Name_____ Date: _____ Course number: _____

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*Name:*_____ *Partners' Names:*_____

*Laboratory Section:*_____ *Table No:*_____

*Laboratory Section Date:*_____ *Grade:*_____

Last Revised on October 22, 2020

EXPERIMENT 14

The Atomic Spectrum of Hydrogen

You should watch Lab 14 video (3:34 min) (Turn CC on for Captions)
https://www.youtube.com/watch?v=XGT15x1t49c

Read the lab manual and the Lab Brief-Notes which includes photos of apparatus. Do the prelab assignment and upload to blackboard. READ IN ADVANCE all the Questions in the postlab section and take notes as to how to answer them. This way, you will take less time to complete the postlab after you do the Lab. If you need clarification ask the TA in lab.

0. Pre-Laboratory Work [2 pts]

1. You will be using a diffraction grating in this lab exercise as a dispersive element in a spectrometer. When you begin to examine the Balmer series of atomic hydrogen, you will observe an indigo line, a red line and a violet line as you move the spectrometer's telescope away from the zero angle (zeroeth order) position. What will be the sequence of the spectral lines, starting from the zero angle position? Explain why, showing some calculations or a diagram. (1pt)

2. What is the expected measured *grating separation*, *d*, if you use a 600 groove/mm grating? a 300 groove/mm grating? Show your work. (1pt)

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The Atomic Spectrum of Hydrogen

1. Purpose

The purpose of this experiment is to verify the quantum nature of the Balmer series, specifically for atomic hydrogen, using sodium as a calibration source.

2. Introduction

One of the earliest successes of quantum mechanics was the explanation of the spectrum of atomic hydrogen. It has long been known that atomic hydrogen had some regular features in its spectrum. These regularities can be expressed as,

$$\frac{1}{\lambda_{i,j}} = R\left(\frac{1}{n_i^2} - \frac{1}{n_j^2}\right) \qquad \textbf{Equation 14.1}$$

where $n_i < n_j$ are both integers and R is a constant. The spectral lines are classified into series that are sets of lines with a common value of the integer, n_i. The expression for wavelength has been written as the wavenumber (inverse wavelength, usually quoted in units of cm^{-1}) of the j^{th} member of the i^{th} series. The various series of the spectrum of atomic hydrogen are listed in *Table 14.1*.

According to the Bohr theory, the Rydberg constant, R, is given to first approximation by,

$$R = \frac{k^2 me^4}{4\pi\hbar^3 c} = 1.097\,x10^{-2}\ nm^{-1} \qquad \textbf{Equation 14.2}$$

where e and m are the electron charge and mass, respectively, c is the velocity of light, $\hbar$ is Planck's constant divided by 2π, and $k = 1/4\pi\varepsilon_o$. Sometimes there is a small correction that takes into account the mass, M, of the nucleus. This involves replacing the mass of the electron, m, with its reduced mass, μ, given by,

$$\frac{1}{\mu} = \frac{1}{m} + \frac{1}{M} \qquad \textbf{Equation 14.3}$$

In this lab you will examine the spectrum of atomic hydrogen in the visible region. This will restrict your test of the theory to three spectral lines of the Balmer Series. The chart on the wall of the laboratory should be sufficient to verify the quantum nature of the expression for the Balmer series and allow you to obtain an estimate of the hydrogen spectrum. You can also verify the value of the Rydberg constant by explicit calculation using *Equation 14.2*.

The apparatus for this experiment consists of a telescope spectrometer with *a diffraction grating* as its dispersive element, as in *Figure 14.1*. A diffraction grating is a planar device with a certain number of parallel "grooves" per unit length. These grooves are separated by a constant distance, *d*. The grating is situated on one side or *face* of a slab of glass. The grating

holder should specify the face upon which the grating has been placed. The grating will also be labeled with the number of grooves per mm. This number is approximate only and the true grating separation must be measured.

In *Section 3.1* you will align your spectrometer so that the telescope and collimator are focused properly on the slit image, and the grating is perfectly perpendicular to the optical path. In *Section 3.2* you will measure the groove separation of your particular grating by using a known wavelength of the sodium spectrum. In *Section 3.3* you will measure the angles of some of the spectral lines of the Balmer series. These angles will be converted to wavelength using the calibration value obtained in *Section 3.2*.

