

EXPERIMENT 9: Optical Spectrometers

DESCRIPTION

PURPOSE

Learn the principles and uses of monochromators, spectrometers and spectrophotometers.

INTRODUCTION

Optical spectrometers are devices that separate (“disperse”) the component wavelengths (“colors”) of light and then select specific wavelengths for individual measurement. Spectrometers can be designed to work with a wide range of electromagnetic radiation, including visible, ultraviolet, infrared, X-ray, microwave, and radio waves.

Spectrometers provide a wealth of information concerning the composition, structure, and dynamics of matter. They are perhaps the most used, and most useful, tool in science. Optical spectrometers are used in astronomy, atomic physics, biology, chemistry, condensed matter physics, environmental studies, forensics, genetics, high-energy physics, materials science, and in numerous other fields. Read the sections about diffraction gratings on pages pp. 903-909 from Young and Freedman (Y&F), or a similar text. There are other devices called spectrometers for use in measuring the energy spectrum of many different kinds of radiation.

The simplest spectrometer is the glass prism, which refracts each wavelength of light at a slightly different angle, producing a “rainbow” effect. The grating spectrometer also produces a “rainbow” effect by diffracting incident light at different angles depending on wavelength according to the diffraction formula. Grating spectrometers are the more common as they offer higher performance and greater versatility. You used a prism spectrometer in Exp. 1 a grating spectrometer in Exp. 3.

There are several terms related to optical spectrometers that need further definition. The following descriptions are generally used, though there is some variation among researchers, engineers, and manufacturers in the precise definitions.

Spectrum: A recording of the component wavelengths (“colors”) of the electromagnetic (EM) **spectrum**. (Y&F Fig. 34-1)

Spectrometer: A device used to measure the wavelength or frequency of waves, such as EM or sound waves.

Spectroscope: A device consisting of a narrow light source (such as a lamp illuminating a narrow slit), a dispersing element (such as a prism or grating), and a viewing screen or telescope. The spectroscope displays a range of the **spectrum** at once. (Y&F, Figure 37-21)

Spectrograph: A spectroscope equipped with sheet of photographic film (or an electric image recording device) to record a selected portion the **spectrum**. (Fig. 9-1)

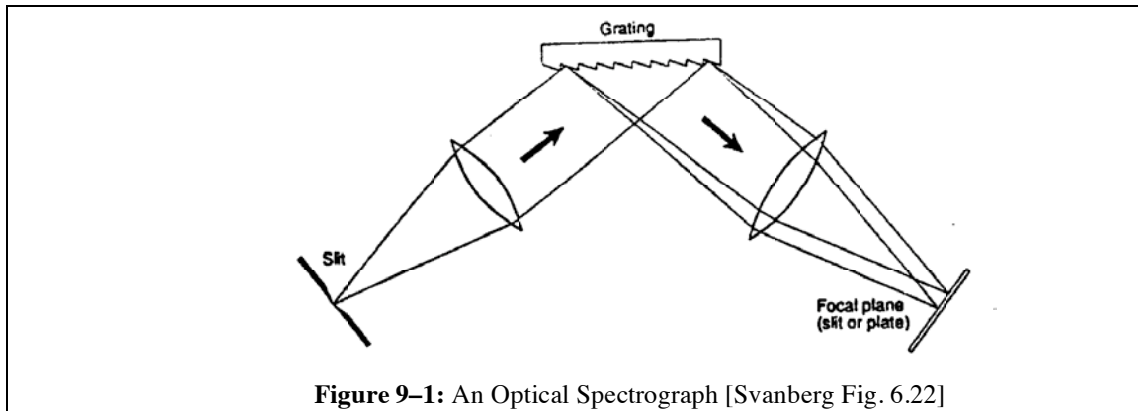


Figure 9-1: An Optical Spectrograph [Svanberg Fig. 6.22]

Monochromator: A **spectroscope** equipped with narrow entrance and exit slits to select only a single wavelength (a ‘monochrome’) component for detailed measurement. A monochromator is usually equipped with a mechanism to move, the spectrum across the slit (or vice versa) to produce a continuous scan of the **spectrum**. (Fig. 9-2)

