

Name:

Partners' Names:

Laboratory Section:

Laboratory Section Date:

Grade:

Last Revised on December 8, 2005

EXPERIMENT 14

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,

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

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,

$$R = \frac{k^2 m e^4}{4\pi \hbar^3 c} = 1.097 \times 10^{-2} \text{ nm}^{-1} \quad \text{Equation 14.2}$$

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 $k = 1/4\pi\epsilon_0$. 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,

$$\frac{1}{\mu} = \frac{1}{m} + \frac{1}{M} \quad \text{Equation 14.3}$$

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*.

| <i>Series Name</i> | <i>Wavelength Range</i> | <i>Series Expression</i> |
|--------------------|-------------------------|---|
| 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 | $\frac{1}{\lambda} = R\left(\frac{1}{5^2} - \frac{1}{n^2}\right), n \geq 6$ |

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.

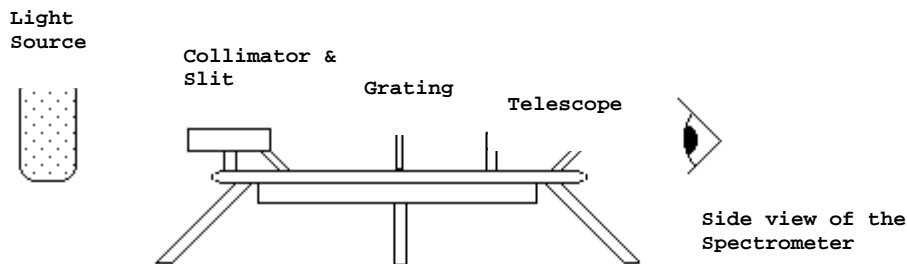


Figure 14. 1

Procedure

Setting up the Spectrometer

1. Turn on the sodium lamp and set it aside. (The sodium lamp is has a label that says “Na Light Source” on the back near the switch.) It needs a few minutes to warm up. You will know it is ready when the emitted light has a warm, yellow glow instead of a harsh purple, glow.
2. In the meantime, familiarize yourself with all of the controls on the spectrometer (listed in Appendix 1 of this laboratory). 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. Using the level, make sure that the diffraction grating holder is level in all directions. To do this, you will have to check the horizontal direction by placing the level on the top of the two posts of the grating holder, and in the vertical direction by placing the level vertically with the long end braced against the wide side of one post. (This is difficult because of the other hardware in the way; do the best you can.)



4. Rotate the *telescope* so that it points at a far wall with no obstruction (i.e. does not look at the slit.) While looking at this distant object, focus the telescope.
5. With the grating removed from the holder, align the telescope with the collimator/slit component as shown in *Figure 14.2*. Adjust the slit so that you only see a narrow slit of light through the telescope. **DO NOT REFOCUS THE TELESCOPE!** The image of

the slit will probably look fuzzy, so to bring the image into focus adjust the *collimator focus knob only*.

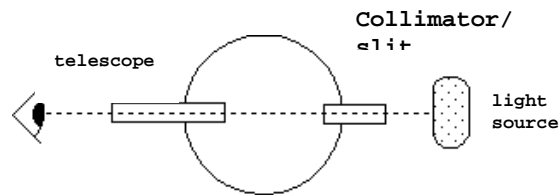


Figure 14. 2

6. After the lamp has had sufficient time to warm up, place it at the end of the collimator and adjust the slit size so as to provide a sharp line in the eyepiece. As you look through the telescope, you will notice there is a set of cross-hairs in the eyepiece. Align the vertical line of the cross hair so that it is in the middle of the slit.
7. Without moving the telescope. You should now rotate the turntable so the vernier scale tells you the telescope is lined up at 90° . (You may find it convenient to lock down the “vernier fixing screw” and make fine adjustments with the “vernier fine adjustment screw”.) To understand how sensitive the vernier scale is, while looking in the telescope, turn the telescope’s fine adjustment screw and notice how far the crosshairs traverse. Now look at the vernier scale and notice how many arc seconds the telescope has moved in relation to the image of the slit. Notice not only the sensitivity in the movement of the telescope but how well you are able to measure its rotation. When you are done, be sure to re-center the cross-hairs on the slit.
8. Record the angle displayed in the window. This angle is your *initial zero angle*. There are windows on either side of the turntable, so be sure to use the same window throughout the whole lab. To learn how to read the vernier scales see Appendix 2 of this lab. Consult your TA or TI if you have *any* questions! It is very important to know how to read this scale properly so as not to make a mistake

