L-5

THE BALMER SERIES

THE HYDROGEN ATOM

The hydrogen atom consists of a single electron bound to a proton. The behavior of the hydrogen atom, and the discrete nature of the light it emits are not explainable by classical electrodynamics. In 1913 N. Bohr proposed his "Quantum Theory" of the hydrogen atom. In this theory the energy of the bound electron takes only discrete values corresponding to orbits with discrete radii.

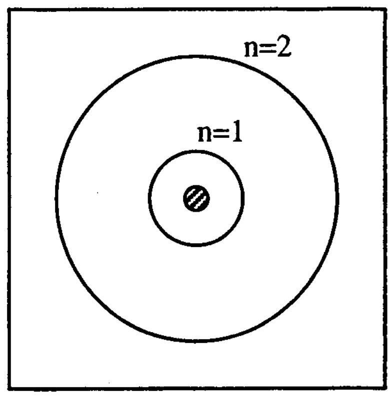

Fig. 1

Radiation occurs only when the electron makes a transition from one energy level to a lower (more tightly bound) level. The electromagnetic radiation that is emitted in this "quantum jump" may be visible light, or it may have shorter (Ultra Violet) or longer (Infra Red)wavelengths, and be invisible. The energy of the various levels is given by:

$$E_n = -\frac{me^4}{8\epsilon_0^2 h^2} \cdot \frac{1}{n^2} \qquad (1)$$

and corresponds to orbits with radii given by

$$r_n = \frac{\epsilon_0 h^2}{\pi m e^2} \cdot n^2 \qquad (2)$$

where n is an integer called the "quantum number" of the orbit. A large quantum number n corresponds to an orbit with a large radius r_n, and a large energy E_n, a small quantum number corresponds to an orbit with a small radius r_n and a small energy E_n. The energy of the levels is negative, this means that the electron is bound to the nucleus.

A NOTE TO THE INSTRUCTOR

You should see that the spectroscopes are properly adjusted, and that the collimator is near ~ 2 *cm* from the source. Students often bump the apparatus, and bring it out of alignment; make sure they know to call you if this happens.

YOU NEED TO KNOW

The formula for the energy of the photon emitted in an electron transition between two discrete energy states in a hydrogen atom is

$$E_{ph} = E_{n_u} - E_{n_\ell} \qquad (3)$$

Where n_ℓ is the quantum number of the lower level which has a small radius and a large negative energy; and n_u is the quantum number of the less tightly bound upper level ($n_u > n_\ell$). The family of transitions which have a common lower quantum number is called a series; the series where $n_\ell = 1$ is called the Lyman series; the corresponding radiation is in the ultraviolet, outside the visible region.
The series that lies in the visible region corresponds to $n_\ell = 2$ and is called the Balmer series. It is this series of transitions that you will be observing in this experiment. Three of the transitions are in the visible region. A graphical representation of the energy levels and energy transitions is shown in fig. 2

$$\lambda_{5-2} = 0.4340\ \mu m$$
$$\lambda_{4-2} = 0.4861\ \mu m$$
$$\lambda_{3-2} = 0.6562\ \mu m$$

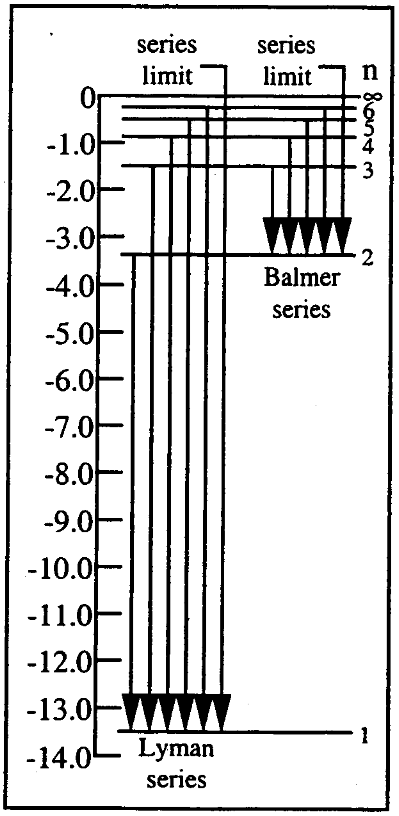

Fig. 2: The energy levels

Using the relationship between the energy of a photon and its frequency $E = hf$ and the relationship between wavelength and frequency $f = c/\lambda$ one obtains

$$\frac{1}{\lambda} = R\left[\frac{1}{n_\ell^2} - \frac{1}{n_u^2}\right] \tag{4}$$

