Experiment 9
The Hydrogen Spectrum

Reading assignment: Chang, Chemistry 9th edition, pp. 274-279.

Goals

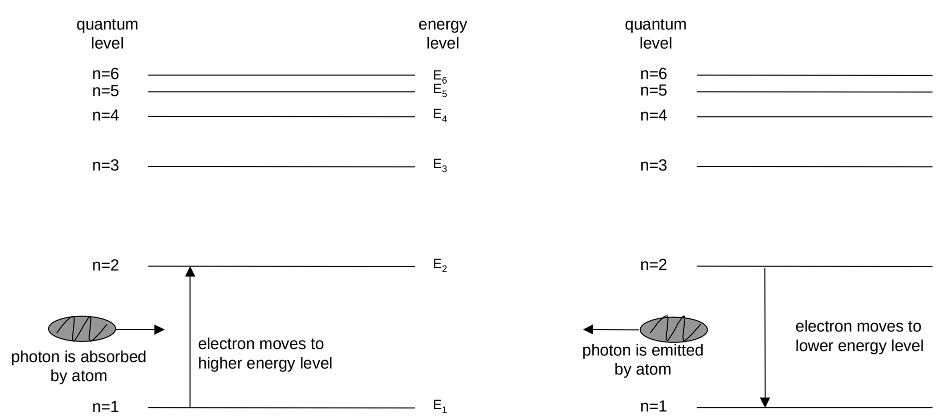
We will become familiar with the operation of the grating spectroscope in order to determine the wavelengths of the Balmer series of the hydrogen spectrum. This will involve the construction of a calibration graph using the known spectral lines of helium.

Equipment and Supplies

Spectroscope, hydrogen gas tube, helium gas tube, USB flash drive

Discussion

At the beginning of the 1900s physicists were unable to adequately explain the spectrum of colors absorbed and emitted by atoms. It wasn't until the 1920s that a satisfactory theory for explaining the spectral properties of even the simplest atom (hydrogen) was complete. The hydrogen spectrum was an important piece of evidence that light interacts with matter through the absorption and emission of discrete packets of energy, called quanta. We now call these quanta "photons." The figure below shows a representation of how we can think of the interaction of photons with hydrogen atoms. When a photon is absorbed by a hydrogen atom the energy of the photon promotes the electron in the hydrogen atom to a higher energy level. When a hydrogen atom emits a photon the electron moves to a lower energy level. These energy levels are said to be quantized, meaning that there are a limited number of energy levels possible.

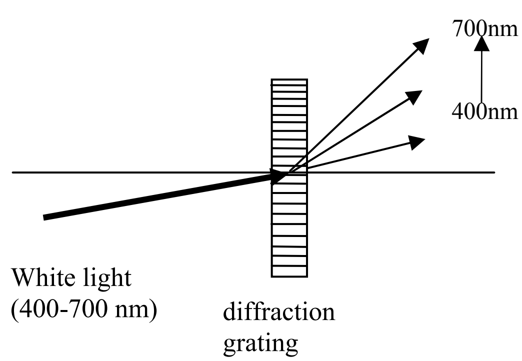


In this experiment we will use a spectroscope to measure the wavelengths of light emitted by the two simplest atoms, hydrogen and helium.

The spectroscope uses a **grating** to disperse light emitted by atoms into individual colors. The light emitted by an atom typically consists of several or more components. A grating is a device that has grooves etched into it at regular spacings.

Each component of this light has an associated wavelength. For example, light with a wavelength of 415 nm is blue. Light with a wavelength of 675 nm is red. The grating scatters or diffracts light according to its wavelength (color). The angle at which the color is diffracted can be found by using the Bragg equation:

$\sin\theta = \frac{m\lambda}{d}$ where λ is the wavelength of the light, m is called the order of diffraction and takes the values of 0, 1, 2, 3,...We will measure the light diffracted for m=1.



