Physics 238

Optical Spectroscopy I: Hydrogen and the Balmer Series

Report **Due April 22, 2026**

Safety

UV: The mercury pencil lamp used in this experiment gives off a significant amount of ultraviolet (UV) light. UV light can be hazardous, particularly to the eyes. It is important to wear UV goggles when working with the light. After everything is set up, you should cover the lamp to shield everyone else from the UV light, and then you may remove the goggles.

Mercury: Mercury is highly toxic. The mercury in the mercury lamp is safely enclosed by quartz. However, if the lamp were to somehow break (very unlikely), you should not attempt to clean it up yourself. Please put a note out to alert your fellow students to the problem, and contact me so we can sort it out together.

1 Introduction

Optical spectroscopy has played a tremendous role in the development of quantum physics and is still an active field of research. The goal of this experiment is to introduce you to the operation of a high resolution optical spectrometer. You will first use a mercury discharge lamp to calibrate the spectrometer and explore its resolution. Then you will measure the wavelengths of light emitted by a hydrogen lamp and compare them to the theoretical predictions for the Balmer series.

The SPEX Model 1250 optical spectrometer is a research grade instrument capable of providing high resolution optical spectra in the range 200 to 1500 nm. Figure 1 shows the optical layout of the optical components inside the spectrometer housing.

The position of the mirrors and the grating in the 1250M spectrometer are characteristic of a Czerny-Turner configuration. In this configuration, light enters through an entrance slit (S1 or S3) and passes to a concave mirror, M1, where it is collimated and reflected to a rotatable reflection diffraction grating. The grating diffracts the light, dispersing the various wavelengths to different angles in the horizontal plane according to the usual relation $2d\sin\theta = m\lambda$. The diffracted light is then reflected and focused by a second concave mirror, M2, through an exit slit (either S2 or S4) and onto the active surface of a detector.

As the grating rotates, different optical wavelengths are focused on the exit slit and de-

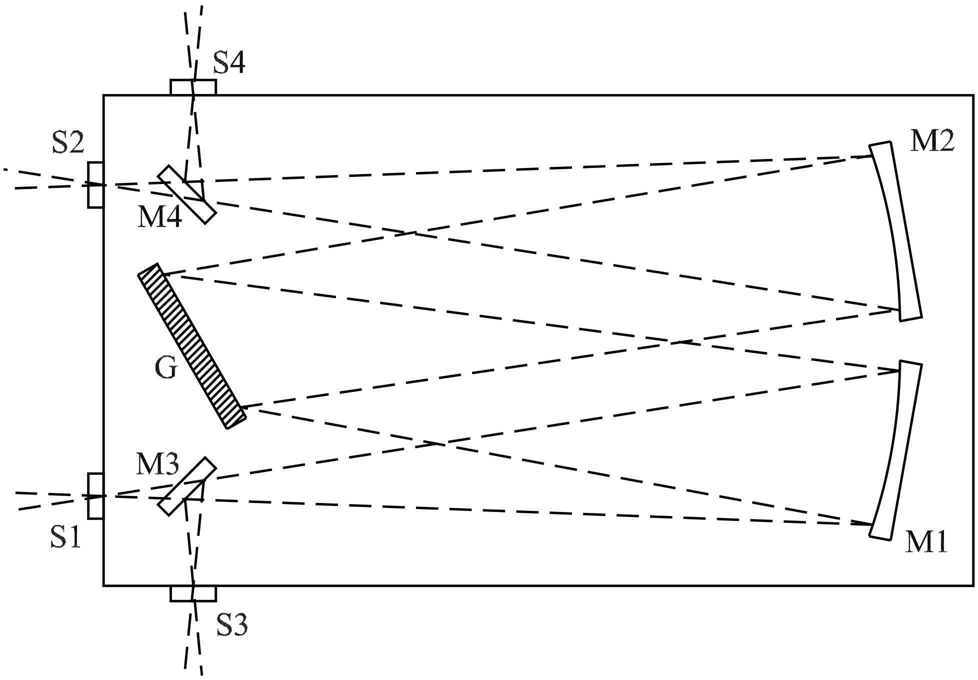

Figure 1: Optical Layout of the SPEX Model 1250M Czerny-Turner Spectrometer. S1 and S3 are entrance slits, S2 and S4 are exit slits, M1 and M2 are concave collimating mirrors, M3 and M4 are swing mirrors and G is the diffraction grating.

tected. You can smoothly scan the grating angle using the Spex MSD 2 Controller via a computer interface. In the 1250M spectrometer, the swing mirrors M3 and M4 are added only for convenience in setting up the external apparatus; they allow either side or end entry and exit. Mirror M4 is not installed in our spectrometer.