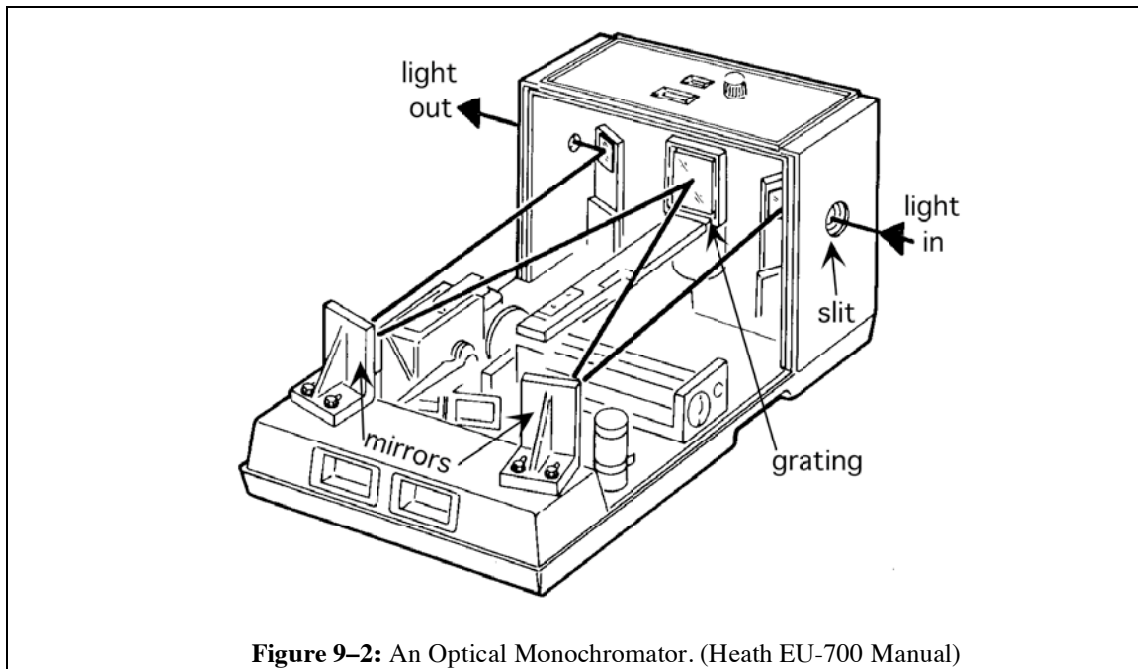


Figure 9-2: An Optical Monochromator. (Heath EU-700 Manual)

Spectrophotometer: A **monochromator** equipped with a light source and, chamber to hold a sample for, e.g., absorption spectroscopy, in front of the entrance slit and a sensor outside the exit slit. Spectrophotometers usually include automated control of wavelength scanning and **spectrum** recording. See the handout “The Spectrophotometer” by Edgar Pearlstein (1975).

The **monochromator** is the most important component of a spectrophotometer and its construction determines the performance and convenience of the overall measurement. This experiment will concentrate on grating monochromators like in Fig. 9-2. The most important features of the spectrometer, the features that most affect performance are the **Slits**, the narrow openings

at the light source and output locations, and the **Grating**, the element that disperses the light into component colors. Scanning is usually accomplished by rotating the grating about an axis perpendicular to the plane of incidence, thus changing the diffraction angle.

The dispersion of light of wavelength λ by a diffraction grating with spacing d is governed by the *grating diffraction equation* (Y&F Eq. 3-22):

$$d \sin \theta = m\lambda, \quad (9-1)$$

where θ is the angle of diffraction, measured from the incident beam direction, and the grating diffraction order m is an integer with values $0 \pm 1, \pm 2$, etc. The resolution of a grating monochromator, the range of wavelengths $\Delta\lambda$ passed through at one angle θ , is limited either by the slit width or by the grating, whichever produces the larger range. The resolution $\Delta\lambda/\lambda$ is the largest of

$$\frac{\Delta\lambda}{\lambda} = \frac{\lambda}{mN} \text{ (diffraction limited),} \quad (9-2a)$$

where N is the number of grating lines illuminated by the beam, or

$$\frac{\Delta\lambda}{\lambda} = \frac{\lambda a}{L \tan \theta} \text{ (slit limited),} \quad (9-2b)$$

where a is the width of the widest slit and L is the distance from slit to grating. For highest performance, one needs a large grating (N) and narrow slits (a).

NOTE: The measurements in this experiment will all be made in air. The wavelength of light in air differs from the wavelength λ in vacuum due to the index of refraction n of air:

$$\lambda = \frac{\lambda_{vac}}{n}, \quad (9-3)$$

where $n \approx 1.0003$ at STP conditions through the visible spectral region. For example, the He-Ne laser emission wavelength is $\lambda_{vac} = 632.8$ nm (in vacuum) but a slightly shorter wavelength $\lambda_{air} = 632.8 \text{ nm}/1.0003 = 632.6$ nm in air. (And the students exclaimed, “Aha, that explains the discrepancy in our data from Exp. 3.”)

ADDITIONAL READING

University Physics, 12th ed., by H. D. Young and R. A. Freedman, (Addison-Wesley, Reading PA, 2007). Physics 211-212 text. (Y&F)

Fundamentals of Optics, 4th edition, by Francis A. Jenkins and Harvey E. White (McGraw-Hill, New York 1976).

