

Modern Physics Lab

Spectroscopy

Purpose of the experiment

- Familiarize you with advanced experimental techniques and equipment.
- Learn how to identify various elements by their emission spectrum.

Background Information

In this lab, you will learn to identify chemical elements by their spectrum. Quantum mechanics tells us that every atom has a set of exact energy levels that the atom's electrons occupy. When an electron transitions from a higher energy level to a lower one, conservation of energy dictates that the energy lost by the electron must go somewhere. This energy shows up as a photon of light with a wavelength λ that is related to the change in energy $E_2 - E_1$ of the electron:

$$E_2 - E_1 = \frac{hc}{\lambda}$$

where E_2 is the energy of the higher energy level and E_1 is the energy of the lower energy level. Since there are many such possible transitions between different energy levels in a given atom, photons of different distinct frequencies will be given off by different transitions. All of these frequencies taken together form the atom's spectrum. Since different elements have different atomic energy levels, the spectrum will be different for each element. Therefore, a spectrum can be used to identify an element. The intensities of each spectral line

will depend on the quantum mechanical probabilities of electrons making transitions between particular states. Intensities are harder to calculate from simple arguments. You can find tables which describe the relative intensities of the spectral lines for each element.

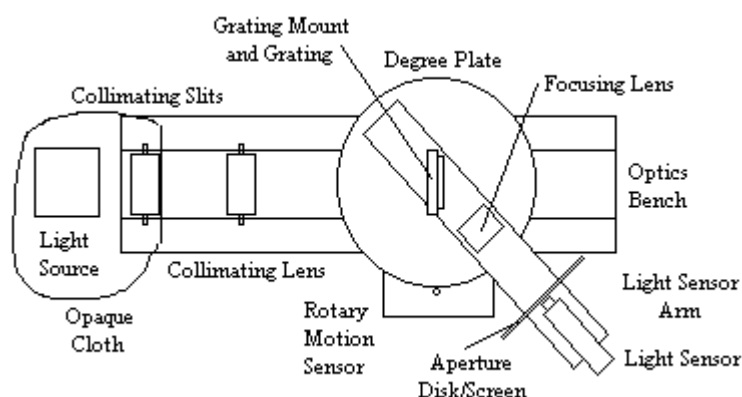


Figure 1: Schematic of Final Setup.

The spectrophotometer allows you to view and measure the spectrum produced by a light source (See Figure 1). The collimating slits and collimating lens produce a narrow beam of parallel light rays. The grating disperses the beam of light into a spectrum with different colors at different angles but with all the light of a given color in a parallel beam. The focusing lens focuses these parallel beams of color into spectral lines. The narrow slit on the aperture disk allows light of a single color to enter the high sensitivity light sensor. The high sensitivity light sensor measures the intensity of light and the rotary motion sensor measures the angle at which the light is diffracted by the grating.

You can find the wavelength of each color of light using the measured angle and the grating spacing d using:

$$d \sin \theta = m\lambda \quad (m = \dots -2, -1, 0, 1, 2 \dots)$$

where d is the distance between the rulings on the grating, m is the order of the particular maximum, θ is the angle of the diffracted light measured from the normal to the diffraction grating, and λ is the wavelength. The grating disperses light into a first order spectrum ($m = 1$) and higher order spectra ($m > 1$). The higher order spectra are broader and less bright than the first order spectra, and may overlap. Notice also that the grating is blazed, so that one side of the spectrum is much brighter than the other.

Prelab

- A screen of regularly spaced slits is called a diffraction grating. Assume that a collimated beam of light of wavelength λ has normal incidence on the grating. Show that the light passing through the grating has its maximum intensities at angles θ given by:

$$d \sin \theta = m\lambda \quad (\text{Equation 1})$$

where d is the spacing between adjacent slits in the grating, and m is the order number. Explain both the significance of the order number and why these maxima occur.

- What causes an emission spectrum, an absorption spectrum and a continuous spectrum?
- Using the Rydberg-Ritz formula, calculate the first 5 wavelengths of the Balmer series.
- Look up the accepted values for the wavelengths of the several brightest emission lines generated by helium, neon, and mercury.
- Use Equation 1 to determine the uncertainty in the wavelength.

Set Up

Warning! An emission tube in this experiment contains mercury vapor. Be extremely careful not to break this (or any) tube. If the tube breaks, *leave the area immediately*.

Caution! Handle all optics carefully. Handle the lenses only by their plastic parts. Also, avoid touching the grating *except by the edges* of the glass plate.

