The Emission Spectra of Light

Objectives:

1. ... measured the wavelength limits of the color bands in the visible spectrum,
2. ... measured the wavelengths of the emission lines of the hydrogen Balmer series,
3. ...determined the transitions in the hydrogen atom responsible for the Balmer series of lines and used this information to calculate the Rydberg constant,
4. ... identified three unknown elements by their emission spectra,

Theory:

A. Emission of Light From Matter

It can be demonstrated that light behaves as a wave as it propagated from one point to another. As with all waves, the relation between the wave speed, frequency and wavelength is given by the formula

$$c = \nu\lambda \qquad [1]$$

where c = the speed of light
= 3×10^8 meters/sec,
ν is the frequency of the light wave, in vibrations/sec (Hz)
and λ is the wavelength of the light wave in meters.

Other units in which wavelengths of light are stated are the Angstrom, the micron, and the nanometer, as defined below:

1 Angstrom = Å = 10^{-10} meters
1 micron = μm = 10^{-6} meters
1 nanometer = nm = 10^{-9} meters.

In a solid, liquid or dense gas, atoms are spaced close together and interact strongly with one another. When heated, this kind of matter will emit a continuous spectrum of light in which all of the visible wavelengths are represented. The light emitted from the tungsten filament in an incandescent lamp is an example of a continuous spectrum. The distribution of the light among the various wavelengths (i.e., the intensity of various wavelengths) depends primarily upon the temperature of the substance rather than its constitutive (molecular) makeup.

Conversely, atoms or molecules in a rarified gas are far removed from their neighbors. In this form, matter emits light characteristic of the atoms or molecules themselves. An excited, rarified gas is observed to emit a discrete spectrum, emission occurs only at specific wavelengths. These wavelengths are characteristic only of the atoms from which the emission occurred, and are not effected significantly by the temperature of the gas. The intensity of light at a specific wavelength is, however, effected by the temperature.

In 1900 Max Plank successfully explained the spectrum emitted from an ideal radiator by proposing that light has a quantum nature. Plank suggested that an electromagnetic wave of frequency, ν, was composed of photons, each having an energy given by

$$E_{\text{photon}} = h\nu = \frac{hc}{\lambda} \qquad [2]$$

Where h = Planck’s constant
= 4.136×10^{-15} ev-sec.

(an ev(electron-volt) of energy is the energy gained by an electron when accelerated through a potential difference of 1 volt). The constant hc may be shown to have the value

$$1.2408 \times 10^{4}\,\text{ev} - \overset{\text{o}}{\text{A}}\,.$$

In 1905 Einstein used the quantum nature of light to explain the photoelectric effect. Neils Bohr also incorporated this feature to explain the discrete emission spectra from rarified gases in 1913. Bohr assumed that the electrons in an atom could only exist in certain energy states, E_i. The lowest energy state, E_1, is called the ground state and the other states are called excited states. If an electron of an atom is somehow promoted to some higher energy state, E_n, for example, by collisions with other atoms or electrons, then it will soon return to its ground state. In order for the electron to return to a lower energy state, the electron will often give up its extra energy through the emission of one or more photons. Thus, an electron in some initial state, E_n, would give up energy ΔE in going to some lower final state, E_m. That is,

$$\Delta E = E_n - E_m = \text{energy of photon.} \qquad [3]$$

From equations [2] and [3], it is seen that the wavelength of the emitted light is determined by the energy difference between two atomic states. The discrete nature of atomic energy levels, thus gives rise to a discrete spectrum of emitted wavelengths. Conversely, the entire energy structure of the atom can be deduced by examining the emission spectrum of the heated gas.

The energy levels of atomic hydrogen are sketched in figure -1, the level number, n, is called the principal quantum number.

