum energy of the photoelectrons as a function of the wavelength and frequency of the light.

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 x10^{14} Hz**	**Stopping Potential volts**
Yellow			
Green			
Blue			
Violet			
Ultraviolet			
Second Order Color	**Wavelength nm**	**Frequency x10^{14} Hz**	**Stopping Potential volts**
Yellow			
Green			
Blue			
Violet			
Ultraviolet			

Technical Information

Theory of Operation

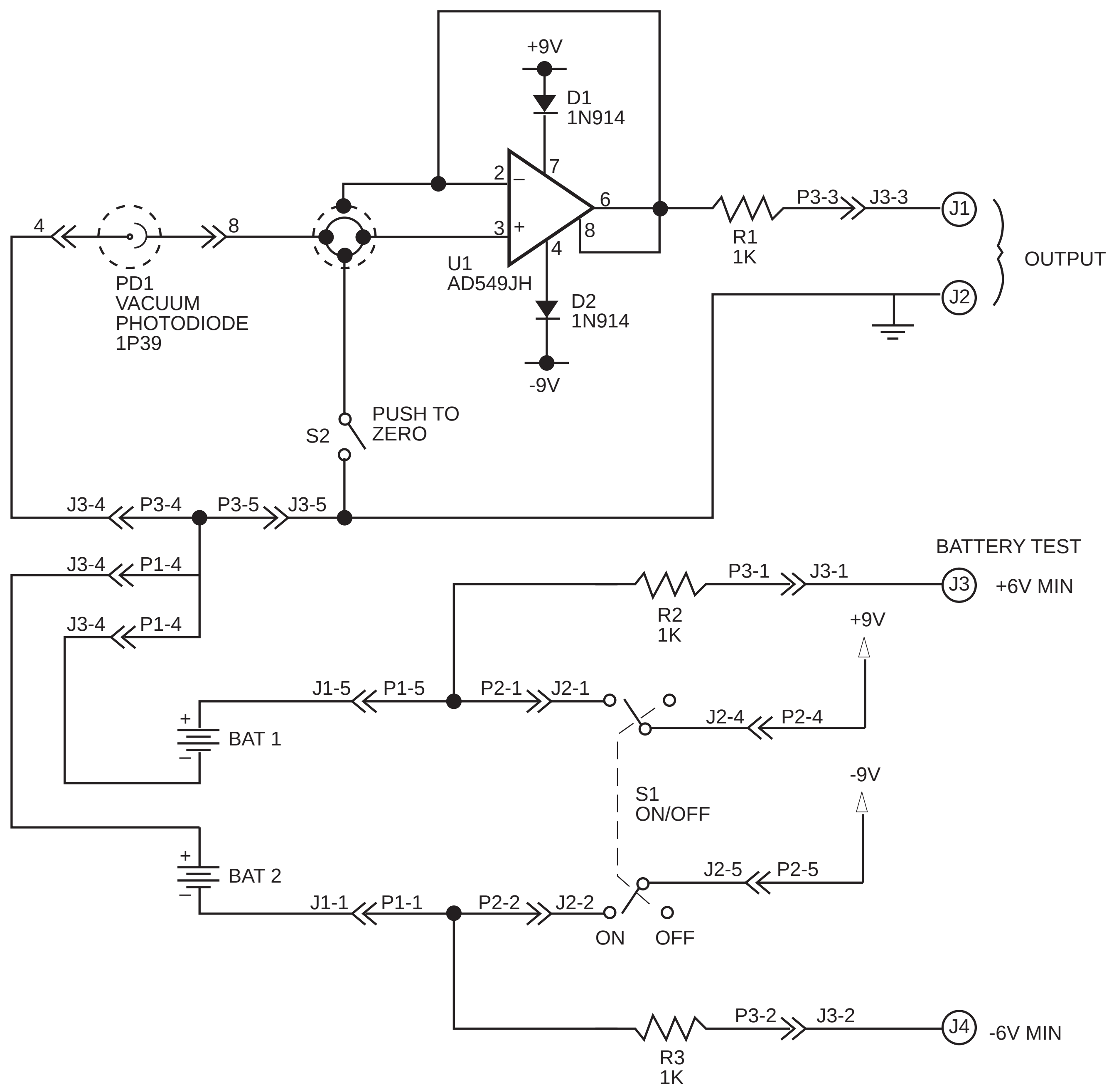
In experiments with the h/e Apparatus, monochromatic light falls on the cathode plate of a vacuum photodiode tube that has a low work function, W_0. Photoelectrons ejected from the cathode collect on the anode.

