

## *NS 102 Lab 2 Spring 2010:*    **Spectroscopy**

### **Background**

In this lab we will study light produced from elements excited in gas discharge tubes. In these tubes, the atoms are excited by electrons under conditions similar to the outer atmospheres of stars. Light from these atoms is concentrated into distinct colors, or wavelengths, of light and the wavelengths at which these spectral lines occur are different for each gaseous element, thus each element has its own “signature” by which it can be identified. Many ordinary elements, such as sodium, can be made to give out light at low temperatures, we can make a gas flame glow yellow if we sprinkle it with salt, and spectroscopy can be used to detect and measure trace elements in a material. Many new elements were first discovered in the 19<sup>th</sup> century by looking at the spectra of rocks in a flame or electric arc.

Although hydrogen and helium are the most abundant elements in the universe, their lines in the sun are quite weak because the strength of the lines depends critically on the physical conditions in the star. Hydrogen was first identified on earth by Angstrom in 1853 using an electric arc to excite the atoms and was detected in the sun a decade later. Angstrom measured the 4 lines of hydrogen very accurately, but it was not until 1885 that Joseph Balmer, (a sixty year old school teacher and mathematician with no physics background ), found the correct mathematical relationship between the wavelengths of hydrogen in 1885. The fact that the mathematical relationship was simple and appeared to be exact within very precise measurements was recognized as being extremely important since it suggested that whatever processes were responsible for making the spectral lines was connected with integer numbers. However, the explanation of the spectrum of hydrogen required the overthrow of 19<sup>th</sup> century classical physics in favor of the first version of quantum theory by Bohr in 1915.

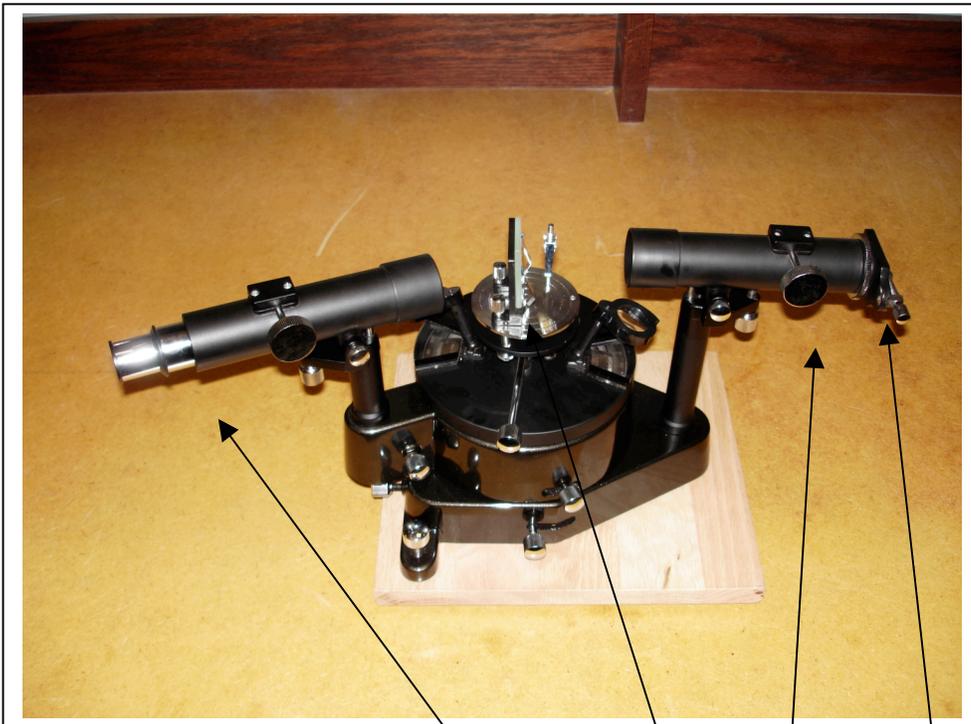
When other elements were identified in the solar spectrum it was realized that, by studying spectra, we can find out what stars are made of. Lines never seen on earth were detected in the solar spectrum in 1869 and were pronounced to be due to an entirely new element Helium not seen on earth. Helium was only discovered on earth in 1895; Ramsey, searching for new elements was taking spectra of rocks containing Uranium and other heavy metals and found the lines by accident, an observation that ultimately led to the development of the nuclear age.

### **The Spectroscope**

The study of spectra was thus essential in the development of modern physics, and most of our knowledge of the universe comes initially from measurements of light from stars and galaxies with spectroscopes. The spectroscope is capable of making extremely precise measurements of wavelength. The spectrograph you are using is also almost identical to the instruments used by scientists of the early 20<sup>th</sup> century, only then these instruments were extremely expensive and made by only a handful of craftsmen in the world!

The spectroscope consists of three basic elements:

- (1) A collimator consisting of a slit and lens. The collimator produces a parallel beam of light in one direction.
- (2) A dispersive device that bends the light at an angle that depends on the wavelength of light (usually a grating)
- (3) A telescope that collects the light and focuses it onto a detector (in your case, your eye).



