

# Experiment 341: The Spectrum of Hydrogen

## Aim

To use a spectrograph and a Charged Coupled Device (CCD) array to obtain high quality optical spectra, and by analysing these carefully, to determine the value of the Rydberg constant,  $R_H$ .

## References

1. Serway, Moses and Moyer, "Modern Physics".
2. "Tables of Spectral Line Intensities", NBS Monograph No 32 Part I.
3. H.G.Kuhn; "Atomic Spectra"

## Introduction

The spectrograph supplied has quartz optics and is capable of operation over a range of wavelengths from about 680 nm to 235 nm. However, the currently available light sources have glass envelopes, which transmit only down to around 325 nm, and the CCD is very inefficient at these short wavelengths. Nevertheless, the apparatus is capable of measuring the wavelengths of the Balmer series in the hydrogen spectrum with relatively high precision.

The spectrum of hydrogen, and also those of cadmium and mercury which are used for calibration purposes, are recorded on the PC using a CCD array in the focal plane of the spectrograph. The output of the CCD is digitised using an analogue to digital convertor (ADC) and appears as a spectrum in 2048 channels (pixels) in which the positions of the intense lines are then located precisely. The techniques involved are discussed below.

Using the known wavelengths of the emission spectra of cadmium and mercury, those of the Balmer series of hydrogen are determined, and the value of the Rydberg constant is derived with a precision exceeding one part per thousand.

## Procedure

There are five steps in this experiment.

1. Familiarisation with the spectrograph, the CCD array and the control panel on the PC.
2. Obtaining good quality spectra for H, Cd and Hg.
3. Obtaining the line positions by fitting the line shapes using Matlab.
4. Identifying the lines.
5. Determining the wavelengths of as many of the hydrogen lines as possible and hence determining the Rydberg constant.

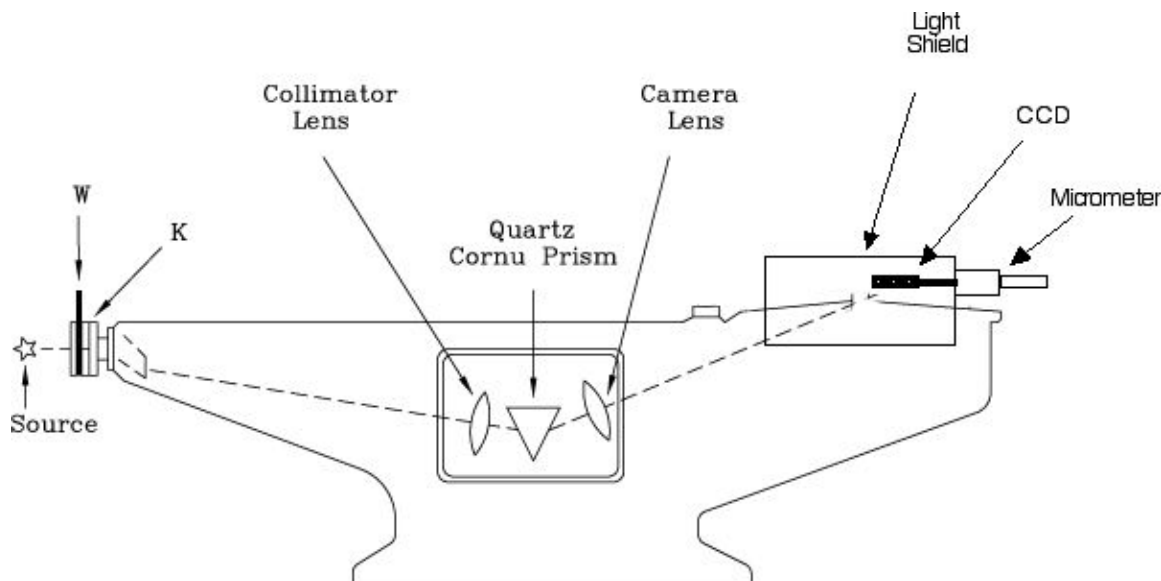


Figure 1: The optical spectrograph

## Step 1. The spectrograph and CCD array

Fig. 1 shows the internal parts of the spectrograph. The light enters through a narrow horizontal slit whose width and length are adjustable using the knurled knob K and moving wedge W. Suitable settings are 5 (thousandths of an inch) and approximately 1cm respectively. The various colours are dispersed by the prism and focussed at points on the surface of the CCD, which is in the focal plane.