Table 1 summarizes the manufacturer's specifications for the Model 1250M fitted with the 1200 groove/mm diffraction grating. The wavelength resolution of the spectrometer is defined to be the minimum wavelength separation between two infinitely narrow peaks such that the two peaks can be readily discerned from one another. In Table 1, the resolution of the 1250M is stated to be 0.006 nm in first order. The theoretical resolution of the instrument increases in second order by a factor of two due to the dispersion characteristics of the diffraction grating.

In practice, the absolute accuracy is limited by our calibration procedure, but the repeatability specification ensures that, once calibrated, subsequent measurements ought to be reliable.

A typical spectrum of a single line is seen in Fig. 2, which shows a scan of the spectrom-

Focal Length (m)	1.25
Aperture	f/11
Spectral Range (nm) (Atmosphere limited)	0–1500
Dispersion (nm/mm)	0.65
Resolution (nm)	0.006
Multichannel Coverage (nm over 25 mm)	16.52
Absolute Accuracy (nm)	±0.05
Repeatability (nm)	±0.005
Drive Step Size (nm)	0.00025

Table 1: Specifications of the SPEX Model 1250M Spectrometer

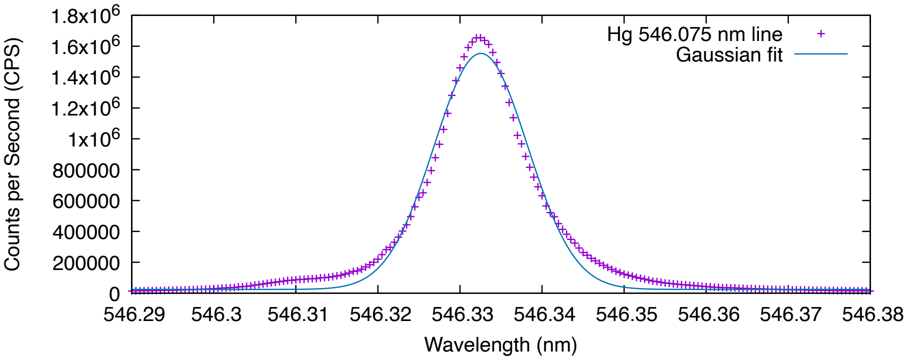

Figure 2: High resolution scan of the 546.075 nm line of atomic mercury.

eter near the 546.075 nm line of mercury. In this scan, the peak actually appeared at a wavelength of 546.33 nm. We will need to account for such shifts by calibrating the spectrometer. Fortunately, one rarely needs absolute wavelengths; in many experiments you can use wavelength differences for making direct comparison to theory.

The peak in Fig. 2 has a full width at half maximum (FWHM) of about 0.013 nm, larger than the instrumental resolution of 0.006 nm. This broader peak likely represents additional minor problems with alignment of the source or adjustment of the entrance and exit slits, as well as the underlying complexity of that 546 nm line due to the hyperfine structure of the multiple isotopes of mercury present in the sample.

The resolution of an optical spectrometer is typically given at 313.2 nm because this wavelength corresponds to the location of a pair of closely spaced, intense, and narrow lines in the ultraviolet emission spectrum of a mercury discharge. The spectrometer passes light

