

# ATM - Atomic Physics

Physics 111B: Advanced Experimentation Laboratory

University of California, Berkeley

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## 1 Introduction

Starting in particular in the 1860s, for example, with the work of Robert Bunsen, scientists recognized that different elemental materials could be distinguished by the specific colors of light (i.e. the spectrum) of light that they either emit or absorb. Within these optical fingerprints of different elements, scientists soon discerned patterns and also characteristic responses to various environmental perturbations (e.g. application of magnetic fields). The effort to explain these patterns eventually led to the theory of quantum mechanics. Today, optical spectroscopy continues to be employed in many variations to understand the structure and dynamics of atoms, molecules, and materials, and also to probe for new physical effects that we cannot explain with current theories.

In this experiment, you will perform atomic spectroscopy by studying the characteristic emissions of electrical discharge lamps containing different elements in gas form. The experiment is divided into two parts. In the first, you will use a diffraction-grating spectrometer to observe and characterise the spectrum of hydrogen. In particular, you will observe the Balmer series, and, after calibrating the spectrometer against the spectrum of atomic mercury, you will check quantitatively whether the Balmer formula explains the observed hydrogen wavelengths, and also use that formula to measure the Rydberg constant. In the second part, you will observe different lines from the atomic spectrum of helium. Then, using an optical Fabry-Perot interferometer to separate spectral lines with small wavelength differences, you will study the effect on these lines of a magnetic field applied to the helium atoms. The observed shift of the spectral lines is known as the Zeeman effect. You will observe and explain various aspects of the Zeeman effect, including differences observed for light of different polarization and direction of emission, and also use the Zeeman line shifts to measure the Bohr magneton.

To conduct this experiment, you will draw on your knowledge of classical optics, e.g. to understand what lenses do, what an imaging system is, how a diffraction grating operates, and what are the polarization properties of light. You will also make use of your knowledge of quantum mechanics and atomic physics to understand concepts like optical spectra, spectroscopic terminology, atomic energy levels, and aspects of atom-light interactions. You are strongly advised to review your notes and consult your textbooks on these topics before, during, and after doing this experiment.

1. Pre-requisites: Physics 137AB (may be taken concurrently)
2. Days Allotted for the Experiment: 6

This lab will be graded 40% on theory, 40% on technique, and 20% on analysis. For more information, see the [Advanced Lab Syllabus](#).

## 2 The Atomic Physics Experiment Photos

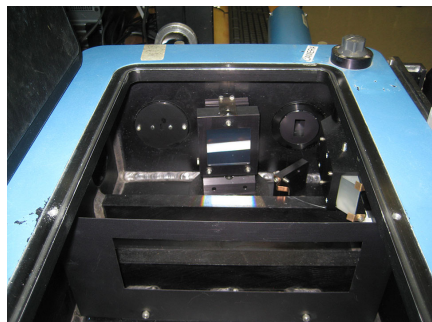


Figure 1: Grating, Entrance, and Exit Slit Interior View  
[Click here to see larger picture](#)



Figure 2: Monochromator Interior Top View  
[Click here to see larger picture](#)

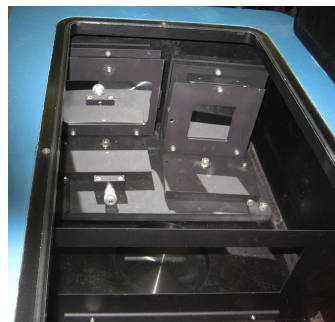


Figure 3: Monochromator Interior Mirror View  
[Click here to see larger picture](#)

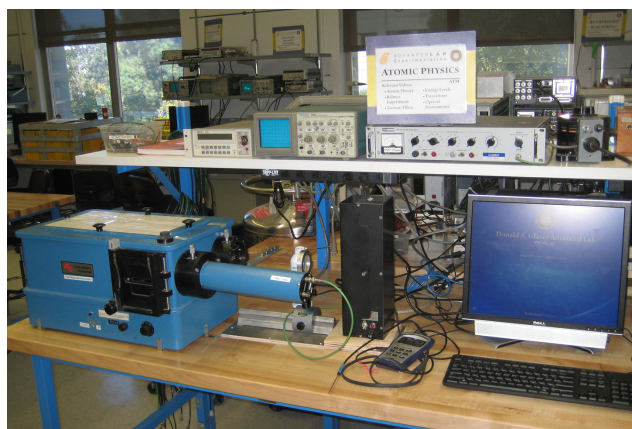


Figure 4: Balmer Setup with the Computer  
[Click here to see larger picture](#)