In the above
$c = 3 \times 10^8$ m/s, is the velocity of light in vacuum.
$h = 6.63 \times 10^{-34}\ J \cdot s$ is Planck's constant.
$R = 10.97 \cdot 10^6\ m^{-1}$ is the Rydberg constant.
The wavelength formula was found experimentally by Rydberg in 1895, and it was first calculated by N. Bohr's quantum theory.
You must also know the grating equation:

$$\lambda = d \sin\theta / m \tag{5}$$

where m is an integer called the "order of the spectrum" and d is the spacing of the grating, i.e., the distance between adjacent lines of the grating. More than one order can be observed by going to large angles but in this experiment you should restrict your observations to the first order; that is, to the spectrum at relatively small angles where $m = 1$.

IN THIS EXPERIMENT

In this procedure you will use a diffraction grating to measure the wavelength λ of the three visible Balmer lines of hydrogen and compare your results with Bohr's theory.

The layout of the experiment is schematically as shown below.

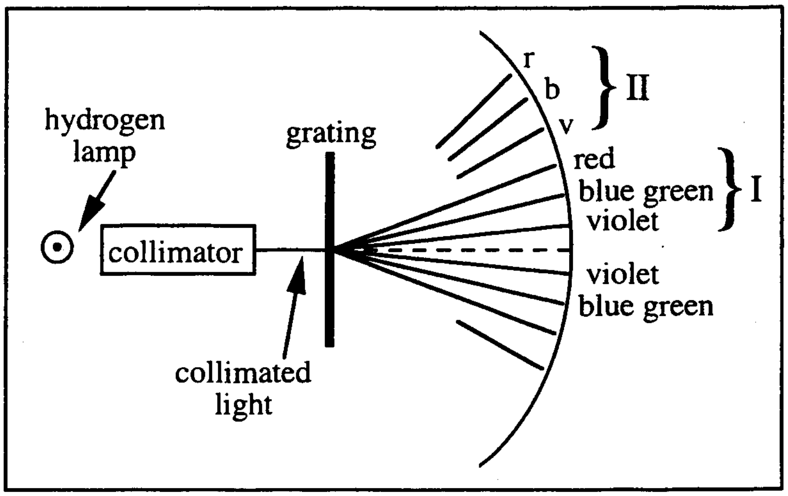

Fig. 3: Schematic setup

You will be finding the angular distance between lines of the same colour on opposite sides of the centerline, this is twice the angle given by (5). Don't forget to use decimal degrees; don't confuse the $\alpha_{1/2}$ with $\alpha_{L/R}$ readings.

THE EQUIPMENT
in this experiment consists of:

⇒ A spectroscope with a light source for alignment.

⇒ A diffraction grating with 600 lines per mm.

⇒ A black cloth for covering the instrument to avoid letting extraneous light into the telescope tube.

⇒ A hydrogen discharge tube with power supply.

THE SPECTROMETER

The spectrometer is a device for measuring angles with great precision. The spectrometers in the laboratory can measure angles to one minute of arc ($\frac{1}{60}$ of one degree).

The spectrometer has a light collimator (C) to gather as much light as possible into the telescope; it consists of a slit and a focusing lens (D).

A grating table with alignment screws permits the grating (A) to be placed perpendicular to the beam of light from the collimator.

The diffracted beam of light from the grating is viewed by a telescope (E). The optics involved are shown schematically in fig. 3.