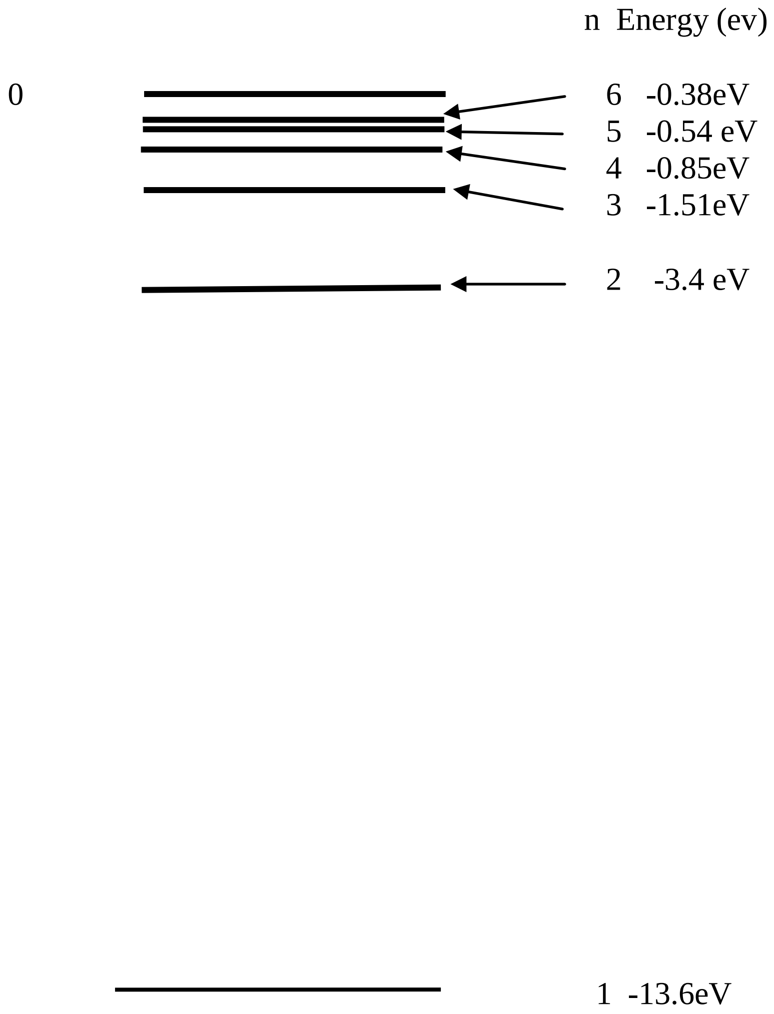


Figure 1

From the figure it is seen that in going from the first excited state (n = 2) to the ground state (n = 1),the hydrogen atom must lose 13.6 – 3.4 ev = 10.2 ev.

Values of ΔE for other transitions to the ground state are summarized in Table .1

Table .1

Transition	**ΔE (ev)**
n = 2 to n = 1	10.2
n = 3 to n = 1	12.1
n = 4 to n = 1	12.75
n = 5 to n = 1	13.09

The transition from the n = 2 state to the n = 1 state results in the emission of a photon with a wavelength (calculated from equation [2]) of

$$\lambda = \frac{hc}{\Delta E} = \frac{1.2408 \times 10^4 \, ev - \overset{o}{A}}{10.2 ev} = 1216.5 \, \overset{o}{A} \qquad [4]$$

This wavelength lies in the ultraviolet region.

Note also that transitions may occur from higher levels to intermediate levels (for example, n = 3 to n = 2 or n = 5 to n = 3). These transitions also result in photons of discrete wavelengths.

Balmer showed that the discrete visible spectrum from hydrogen gas could be fitted by a formula of the form:

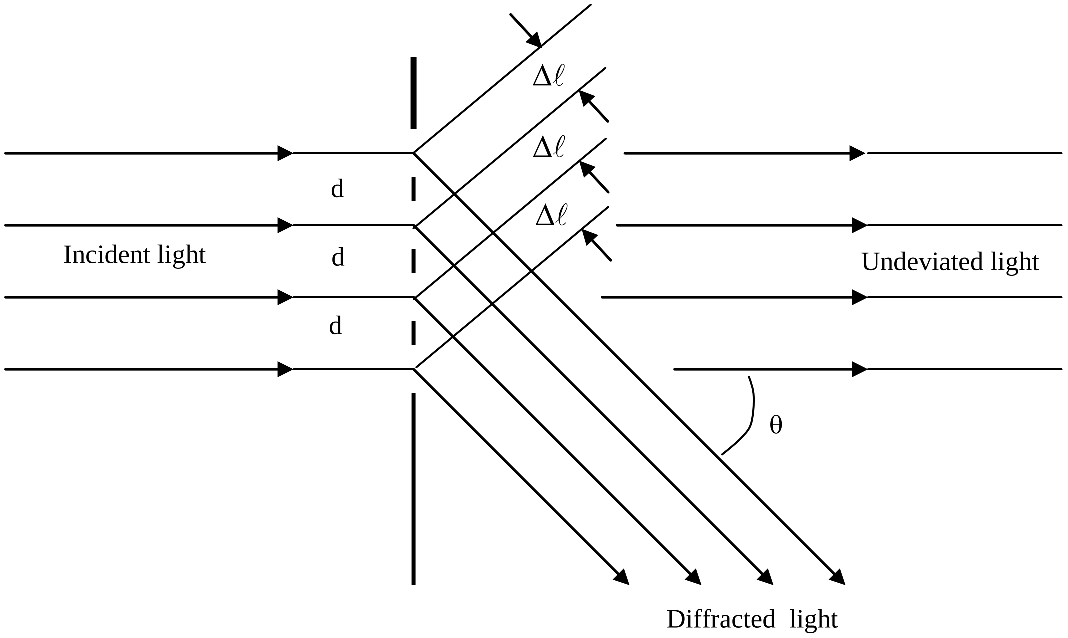
$$\frac{1}{\lambda} = R\left(\frac{1}{m^2} - \frac{1}{n^2}\right) \qquad [5]$$

Where m is the principal quantum number, of the lower energy state and n is the quantum number of a higher energy state, and R is Rydberg's constant. In this experiment, we will determine the value of this constant.

B. The Optical Spectrometer

Visible light may be studied by using a grating spectrometer, which resolves the incoming light into its component wavelengths or colors. In this instrument, a diffraction grating is used to separate the various wavelengths of light. The grating is very carefully spaced transparent openings ruled on a sheet of plastic such that each is separated from the adjacent openings by a distance d.

When light is incident on a diffraction grating, each opening acts as a new source of light spreading light from that opening. The waves from these openings may either reinforce or cancel each other at some angle θ. The condition for reinforcement is that the path difference, $\Delta \ell$, for the light from adjacent openings be a whole number of wavelengths. The light waves from adjacent slits traveling away from the grating will then be in phase and will reinforce one another. This case is illustrated in Figure -2.



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The condition for constructive interference requires that

$$\Delta\ell = \kappa\lambda$$

where κ is a whole number called the order of the diffraction pattern. Pictured in figure 3 are two adjacent openings enlarged from figure 2.

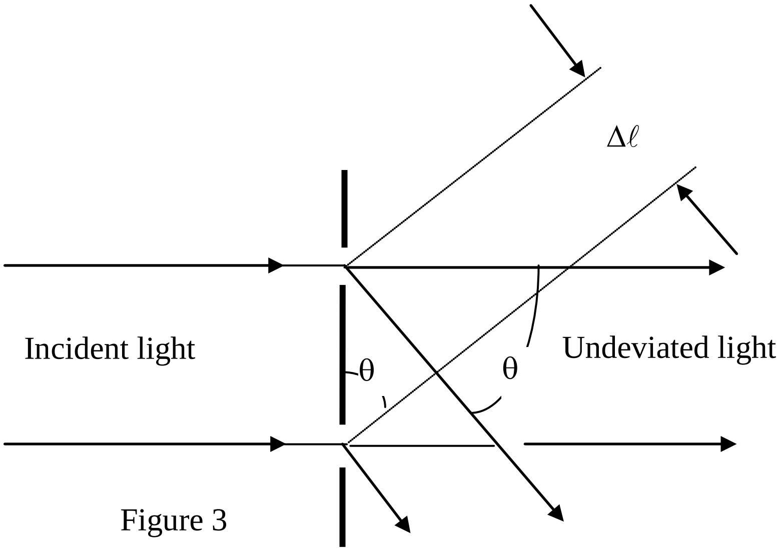


Figure 3

From figure 3 it is seen that $\Delta\ell = d\sin\theta$, so that

$$d \sin \theta = \kappa\lambda \qquad [6]$$

Since for a given order, κ, (other than κ = 0), sin θ is proportional to λ, and the grating spectrometer may be used to analyze the spectrum of the incoming light.