Determining Grating Orientation

1. Be careful handling the grating! The emulsion is very fragile. Always handle the grating by the sides and be careful not to scratch off the emulsion when placing the grating in the holder.
2. Before we set the grating, we need to check that the orientation of the grating is perpendicular to the platform, i.e. that the etched lines are oriented vertically. To check your grating’s orientation, use the supplied laser point in the lab kit and shine the laser through the grating and **towards the wall!** You will see the zeroth-order beam directly in front of you. When you have your grating perpendicular to the platform the $\pm 1^{\text{st}}$ order beams will be to the left and right of the zeroth-order beam. If your 1^{st} order lines are

above and below your zeroth-order beam, then you need to rotate your grating 90 degrees. If you have *any* questions ask your TA or TI for assistance for this is a crucial step!

3. Place the grating back into the grating holder with the emulsion side of the grating facing the Na lamp and the grating lines perpendicular to the platform. Record the number of lines/mm of your grating in *Section 4*.

Aligning the Grating

1. With the grating fixed in place, rotate the telescope exactly 90° as shown in *Figure 14.3*. As a result of this rotation, the vernier scale should now read 0° . To check this, fix the telescope in place with the telescope fixing screw and use the fine tuning screw to adjust the telescope more accurately (see Appendix 1).
2. As shown in *Figure 14.3*, rotate the grating until the slit image of the sodium light source is centered on the crosshairs (the zero order ray, i.e. the reflection of the light source itself, not a spectral line). The incident angle of the light is now certain to be 45° . If you do not see the image of the light source you may not have properly aligned your grating stage. You may see multiple images of the light source through the slit due to reflections within the grating; the brightest one in the one you should use for your alignment.
3. Fix the grating in place and make sure that the crosshairs stay centered on the light. It is *very* important the grating does not move from this position. Be careful!

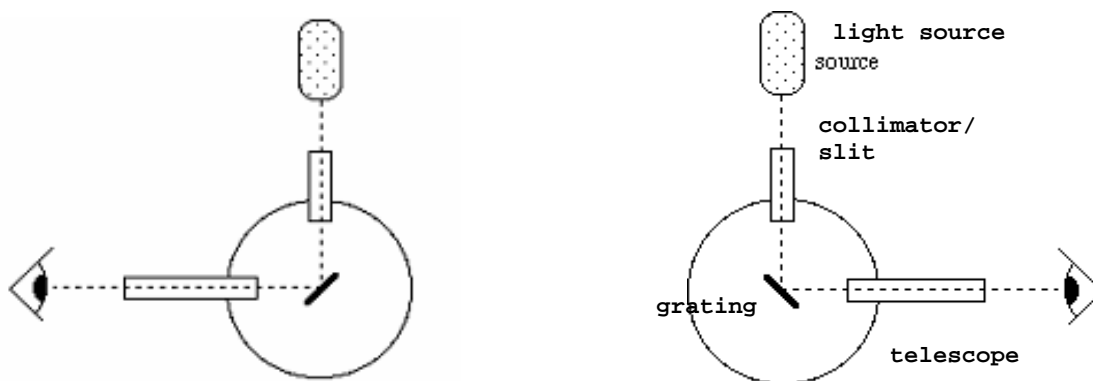


Figure 14. 3: The grating alignment setup. Depending on which vernier window you read from when you set the telescope to zero degrees, you will have one or the other of these configurations.

4. 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 with the emulsion side of the grating facing the telescope portion of the spectrometer. 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.

