Atomic Spectra

HISTORY AND THEORY

When atoms of a gas are excited (by high voltage, for instance) they will give off light. Each element (in fact, each isotope) gives off a characteristic atomic spectrum, a set of particular wavelengths. One of the great early triumphs of quantum theory was in explaining these spectra. Quantum theory tells us that electrons can only occupy particular energy levels. The energy levels are quantized, in other words. To conserve energy when an electron makes a transition from a higher-energy state to a lower-energy state, a photon, with an energy corresponding to the energy difference between the electron energies, is emitted.

The Danish physicist Neils Bohr presented a solar-system model of the atom, in which the electrons occupy particular circular orbits centered on the nucleus. It is important to understand that the Bohr model is not a true picture of how the electrons behave in an atom, but we use the Bohr model because it is a good starting point in understanding how to determine the energies of the energy levels.

Using his model Bohr predicted that the energy levels of the electron in a hydrogen atom are given by:

$$E_n = -\frac{\mu e^4}{8\varepsilon_o^2 h^2 n^2} = -\frac{13.6 eV}{n^2} \qquad \text{Equation 1}$$

where n is any positive integer, and μ is known as the reduced mass. If m_e is the mass of an electron and m_H is the mass of the hydrogen nucleus, the reduced mass is given by:

$$\mu = \frac{m_H m_e}{m_H + m_e} \qquad \text{Equation 2}$$

ABOUT THIS EXPERIMENT

This is a challenging experiment that requires you to work hard at your experimental techniques. Note that the room should be dark when you do your measurements, so the room lights do not overwhelm the light from your light source.

THE DIFFRACTION GRATING

In the laboratory you will use a diffraction grating to split a particular atomic spectrum into its constituent colors. For a grating with a grating spacing of d, constructive interference occurs at angles given by:

$$d \sin \theta = n\lambda \qquad\qquad \text{Equation 3}$$

where n is an integer representing the order and λ is the wavelength. The figure below shows the ray diagram for a particular first-order line.
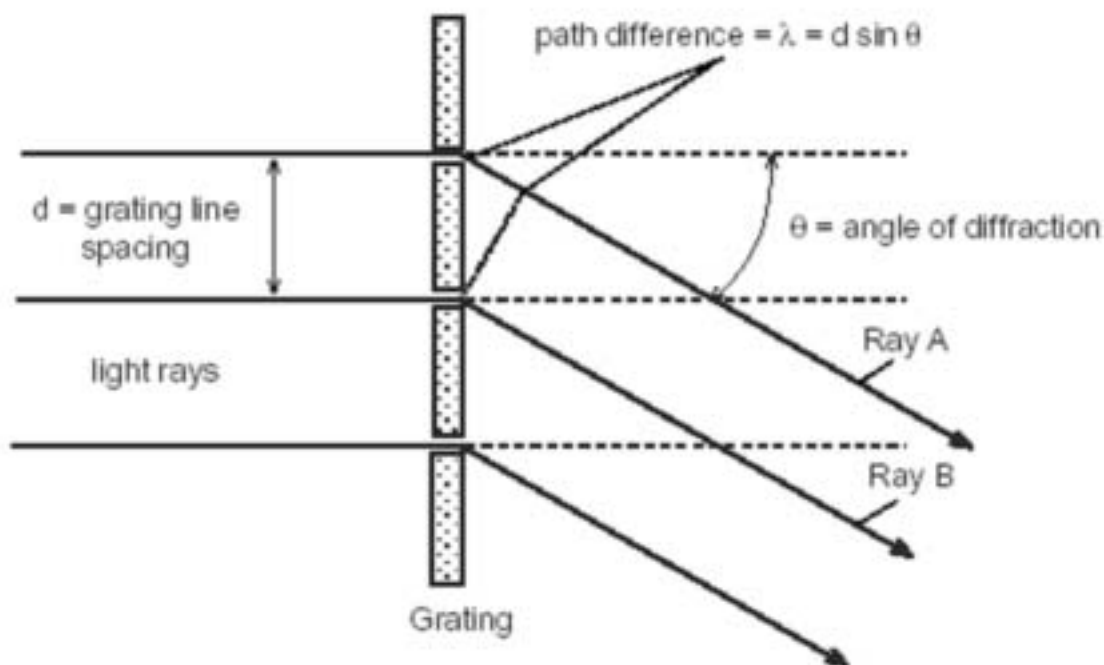