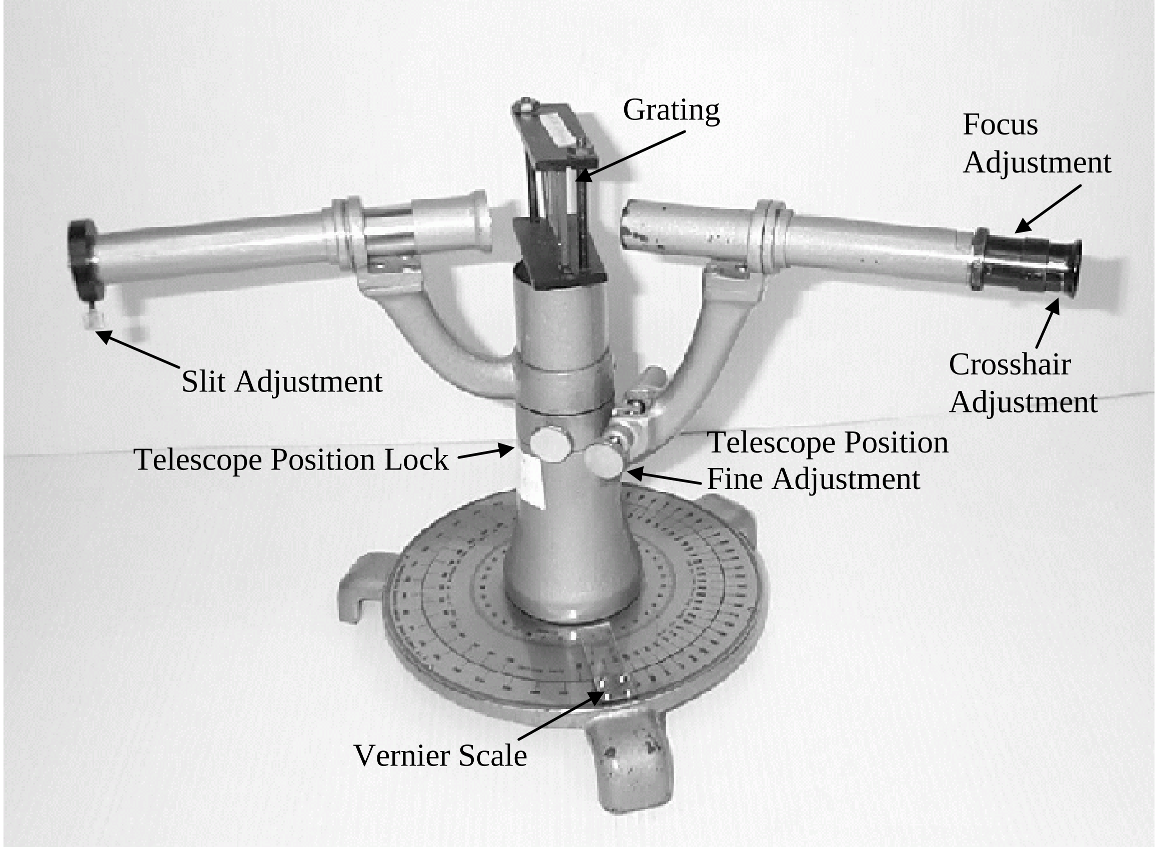


Figure 4

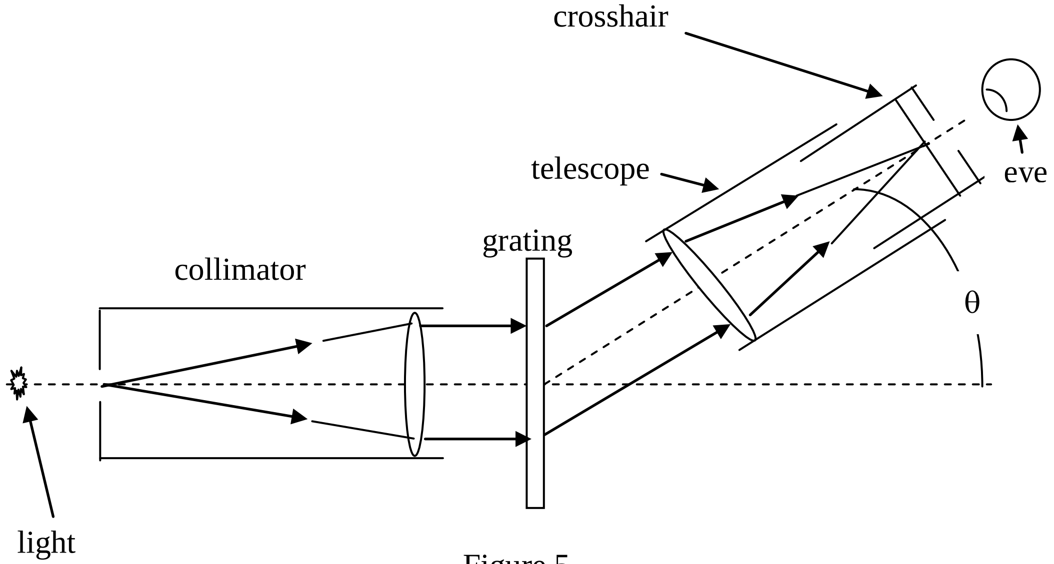