Series Name	*Wavelength Range*	*Series Expression*
Lyman	Ultraviolet	$\frac{1}{\lambda} = R\left(\frac{1}{1^2} - \frac{1}{n^2}\right)$, $n \geq 2$
Balmer	Near UV & Visible	$\frac{1}{\lambda} = R\left(\frac{1}{2^2} - \frac{1}{n^2}\right)$, $n \geq 3$
Paschen	Infrared	$\frac{1}{\lambda} = R\left(\frac{1}{3^2} - \frac{1}{n^2}\right)$, $n \geq 4$
Brackett	Infrared	$\frac{1}{\lambda} = R\left(\frac{1}{4^2} - \frac{1}{n^2}\right)$, $n \geq 5$
Pfund	Infrared	$\frac{1}{\lambda} = R\left(\frac{1}{5} - \frac{1}{n^2}\right)$, $n \geq 6$

Table 14. 1

3. Laboratory Work

3.1 Spectrometer Alignment

The spectrometer needs to be aligned to ensure accurate measurements of the sodium spectral lines (also on the chart on the wall) and hydrogen spectral lines. A side view of the spectrometer is shown in *Figure 14.1*. Below the telescope there is a pair of knobs. If you loosen the top knob, then the telescope will be free to move. Loosening the bottom knob allows the grating platform to rotate. If you rotate the platform, then the angles visible in the window on the platform will change. Learn how to keep careful track of these changes.

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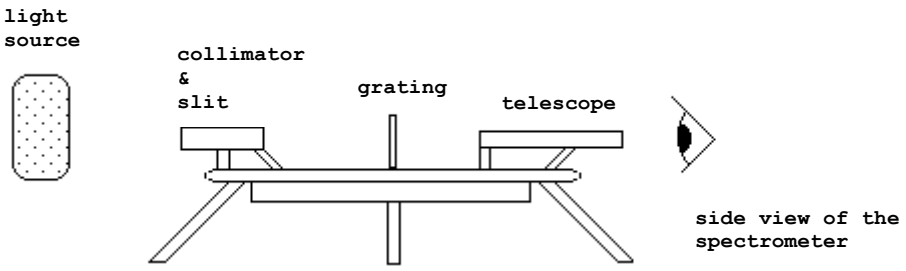

Figure 14. 1

Procedure

1. Turn on the sodium lamp. It needs a few minutes to warm up. You will know it is ready when the emitted light has a warm yellow glow. Place the lamp in front of the slit. Center it by eye as well as you can.
2. Familiarize yourself with all of the controls on the spectrometer. Learn the effect of loosening and tightening each knob as described in the paragraph above. By mastering the operation of the spectrometer *now*, you will save yourself time and frustration were you to loosen or tighten something incorrectly *later*.
3. Rotate the *telescope* so that it points at a far wall with no obstruction (i.e. does not look at the slit.) Focus the *telescope* at infinity. For instance, focus upon an object on a faraway wall.
4. With the grating removed, align the telescope with the collimator/slit component as shown in *Figure 14*.2. Adjust the slit and *collimator* for a sharp, narrow image of the source (slit). DO NOT REFOCUS THE TELESCOPE.

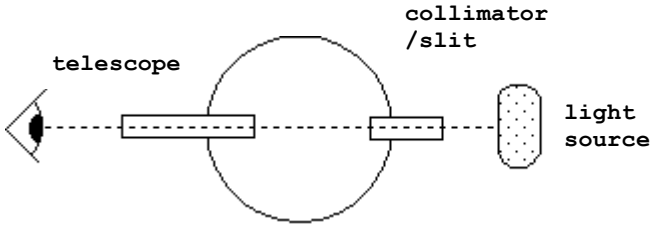

Figure 14. 2

5. Center the crosshairs on the image of the slit.
6. Record the angle displayed in the window. This angle is your *initial zero angle*. Be sure to use the same window throughout the whole lab. The instructor will explain how to read the vernier scale (the bottom scale is given in degrees and the top scale is given in arc seconds.) There should also be a handout on your lab table explaining the vernier scale's use.
7. Replace the grating. Make sure the grating lines or "rules" are perpendicular to the platform, i.e. they should point toward the ceiling. The grating face should face the slit side of the spectrometer. Record the number of lines/mm of your grating in *Section 4*. If

you have the option, choose the 600 grooves/mm grating. With the grating fixed in place, rotate the telescope exactly 90° as shown in *Figure 14.3*. Fix the telescope in place.