Figure 1 : Ray diagram for first order diffraction pattern

The resolution of the diffraction grating is the smallest wavelength difference Δλ necessary to produce separate (resolved) images. For a grating with N lines the resolution is given by:

$$\Delta\lambda = \frac{\lambda}{nN} \qquad\qquad \text{Equation 4}$$

The dispersion of the grating is:

$$\frac{d\theta}{d\lambda} = nd \cos\theta \qquad\qquad \text{Equation 5}$$

OBJECTIVES AND APPARATUS

In this experiment your objective is to measure the wavelengths of light emitted by hydrogen and other sources. You will then compare your results with the wavelengths predicted by the Bohr Model. To do this you will make use of a spectrometer. The spectrometer uses a diffraction grating to split the light into its constituent wavelengths, and also has a sensitive light sensor to record the intensity of light observed at particular angles. To help you analyze the data the readings from the light sensor, as well as readings of the angle, are passed to a computer so you can easily obtain graphs of light intensity as a function of angle.

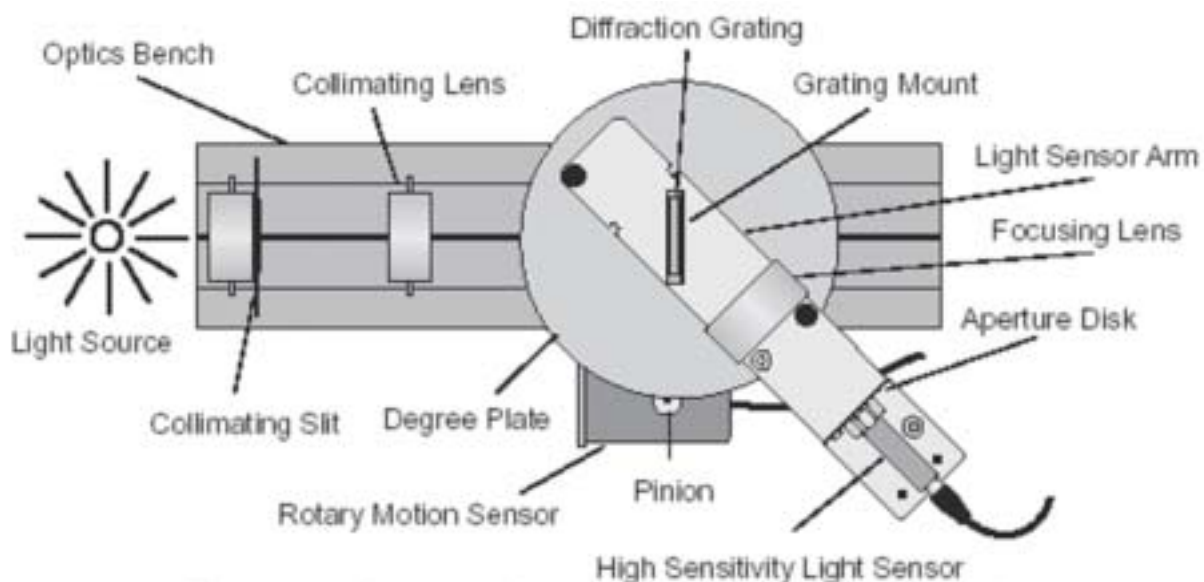The basic components of the spectrometer are shown below.

Figure 2: Spectrophotometer System (Top View)

- The rotary motion sensor is used to measure the angle. The pinion connecting the rotary motion sensor and the degree plate is designed to rotate 60 times for each full revolution of the degree plate, and the calculations in the computer take that into account.

- The diffraction grating is blazed. The implication of this is that the spectral lines on one side of the diffraction pattern will be brighter than the spectral lines on the other, as you will notice when you take measurements. **You should not touch the diffraction grating with your fingers, nor try to clean it because it scratches easily. If you need to move the grating touch the glass slide only by the edges.**

- The light sources you will use include hydrogen, helium, and deuterium discharge tubes, as well as a sodium arc lamp. In each case the gas will be excited by a high voltage, and will emit photons of particular wavelengths.