The CCD proper is an array of 2048 pixels, on a  $14\text{ }\mu\text{m}$  pitch and  $200\text{ }\mu\text{m}$  long, covering approximately 28mm in the focal plane. A further 39 pixels are present on the sensor, 33 preceding the array proper and 6 following for a total of 2087. An identical, but “dead”, CCD is mounted on a wooden block for you to examine. When light strikes a CCD pixel, the output voltage varies linearly with the total incident energy, so, if the CCD is activated for a fixed time, and then the output voltages from each pixel are sequentially digitised using an ADC, and plotted as a histogram, a spectrum of intensity vs pixel number is produced. The sensitivity of the pixels to photons, however, is not uniform. Maximum sensitivity is at 461 nm and drops to 50% of maximum at 700 nm and 15% at 900 nm. So relative intensities will not be exact.

One such spectrum is shown in Fig. 2.

To obtain a similar spectrum, switch on the Cd lamp and the computer. After 5 minutes the PC will have booted up and the lamp will have warmed up. Place the lamp horizontally a few cm from the entrance slit. Double click on the “Spectrum of Hydrogen v2” icon on the PC screen and a display similar to Fig. 2 should appear, but with no data.

The various controls are covered in appendix A. Notice in particular the integration time (the “exposure time”), the total number of accumulated integrations (“Samples”), “Start”, “Stop” and “Save Data” (which will be your spectra). Notice also the two graphs, one for the result of the last exposure, the other for the accumulated integrations. When you save data, make the file extension “txt” so it will be easy for Python to read it later.

Adjust the micrometer, which longitudinally translates the CCD, to a setting of around 6 mm. Turn the light out. Click “Start”. The first integration after startup always produces rubbish. Click “Start” again. If a spectrum similar to that in Fig. 2 does not appear, adjust the distance and height of the lamp until it does. When that happens, set the number of integration accumulations to 100 (or whatever you fancy), and notice the buildup of the less intense lines in the accumulative display. The “background” level in each readout is around 600 if you have the room lights out and this is caused by the electronic noise from the CCD and its amplifier.

Be aware of the clipping levels of the CCD: the ADC limits at 1023, so any pixel in the single accumulation