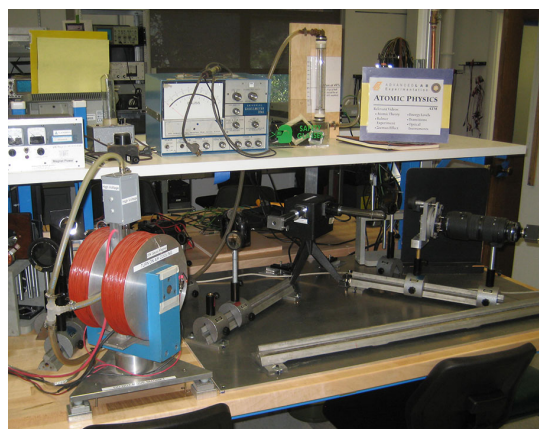


Figure 5: Zeeman Effect Apparatus  
[Click here to see larger picture](#)

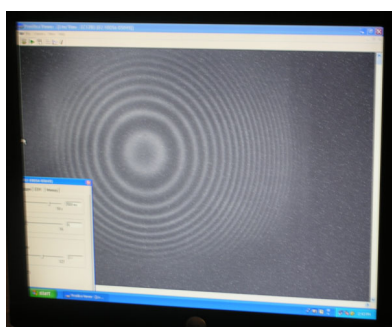


Figure 6: Captured Image from Fabry-Perot Interferometer  
[Click here to see larger picture](#)

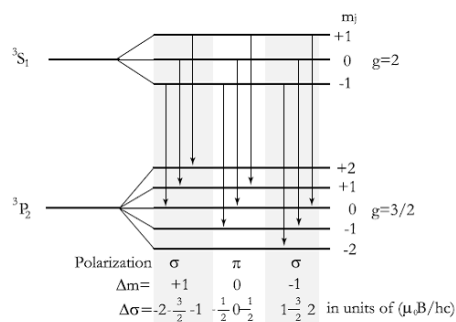


Figure 7: Zeeman Multiplet Splitting  
[Click here to see larger picture](#)



Figure 8: Wear Your Safety Glasses

### 3 Before the 1st day of Lab

Complete the ATM Pre Lab found in the [Signature Sheet](#) for this lab. Print the signature sheet, discuss the experiment and pre-lab questions and answers with any faculty member or GSI, and receive their signature. In the course of the lab there will be examination points where you must STOP and get a GSI or professor to verify your understanding and/or verify proper experimental setup. You cannot skip these checkpoints, and must receive signatures demonstrating that you've consulted the staff. Some experiments may have mid lab questions that must be completed by specific days of the experiment. The completed [Signature Sheet](#) MUST be submitted as the first page of your lab report. Quick links to the checkpoint questions are found here: [1](#) [2](#) [3](#) [4](#) [5](#)

1. **Note: In order to view the private Youtube videos hosted by the university, you must be signed into your berkeley.edu Google account.**  
View the three videos [Atomic Theory Only Video](#) (Great Introduction to ATM, 37 minutes long), [Video on Balmer Series Part-1](#) (20 minutes long), and the [Video on Zeeman Effect Part-2](#) (30 minutes long).
2. View the optics tutorial article (7pgs), a great review of the principles of optics, [Fundamentals of Optics Tutorial](#) and the [Light and Optical Instruments Video](#) (Good introduction to light and optics, 50 minutes long), [Light Sources and Detectors](#) (Good source for Light Sources & Detectors 37 minutes), [Energy Levels \(part 1\) Video](#) (34 minutes long), and [Energy Levels \(part 2\) Video](#) (33 minutes long).
3. **Atomic Physics Additional References and Resources.** Your reflex is probably to google anything you don't know, but this list of references is a better place to search! The knowledge for the Pre-Lab is in these resources.
4. Research the following topics in the suggested readings below;
  - Diffraction Grating Information: [ARC SpectraPro Grating](#)
  - Fabry Perot Etalons: [Fabry-Perot](#) (For an explanation of resolution, see Hecht-Zajac "Optics" [Ch.9-pp. 307-310](#), and [Ch. 10: Diffraction](#))
  - Rydberg Constant, Balmer Series, Zeeman Effect, Bohr Theory for Balmer Series: [Herzberg](#)
  - Atomic energy level data for [Hydrogen](#), [Helium](#), and [Potassium](#).
  - Grotrian diagrams for [Hydrogen](#), [Helium](#), [Mercury](#), and [Potassium](#).
  - Last day of the experiment please fill out the [Experiment Evaluation](#).