EQUIPMENT SET-UP

It is important that the light reaching the diffraction grating is made up of parallel beams. The apparatus includes collimating slits and a collimating lens near the light source to ensure this (see figures 3 and 4). The slits are mounted on a movable slide. If you loosen the thumbscrew in the slits plate you can move the slide back and forth to choose which slit the light passes through.

Positioning the collimating slits and collimating lens:

1. If the diffraction grating is magnetically mounted on the degree plate, remove it carefully. **Hold the glass slide at the edges.**

2. Position the collimating lens about 10 cm from the slits. Arrange a source so light passes through a slit and then through the collimating lens. Rotate the light sensor out of the way so the light travels for a long distance.

3. Adjust the distance between the slits and the collimating lens so that, after passing through the slit and lens, the beam of light is neither converging nor diverging (i.e., the beam has a constant width). You can check the beam width by holding a piece of paper in the beam at various distances from the collimating lens.

4. If the light beam is not perfectly vertical, either loosen the thumbscrew that holds the slits slide and adjust the slide, or loosen the brass thumbscrews that hold the slits plate onto the holder and adjust the plate, until the collimated beam is vertical. Tighten the screws again once the orientation is correct.
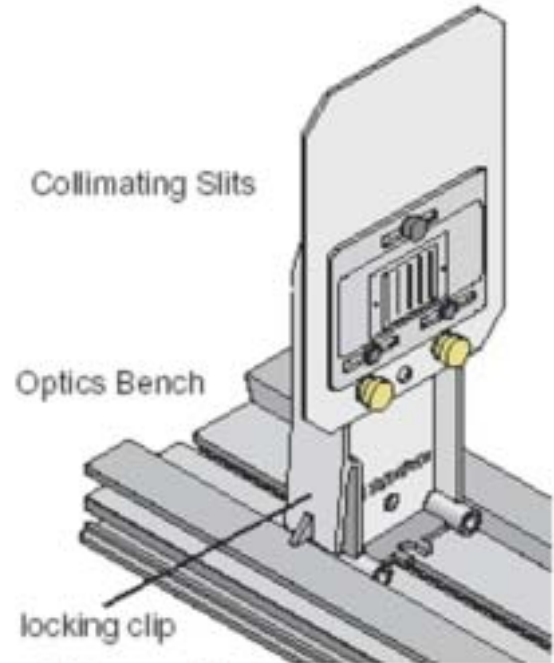
Collimating Slits

Optics Bench

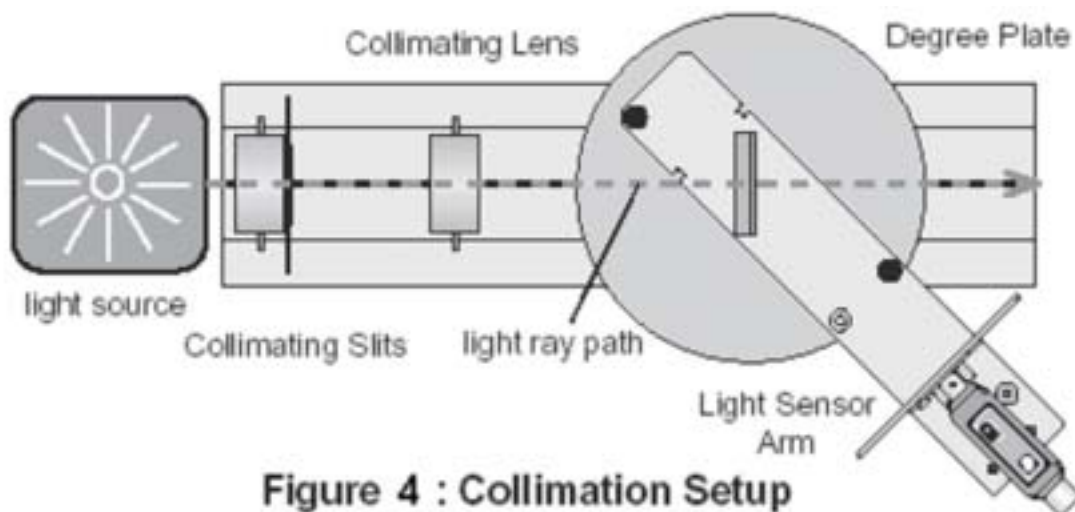locking clip

Figure 3 : The Slits

Figure 4 : Collimation Setup

Mounting the diffraction grating:

The diffraction grating is mounted on one side of a rectangular glass plate, on the same side of the plate as the magnetic strips that hold the grating to the grating mount. Attach the grating to the grating mount so the glass side of the grating faces the light source. **Once again, remember that the diffraction grating is very delicate, and it should not be touched or cleaned for any reason.**

Positioning the Focusing Lens

The focusing lens has magnets to hold it in place on the light sensor arm. Position the focusing lens between the grating and the light sensor, about 10 cm in front of the aperture disk. Markings on the degree plate indicate the approximate position in which to place the lens.

Arrange a light source and the collimating slits and lens so a beam of light shines through the grating and focusing lens. The room should be fairly dark at this point. Position the light sensor arm so the central ray of light (the "zeroth order") is centered on the slit at the bottom of the aperture disk. Adjust the position of the focusing lens until the spectral lines, which should be visible on the aperture screen on either side of the zeroth order are sharply focused.
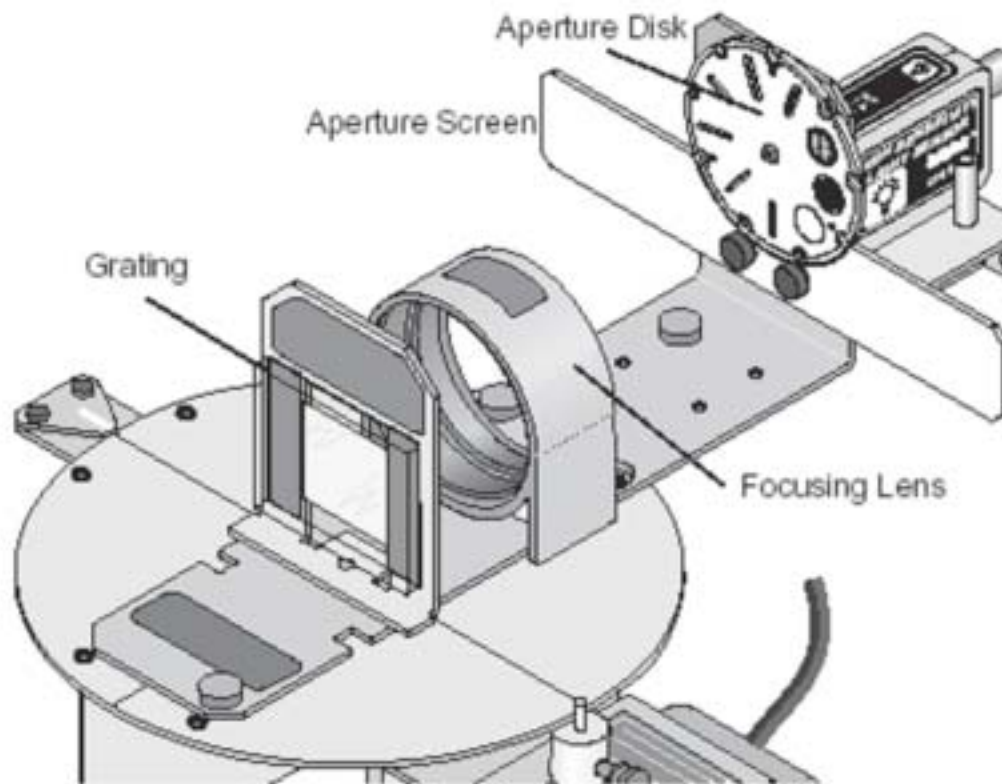
Figure 5 : Position Focusing Lens

GENERAL INFORMATION

The Light Sensor

The High-Sensitivity Light Sensor has a gain (amplification) switch on the top with three settings. When you measure a spectrum start with the lowest gain setting (1) to measure the brightest lines. Then switch to the next setting (10) and re-scan the spectrum to measure the dimmer lines. Then re-scan again at the highest setting (100) to measure the dimmest lines.