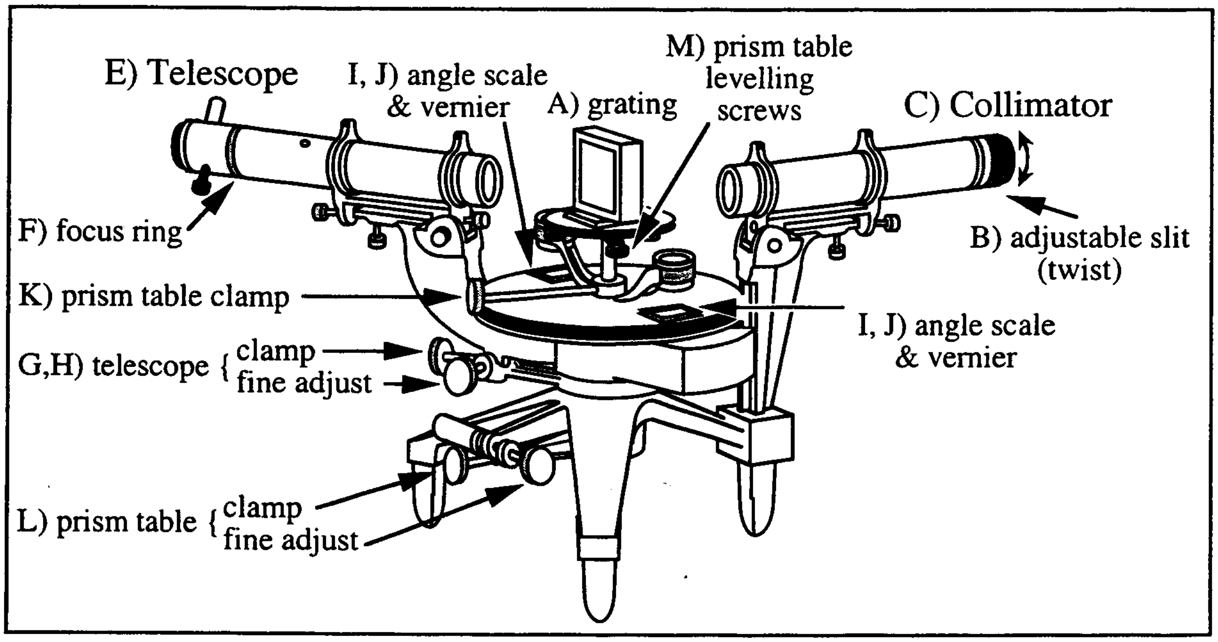

Fig. 4: The spectrometer

The angles are measured by viewing a graduated scale (I) with a magnifier (J). The graduated scale is engaged by means of a friction clutch (G). The table is also locked to the scale by a clutch (L). Both the table and telescope have verniers for small motions which operate when they are locked.

PRECAUTION

The spectrometer grating table has been previously aligned by adjustment of screws M. Do not change their positions. You will need to adjust the Slit B and focus the telescope F. **The spectrometer is a precision piece of equipment costing about $1000. If something seems to be inoperative, do not force it. Call your instructor.**

A REMINDER ON READING A VERNIER

a) Position and tighten the telescope.

b) Move the magnifying glass to see the upper scale markings. The <u>degree</u> reading is the first <u>full</u> degree mark to the <u>left</u> of the zero (210° in the top figure; 229° in the bottom figure).

d) Now make the <u>minute</u> reading: if the zero mark on the upper scale comes <u>after</u> a $\frac{1}{2}$ degree mark (the short lines on the lower scale) then start at 30′, otherwise at 0′.

e) Next look for the two lines which match up the best between the two scales. Read the number of the appropriate line on the upper scale and add it to the number of minutes you started with. In the figure the zero mark is just past a $\frac{1}{2}$ degree mark so we begin with 30′. The 15′ mark is the one that lines up best so we get 210°15′ for the top reading, and 229°46′ for the bottom one

f) Now convert to decimal degrees, in this case $15/60 = 0.25$, so $\theta = 210.25°$.

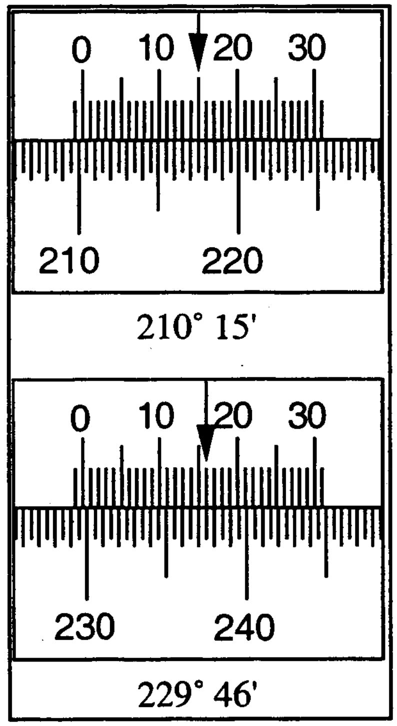

Fig. 6: The verniers

<u>PROCEDURE I</u> (60 min)

1.0 CONDUCTING THE EXPERIMENT

1.1 Open the collimator slit all the way by twisting the end marked (B). Turn on the discharge tube source and place it <u>directly</u> in front of the slit (position the source so that the ***image is as bright as possible*** when viewed through the telescope). Swing the telescope around so that it is directly opposite the collimating tube. With the light source on and the telescope and collimator properly adjusted, you should see a bright, white image of the vertical collimator slit.

1.2 Loosen nut (G) (see Fig. 4).

1.3 Move the telescope until the image of the slit is within the field of view and close to the crosshairs; twist the slit so that it is vertical, if necessary.