Optics, 4th ed., by Eugene Hecht (Addison-Wesley, Reading MA, 2002).

Atomic and Molecular Spectroscopy, by Sune Svanberg (Springer-Verlag, Berlin 1991).

Diffraction Grating Spectrographs, Sumner P. Davis (Holt-Rinehart-Winston, New York 1970).

Heath Instrumentation for Spectroscopy, Model EU-700 system operation manual.

PROCEDURE

ACTIVITY 1: GRATING SPECTROSCOPE-INCANDESCENT & FLUORESCENT LIGHTING

Equipment: blue plastic “STAR” spectrometer, incandescent and fluorescent lamps

Adjust the STAR spectrometer scale as described on the label. View the output of incandescent and fluorescent lamps with the STAR spectrometer and record the emission wavelengths or wavelength range. Look up the emission wavelengths from the fluorescent lamp in the MIT wavelength tables to identify several elements present in the tube.

ACTIVITY 2: GRATING SPECTROSCOPE-EMISSION SPECTROSCOPY

SAFETY NOTE: The mercury lamp emits harmful ultraviolet radiation (UVB), which will ‘sunburn’ the retina or skin. The lamp opening(s) must have a glass window or some other UV filter cover to block the harmful UV light.

Equipment: incandescent, mercury (Hg), and sodium (Na) lamps; spectroscopy table; grating

NOTE: Additional details are given in the handout “Notes on Adjustment of a Spectrometer,” by R. D. Kirby, 1984, reproduced in the master “Husker Red” lab. manual.

Illuminate the spectroscopy input slits with an incandescent lamp. Line up the viewing telescope with the slit tube and focus the image of the slits. Record the angle reading of the viewing telescope. Center the grating on the spectroscopy table and rotate the grating so that it is facing normal to the slits. Swing the viewing telescope both right and left and observe the optical spectrum. Make the slits as narrow as possible while still being able to view the complete spectrum. You may need to turn off the room lights. Measure the angles of the red, yellow, green and violet colors as viewed through the telescope.

Illuminate the slits with the mercury lamp and record the angles for at least four emission lines. Record the angle for the strong yellow emission of the sodium lamp. Obtain the standard wavelengths of strong emission lines of Hg and Na from the *MIT Wavelength Tables* or other source. Plot your angle measurements for all the Hg and Na emission lines vs. the standard wavelengths. From the slope of the line, determine the grating spacing according to the grating diffraction equation 9-1.

Questions:

- 1) Why is there more than one complete spectrum formed by the grating?
- 2) Must the grating face exactly normal to the slit? Why or Why not?

ACTIVITY 3: GRATING MONOCHROMATOR-RESOLUTION AND SLITS

Equipment: He-Ne laser, sodium lamp, EU 700 Heath grating spectrometer, chart recorder

NOTE: It is assumed that you have a basic understanding of the operation of the Heath spectrometer from Exp. 3. Ask the instructor or TA for help if you do not know how to operate it properly. Additional details are given in the handout “The Spectrophotometer,” by Edgar Pearlstein (1975), reproduced in the master “Husker Red” lab. manual.

Remove the spectrometer cover and examine the interior. It is *very important* to keep dust, fingerprints, and other contamination off of the mirror and grating surfaces. Compare what you see to Fig. 9-2. Operate the spectrometer scan and slew controls and observe the motion of the grating and other components. Sketch and analyze the motion of the ‘sine’ drive.

Focus the light from the He-Ne laser on the entrance slit to the Heath Spectrometer using two lenses so that the cone of focus has an opening angle of at least 15° . Place the PMT module, with its input shutter closed and the power off, immediately after the exit slit. Slew the spectrometer to the expected He-Ne emission wavelength. Set the slit width to $20\ \mu\text{m}$, accounting for any offset in the slit-width indicator dial. Connect the PMT output to a picoammeter and its output to the chart recorder. Close the PMT housing shutter and set the PMT voltage to approximately 1,000 V. Slowly open the PMT shutter, making sure the PMT output current does not exceed 0.1 mA. Adjust the He-Ne beam alignment and the spectrometer wavelength to maximize the PMT signal. Adjust the PMT voltage and Chart Recorder span to use 80-90% of the full scale. Set the chart recorder in “auto repeat” mode. Set the spectrometer wavelength $6300\ \text{\AA}$. Scan the wavelength at $0.2\ \text{\AA}/\text{s}$ from $6320\ \text{\AA}$ to $6335\ \text{\AA}$, recording the spectrum on the chart recorder and marking the wavelength in $1\ \text{\AA}$ intervals. Repeat until you obtain a good, clean spectrum and can operate the spectrometer and chart recorder such that the scan can be repeated precisely on the same section of chart paper.