It is also possible to amplify the signal from the light sensor using the Data Studio software. The normal sensitivity setting is "Low(1x)". The other settings are "Medium(10x)" and "High(100x)". In general, your data will be better if you increase the gain setting on the sensor before you increase the sensitivity setting in the software.

Note that using the switch on the light sensor, and amplifying the signal in the software, is crucial to the success of the experiment. With the spectrum tubes in particular you are trying to measure very low light levels. Blocking out as much stray light as possible (in particular, turning the computer monitors away from the detector), and making extensive use of the amplification you have available, will give you the best chance to see the low-intensity lines that are present.

You can even change the gain switch on the light sensor in the middle of taking data. For instance, you might want to keep it at 100 when you're scanning through the spectral lines but move it to 1 when you move the sensor through the zeroth order, then switch back to 100 again.

Slit Widths

There are five slits on the collimating slits slide and six slits on the aperture disk. Using wider slits allows more light to pass through to the light sensor but decreases the accuracy of the measurements. If you don't pick up any spectral lines, or you're trying to find additional lines, use wider slits on the collimating slide and/or the aperture disk. If you have plenty of spectral lines try using narrower slits.

Angular Resolution

For every full rotation of the degree plate, the shaft of the Rotary Motion Sensor should rotate approximately 60 times. Thus, a single rotation of the Rotary Motion Sensor shaft represents approximately 6° of angular displacement for the degree plate. The maximum resolution of the Rotary Motion Sensor is 1440 divisions per rotation, so the best-case angular resolution of the spectrometer is 6°/1440, which is one quarter of a minute of arc, or 15 seconds of arc. This corresponds to a wavelength resolution of about 2 nm, given the grating line spacing of about 1667 nm.
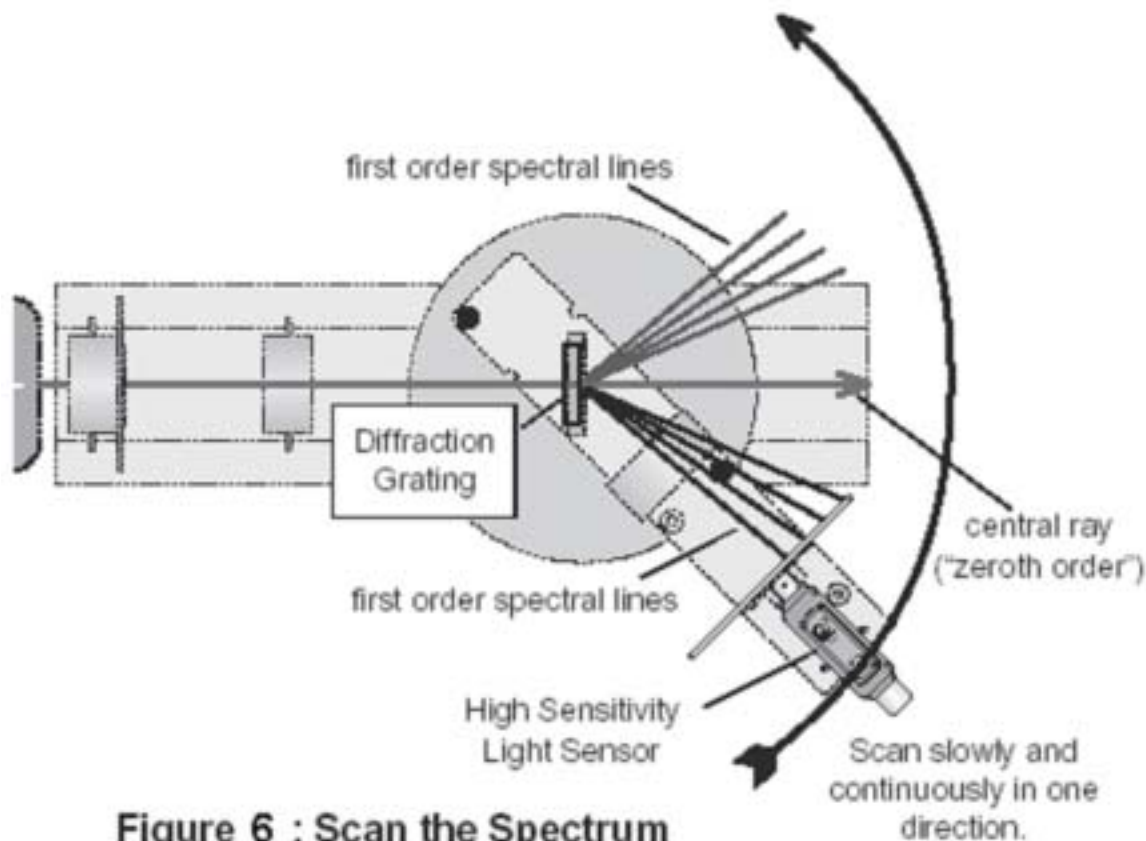
Scanning a Spectrum