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 (Vout/Vin = 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 volatge jump and/or oscillate. Once photoelectrons charge the anode the input voltage will stabilize.

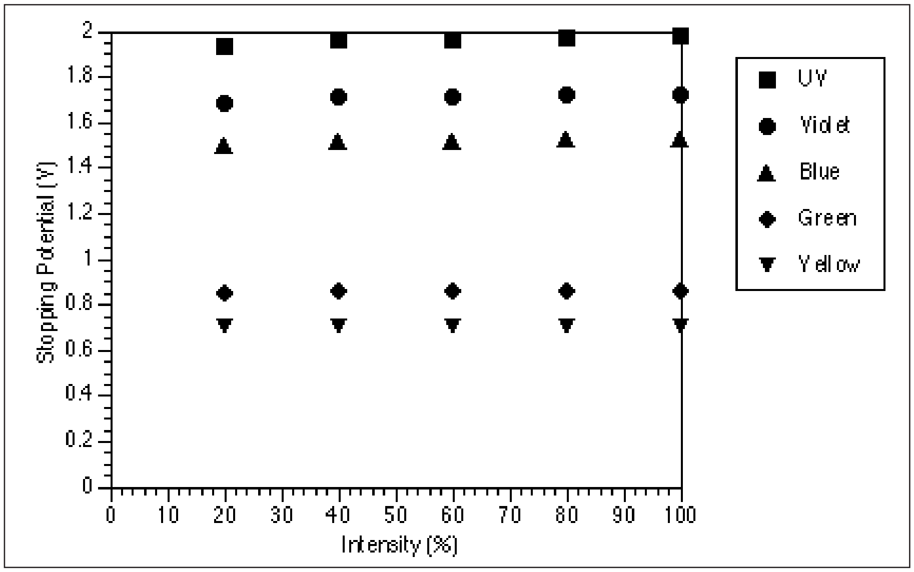


Schematic Diagram

Teacher's Guide

Exp 1-h/e Apparatus and Accessory Kit

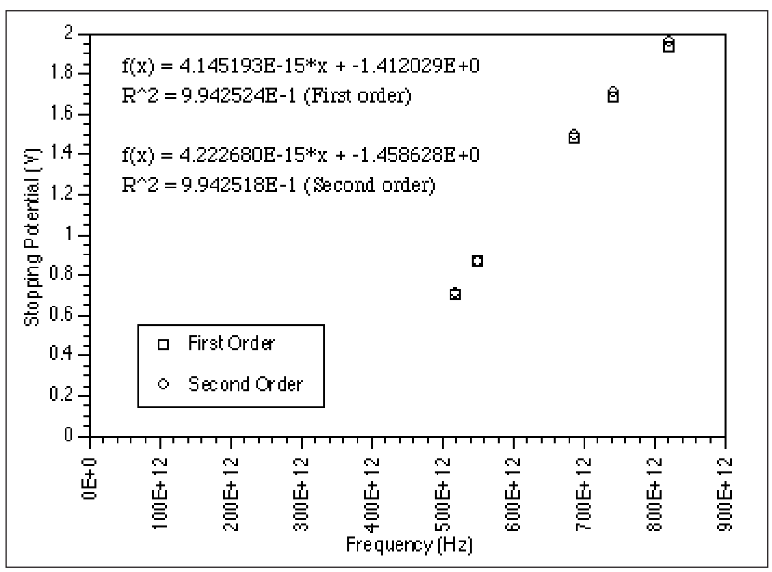
Part A



In each case, the time to reach full voltage increases dramatically with decreasing intensity. (up to a minute for 20% intensity)