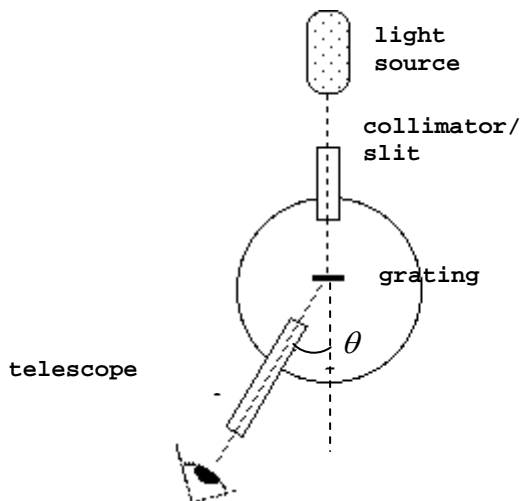


Figure 14. 4

3.2 Spectrometer Calibration

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

$$d \sin \theta = k\lambda \quad \text{Equation 14.4}$$

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.

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 the angles of the two lines in the doublet in *Table 14.2*. (If you are having difficulty resolving the doublet, it might be because your light source is too close to the slit giving lines that are too bright. Try moving the lamp further from the slit.)

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 ($k = 2$).
3. 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.

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*

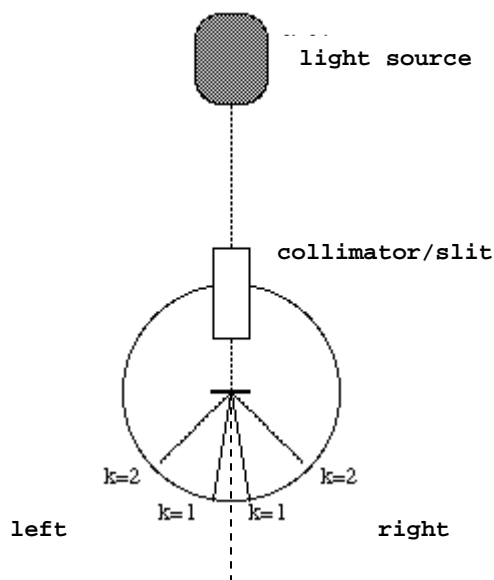


Figure 14.5

Name:
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Laboratory Section Date:

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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)

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)

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)

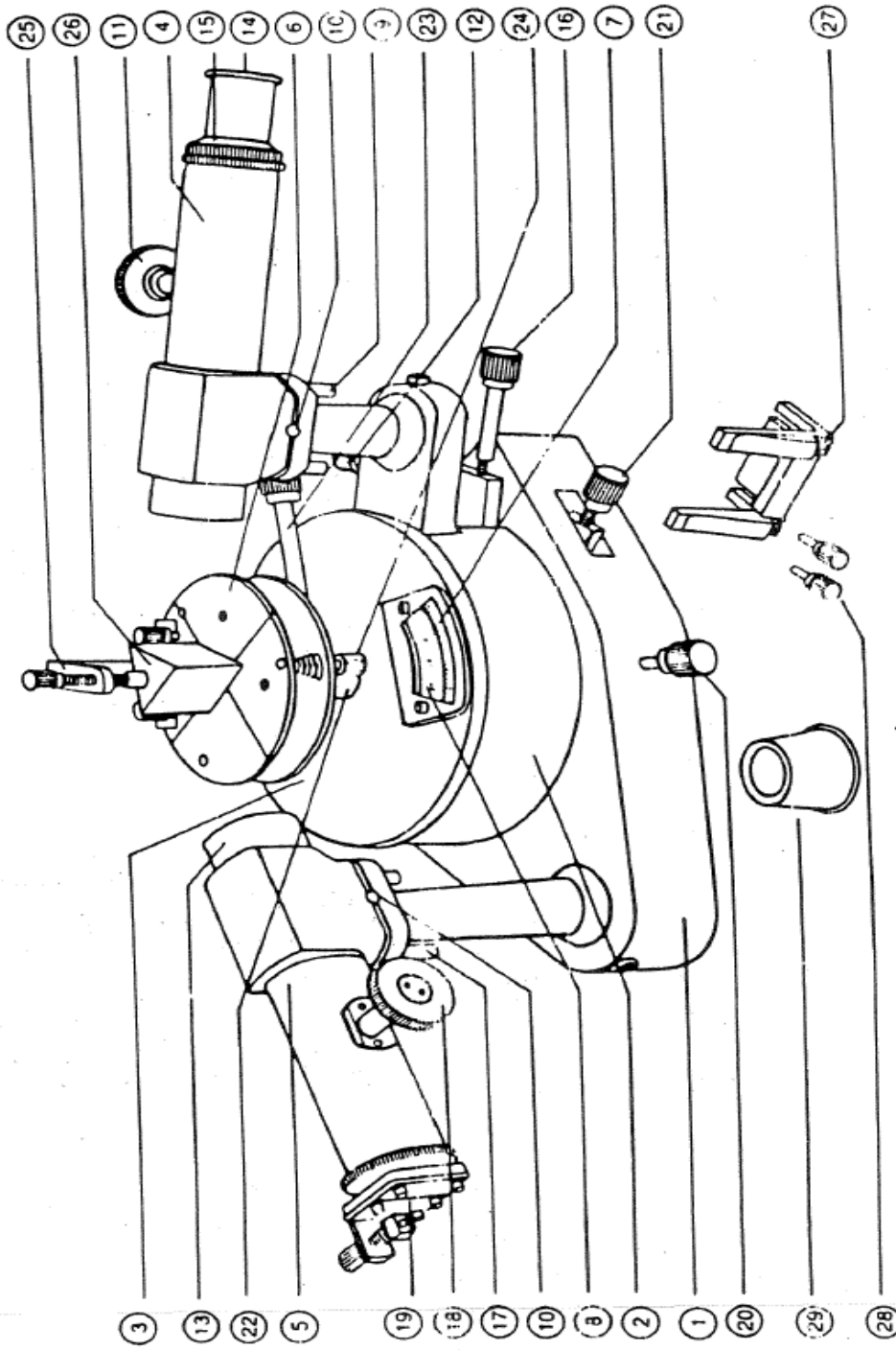
$$\left(\frac{\Delta\lambda}{\lambda}\right)^2 = \left(\frac{\Delta d}{d}\right)^2 + \left(\frac{\Delta\theta}{\tan\theta}\right)^2 \quad \text{Equation 14.5}$$