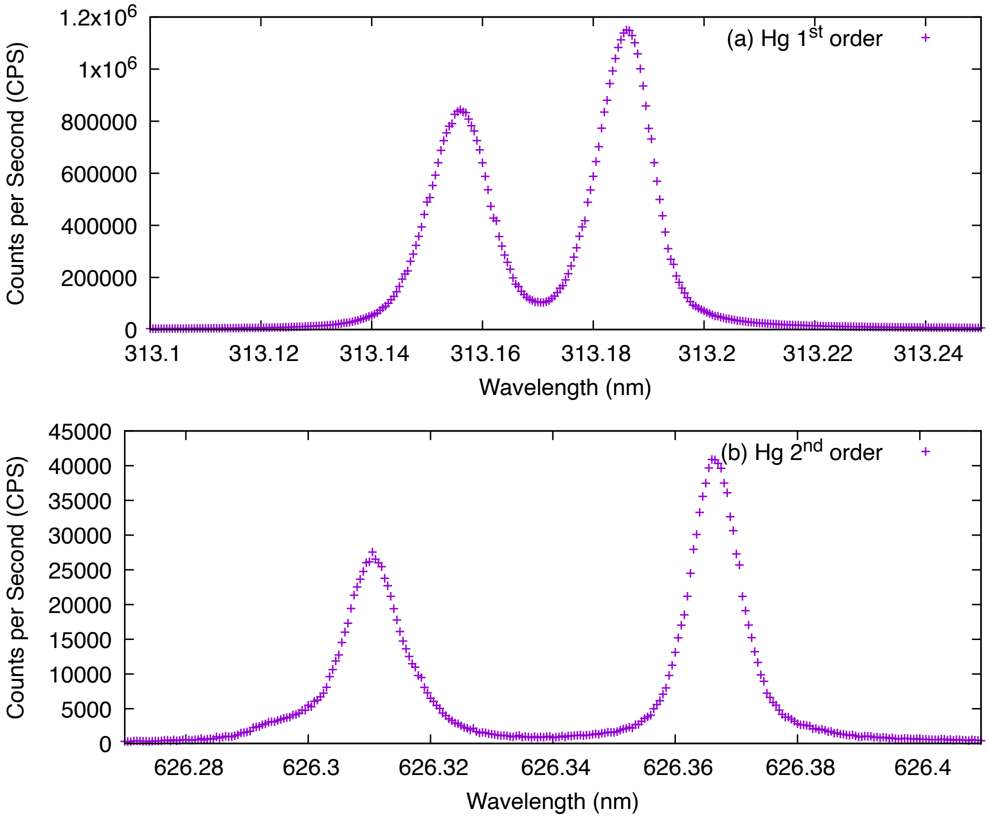

Figure 3: High resolution spectra of the atomic mercury 313.1555 nm and 313.1844 nm lines in *a*) first order and *b*) second order.

from the entrance to exit slits whenever the angle of the diffraction grating meets the condition for constructive interference, $2d \sin\theta = m\lambda$. This represents a series of angles, each for a different *order* m of the grating. Thus, light at 313.2 nm will also pass through the spectrometer when it is set at 626.4 nm (second order) and 939.6 nm (third order).

Figure 3 shows the spectra of these two emission lines taken in both first order and second order on the SPEX 1250M. The FWHM of the peaks in Fig. 3a and Fig. 3b are both about 0.01 nm. However, notice that the peaks in Fig. 3b are more clearly separated than those in Fig. 3a. In second order, the peaks retain the same width, but they have been dispersed twice as far and the effective resolution of the instrument has been doubled, although the intensity of the signal is significantly decreased. For this reason, high resolution spectroscopy is often done in as high an order as possible.

2 Experiment

Before starting, consult the Safety notices at the beginning of this writeup.

2.1 Calibration with Mercury

The first step before any spectrometer experiment is a calibration. In this experiment, we will be using using a mercury pencil lamp, which is set up on the side ("Lateral") entrance to the spectrometer.

General instructions for using the spectrometer are given in "Acquiring a spectrum with the SPEX 1250M" document, which is in the room with the spectrometer, and also available from the course website.

1. Put on the UV goggles.
2. The mercury pen lamp and entrance slit should already be set up. The entrance slit is set to the bottom "dot" and the width is set to about 10 µm. The exit slit is set to about 10 µm.[1]
3. Cover the pen lamp with the box and then turn it on. Once the lamp is shielded, you may remove the UV goggles.
4. If you haven't already, create a folder on the Desktop to store your data.
5. Launch the `SynerJY` program.
6. Use `Experiment -> Collect` to open the Collection menu. Select the "Monos" button, and set the entrance to "Lateral." Select the "Detectors" button and set the voltage to 850 V and the integration time to 0.1 s.
7. *If necessary,* perform a rough scan over the range 400 nm to 600 nm in order to identify intense peaks in the mercury spectrum. A resolution of about 0.05 nm is useful for this first-pass scan. Click on the "Data" tab and export the data as an `ASCII` file. *If there is a recent rough scan, you may be able to skip this step and proceed to the next step.*

   If you do a full scan, please leave a copy of the scan on the Desktop so that other students can refer to it as well.