Record the HeNe laser spectrum on a fresh section of chart paper for slit widths of $200\ \mu\text{m}$, $150\ \mu\text{m}$, $100\ \mu\text{m}$, $50\ \mu\text{m}$, $25\ \mu\text{m}$, and $10\ \mu\text{m}$. You may need to change the picoammeter and/or recorder scales at smaller slit widths so your spectrum will be a reasonable size. Measure the full-width at half-maximum (FWHM) of each of these spectra and plot the FWHM vs. slit opening. From this graph, determine the minimum possible FWHM. Compare your graph with Fig. 7-5 (p. 7-5) of the Heath instrument manual.

Replace the HeNe laser with the sodium lamp and record a spectrum of the two “D” lines located at approximately 590 nm.

Questions:

- 1) Why must the He-Ne beam be focused with such a wide cone?
- 2) What are likely causes of differences between your graph of FWHM vs. slit width and the one in the manual?
- 3) Why couldn't you see the two individual lines of the Na lamp using the handheld spectrometer but you can resolve them with the Heath spectrometer? (See Eqs. 9-2.)

ACTIVITY 4: MONOCHROMATOR-FLUORESCENCE SPECTROSCOPY

Equipment: mercury lamp, 4358\AA line filter, grating spectrometer, laser dye, chart recorder

Place a 4358\AA line filter immediately in front of the Hg lamp. Focus the Hg Lamp output into the vial containing the laser dye. Focus the fluorescence emission of the laser dye on the spectrometer entrance slit. Set the slit width somewhere in the range $200\text{-}400\ \mu\text{m}$ and the wavelength at $6200\ \text{\AA}$. Adjust the PMT voltage and chart span to fill 80-90% of the chart span. Record the fluorescence spectrum of the light source at $2\text{\AA}/\text{s}$ over the range $5000\text{-}7000\ \text{\AA}$, marking at $200\ \text{\AA}$ intervals.

Question: 1) At what wavelength is the dye emission largest?

ACTIVITY 5: SPECTROPHOTOMETER-ABSORPTION SPECTROSCOPY

Equipment: spectrophotometer, laser dye in spectrometer cuvette

Arrange the spectrophotometer with source module (tungsten lamp), monochromator module, sample chamber, and PMT module. Place the cuvette containing a laser dye solution into slot 2 in the Sample Chamber. Set the Sample Chamber so that slot 1 (empty) is in the beam path. Set the slit width at 100 μm and the wavelength at 5000 \AA . Adjust the PMT voltage, picoammeter scale, and Chart span to fill 80-90% of the chart span. Set the chart “auto repeat” mode on. Record the spectrum of the light source at 2 $\text{\AA}/\text{s}$ over the range 3000-7000 \AA , marking the wavelength at 200 \AA intervals. Move the Sample Chamber to slot 2 (containing the laser dye sample) and record the spectrum.

From your chart, calculate the relative transmission $T = (\text{signal with sample})/(\text{signal without sample})$ from your two spectra at 200 \AA intervals. Plot the transmission T vs. the wavelength λ .

Questions:

- 1) At what wavelength does the dye solution absorb the most?
- 2) At what wavelength does the dye solution absorb the least?
- 3) Comment on the differences between the spectra obtained in activities 4 & 5?

ACTIVITY 6: PRISM SPECTROMETER-DISPERSION (OPTIONAL)

Read Tipler, p. 991 (dispersion) and Jenkins and White, pp. 30-32 and 474-478. See also “Notes on Adjustment of a Spectrometer,” by R. D. Kirby, 1984.

SAFETY NOTE: The mercury lamp emits harmful UV radiation, which will ‘sunburn’ retina or skin. The lamp opening(s) must have a UV filter cover to block the harmful UV light.

Equipment: mercury lamp, spectroscopy table, prisms

Illuminate the spectroscopy slits with a mercury lamp. Line up the viewing telescope with the slit tube and focus the image of the slits. Record the angle reading of the viewing telescope. Center a prism on the spectroscopy table and rotate the prism so that one face is facing normal to the slits. Swing the viewing telescope around until you can observe the optical spectrum. Make the slits as narrow as possible while still being able to view the complete spectrum. You may need to turn off the room lights.

Illuminate the slits with the mercury lamp and record the angles for at least 4 emission lines. Obtain the standard wavelengths of strong emission lines of Hg from the *MIT Wavelength Tables* or other source. From each angle measurement, calculate the index of refraction using Eq. 2k (p. 31) of Jenkins & White. Plot your angle measurements for all the Hg emission lines vs. the standard wavelengths. Compare your graph with Fig. 23B (p. 477) of Jenkins & White.

Examine the Gaertner Prism spectrometer and sketch the optical path.

Questions:

- 1) Calculate dispersion $\eta_D = \Delta\theta/\Delta\lambda$ of the prism.