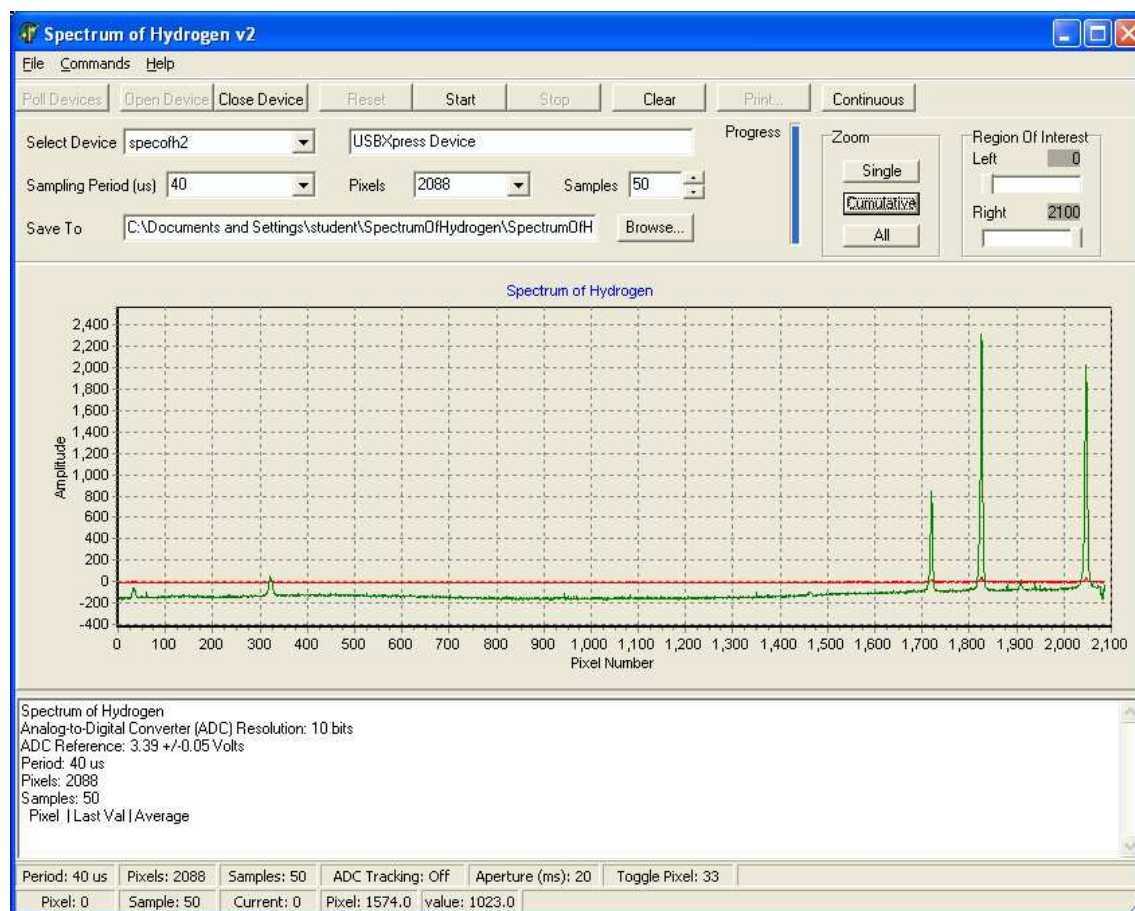


Figure 2: A cadmium spectrum

graph with a content of more than around 1000 is invalid. Be aware also that the output of the CCD contains the occasional artificial “glitch”, either negative dips (such as at around pixel 2080 in Fig. 2 above) or positive spikes that have zero width. These should not be interpreted as optical lines.

Now move the micrometer a few mm in either direction and watch the lines move in the spectrum. Get a feel for what is happening.

## Step 2: Obtaining Cd, Hg and H spectra

You are going to use the known wavelengths of Cd and Hg to calibrate the CCD pixel number in terms of nm in order to measure the wavelengths of as many of the H Balmer series lines as you can detect. To give you an overall feel for the spectra, you can use the “Star” spectrometer provided. With the side with the writing on facing upwards, point the right hand edge at one of the lamps, and look straight through the eyepiece where you will see the spectrum displayed on a wavelength scale.

The use of the CCD should be straightforward, although there is a problem.

The length of the CCD is 28 mm, whereas the length of the focal plane you need to examine is around 50 mm. You can overcome this difficulty by taking spectra with the CCD in 2 positions, say with the micrometer set at 5 mm and at 25 mm. You can then work out effectively how many pixels this movement corresponds to by comparing the positions of strong lines in the Cd and Hg spectra which appear at both positions.

So, for each of the CCD micrometer positions, take Cd and Hg spectra. Try to take spectra with good statistics, so you will be able to locate the peaks accurately, but don’t of course exceed the clipping levels mentioned above.

The hydrogen spectra will require more care. The source is not very bright. On the other hand, although  $H_\alpha$  is intense, the other lines aren't and so the intensity of the H light into the spectrograph needs to be maximised. One method is to use the converging lens given, placing the hydrogen light at 20-25 cm from the input slit and focussing the light to a fine line on the slit. But if you devise a better system, your demonstrator will be pleased to hear about it. Also you will need to take several H spectra at each position, short exposure and small accumulation numbers for the intense lines and longer and more for the faint ones. To obtain the positions of four H lines is straightforward, and a fifth comes with some ingenuity.

Since the H setup takes a while to establish, but you should not move the CCD in between taking the Cd and Hg calibration spectra and the corresponding H exposure, a logical procedure might be:

1. Position 1 - Cd, Hg spectra; various H exposures, as above.
2. Position 2 - H exposures; Cd, Hg spectra.

### Step 3: Obtaining the line positions

Although the pure shape of an emission line is Lorentzian

$$y(x) = \frac{A}{(x - x_0)^2 + \Gamma^2/4}$$

with  $\Gamma$  being the line width and  $x_0$  its position, the physical processes taking place in the discharge tubes mean that the actual line shapes approximate closely to Gaussian

$$y(x) = A \exp\left(-\frac{(x - x_0)^2}{2\sigma^2}\right).$$

Accordingly, the shape of each line can be analysed using non-linear least squares fitting in Python. Fit the peaks with Gaussian curves sitting on a constant background, and find the peak position with an uncertainty. See the Stage 2 experiment "Experiment 214, Non-Linear Curve Fitting" for an adequate introduction.

### Step 4: Identifying the lines

The lines may be identified, and the corresponding wavelengths assigned to their positions using the information in Ref. 2. Since the position of an intense line may be determined to better than  $\pm 0.1$  pixel, you will need the wavelengths to five significant figures. As the efficiency of the CCD is a maximum at 460nm and falls off linearly on either side of there, the relative intensities of the lines from a particular source will not be exactly as given in Ref. 2.

### Step 5: Measuring Hydrogen wavelengths; Determining $R_H$

At this stage you should have the positions and corresponding wavelengths of ten or more calibration lines, and the positions of 4 or 5 hydrogen lines, some of them from more than one spectrum. As a calibration graph, plot  $\ln(\lambda - 290)$  vs pixel, with the range of the horizontal axis being roughly 3500 pixels. A smooth curve should result.

The wavelengths of the hydrogen lines could then be read off this graph from the knowledge of their positions, but the high quality of the data is such that a better procedure should be used. Fitting the calibration curve to a polynomial in  $x$  will give more reliable results.