Please refer to the Figure 1 above as needed when setting up this experiment:

- Be sure that the power cord for the light source is plugged into a different outlet than the one used for the computer.
- Make sure that the Science Workshop 500 Interface box is connected to computer and plugged into power. The light sensor should be connected to Analog Channel A of the interface. The rotary motion sensor should be connected to Digital Channels 1 and 2. Turn on the interface power switch (on the back).
- Boot up the computer.
- The ratio of the degree plate to the small pinion post on the rotary motion sensor is approximately 60 to 1, meaning that the pinion rotates 60 times for 1 revolution of the degree plate.
- If the small pinion slips rather than turns, make sure that the thumbscrews that hold the rotary motion sensor onto the hinge are tight. You may need to loosen the screws and then push the rotary motion sensor so it is as close to the base as possible before re-tightening the screws.
- The number of grating lines on the grating is approximately 600 lines per millimeter. This translates to a grating spacing of approximately $d = 1666 \text{ nm}$.
- Using the black cloth and binder clips provided, you may want to mask off the light source so that the only light that reaches the spectrophotometer from the light source comes through the collimating slit. (The first light source you will be using is the hydrogen Balmer source.) The black cloth should be clipped to the collimating slits (see Figure 1).

Alignment of optics

The first step in almost any optical experiment is to make sure that all of the optics is positioned and aligned properly. The previous lab group may have left everything in order for you - but they also might have worked with something out of alignment. The quality of your results will often depend on how well your equipment is set up!

- Make sure the inner and outer slits on the collimating slits are aligned.
- Using the ring stand clamps, adjust the level of the optics bench such that it is at the same

level as the light source.

- Make sure that the diffraction grating is perpendicular to the incident beam. (You might check that the back-reflection of the incident light goes right back to the source.)

Positioning the Collimating Slits and Lens

The focal length of the collimating lens is about 10 cm, so the lens should be positioned about 10 cm from the slits. Use the following procedure to position the lens more precisely:

- Darken the room.
- Set up the hydrogen Balmer source at one end of the optics rail and mask it off using the procedure outlined above. Make sure the light from the source passes through one of the slits on the collimating slits and then through the collimating lens.
- Play with both the level of the optics bench and the alignment of the light source with the slits until you get the brightest light beam possible passing through the collimating lens. This is critical to getting good data.
- Rotate the light sensor arm so the aperture bracket and light sensor are out of the way and the beam of light can shine onto a distant vertical surface such as a wall.
- Adjust the distance between the collimating slits and the collimating lens so that the beam of light is neither converging nor diverging. The beam of light should stay about the same width all the way to the distant vertical surface. Hold a piece of paper in the light beam's path at various distances along the beam's path. Check to see that the light beam's width is about the same at each distance. Note that the light may not be in focus during this process.
- Adjust the collimating slits until the light beam is vertical.

Mounting and Positioning the Focusing Lens

The degree plate has markings on either side of the light sensor arm that indicate the approximate position in which to place the focusing lens. The focusing lens has two small magnets in its base that hold it in place on top of the light sensor arm. Place the focusing lens

on the light sensor arm between the grating mount and the high sensitivity light sensor.

The focusing lens focal length is about 10 cm, so the lens should be positioned on the light sensor arm about 10 cm in front of the aperture disk.

- With the room dark, set up the optics bench such that the light from the collimating slits and collimating lens shines through the grating and focusing lens. (Do not readjust your collimating slits and collimating lens since they should already be in place.)
- Move the light sensor arm so the central ray of light (zeroth order) is centered on the slit at the bottom of the aperture disk. You should be able to see the first order spectral lines on the aperture screen on either side of the central ray.
- Adjust the position of the focusing lens until the spectral lines are sharply focused.

Data collection and analysis

Now that the optical equipment is aligned and positioned correctly, you are ready to collect data:

The following instructions are for the Macintosh version of the software:

Start the data collection and analysis software on the computer by launching "Data Studio". Choose "Create Experiment". The computer should find and initialize the interface box. Next we need to tell the software what sensors are connected. Double click on "Light Sensor" on the scroll down menu. It should show the light sensor connected to Analog input A. Double click on the "Rotary Motion Sensor" which should then show up as connected to Digital inputs 1 and 2.

To create a graph to view the data as you collect it, double click on "graph" in the "displays" window. Select "Voltage - Ch. A" for the y axis. The x-axis will default to "time". To change this, drag "angular position" from the "data" window onto the graph and place it over "time". This should change the x-axis to angular position.

Position the light sensor to where you will want to begin taking data. Do not grab the sensor itself. Move the supports around the sensor. Once you are ready, click "Start" at the top of the computer screen to begin taking data.

Move the light sensor through the desired range. Note that the spacing between data points

will depend on how quickly you move the sensor since the actual data is still collected as a function of time. The data should appear on the graph as you collect it.

When you have completed the data collection, click "Stop". (Note that the light sensor saturates at a value around 5 volts. Adjust the range button on the sensor if you are saturating).

To analyze the data, begin by clicking on the "Scale to fit" button which is the first button on the top of the "graph" window.