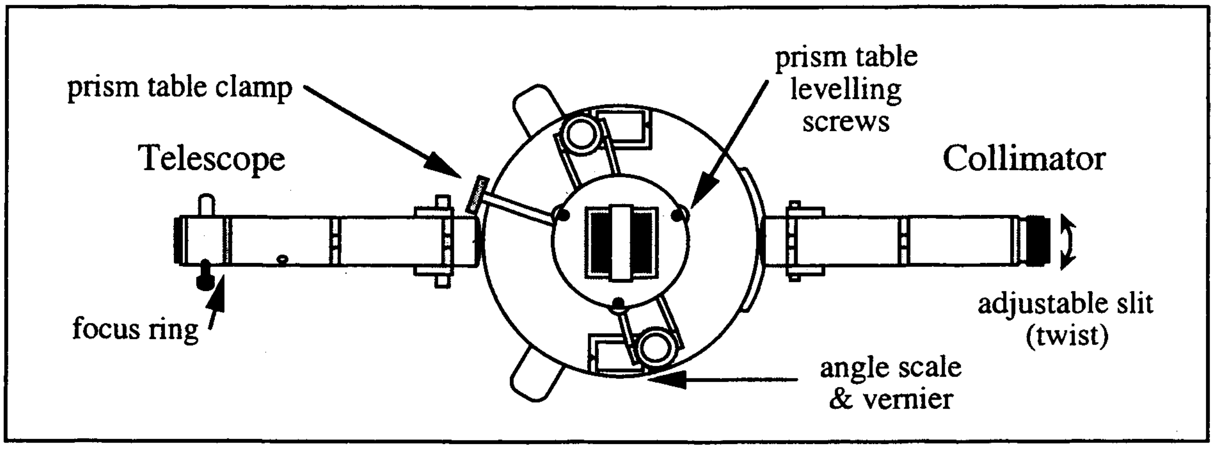

Fig. 5: The spectrometer

Try centering the image of the slit in the telescope with the crosshairs. The procedure for moving the telescope is the following:

1.4 Tighten nut (G). Make fine adjustments with nut (H) until the image of the slit is centered under the crosshairs.

1.5 Close the slit (B) all the way and then open it 1/8th turn. You should now be able to loosen nut (G), swing the telescope left and right, and view three distinct lines through the telescope–a violet, a blue-green, and a red line.

1.6 Prepare a table in your notebook like the one shown below.

Table I

	V_{1L}	V_{2L}	V_{1R}	V_{2R}
Violet				
Blue-Green				
Red				

1.7 Center the crosshairs on the violet line. This line is very dim, so you will have to play around with putting the cloth over the apparatus to cut out just enough ambient light so that you can see the line clearly, but leaving enough so you can also see the crosshairs.

1.8 Read the left vernier (V_{1L}) and the right vernier (V_{2L}). (Notice that 1 and 2 refer to the left- and right-hand side verniers, while L means that the telescope is swung to the left side of center.) Ask your instructor if you are unsure about reading the vernier. vskip -0.3cm

1.9 Record V_{1L} and V_{2L} in a table like the following in your lab book, and repeat for the two other lines while the telescope is left of center. Your measurements should be in degrees and minutes of arc! vskip -0.3cm

1.10 Swing the telescope around to the right of center, locate the corresponding lines, and repeat the process to obtain V_{1R} and V_{2R}. Fill in the rest of the table.

2.0 ANALYSIS OF THE DATA

2.1 Make a table in your notebook as the one shown.

Table II

	V_{1L}	V_{2L}	V_{1R}	V_{2R}	α_1	α_2
Violet						
Blue-Green						
Red						

2.2 Change all your measurements into decimal degrees from degrees and minutes (1 minute = $\frac{1}{60}$ of one degree). And record them in the table, keep two decimal places.

2.3 Calculate $\alpha_1 = V_{1L} - V_{1R}$ and $\alpha_2 = V_{2L} - V_{2R}$ and record them in the table.

2.4 For each line, α_1 and α_2 should not differ by more than 0.04^o. If they do, check your conversion from degrees and minutes to decimal degrees. Retake the measurement if the error was not in the conversion.

2.5 Calculate λ_{Violet}, λ_{BG}, and λ_{Red}. Show your calculations. Use $\lambda = d \sin\theta$, where $\theta = \alpha/2$. The slit spacing, d, is found from the number of lines per millimeter on the grating. Express λ in μm and Angstroms (10^{-10} meters) and compare with the accepted. Calculate the percent error between each of your values and the accepted values shown near figure 2.

2.6 Write a conclusion. Include a short explanation of why the emission spectrum of hydrogen consists of distinct lines rather than a continuous rainbow of color.