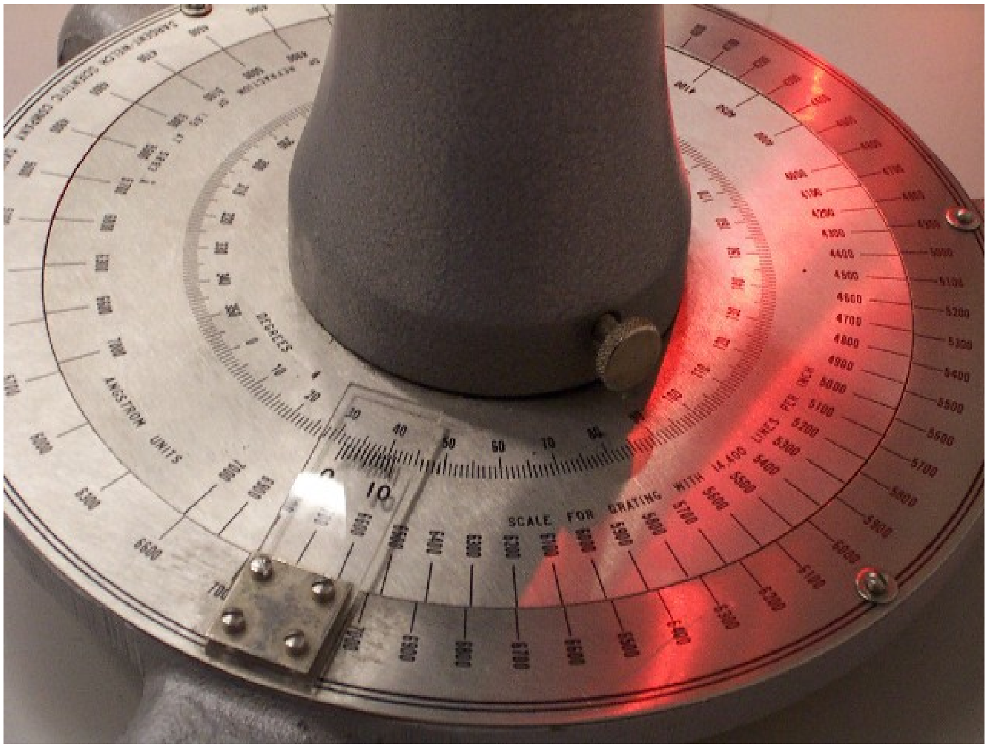
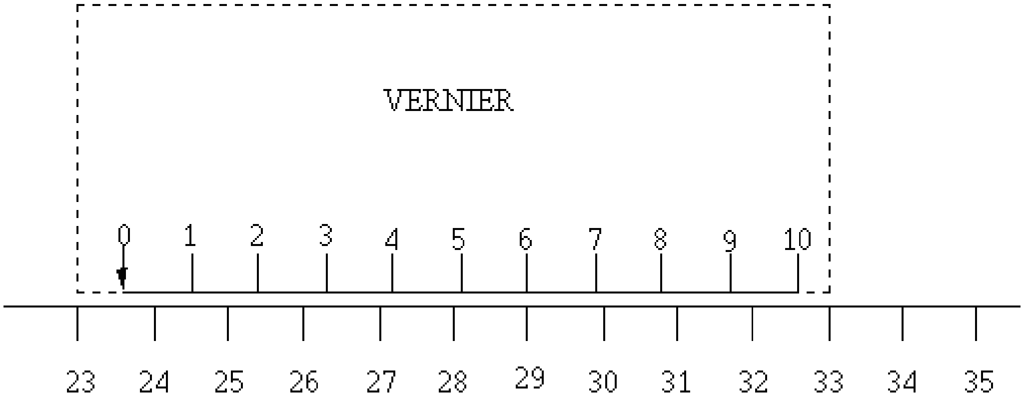