Part B

Analysis

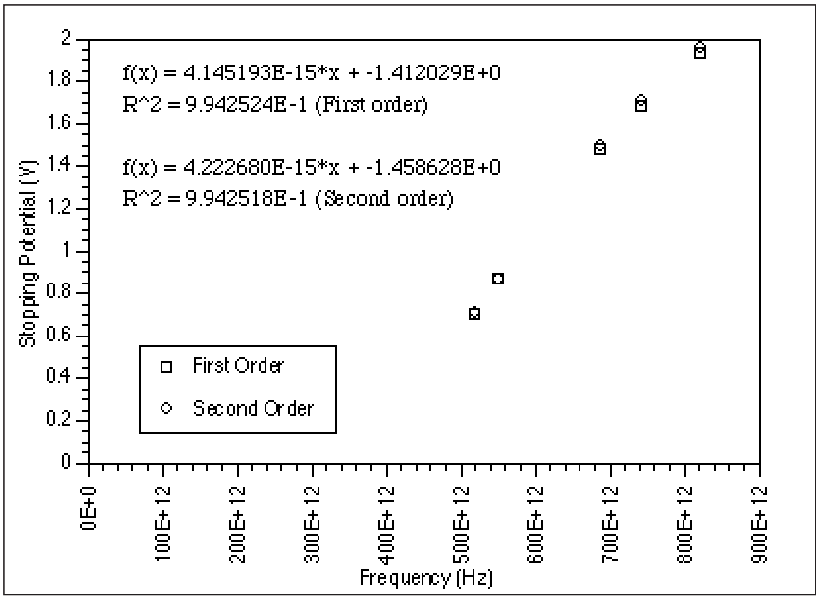


1. The amount of light does not significantly affect the stopping potential. It does affect the time it takes to reach this potential. From this we can determine that the intensity of the light affects the number of electrons emitted, but not the maximum energy of the electrons.
2. Different colors of light do affect the maximum energy of the photoelectrons. The relationship appears to be linear.
3. This experiment supports a quantum model of light.

The slight drop in the measured stopping potential is due to the leakage of charge through the zero-gain amplifier. As the intensity decreases, the equilibrium point between the electrons arriving and the electrons leaving through the amplifier becomes lower.

Exp 2-h/e Apparatus and Accessory Kit

Analysis



First order:

h = 6.6406E-34 (0.22% off)

W_o = 1.412 eV

Second order:

h = 6.7647E-34 (2.1% off)

W_o = 1.459 eV

Technical Support

Feed-Back

If you have any comments about this product or this manual please let us know. If you have any suggestions on alternate experiments or find a problem in the manual please tell us. PASCO appreciates any customer feed-back. Your input helps us evaluate and improve our product.

To Reach PASCO

For Technical Support call us at 1-800-772-8700 (toll-free within the U.S.) or (916) 786-3800.

ax: (916) 786-3292

e-mail: techsupp@pasco.com

web: www.pasco.com

Contacting Technical Support

Before you call the PASCO Technical Support staff, it would be helpful to prepare the following information:

➤ If your problem is with the PASCO apparatus, note:

- Title and model number (usually listed on the label);
- Approximate age of apparatus;
- A detailed description of the problem/sequence of events (in case you can't call PASCO right away, you won't lose valuable data);
- If possible, have the apparatus within reach when calling to facilitate description of individual parts.

➤ If your problem relates to the instruction manual, note:

- Part number and revision (listed by month and year on the front cover);
- Have the manual at hand to discuss your questions.