

DIFFRACTION SPECTROSCOPY

INTRODUCTION

A spectrometer is a device for examining the spectrum of a light source, i.e. the intensity distribution as a function of wavelength. Almost all present spectrometers use diffraction gratings for this purpose rather than prisms. We have previously examined the diffraction and interference patterns produced when light shines through a narrow single slit or through a pair of closely spaced slits. If we have a larger number of equally spaced slits, the brightness maxima occur at the same locations as for just two slits, but they are much narrower.

If the spacing between adjacent slits is narrower, the spacing between adjacent maxima is greater. If we want the maxima corresponding to different wavelengths to be widely separated and not overlapping, we need to use a "transmission grating" with a large number of very closely spaced slits, perhaps 10,000 per inch as a typical order of magnitude. Sometimes a "reflection grating" is substituted for a transmission grating. Here light is reflected from a series of closely spaced steps in the grating surface, but the resultant pattern of brightness maxima looks just the same.

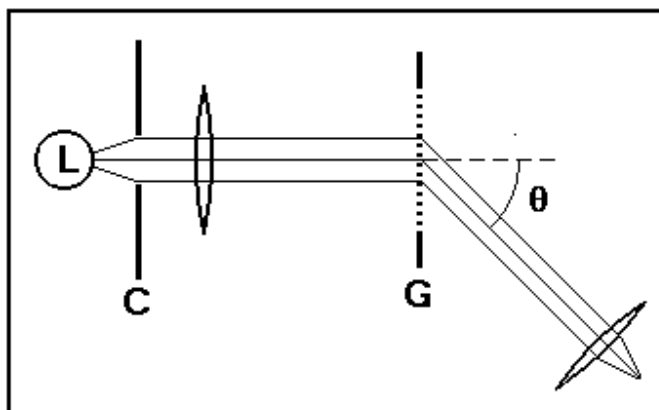


Figure 13.1. Schematic diagram of a spectrometer.

Figure 13.1 is a schematic diagram showing the essential features of an optical spectrometer with a transmission grating. Light from a source L passes through a collimating slit C and through a lens which makes the light rays parallel to each other as they travel toward the diffraction grating G . The transmitted light is observed through another lens. The angles q at which intensity maxima of order m are observed are given by

$$\sin q = ml/d, \dots\dots\dots (13.1)$$

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where d is the spacing between adjacent slits in the grating, and λ is the wavelength of the light.

PROCEDURES

You will investigate the spectra of several different light sources during this experiment. Position the lamp as close to the slit as the housing permits and set the lamp on the axis of the collimator so as to fill the collimator objective as well as possible with light. Use the leveling screws to adjust the positioning of the grating. The important angular adjustment is the one about the axis normal to the grating. It is approximately correct when light reflected by the grating returns to the collimator, illuminating its edge. Errors of a few degrees in this adjustment can be corrected for to good approximation by averaging the two values of q obtained for the maximum of order for a given wavelength on either side of the central maximum.

The maximum at $q = 0$ is independent of wavelength, and can therefore be quite bright. You may need to close down the collimating slit in order to observe this line comfortably. Determine the scale reading for the position of your eyepiece telescope that corresponds to the zero order maximum. You will have to subtract this reading from your angle measurements for the maxima of order m for various wavelengths in order to obtain the corresponding values of q .

Qualitatively scan the spectrum resulting from a particular light source in order to determine how many orders are visible. (As q approaches 90° , optical imperfections in the grating or the glass plate on which it is mounted may limit your range of observation.) The range of wavelengths of visible light is from $4.0 \cdot 10^{-7}$ m (violet) to $7.0 \cdot 10^{-7}$ m (red). Use this information to estimate the slit spacing of your grating and whether in some order maxima of order $(m+1)$ for blue light will overlap maxima of order m for longer wavelengths.

Measure the angles on both sides of the central maximum at which spectral lines of various order occur for at least two different light sources. Estimate the uncertainties in your measurements and in the values which you deduce from them. Light sources available in our laboratory and the wavelengths of their spectral lines in the visible range include the following:

- Hydrogen: 410.3, 434.2, 486.3, and 656.5 nm.