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)

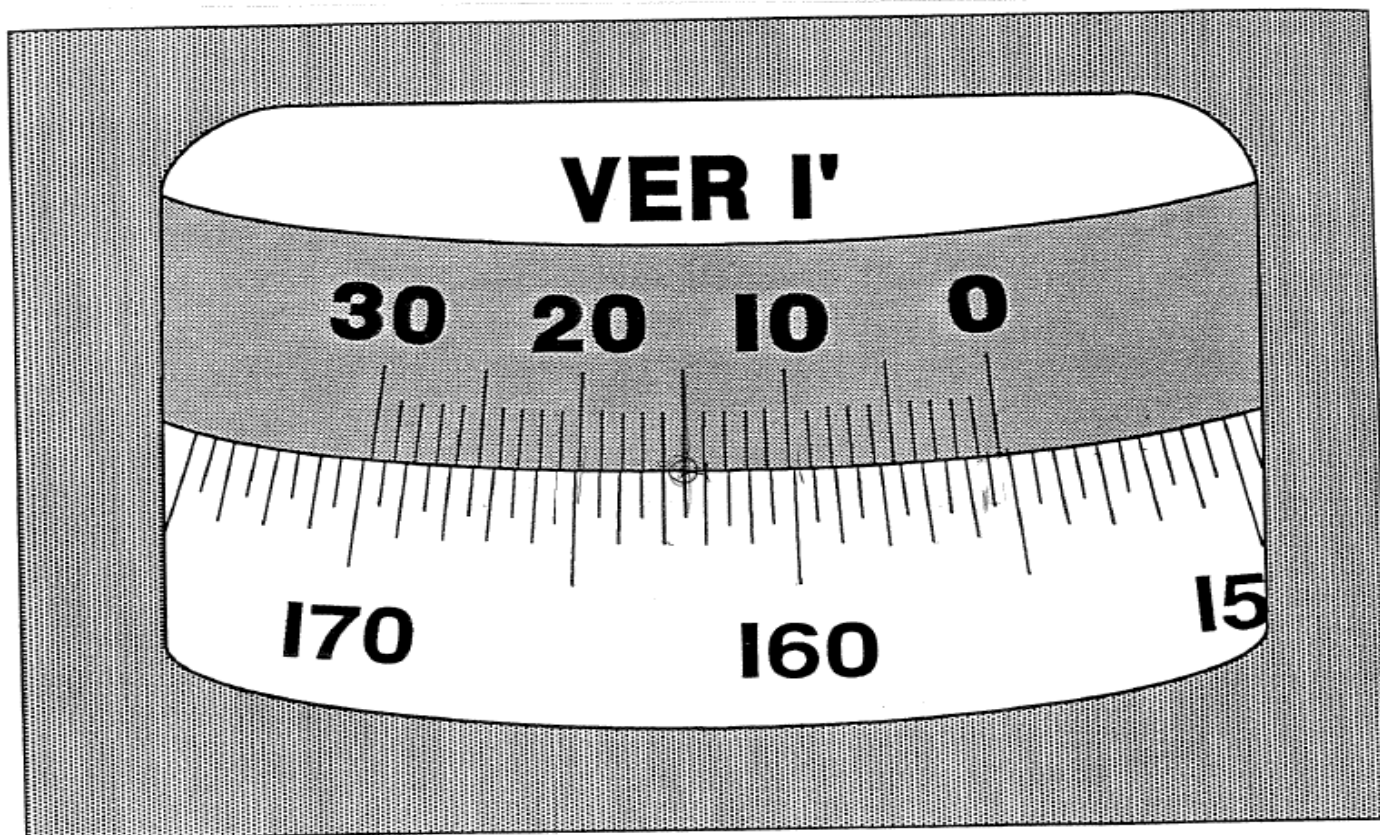
10. Ordinary hydrogen has a nucleus consisting of one proton. However, naturally occurring hydrogen contains a small amount of *deuterium*, hydrogen having a nucleus consisting of one proton and one neutron. If deuterium existed in sufficient quantity in your source to produce observable spectral lines, 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)