#### Suggested Reading:

1. Herzberg, Gerhard. [Atomic Spectra & Atomic Structure](#), Dower Publisher, 1944, New York. Preface pg. 1-257. #QC451.H43. (Read Introduction and skim Chapter 1 pg.11-70)
2. *Experiments in Modern Physics*, A. C. Melissinos and Jim Napolitano 2nd Edition:
  - (a) [Ch. 1.4-1.6: The Hydrogen Spectrum — The Spectra of Sodium and Mercury](#), 25pgs
  - (b) [Ch. 4.6: The Fabry-Perot Interferometer](#), 7pgs
  - (c) [Ch. 5.2-5.5: Various Information About Diffraction](#), 18pgs
  - (d) [Ch. 6.2: The Normal Zeeman Effect](#), 11pgs
  - (e) [Ch. 6.5: The Zeeman Effect of the Green Line of 198Hg](#), 7pgs

#### More [References](#)

You should keep a laboratory notebook. The notebook should contain a detailed record of everything that was done and how/why it was done, as well as all of the data and analysis, also with plenty of how/why entries. This will aid you when you write your report.

## 4 Objectives

- Learn spectroscopic notation and learn to read atomic energy level data sheets and graphs
- Understand diffraction as a tool for spectroscopy
- Apply geometric optics
- Learn to operate a monochromator
- Understand the mechanism of a Fabry-Perot interferometer
- Learn about the different mechanisms of finite linewidth (Doppler, pressure, etc.)
- Understand the effect of a magnetic field on atomic energy levels (witness the Zeeman effect)

## 5 Background

Quantum mechanics describes an atom as having energy eigenstates. For bound states, which have energies below that required to strip a single electron from the atom and ionize it, the energies of these eigenstates are discrete. Above ionization, the energy level distribution is continuous.

Atoms in excited states can decay to lower energy state by emitting photons of light. The photon energy  $E = E_e - E_g$  is then the difference between the energy of the excited state  $E_e$  in which the atom starts, and that of the lower-energy state  $E_g$  in which the atom end up. The photon energy is related to its optical frequency  $\nu$ , angular frequency  $\omega$ , wavenumber  $k$ , and wavelength  $\lambda$  as  $E = h\nu = \hbar\omega = hc/\lambda = \hbar ck$ , where  $h$  is the Planck constant and  $\hbar = h/2\pi$ , and where  $c$  is the speed of light. These relations hold perfectly in vacuum. In air, one must account for the index of refraction being different that unity.

In this lab, we perform optical spectroscopy where we detect light emitted by the relaxation of atoms from high-lying to low-lying states, measuring the optical wavenumber of wavelength (in the first part of the lab) or differences between wavenumbers or wavelengths (in the second part of the lab). We use this information about the emitted photons to infer some of the properties of the atoms that emitted them.

### 5.1 The Balmer Spectrum of Hydrogen

In principle, the energy levels and states of atoms can be calculated using quantum mechanics and our knowledge of the Hamiltonian that governs the atoms. In reality, nearly all atoms are just too complex for us to make these calculations from first principles.

One amazing exception to this complexity is atomic hydrogen, composed of a single electron bound to a single proton. As you have probably seen in your lectures on quantum mechanics, amazingly, the eigenenergies and eigenstates of hydrogen can be calculated analytically in just a few pages of a textbook (or about 80 minutes of lecture). Neglecting effects of relativity and of the electron and nuclear spin, the bound-state energies of hydrogen are given as

$$E_n = -\frac{hcR}{n^2} \quad (1)$$

where  $R$  is the Rydberg constant (with units of 1/length), The principal quantum number,  $n$ , is a positive integer.