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- Helium: 402.7, 438.9, 447.3, 471.4, 492.3, 501.7, 587.7, and 668.0 nm.
- Sodium: 589.2 and 589.8 nm.
- Potassium: 404.4, 404.7, 766.5, and 769.9 nm.
- Cadmium: 508.6 nm.
- Mercury: 404.8, 407.9, 436.0, 491.7, 546.2, 577.1, and 579.2 nm.

SPECIFIC TASKS

1. Calibration: Determine the grating constant for your grating. This is the number of slits per cm, i.e. the reciprocal of the spacing between slits. Obtain separate values from the locations of the spectral lines of different order for one of the vapor lamps. Your "adopted value" will be the average of the individual results. Preferably each result should be weighted by a factor equal to the reciprocal of the square of the estimated uncertainty. If you had three results N_1 , N_2 , and N_3 , with standard deviations s_1 , s_2 , and s_3 , the weighted average N and its standard deviation s are given by

$$N = \frac{(N_1/s_1^2) + (N_2/s_2^2) + (N_3/s_3^2)}{(1/s_1^2) + (1/s_2^2) + (1/s_3^2)}, \dots \dots \dots (13.2)$$

$$\text{and } s = \frac{1}{\sqrt{(1/s_1^2) + (1/s_2^2) + (1/s_3^2)}} \dots \dots \dots (13.3)$$

You may wish to include only a selected number of individual results with especially small uncertainties, since the weighted average is not changed significantly by the inclusion of results with large uncertainties.

2. Resolution: From your observations so far, estimate whether some closely spaced lines will be sufficiently separated to allow you to measure their individual wavelengths rather than just an average wavelength for the pair. The sodium, potassium, and mercury spectra include doublets which may be suitable for this investigation. Test whether you can in fact resolve the two lines. If the first order lines are not resolved, might it be possible to resolve higher orders?

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3. Unknown wavelengths: Having calibrated your spectrometer, you can determine the wavelengths of unknown spectral lines. You can use this to determine what elements are present in a sample if you know the wavelengths emitted by different elements, or to study the spectral properties of atoms, ions, or compounds for which such information is not available or incomplete. Determine the wavelengths of a light source other than the one used in your calibration procedure, and compare your results with the "accepted" values given above.

An important step in understanding atomic structure was the realization that the energy levels of hydrogen atoms have a simple sequence of values given by

$$E_n = -13.6 \text{ eV} / n^2, \dots \dots \dots (13.4)$$

and that the frequencies of the hydrogen spectral lines are proportional to the energy differences between two levels, while the wavelengths are proportional to the reciprocals of the frequencies:

$$f \propto E_m - E_n \propto \frac{1}{n^2} - \frac{1}{m^2}, \quad \lambda \propto \frac{n^2 m^2}{n^2 - m^2} \dots \dots \dots (13.5)$$

You may wish to verify that the visible spectral lines of hydrogen correspond to transitions from levels $m = 3, 4, 5,$ and 6 to level $n = 2$.

Laser Applications

1. Calibration. Light source used: _____

$$N = 1/d = \sin \theta / \lambda, \quad s = (\cos \theta / \lambda) D \theta$$

m	1	N	s
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Weighted average of calibration: N _____
 s _____

Resolution.

Minimum measurable separation Dq between two lines:

For two wavelengths λ_1 and λ_2 , let $l = (\lambda_1 + \lambda_2) / 2$, and $Dl = (\lambda_2 - \lambda_1)$. Then for the m -th order, the separation between the two lines is

$$Dq = NmDl \cdot [1 - N^2m^2 l^2]^{-1/2}$$

Sodium 589.2 nm/589.8 nm doublet. Dq for:

$m = 1$: _____ $m = 2$: _____ $m = 3$: _____

Potassium 766.5 nm/769.9 nm doublet. Dq for:

$m = 1$: _____ $m = 2$: _____ $m = 3$: _____

Mercury 404.8 nm/407.9 nm doublet. Dq for:

$m = 1$: _____ $m = 2$: _____ $m = 3$: _____

Which of these doublets are predicted to be resolved? Can you see two separate lines experimentally?

Unknown wavelengths. Light source used: _____

$$l = \sin q / Nm$$

m	q	experimental l	accepted l
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