Appendix 1



- | | | | |
|--------------------------------|---------------------------------|--------------------------------|---|
| 1. Spectrometer Base | 2. Turn Table | 3. Turn Table Cover | 4. Telescope |
| 5. Collimator | 6. Prism Table | 7. Circular Main Scale | 8. Vernier Scale |
| 9. Telescope Levelling Screws | 10. Horizontal Pin | 11. Telescope Focussing Knob | 12. Telescope Fine Adjustment Screw |
| 13. Converging Lens | 14. Ramsden Eye Piece | 15. Crosswire Assembly | 16. Telescope Fixing Screw |
| 17. Collimator Levelling Screw | 18. Collimator Focussing Knob | 19. Slit | 20. Vernier Fine Adjustment Screw |
| 21. Vernier Fixing Screw | 22. Receptacle | 23. Prism Table Fixing Screw | 24. Prism Table Levelling Screw |
| 25. Prism Holder | 26. Prism (supplied separately) | 27. Diffraction Grating Holder | 28. Screws for Diffraction Grating Holder |
| 29. Hand Magnifier | | | |

Reading the Vernier Scales



The relative rotational positions of the telescope base and the table base are measured using the vernier scales.

First, find where the zero point of the vernier scale aligns with the degree plate and record the value. If the zero point is between two lines, use the smaller value. (In the above photograph, the zero point on the vernier scale is between the 155° and $155^\circ 30'$ marks on the degree plate, so the recorded value is 155° .)

Now use the magnifying glass to find the line on the vernier scale that aligns most closely with any line on the degree scale. (In the picture, this is the line corresponding to a measurement of 15 minutes of arc.) Add this value to the reading recorded above to get the correct measurement to within 1 minute of arc (that is, $155^\circ + 15' = 155^\circ 15'$).

Important: Notice that the vernier scale measures only the relative positions of the table and telescope rotating bases. When using the scales to measure angles of diffraction, first align the vertical cross-hair of the graticule with the fixed edge of the slit image for the undeflected beam. Then read the vernier scale. This is the zero point reading. All successive measurements (measured with the cross-hair on the fixed edge of the diffracted slit images) are meaningful only with respect to that zero point. If the table base is rotated, the zero point changes.

$155^\circ 15'$

$166 + 13/2$