The intensity of the diffracted light is too small to see with the eye. The variable d is the distance between the grooves of the grating and is of the order of 0.002 mm spacing. The Bragg equation shows that longer wavelengths of light are diffracted at larger angles. So red light (~670 nm) is diffracted at a greater angle than blue light (~450 nm). This is why we can use the spectroscope to see the colors of light emitted by atoms. Blue light has a shorter wavelength than red light so it will be diffracted through a smaller angle. In this experiment we will use the spectral lines from helium to construct a calibration line that relates wavelength and sin θ. We will then use that calibration to determine the wavelengths of the spectral lines emitted by hydrogen.

The wavelength (λ) and frequency (υ) of a wave is related to the speed of the wave:

c = speed of a wave = $\lambda\upsilon$

For electromagnetic waves the speed in a vacuum is called the speed of light (c). The value of c is 2.997×10^8 m/s.

Electromagnetic radiation is actually composed of particles called photons. The energy of a photon is related to its frequency by Planck's constant (h):

$E_{photon} = h\upsilon$

The value of h is 6.626×10^{-34}Js

Sample Calculation

Lasers are can produce light at one specific. A nitrogen laser produces photons with a wavelength of 337.1 nm. What is the energy of one of these photons? What is the energy of 1 mole of these photons.

Solution

The frequency of a photon can be found from its wavelength and the speed of light:

We need the energy of one photon. $E = h\upsilon = \dfrac{(6.626 \times 10^{-34}\ \mathrm{J \times s})(2.997 \times 10^{8}\ \frac{\mathrm{m}}{\mathrm{s}})}{337.1 \times 10^{-9}\mathrm{m}} = 5.891 \times 10^{-19}\,\mathrm{J}$

Note that $\nu = \dfrac{c}{\lambda}$ and that 1 nm = 10^{-9} m

The energy of 1 mol of these photons is:

$E = NE_{photon} = \dfrac{6.022 \times 10^{23}\ \text{photons}}{1\,\text{mol}}(5.891 x 10^{-19} J) = 3.548 \times 10^{5}$ J/mol

This corresponds to 354.8 kJ/mol, in the range of the amount of energy associated with some chemical reactions.

The wavelengths of photons emitted from high temperature hydrogen atoms can be calculated easily using a version of the Rydberg equation:

$\lambda = \dfrac{91.15\ \text{nm}}{\left(\dfrac{1}{2^2} - \dfrac{1}{n^2}\right)}$ where λ is a series of values calculated using n = 3, 4, 5, 6, ...

The simplicity of this equation led physicists to believe that the structure of the hydrogen atom (and other elements) could easily be deduced. In fact, hydrogen is the only element with such a simple mathematical relationship. The quantum mechanical model of the atom must be used for other elements.

Procedure

SAFETY PRECAUTIONS
Safety glasses are not required for this experiment. The power supply for the hydrogen and helium tubes use 120 VAC. Care should be taken when using this equipment. The glass tubes are fragile and should be handled with care.

Students work in groups of two to three. Each student acquires one set of data for helium and hydrogen. The spectroscope should be calibrated at 0° by the students or by the instructor using the helium tube. Bring a 3-1/2 inch PC-formatted diskette or a USB flash drive.

Measuring the Lines of the Helium Spectrum

There are six emission lines from helium visible with the spectroscope.

1. Set the spectrocope to an angle of 0°.

2. Slowly rotate the telescope clockwise until the violet line is visible. Continue rotating the telescope until the violet line is centered in the cross-hairs of the telescope.

3. Record the angle of this line to 0.1° from the vernier.

4. Continue rotating the telescope to larger angles, measuring and recording each of the five remaining lines in the data sheet.