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[1] Be very gentle with the slit micrometers. The numbers on the micrometers are no longer accurate measurements of the actual slit width, so a bit of trial and error is sometimes needed. Usually, the slits should already be set appropriately.

8. Compare these peaks to known peaks in the Hg spectrum (*e.g.* the supplied table from an article by Sansonetti, Salit, and Reader[1]). Note that some visible peaks may be second-order peaks, given by $2d \sin\theta = 2\lambda$. That is, the line at 253.65 nm will also show up (more faintly) at 507.30 nm. The `Data` tab below the spectrometer graph is often useful for this first look at finding the peaks.

9. Perform a detailed, "zoomed-in" scan for the 546.08 nm green line, similar to Fig. 2. Adjust the Start and End wavelengths to include the range around the peak shown in the rough scan. A resolution of 0.001 nm works well.

   Look at the resulting graph carefully. You should get a nice peak similar to that in Fig. 2. If the peak has dips or flat parts at the top, then the intensity of the source is too high. Either make a smaller incoming slit (or a smaller exit slit) or turn down the photomultiplier voltage. Conversely, if the peak is too small (*i.e.* the number of "counts" never gets above a few thousand) then consider increasing either the slit width or the photomultiplier voltage. You may have to experiment a few times to get a satisfactory result. Record your final settings.

   Export your data.

10. Perform detailed, "zoomed-in" scans for about 3 or 4 more intense peaks covering a wide range of wavelengths. Wavelengths of 404.66 nm, 435.83 nm, and 576.96 nm should work well.

    Export each zoomed-in scan.

11. Make a quick estimate of each of your peak locations. A look through each data table is sufficient for now. Usually, the peaks will be offset by about the same amount. Compare your peak positions to the know positions to find the average offset. You will use that offset to help find the correct regions to scan in the next section. You will do a more careful calibration in the analysis section below.

2.1.1 Calibration Analysis

Find the location of each of your peaks by fitting to a Gaussian of the form

$$I(\lambda) = Ae^{-\frac{(\lambda-\lambda_p)^2}{2\sigma^2}} + I_{\text{off}} \tag{1}$$

The measured peak shape results from a range of effects, both physical and instrumental, but a Gaussian fit usually gives reasonable results.