***Photo 1: The spectroscope showing the telescope, grating, collimator and slit***

The dispersive device almost universally used is a grating that consists of an enormous number of lines ruled on a substrate. The grating you use is a replica of a master grating ruled at one of a small number of places in the world, using a process similar to that used in making CDs. The spacing between the lines is about 1/10 of the diameter of a human hair and the distance between each line is controlled to less than the diameter of a single atom. Light falling on the grating is diffracted into a pattern of maxima and minima. The zeroth order maximum is produced by light passing straight through the grating undiffracted, but the grating diffracts the light into other maxima. The spectrometer contains a number of locking screws that enable you to move the scales and parts of the spectrometer to different positions. You should familiarize yourself with

which screw locks which part of the apparatus and discuss the adjustment of the instrument with your TA>

The relationship between the angle of diffraction and the wavelength is given by

$$m \cdot \lambda = d \cdot \sin\theta$$

Where m is the order of the maximum

$\lambda$  is the wavelength in microns

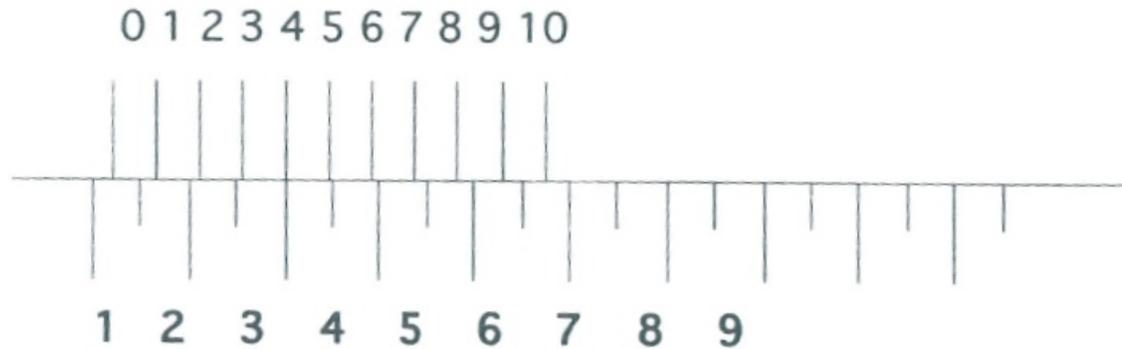
d is the spacing of the lines on the diffraction grating, also in microns

( 1 micron = 1  $\mu\text{m}$  =  $10^{-6}$  meters)

Visible light has a wavelength of about 0.5 microns and the ruling spacing is about 2 microns. [Question: What is a typical angle of diffraction for a grating with a ruling of 600 lines/mm?]

You will notice that the telescope is mounted on a table with a Vernier scale that is similar to the one used in the parallax equipment. The angle is measured in two parts, the angle in degrees (the big divisions on the outer dial are in degrees; the smaller divisions halfway between the degree marks are half degree positions) and a so-called Vernier scale that enables you to measure the angle much high accuracy than estimating the distance between two marks by eye. The Vernier scale works because we can determine whether two lines are continuous or broken to very high accuracy. Using the magnifying lens, you should look at the scale and see at which position the marks on the Vernier and outer scale match up.

Figure 1 gives an example of a Vernier capable of measuring to 0.1 divisions.



**Figure 1. Base 10 Vernier. Position is 1.4**

## Experiments

In the first experiment, we will use one of the direct viewing spectroscopes available in the lab. This spectroscope consists of a very clever grating that acts both as

the collimating and telescope optics. There is a scale underneath the lines. The red lines are at about 633 nanometers (nm).  $1 \text{ nm} = 10^{-9}$ . A typical atom is a few tenths of a nm in “size”.

Point the device at one of the overhead fluorescent lamps and you should see a series of lines of different colors. You should also see a background spectrum which goes continuously from black to red to blue and then on to black again. If you look out the window you should see the lines disappear and the background light get stronger. This is a general feature of most astronomical spectra; there is a smooth spectrum determined by the temperature of the body (called the Blackbody Temperature), and there are often a number of lines superimposed on this background. The spectrum of the sun appears to be mostly continuous with occasional dark lines. This is caused by elements in the atmosphere of the sun absorbing light strongly at certain wavelengths.

The gas discharge lamps you will use in this lab work in a different way, resulting in a spectrum of lines rather than a continuous spectrum. The lamps consist of two electrodes at either end of a narrow tube. The tube is evacuated to less than a millionth of the pressure of the atmosphere, and an electric voltage is applied across the tube, exciting the electrons in the atoms of the gas. The excited electrons then transition back to lower energy levels, giving off the extra energy as a photon with a wavelength corresponding exactly to the energy difference of the transition. As a result, the gas in the tube emits a number of bright lines.



*Photo 2: Spectrometer set up to measure gas discharge tube spectrum.*

## Using the Spectroscope

In the first part of the lab you will measure the wavelengths of the lines emitted by different gas discharge lamps and identify the element in the tube.

**(1) Assemble the lamp.** The first thing to do is check to see if the lamp is in the OFF position. If not, switch the lamp into the OFF position. Then insert the lamp marked “Hydrogen” into the lamp holder, and then move the switch on the lamp to ON. The lamp will now be illuminated when the pedal is pressed. **DO NOT TOUCH ANY PART OF THE TUBE** since there are 5000 volts across it! Moving the whole unit by the base is fine. Roughly align the lamp with the slit.