To change the appearance of the graph further you can use the "Zoom In" or "Zoom Out" buttons on the "graph" window. You can also drag the origin of the graph to place it where ever you would like it on the graph. You can drag the values along the x or y axes in or out along the axis to change the scale of the axes.

To determine the exact position of your spectral peaks, you can use the "Smart Tool" button (6th button along the top of the "graph" window) which provides you with x,y values for any location on the screen.

If you need to clean up your data, you can remove data from the graph only by using the "Data" button on the "graph" window. To completely remove data from the program, select "Run x" on the "data" window and hit the delete key. You will have to do this under each section to completely remove the data.

You can save your data or export the data as well. Under "File" you can save your data (activity) to the hard drive or a floppy disk. This file can only be read by the Data Studio software. If you would like to do further analysis of your data using a spreadsheet or plotting program, you can export the data in tab-delimited format.

Calibration of Angle scale

The data acquisition program will give you data as voltage (intensity) vs. degrees of rotation of the motion sensor. The number of degrees of rotation is related to the angle of the diffracted beam. You can convert these values using the 60:1 ratio of rotations mentioned earlier. You can also estimate the angle by looking at the angles marked on the angle plate to make sure that your calculations make sense.

One other difficulty is that the motion sensor only detects relative motion. It starts each measurement at zero no matter where you place it. You will need a reference for your

measurement zero. Usually it is easiest to use the white light which passes straight through the diffraction grating as your zero. As long as the data you collect includes this straight through light, you will always be able to define zero.

Another way of calibrating this scale is to measure a known sample and use the known values to calibrate the scale.

- Scan the Hydrogen Balmer spectrum. You will want to slowly and continuously scan the spectrum in one direction only. Scan the first order spectrum on one side of the central ray (zeroth order), through the central ray, and through the first order spectrum on the other side. Press the Stop button when you are finished.
- Using Equation 1 for the first order spectrum ($m = 1$), the line spacing is:

$$d = \lambda / \sin \theta$$

where λ is the known wavelength of the first Balmer transition (from $n = 3$ to $n = 2$, called the hydrogen alpha transition) calculated from the Rydberg-Ritz Equation. To find the angle θ , first find the two hydrogen alpha peaks in the spectrum (one on each side of the undiffracted peak. The hydrogen alpha peak will be the tallest peak in both the dim side and bright side spectra. Then find the difference in angle between these two peaks and divide by 2. This should allow you to convert the motion sensor rotation scale to an angular scale for θ .

The Lab

**Remember to include the uncertainty
in your measurement and include units**

Data Collection

Consider the following when performing this experiment:

- Once the spectrometer is calibrated using the hydrogen spectrum, you will examine the spectra of helium, mercury, and neon. You may want to continue with more detailed analysis of the Hydrogen spectrum as well.

- Compare your values for the wavelengths of color in the helium, mercury, and neon to the accepted values for these wavelengths. Don't forget error analysis and propagation of error when doing so. You need to be able to state how confident you are in your results.
- There are five slits on the collimating slits slide and six slits on the aperture disk. You can select wider slits in order to increase the amount of light that passes through the grating and into the light sensor, but this will make a wider spectral pattern and decrease the accuracy of your measurements.
- Notice that the distance between the light source and the collimating slits and between the collimating slits and the rest of the spectrophotometer are not critical. However, the brighter the source, the brighter the spectrum.
- The high sensitivity light sensor has a GAIN select switch on top with three settings (1, 10, and 100). When you measure the spectrum, you will need to determine which one(s) to use.
- When taking data, you will want to slowly and continuously scan the spectrum in one direction only. You will need to include the central peak (zeroth order peak) of the undiffracted light to know where zero is. You may, however, choose to do some additional scans over smaller angle ranges which you can reference to less intense peaks. The instrument is sensitive to lines in the near-UV and near-IR parts of the spectrum so scan a little ways beyond what you can see visibly.
- Because the grating is strongly blazed, the spectral lines on one side of the central ray will be less bright than the spectral lines on the other side.
- The angle θ of a particular line in the spectral pattern is one half of the difference of the angle between the chosen spectral line in the first order on one side of the central ray (bright spectrum) and the matching spectral line in the first order on the other side of the central ray (dim spectrum).
- The angular resolution of the rotary motion sensor is 1440 divisions per rotation. One rotation of the pinion is 6 degrees on the degree plate. So, the resolution is fifteen seconds of arc, assuming a grating line spacing of 1666 nm.
- You may want to record the color of each spectral line in addition to any other data that you take.

- It is a good practice to save any data you wish to keep to disk. In any case, you will need to print the spectra for your lab write up.

Shut Down

- Turn off the light source.
- Be sure you have saved any data to disk that you want to keep and then Quit the program (under "File").
- Turn off the Interface box power.
- Make sure all equipment is accounted for and in place. Be sure the mercury vapor tube is put away and the grating is back in the orange box.