5. Each remaining student in the group should repeat these measurements and record the data in the data sheet.

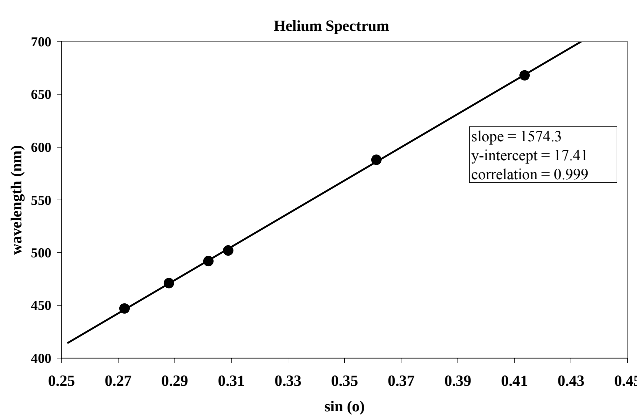
Measuring the Lines of the Hydrogen Spectrum

The visible wavelength of the hydrogen spectrum consists of four lines. However, only three of these lines are clearly visible using the spectroscope. Use the same method to measure the wavelengths of the lines of hydrogen that was used with the helium spectrum. Record the color you observe with each of the three lines.

Calculations

The Helium Spectrum

The wavelengths for the helium spectrum are given in the data sheet for each of the six lines that were measured. So the relationship between wavelength and angle can be shown through a graph. The plot of wavelength versus sin (θ) is linear. This linear relationship can be used to calibrate the spectroscope. Since wavelength varies linearly with sin (θ) we can used the calibration to determine the wavelength for any line if we know the angle (θ).



1. Construct a graph of wavelength versus sin (θ) using the data from the helium lines.

2. Determine the line of best fit for the graph and record the slope and y-intercept of this line.

3. The values of the slope and y-intercept will be used to determine the wavelengths of the hydrogen spectrum.

The Hydrogen Spectrum
1. Calculate the wavelengths of the three hydrogen lines using the following method:

The angle (θ) for each line of hydrogen was measured. Combining this data with the linear relationship between wavelength and sin (θ) we can determine the wavelengths of the lines of hydrogen. This is done by using the equation for the line of best fit from the helium data:

y = mx + b

where **m** is the slope and **b** is the **y-**intercept found from the line of best fit. Replacing wavelength for **y** and **sin (θ)** for **x**:

λ = msin (θ) + b

Sample Calculation
Consider the graph shown above of wavelength versus sin (θ) for helium. The slope = 1574.3 and the y-intercept = 17.41. If we measure a spectroscopic line from another atom and the angle (θ) that this line is measured at is 21.7°. What is the wavelength that this line corresponds to?

Use the linear fit to determine the wavelength. Since wavelength is plotted on the y-axis and sin (θ) is plotted on the x-axis:

λ = msin (θ) + b

λ = (1574.3 nm)(sin (21.7°) + 17.41

λ = 599.5 nm

Using this graphical method we can calculate the wavelength of all three lines of hydrogen to a high degree of accuracy.

2. The spectral lines of hydrogen can also be calculated accurately using a simple relationship.

$$\lambda = \frac{91.15 \text{ nm}}{\left(\frac{1}{2^2} - \frac{1}{n^2}\right)}$$

where n can be 3, 4, 5, 6, 7, 8,...

Calculate λ for n = 3 through n= 10.

3. Calculate λ for n = ∞ **.** To calculate this consider what happens when n becomes very large. If n is very large then 1/n is very small. The value of $1/n^2$ is even smaller:

$$\lambda = \frac{91.15 \text{ nm}}{\left(\frac{1}{2^2} - \frac{1}{n^2}\right)}$$

when n becomes very large: $\frac{1}{n^2} = \frac{1}{\infty^2} = 0$

To see that this is the case try using n = 100 or 1000. When $1/n^2$ becomes very small it can be ignored in the denominator of the wavelength equation. So,