**(2) Focus the crosshairs.** Cover the lamp with a piece of white paper. Move the telescope out of the way (unclamp it first using screw #4 if necessary), and look through the grating into the collimating lens. You should be able to see an image of the slit. Use screw #11 to open the slit as wide as possible. Now, use the telescope to look directly into the collimator lens. Rotate the telescope until you can see the slit clearly in the eyepiece, then re-clamp the telescope with screw #11.

As in the parallax lab, you should be able to see a vertical and horizontal crosswire in the field superimposed on the image of the slit. To bring the crosshairs into focus, push the eyepiece tube all the way in and then pull it towards you until the crosshairs are sharp. Rotate the eyepiece until the crosshairs are vertical and horizontal.

Now close the slit as small as possible (screw #11), simultaneously adjusting the position of the telescope (using the fine adjustment knob, screw #2) so that the vertical crosshair remains visible in the slit.

**(3) Align the lamp.** Now remove the white paper and turn the lamp on by pressing the pedal. Carefully adjust the position of the lamp until the slit is illuminated as brightly as possible.

The image of the slit is the undiffracted (zeroth order) maximum. All wavelengths of light will be present in this image, so it should appear to have the same color as the lamp. Move the telescope with the fine adjustment knob (#2) if necessary so that the image of the slit is on the vertical crosshair.

**(4) Set the Vernier scale.** Release the appropriate screw #1 and rotate the table by hand until the scale reads a multiple of 90 degrees. Tighten this screw carefully, and then adjust the scale to zero minutes by using screw #2. Record this angle measurement; this will be your ‘zero’ point. **DO NOT ADJUST SCREW #2 AGAIN**, or you will effectively recalibrate the scale and need to redo all measurements!

**(5) Measure the angle of the spectral lines.** Move the telescope in either direction until you see some spectral lines. Red is the longest wavelength we can see (out to about 670 nm), violet is the shortest (about 360 nm); there is radiation on either side of these wavelengths but the eye is not sensitive to these wavelengths. [Question: Which color will you see first? You should be able to figure this out from the grating equation.] You will see some bright lines, similar to those you saw in the handheld spectroscope; you may also see many more faint lines which may be from contaminants in the gas (spectroscopy is very sensitive and you can detect very small quantities of other elements!). If you have difficulty seeing the lines use the black cloth to reduce the effect of ambient light.

Measure as many bright lines as you can. You should be able to see 3 fairly easily, but the fourth one is quite hard to see. It is important to accurately center the telescope crosshair on the line (don't forget to clamp the telescope!). You will have to take the black cloth off the spectroscope and measure the angle using a flashlight to illuminate the vernier scale if the room is too dark. Record each angle along with the color of the line.

**(6) Determine the wavelength of the lines.** Calculate the wavelength of each line using the grating formula and the spacing between the lines of the grating. Compare these with the known Hydrogen wavelengths given below. If your measurements do not agree with the known wavelengths, redo the measurement and/or calculation.

Wavelength (nm)	Transition	Color
410.2	6 → 2	violet
434.0	5 → 2	violet
486.1	4 → 2	cyan
656.3	3 → 2	red

**(7) Graph the Balmer series.** The spectral lines you observe correspond to the first four transitions in the Balmer series, the transitions of electrons to the n=2 level from higher energy levels. Plot a graph of the wavelength you measure vs the number of the line (n), numbering the first line as n=3, the second as n=4, etc. The numbering starts at 3 because that is the first transition in the Balmer series, as you can see from the table above. This plot should look smooth so that you could imagine using it to predict where the missing line would be if you had missed one, or to predict the next line in the series if there are more. The wavelength of the photon emitted in a transition is given by the following relation:

$$\frac{1}{\lambda} = R \left( \frac{1}{n_2^2} - \frac{1}{n_1^2} \right)$$

Where  $\lambda$  = wavelength of emitted photon  
 R = Rydberg constant  
 $n_1$  = starting energy level  
 $n_2$  = final energy level

For the Balmer series,  $n_2 = 2$ .

**(8) Determine the Rydberg constant.** Plot a new graph of  $1/n^2$  vs  $1/\text{wavelength}$ , where  $n$  is again the number of the line. This graph should be a straight line, as can be seen by solving the above equation for  $(1/n_1^2)$ . Using this graph, determine the value of the Rydberg constant.

**(9) Identify unknown elements.** Turn off the lamp using the switch on the side, and replace the bulb with one of the color-coded bulbs. As before, use the spectrometer to measure the angle of the spectral lines (start from step (3)). Determine the wavelengths of the lines you measure, and identify the element using the following table.

Helium	Argon	Neon	Mercury
447	501	454 651	399
469	519	471 660	436
492	544	475	546
502	547	483	571
588	550	488	579
668	557	496	615
707	559	534	691
	560	540	
	565	585	
	591	603	
	697	607	
	750	614	
		616	
		622	
		627	
		633	
		638	
		641	