8. Rotate the grating until the slit image of the sodium light source is centered on the crosshairs (the zero order spectrum, i.e. the reflection of the light bulb itself, not a spectral line). The incident angle of the light is now certain to be 45°.
9. Fix the grating in place, making sure that the crosshairs stay centered on the light.
10. Turn the *telescope* back 90° to its original position as in *Figure 14.2*. Rotate the *platform* 135°, so that the light from the source is normal to the grating. The grating face is now facing the telescope side of the spectrometer so that the light from the source passes through the grating last of all. The crosshairs should be centered on the slit. Record the *final zero angle*, if different. You will be using this final zero angle in all subsequent measurements with the spectrometer, as you will be subtracting it from your measured values of angle for all spectral lines.

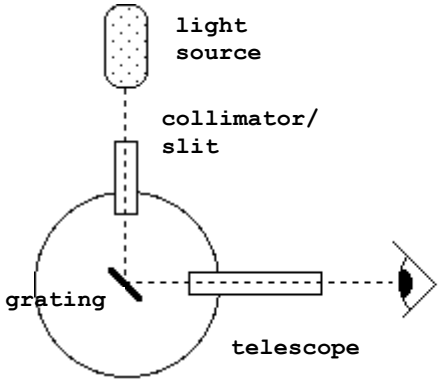

Figure 14. 3

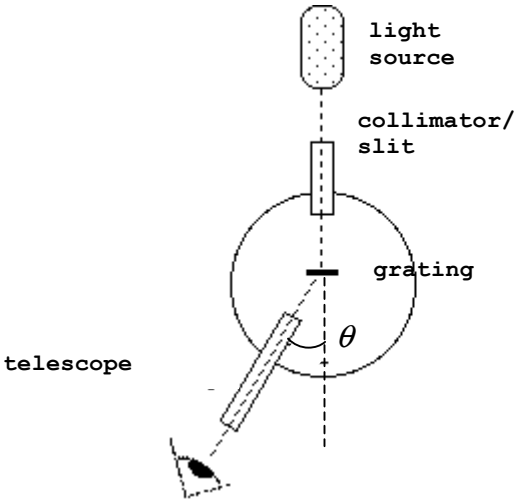

Figure 14. 4

3.2 Spectrometer Calibration

Light passing through a diffraction grating is dispersed into distinct directions, θ, given by,

$$d \sin\theta = k\lambda \qquad \textbf{Equation 14.4}$$

where d is the separation between the lines on the grating, k is an integer and referred to as the *order* of the spectral line, λ is the wavelength of light, and the angle, θ, is measured from the normal to the grating as in *Figure 14.4*. In this part of the experiment you will determine your grating separation by measuring the angle at which the sodium D spectral lines appear. The sodium D lines are a pair of yellow spectral lines, a "doublet", that have wavelengths of 589.0nm and 589.6nm. You should be able to resolve the doublet, and thus

measure a distinct angle for each spectral line, if you use care. It will also be helpful if you are using a 600 groove/mm grating and minimize the width of the slit using the slit housings thumbscrew. If you cannot resolve the doublet, measure the average angle at which the yellow line appears and average the two wavelength values given above.

Procedure

1. Start with the telescope set to the *final zero angle* position. Move the telescope to the left until you come across the first pair of yellow lines. This angle will be the first order spectrum value (k = 1). Record this angle (or angles if you can resolve the doublet) in *Table 14.2*. Now measure the first order position(s) in the opposite direction (the right side). Record this angle(s) in *Table 14.2*. You should now be able to determine the grating spacing of your particular grating, using *Equation 14.4* and the average first order angle(s) of the sodium line(s). You do not need to measure the second order lines (k = 2).
2. In filling out *Table 14.2*, the *Measured Angle* is the number read from the vernier scale, the *Difference Angle* is the positive angle difference of the *final zero angle* and the *Measured Angle*, and the *Average Angle* is the average of the two *Difference Angles*. *Average Angle* is the value you use to calculate the grating separation according to *Equation 14.4.*

3.3 Balmer Series

Now you should be able to accurately measure the Balmer series for atomic hydrogen. You should be able to measure the first and second order for three Balmer lines: a violet line, an indigo line, and a red line. See *Figure 14.5* for a picture of the relationship between first (k = 1) and second (k = 2) orders.