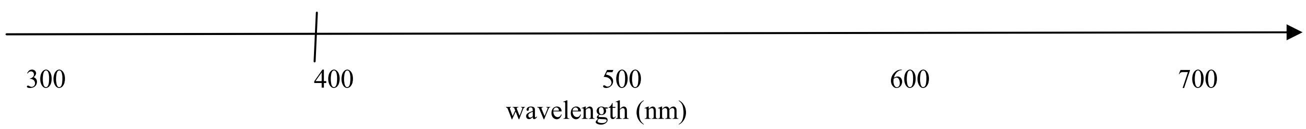
$$\lambda = \frac{91.15\ \text{nm}}{\frac{1}{2^2}}$$ Calculate this value of wavelength.

4. Calculate the percent difference for the three hydrogen lines that were measured.

$$\%\ \text{difference} = \frac{|\text{measured value} - \text{calculated value}|}{\text{calculated value}} \times 100$$

Questions

1. Make a hand-drawn sketch of the calculated values of λ for n=3 through n=10 and n = ∞ somewhere on the graph from step 1. The sketch should look something like the following:



Draw a vertical line at each wavelength calculated in step 3. For example, at n = 7 we can calculate the value of λ to be 397 nm. A vertical line is shown on the sketch above to represent this transition at 397 nm.

Look at the pattern of the lines. As n increases what happens to the distances between the lines?

2. Calculate the frequency and energy of the photons that are emitted for the three visible lines of hydrogen.
$E_{photon} = hc/\lambda = h\upsilon$ where $c = 2.997 \times 10^8$ m/s and $h = 6.626 \times 10^{-34}$ Js

3. What can we deduce about the electronic structure of the atom from this experiment?

4. The hydrogen spectrum was used by Bohr to develop his model of the hydrogen atom. Describe the problems with the Bohr model of the atom. In your description, include an explanation of what the Bohr model was able to explain and what it wasn't.

5. Does a photon of visible light have enough energy to excite an electron from the n = 1 level to the n = 5 level?

6. Submit a one-paged (typed) report that discusses the following topics:
   a. What were the goals or objectives of the experiment
   b. What were your results as they relate to the goals and objectives.
   c. Discuss the quality of your results.

Date ______________

Data Sheet
Experiment 9: The Hydrogen Spectrum

Name______________________________________

Names of partner (s)______________________________ __________________________________

Helium Spectrum

Color	**λ (nm)**	**Angle (θ) student 1**	**Angle (θ) student 2**	**Angle (θ) student 3**	**Average angle(θ)**	**Sin (θ) average***
Red	668	_______	_______	_______	_______	_______
Yellow	588	_______	_______	_______	_______	_______
Green (bright)	502	_______	_______	_______	_______	_______
Green (dull)	492	_______	_______	_______	_______	_______
Blue	471	_______	_______	_______	_______	_______
Violet	447	_______	_______	_______	_______	_______

Hydrogen Spectrum

Color	**Angle (θ) student 1**	**Angle (θ) student 2**	**Angle (θ) student 3**	**Average angle(θ)**	**Sin (θ) average***
_______	_______	_______	_______	_______	_______
_______	_______	_______	_______	_______	_______
_______	_______	_______	_______	_______	_______

*Be sure that your calculator is set to calculate the sin of the angle in degrees and not in radians.

Hydrogen Spectrum

n	λ (nm) measured*	λ (nm) calculated**	% difference
3	______________	______________	______________
4	______________	______________	______________
5	______________	______________	______________
6	not measured	______________	
7	not measured	______________	
8	not measured	______________	
9	not measured	______________	
10	not measured	______________	
∞	not measured	______________	

*From graph

** From $\lambda = \dfrac{91.15 \text{ nm}}{\left(\dfrac{1}{2^2} - \dfrac{1}{n^2}\right)}$

Wavelength, frequency, and energy for hydrogen

λ (nm)	υ (s^{-1})	E (J)
______________	______________	______________
______________	______________	______________
______________	______________	______________