Using your hydrogen wavelengths, along with their uncertainties, plot an appropriate straight line graph and determine  $R_H$ , the Rydberg constant.

Finally, tabulate your values for the wavelengths of the Balmer series, complete with your assigned experimental uncertainties, and compare with the accepted values. Comment on any differences. How does your value for  $R_H$  compare with the accepted value ?

## List of Equipment

1. Bellingham & Stanley Spectrograph with CCD image sensor attachment (Sony ILX 511)
2. Cenco (H) Spectral Lamp powered by Electro-Technic SP200 Power Supply
3. Philips (Cd) Spectral Lamp powered by Analite Power Supply
4. Philips (Hg) Spectral Lamp powered by Analite Power Supply
5. Converging lens
6. “Star” spectrometer
7. PC
8. USB data acquisition box

P.H. Barker 10 September, 2003.

M.D. Hoogerland July 29, 2011.

Python: R. Au-Yeung, 30 October 2014

## Appendix A: Software: Spectrum of Hydrogen v2

Control descriptions:

1. Poll Devices: The computer is connected to a SiLabs microcontroller device via a USB cable. To get the computer to poll for attached devices, click this button. If the device is recognized, it appears in the “Select Device” chooser as specofh2 and the button ‘Open Device’ is enabled.
2. Open Device: Click this to open a channel to the device in the ‘Select Device’ chooser.
3. Close Device: Terminates communication with selected device.
4. Sampling Period: The CCD pixels can be read out with a period of 0.5 microsecond. The device’s ADC minimum sampling period is 5 us. This plus other limitations mean that the minimum sampling period is approx 36 us. Choose 40 to leave some margin. You shouldn’t need to change this setting.
5. Pixels: The CCD sensor has 2048 effective picture elements plus some ‘dummy’ elements before and after. Pixels can be read out in one of two modes: Without S/H mode and With S/H mode, which leads to either 2086 or 2087 pixels respectively. The latter value used here. In this mode the first 33 pixels are dummy pixels. Sampling more pixels has no adverse effects and the default number used here is 2088. You should not need to change this setting.
6. Samples: Due to low light intensity at some wavelengths, the ‘signal’ can tend to get lost in the noise. Taking multiple samples helps to accentuate the peaks.
7. Browse: The contents of the memo can be saved into a location determined by the user. Use the browse button to select an output directory and file name.
8. Single: If you want the single sample result to fill the whole chart, click here.

9. Cumulative: If you want the cumulative result to fill the whole chart, click here.
10. All: If you want both single and cumulative results to fill the whole chart, click here.
11. Left: Track bar to change the value of the pixel-value origin.
12. Right: Track bar to change the value of the maximum pixel value.
13. Reset: Resets the microcontroller. Not used.
14. Start: Press to start collecting sample data.
15. Stop: Automatic. However, press to stop data collection prematurely.
16. Clear: Clear the contents of the memo control.
17. Print: Print the graph on the default printer.
18. Continuous: If you click on this and then press 'Start', the sequence of N sample collections continues indefinitely or until 'Continuous' is pressed again.
19. Chart: Two results are graphed, the results from the last sample (red) and the cumulative result of the N samples (green).
20. Memo: The sample results are printed here.
21. Status Bar: The current status of various parameters are collectively displayed here. Also, running your cursor over the graphs result in pixel and intensity values being displayed.  
Under the 'File' menu is a submenu: Setup. This is enabled if the 'Open Device' button is enabled.
22. Light Collection Time: The CCD sensor samples the incoming light for a certain period (the integration time) before the separate pixel results are read out. A value of 20 ms here is good.
23. Toggle Output At: For debug purposes, one of the microcontroller's pins can be toggled when a particular pixel's data is being read.
24. Chart max Amplitude: Set the maximum amplitude of the Chart's left axis.
25. Chart Min Amplitude: Set the minimum amplitude of the Chart's left axis.
26. ADC Tracking: A low power setting of the microcontroller's ADC. Not used.
27. Write To Memo: On some older computers, writing to the memo can take up a lot of time. Enable or disable writing to the memo here.
28. Inter-Sample Delay: When 'Continuous' mode is enabled, a delay can be introduced between successive samples.
29. Subtract Per Sample: Each CCD sensor pixel voltage starts at approximately 5V and decreases proportionally according to the light intensity falling on it. Before being plotted, results are inverted so that peaks rise rather than fall. Also there is a small dark voltage of about 6 mV that needs to be accounted for. This feature allows the user to correct for the dark voltage.
30. Chart Start Conditions: Set the chart axes max and min values to be used at the start of each run.