Figure 5

How to Read a Vernier Scale

A vernier scale, shown below in the dashed box, is used to interpolate an extra digit of accuracy. The position of the zero is used to read the scale to the accuracy of the drawn or "ruled" lines. The extra vernier's digit will line up with the scale's ruled lines to indicate the next digit of accuracy. Below, the vernier zero lies between 23 and 24. Notice that the vernier's "6" lines up with a ruled line on the scale. This means the answer is 23.6.





Procedure:

Examining the Spectrometer:

The spectrometer consists of a telescope with an adjustable slit on the fixed end and a eyepiece on the other rotatable end.

A 20000 lines per inch transmission grating lies within the optical path of the two ends.

The base of the spectrometer has calibrated scales for angle and wavelength measurements.

The wavelength scales are of no use as they are calibrated to a different grating. However the angle scale can be utilize in conjunction with equation [6]. Where d is the spacing between the grating lines in meters.

$$d = 0.0254/20000$$

$$d=$$

Task 1: Setting up the Spectrometer.

☐ Adjust the Telescope Position Fine Adjustment so that the metal tab is approximately centered between the adjustment screw and the plunger.

☐ Loosen the Telescope Position Lock. Adjust the position of the telescope so that fixed end and rotating end of the telescope lines up. Tighten the position lock.

☐ Adjust the slit adjustment on the fixed end to widen the slit width.

☐ Position the white light source so that it illuminates the slit.

☐ Look though the telescope. If the slit with the white light source shining thru cannot be seen loosen the telescope position knob and rotate the telescope until it is seen.
Note: it may be out of focus.

☐ The focus adjustment moves in and out of the telescope. Looking thru the eyepiece adjust the focus so that the slit on the other end comes into focus.

☐ Align the thick crosshair line so that it is in the center of the slit.

☐ Adjust the slit for a smaller slit size. Readjust the telescope and cross hair as needed. To keep everything aligned

☐ Once a satisfactory alignment has been made. Loosen the knob near the base. Rotate the scale and align the 0 degree with the 0 on the vernier scale. Use the +100mm lens to magnify the scale for easier reading. Tighten the knob.

☐ There should be a dark cloth on the table. Drape the cloth over the two portions of the telescope and the transmission grating. You want prevent any unnecessary light entering the system, yet allowing the desired light to pass through the telescope unhindered.

Task 2: Continuous Spectrum.

☐ While looking though the telescope rotate it so that you are increasing from zero degrees. Eventually you should encounter the continuous spectrum. Within the bands of color violet, blue, green, yellow orange and red make an angle measurement. Also make a measurement for the start of the spectrum and the end of the spectrum.

☐ Move the telescope back to zero and the go in the opposite direction and make similar measurements. Remember it is the angle deviation from zero that you are measuring.

☐ Determine the wavelengths. Equation [6].

Task 3: Hydrogen gas

☐ Return the telescope so that when looking thru it you once again see the slit.

☐ Remove the white light source and move the spectrum tube power supply in front of the slit.

☐ Carefully install the Hydrogen tube into the power supply. It is spring loaded. Bottom end first then pushing downward to install the top end.

☐ Turn on the power supply. Open up the slit once again. Look through the telescope. Position the power supply so that you can see the spectral source. Narrow the slit. A wide slit will allow more light through but will produce a brighter but diffused spectral line. While a narrow slit will create a sharper line but fainter.

☐ Check you zero. Adjust if necessary. Rotate the telescope and find you first spectral line. Some of these may be faint. For those a wider slit might be better. Make the angle measurement.

☐ Find all of the visible spectral lines for hydrogen.

☐ As part of your write up you are to determine the energy transitions that produces each wavelength(for example from n=4 to n=2 produces a $\Delta E = 2.55$eV

Also find the Rydberg's constant. From equation [5] a graph can be made that yields a linear slope equal to the Rydberg's constant.