first order spectral lines

Diffraction Grating

central ray ("zeroth order")

first order spectral lines

High Sensitivity Light Sensor

Scan slowly and continuously in one direction.

Figure 6 : Scan the Spectrum

To scan a spectrum:

- Use the threaded post under the light sensor to move the light sensor arm so the light sensor is beyond the far end of the first-order spectral lines on one side (but not within the range of the second-order lines).

- Start collecting data in the Data Studio program.

- Scan the spectrum continuously but slowly in one direction by pushing on the threaded post to rotate the light sensor arm. Scan through the first-order spectral lines on one side of the central ray and continue all the way through the first-order spectrum on the other side.

- The angle θ of a particular line is half the difference between the angle of that line on one side of the zeroth order and the angle of the corresponding line on the other side of the zeroth order. If a dim line appears on only one side you can find its angle by taking the difference between its angle and the angle at which the zeroth order appears.

THE EXPERIMENT

PART I

On the computer double-click on the "Spectroscopy" program in the "Modern" folder. This will start the *Data Studio* program with appropriate settings and a graph window.

The number of lines on the diffraction grating is roughly 600 per millimeter. This corresponds to a line spacing of about d = 1667 nm.

To find a more precise value for the line spacing, use the sodium lamp to calibrate the grating. Note that the sodium lamp takes a few minutes to warm up. The average wavelength of the sodium doublet (the two closely spaced yellow lines) is 589.3 nm. Measure the angle between the two first-order yellow lines, one on one side of the zeroth order and one on the other, and then divide by two to get the diffraction angle for the 589.3 nm wavelength. Use this information to determine the grating spacing for your diffraction grating.

To do the measurement, scan through the spectrum following the procedure outlined on the previous page. Position the light sensor beyond the last first-order spectral line on one side, and then hit the "Start" button in the *Data Studio* program. Scan slowly through the spectrum (see figure 6) and then hit the "Stop" button in the *Data Studio* program when you are finished. The Smart Tool is useful for taking readings off the graph on the computer – you can find the Smart Tool by clicking the appropriate button above the graph.

Note that you can delete data runs from *Data Studio* by using the Experiment menu.

Question 1: What is your value of d? Is the above method a reasonable way of calibrating the grating? Comment on whether you think it would be better to use the second-order yellow lines for sodium, in particular.

PART II

Now you are ready to scan through the spectra from the different elements you have available. You should set up a reasonable table before each step to help you keep track of your data and streamline your calculations.

For each trial, the *Data Studio* program takes the initial position of the Rotary Motion Sensor as the zero position. For some measurements it may be helpful to start each trial at the same position. If you take one of the small thumbscrews that are stored on the light sensor arm and screw it into one of the holes near the outer edge of the degree plate, it will act as a stop so you can start the degree plate from the same angle each time.

1. Hydrogen: carefully insert a hydrogen discharge tube into the power supply and scan through the second-order and first-order spectra on both sides of the zeroth order. Determine the angles and wavelengths of the lines in the hydrogen spectrum. You will probably need to scan through the spectrum a few times to get good data. Use the gain settings on the light sensor, and adjust the slit widths, as discussed in the "General

Information" section of this write-up. Also, remember to try to block as much stray light as possible from entering the light sensor while you are recording data.