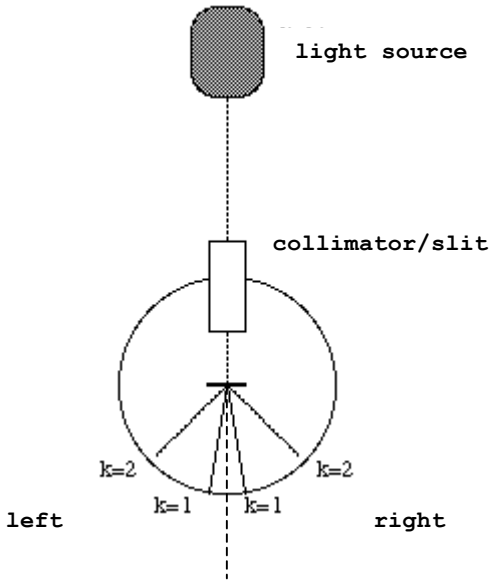

Figure 14. 5

Procedure

1. Replace the sodium lamp with the hydrogen lamp. Make sure that the center of the hydrogen bulb aligns well with the spectrometer slit. This will maximize the intensity of the spectral lines. You will need to protect your line of sight from all stray light to clearly see and measure the violet lines. It may be helpful to carefully drape black cloth around your hydrogen lamp or over your spectrometer to prevent any unneeded light from entering the spectrometer or from interfering with your ability to view the spectrum.

2. Record the angles at which each spectral line appears. You should measure both first and second orders on both the left and right sides of the zero angle of the red, violet and indigo lines, for a total of 12 measurements. Record your data in *Table 14.3*

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EXPERIMENT 14

The Atomic Spectrum of Hydrogen

4. Post-Laboratory Work [18 pts]

4.1 Alignment & Calibration [5pts]

Initial Zero Angle:_____ Final Zero Angle: _____ Grating: _____

Table 14.2 (2pts)

Spectral Line	Measured Angle	Difference Angle	Wavelength (nm)	Order, k	Grating Separation, *d* (nm)	$\bar{d}$ (*nm*)
Left, Line 1						
Right, Line 1						
Left, Line 2						
Right, Line 2						

1. Show an example calculation of how you determined the grating spacing, *d*, using data from *Table 14.2*. Calculate an average value for *d*. (1pt)

2. Calculate the uncertainty in grating separation, Δd, using the standard deviation of your two (or four) values for *d*. Hopefully you were able to resolve four! (2pts)

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4.2 Balmer Series [13pts]

Table 14.3 (2pts)

Spectral Line	Order	Measured Angle	Difference Angle	Average Angle	k	Wavelength (nm)	**Average Wavelength (nm)**
Red, Right	First						
Red, Left	First						
Red, Right	Second						
Red, Left	Second						
Violet, Right	First						
Violet, Left	First						
Violet, Right	Second						
Violet, Left	Second						
Indigo, Right	First						
Indigo, Left	First						
Indigo, Right	Second						
Indigo, Left	Second						

3. Show the calculation for how you found the wavelength of the *first* order *violet* line. (1pt)

4. Show the calculation for how you found the wavelength of the *second* order *red* line. (1pt)

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5. Calculate the uncertainty in wavelength, $\Delta\lambda$, for the *first* order *indigo* line using error propagation. Use the uncertainty in grating separation that you determined in Question #2 and estimate a value for the uncertainty in angle, $\Delta\theta$, which you must convert to radians. Use the *Average Angle* in computing the tangent. Use this value of $\Delta\lambda$ later for the red and violet lines. In this case, the equation for propagation is, (2pts)

$$\left(\frac{\Delta\lambda}{\lambda}\right)^2 = \left(\frac{\Delta d}{d}\right)^2 + \left(\frac{\Delta\theta}{\tan\theta}\right)^2 \qquad \textbf{Equation 14.5}$$

6. Show the calculation for the theoretical Balmer wavelength for n = 3 using *Table 14.1* and *Equation 14.2*. (1pt)

7. Show the calculation for the theoretical Balmer wavelength for n = 4. (1pt)

8. Show the calculation for the theoretical Balmer wavelength for n = 5. (1pt)

9. Are the theoretical Balmer wavelengths consistent with your measured wavelengths (and uncertainties). Why or why not? (2pts)

10. Ordinary hydrogen has a nucleus consisting of one proton. However, naturally occurring hydrogen contains a small amount of *deuterium*, hydrogen having a nucleus consisting of one proton and one neutron. If deuterium existed in sufficient quantity in your source to produce observable spectral lines, would you expect to resolve its lines from those of ordinary hydrogen with our equipment? Let the neutron mass be equal to the proton mass, and let the proton mass be about 1840 times greater than the electron mass.(2pts)