Task 4: Calibration can be down outside of lab

☐ It might be necessary to find a calibration constant for the spectrometer. Given the known Balmer series wavelengths of the Hydrogen spectral lines. Plot the known values vs. the measure values. The slope of this line can be used as a calibration constant such that. $\lambda_{known} = k * \lambda_{measured}$

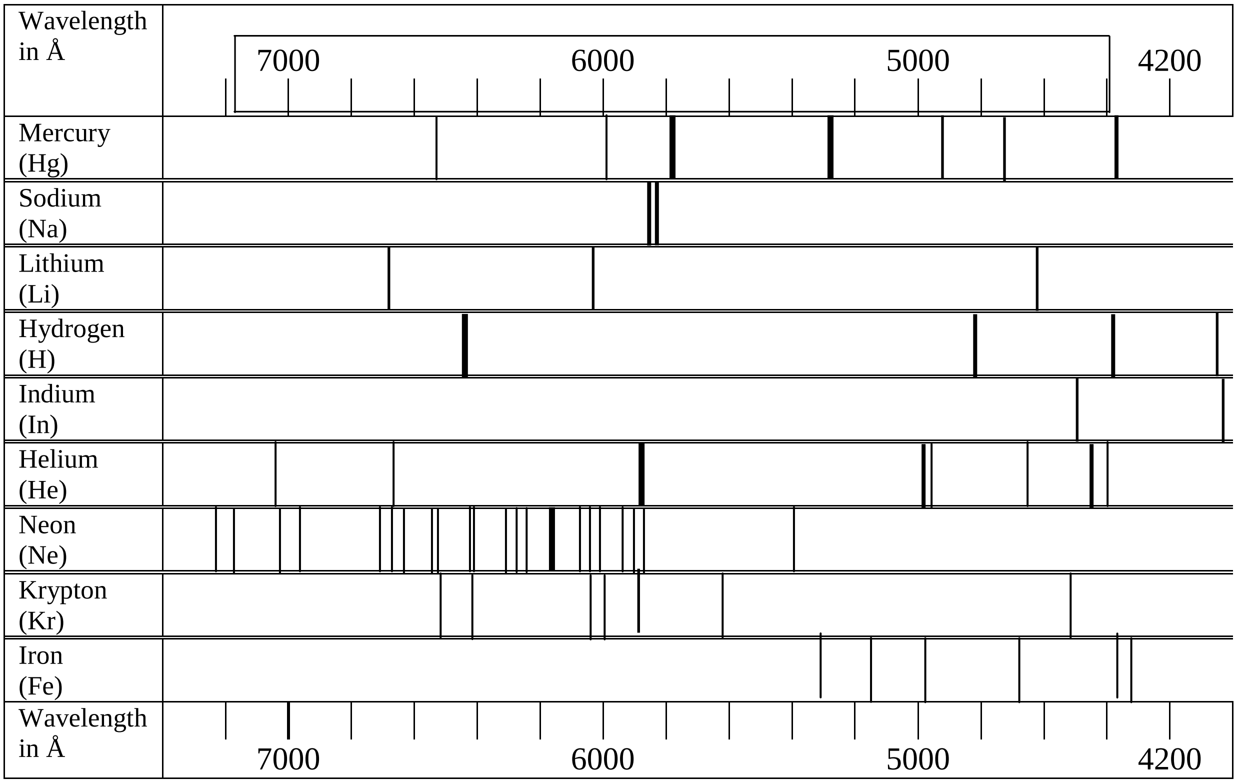
Accepted Balmer series wavelengths
Red 656nm, cyan 486nm, violet 434nm

Task 5: Identify Unknown Element Gases

☐ Determine the wavelengths for the other spectral tubes. 1,2,3,and 4. Don't forget to use the calibration constant. If the spectrum has more than 5 spectral lines then just find 5 across the spectrum it spans.

☐ Compare the wavelength to that given in the chart. Determine the element.

SPECTRAL LINE WAVELENGTHS



Wavelengths in nm

Neon
489, 496 (blue-green), 534 (green), 585 (yellow)
622, 633, 638, 640, (orange-red) 651, 660, 693 (red)

Helium
447 (blue) 471 (turquoise) 492 (blue-green) 501 (green) 587 (yellow) 667 (red)

Mercury
404 (violet) 435(blue) 491 (green)546 (green) 576(yellow) 579 (yellow)