The "Scale-to-fit" button, the left-most button above the graph, is rather useful. Press it to see what happens, and then click-and-drag on the graph to select a region you want to zoom in on and hit the "Scale-to-fit" button again.

2. Deuterium: the object here is to see if you can tell the difference between the deuterium spectrum and the hydrogen spectrum. With the hydrogen spectrum still on the screen, carefully replace the hydrogen tube with the deuterium tube without moving the positions of any other part of the system. Then scan through the second-order and first-order lines for deuterium. Keep the slit widths as narrow as possible to maximize your resolution.

3. Sodium: see if you can measure the separation between the sodium D lines (the two yellow-orange lines). Measure the angular displacement between these two lines for as many orders as you can.

4. Helium: carefully insert a helium discharge tube into the power supply and scan through the first-order spectrum on both sides of the zeroth order. Determine the angles and wavelengths of the lines in the helium spectrum.

QUESTIONS AND ANALYSIS

Question 2: For hydrogen, compare your measured wavelengths to the predicted wavelengths for hydrogen. Assuming the lower level is the same for all the lines you observed in the hydrogen spectrum, make an energy level diagram for hydrogen. Label the energy axis in electron volts.

Question 3: A deuterium nucleus has a mass twice that of hydrogen – while the standard hydrogen nucleus consists of just a proton, the deuterium has a proton and a neutron. Calculate the difference in wavelength produced by the difference in reduced mass μ for two or three of the visible lines. Predict the angle between these hydrogen and deuterium lines. Can you resolve them with your spectrometer?

Question 4: Sodium "D" lines are at wavelengths of 5889.95Å and 5895.92Å. Based on this, what angle do you expect to observe between them in the first order spectrum? What angle did you actually measure?

Question 5: Based on your observations of deuterium and sodium, was the resolution of the spectrometer limited only by diffraction? What else, if anything, limits the resolution of the spectrometer?

Question 6: Because helium has two electrons we expect its spectrum to differ from that of hydrogen. However, for one electron in the ground state and the other in an excited state, the effective charge seen by the excited electron is still just e$^+$. Therefore, you should observe transitions between states with similar energies as those seen in hydrogen. If the two electrons have their spins aligned opposite to one another we call that the singlet state, or parahelium; if the spins are parallel to one another that is the triplet state, or orthohelium.

The difference in binding energy for the singlet and triplet states causes each energy level to split into two states, leading to spectral line pairs (doublets). Examine your helium data and identify the hydrogen-like transitions that you observed. Because the lower level differs for different transitions, an energy level diagram (see Figure 7) is very difficult to produce. You may simply want to compare your wavelengths to those in Figure 8.
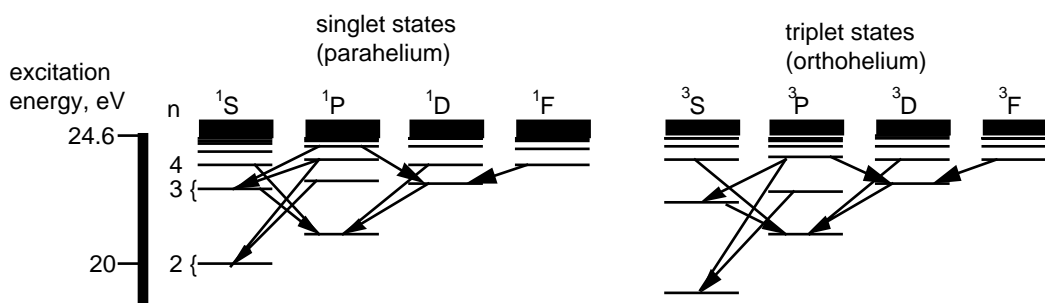

Figure 7. Excitation Energies.

Figure 8. Spectrum of Helium.

     Try to make an energy level diagram for helium. Compare it with Figure 7; note that you probably observed transitions between the higher levels and any one of the four n=2 levels. Only transitions indicated by arrows are allowed (by the selection rules under spin-orbit or LS coupling, namely $\Delta L = \pm 1$).