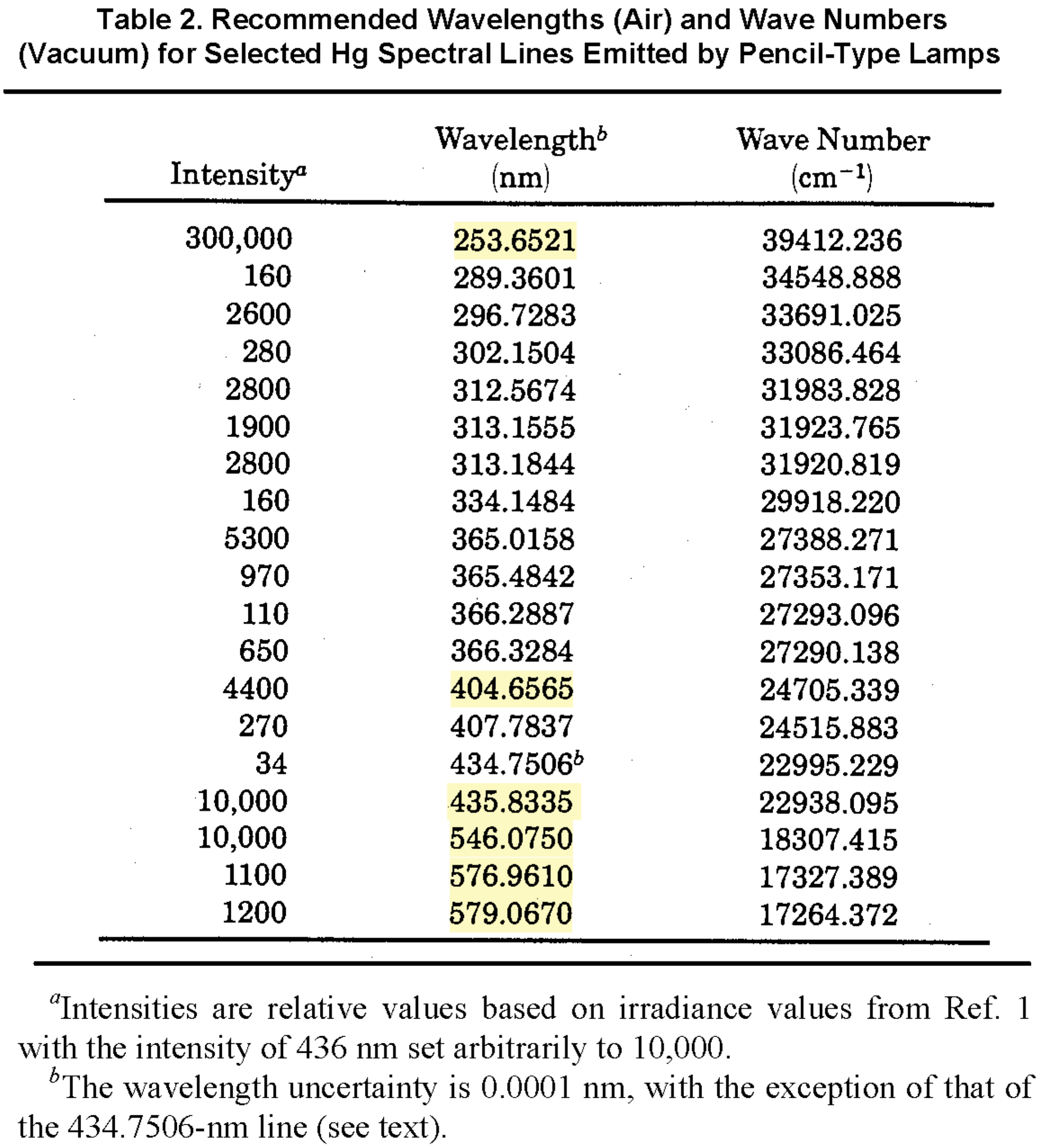

Table 2. Recommended Wavelengths (Air) and Wave Numbers (Vacuum) for Selected Hg Spectral Lines Emitted by Pencil-Type Lamps

Intensity[a]	Wavelength[b] (nm)	Wave Number (cm^{-1})
300,000	253.6521	39412.236
160	289.3601	34548.888
2600	296.7283	33691.025
280	302.1504	33086.464
2800	312.5674	31983.828
1900	313.1555	31923.765
2800	313.1844	31920.819
160	334.1484	29918.220
5300	365.0158	27388.271
970	365.4842	27353.171
110	366.2887	27293.096
650	366.3284	27290.138
4400	404.6565	24705.339
270	407.7837	24515.883
34	434.7506[b]	22995.229
10,000	435.8335	22938.095
10,000	546.0750	18307.415
1100	576.9610	17327.389
1200	579.0670	17264.372

[a] Intensities are relative values based on irradiance values from Ref. 1 with the intensity of 436 nm set arbitrarily to 10,000.

[b] The wavelength uncertainty is 0.0001 nm, with the exception of that of the 434.7506-nm line (see text).

Figure 4: Calibration wavelengths from Ref. [1].

Plot the standard wavelengths *vs.* your measured wavelengths. Fit a straight line to your data and use the fit to create an equation to convert your measured wavelengths to "corrected wavelengths".

References

[1] Sansonetti, Salit, and Reader, "Wavelengths of spectral lines in mercury pencil lamps", *Applied Optics* 1996.

3 Hydrogen Spectrum and the Balmer Series

The second part of this experiment is to measure the spectrum of a hydrogen lamp.

3.1 Introduction

When an electric discharge passes through a gas of neutral atoms, all of the same chemical element, spectral lines (each consisting of light of a specific wavelength) are produced. These lines can tell us a great deal about the internal structure of the atom, since they are produced when electrons in the atoms make transitions from one energy level to another.

The spectrum of wavelengths emitted by hydrogen has an especially simple regularity that was found empirically to be given by:

$$\frac{1}{\lambda} = R_H \left(\frac{1}{n_l^2} - \frac{1}{n_u^2} \right) \tag{2}$$

where R_H a constant known as the Rydberg constant (for Hydrogen), and n_l and n_u are integers. One of the great triumphs of Bohr's model of hydrogen was its ability to reproduce the observed spectrum of hydrogen and provide a first-principles value for the Rydberg constant.

3.2 Theory for the Hydrogen Spectrum

The energy levels for an electron in a hydrogen atom are given by

$$E_n = -\frac{m_e e^4}{(4\pi\epsilon_0)^2 \, 2\hbar^2} \frac{1}{n^2},$$

where m_e and e are the mass and charge of an electron, ϵ_0 is the permittivity of free space, $\hbar$ is Planck's constant, and $n = 1, 2, 3...$ is the quantum number denoting the energy level, and where it is assumed that the nucleus is infinitely massive (so that it does not move). An atom making a transition from an upper state n_u to a lower state n_l loses energy ΔE,

$$\Delta E = E_u - E_l = \frac{m_e e^4}{(4\pi\epsilon_0)^2\, 2\hbar^2}\left(\frac{1}{n_l^2} - \frac{1}{n_u^2}\right) .$$

The atom loses energy ΔE by emitting a photon of wavelength λ:

$$\begin{aligned} \Delta E &= \frac{hc}{\lambda} = \frac{2\pi\hbar c}{\lambda} \\ \frac{1}{\lambda} &= \frac{\Delta E}{2\pi\hbar c} = \frac{m_e e^4}{(4\pi\epsilon_0)^2\, 4\pi\hbar^3 c}\left(\frac{1}{n_l^2} - \frac{1}{n_u^2}\right) , \end{aligned}$$

where c is the speed of light.

This can be written as

$$\frac{1}{\lambda} = R_\infty \left(\frac{1}{n_l^2} - \frac{1}{n_u^2}\right) \tag{3}$$

where R_∞ is called the Rydberg constant, and is equal to

$$R_\infty = \frac{m_e e^4}{(4\pi\epsilon_0)^2\, 4\pi\hbar^3 c} = 1.097\,373 \times 10^7\,\mathrm{m}^{-1} .$$

This value would be appropriate if the nucleus were infinitely massive. For a nucleus of finite mass m_N, the reduced mass μ should be used instead of the electron mass m_e:

$$\mu = \frac{m_N m_e}{m_N + m_e} \tag{4}$$

With this reduced mass, you obtain different values of the Rydberg for hydrogen (R_H) and for deuterium (R_D).

For most combinations of n_l and n_u, the lines produced are not within the visible spectrum.

When $n_l = 1$, the resulting series of lines is called the *Lyman* series. All Lyman lines are in the ultraviolet range (91 to 121 nm), so they will not be seen using this apparatus.

When $n_l = 2$, the *Balmer* series is produced. The only visible Balmer lines occur when n_u = 3, 4, 5, and 6; the remainder are in the ultraviolet range.

When $n_l = 3$, the *Paschen* series is produced. All Paschen lines are in the infrared range (820 to 1875 nm).

In this experiment, you will measure the wavelengths of lines from the Balmer series of hydrogen ($n_l = 2$) and use those wavelengths to determine the Rydberg constant.

3.3 Experiment

The hydrogen lamp should be set up at the front ("Axial") entrance slit of the SPEX 1250M spectrometer. Align the source carefully with the input. An input slit width of 5 µm and height of 0.2 cm usually works well.

Launch the `SynerJY` program. Use the `Monos` button to select the "Axial" input. Use the `Detectors` button to set the voltage to 850 V. The hydrogen lamp tends to flicker, so setting a slightly longer integration time, such as 0.2 s, usually works better.

Record a spectrum for each of the first four lines of the Balmer series. (The tube is made from glass that blocks ultraviolet light, so you will get the strongest signals from the first three or four lines which are in the visible range.) You will probably find it useful to pre-calculate where the peak ought to be, and then do a quick scan in that vicinity to be sure you have the appropriate range. A resolution of 0.001 nm works well for these final high-resolution scans. Export your data for each peak.

4 Analysis

4.1 Hydrogen

1. For each of your four hydrogen wavelengths, fit a Gaussian to determine the wavelength of the peak.
2. Using your calibration function, make any adjustments necessary in your measured wavelengths for hydrogen.
3. Plot wavelength vs quantum number n_u for your 4 data points. Fit Eq. 2 to your data and include that fit on your graph.
4. Compare your fitted value for R_H to the theoretical value. Comment on any discrepancies. Do your data support the Bohr model?