In the 1880's, spectroscopists observed a clear pattern in the spectrum of hydrogen. Specifically, Balmer examined spectral lines of hydrogen in the visible part of the optical spectrum, and found that the observed wavelengths  $\lambda_n$  followed what is known as the Balmer formula:

$$\frac{1}{\lambda_n} = R \left( \frac{1}{4} - \frac{1}{n^2} \right) \quad (2)$$

We now know that this spectrum is explained by Eq. 1, with the Balmer lines coming from the decay of a hydrogen atom from a level principal quantum number  $n \geq 3$  to a lower level with principal quantum number 2.

## 5.2 The Normal and Anomalous Zeeman Effects

When the atom is placed in a magnetic field a new term is added to the Hamiltonian. It is a perturbation which discerns between degenerate states based on their respective angular momenta (the original Hamiltonian has no angular dependence). The result is that a previous energy level can split into several new levels, called Zeeman levels after the Dutch physicist. The optical electron circulating around the nucleus acts like a magnetic dipole in a magnetic field, and the energy added by an external magnetic field is therefore  $H' = -\vec{\mu} \cdot \vec{B}$ .

Considering an atom as a magnetic dipole of fixed magnitude, a classical description of the atom would allow it to adopt any orientation from a continuous distribution of orientations. In contrast, quantum mechanics quantizes the orientations of atomic energy eigenstates to a finite number, corresponding to a finite number of orientations. The interaction with the magnetic field separates the energies of these different orientations, so that a single atomic energy level is now potentially split into several different energy levels. Optical transitions to/from these split energy levels now cause a single spectral line to be split into several lines. The splittings of both the atomic energy levels and also of the optical spectrum lines are both referred to as Zeeman splitting.

Understanding fully how an atom responds to the application of a magnetic field can be quite difficult. However, in the limit that the magnetic field is weak, a first-order perturbation treatment explains the effects to a very good approximation. One finds specifically that an atomic energy level, which has the energy  $E$  in the absence of magnetic field, splits up into several energy levels that have the energy

$$E_{m_J} = E + g_J m_J \mu_0 B \quad (3)$$

Here, we consider that the energy level under consideration has an angular momentum with quantum number  $J$ . The magnetic quantum number  $m_J \in \{-J, -J+1, \dots, J\}$  enumerates the different possible orientations of the atomic angular momentum. The quantity  $g_J$  is the Lande-g factor (great name!), which quantifies the proportionality between the angular momentum and the magnetic moment of the given atomic state (also related to the “gyromagnetic ratio”). The quantity  $\mu_0 = e\hbar/2m_e$  is the Bohr magneton with  $e$  being the electron charge and  $m_e$  the electron mass, and  $B$  is the magnitude of the magnetic field.

In this lab, we analyze optical emission and observe the difference between two energy levels of an atom. Let us make use of Eq. 3. The emitted photon energies are then the following:

$$\Delta E(m_J, m'_J) = (E' - E) + (g'_J m'_J - g_J m_J) \mu_0 B \quad (4)$$

Here, we use the primed symbol to characterize the excited state, and the unprimed symbol to characterize the lower-energy state.

Optical transitions occur only for specific values of  $m_J$  and  $m'_J$ . We’ll assume the optical emission is from an electric dipole transition, and then recall the selection rule that optical transitions can occur only between states for which the magnetic quantum number differs by  $\Delta m_J = m_J - m'_J = \{-1, 0, 1\}$ . Each value of  $\Delta m_J$  corresponds to photons emitted with different polarization and with a different emission pattern:  $\Delta m_J = \pm 1$  correspond to circular polarizations  $\sigma^\pm$ , while  $\Delta m_J = 0$  corresponds to linear polarization  $\pi$  along the  $B$ -field axis.

The history of research on the Zeeman effect led to the distinction between a *normal* Zeeman effect and an *anomalous* Zeeman effect. The normal Zeeman effect occurs when the upper- and lower-energy states have the same value of  $g_J$ . In this situation, the Zeeman effect causes a spectral line to split into three spectral lines, each corresponding to a different allowed value of  $\Delta m_J$  and thus to a different polarization. The normal Zeeman effect occurs typically on transitions between two levels that have zero electron spin angular momentum:  $S = S' = 0$ . In this case, the atomic angular momentum is entirely in the form of orbital angular momentum, and we have  $g_J = g_L = 1$ .

The anomalous Zeeman effect occurs when the upper- and lower-energy states have different values of  $g_J$ . This situation occurs typically when the upper- and lower-energy states have both non-zero electron spin and also non-zero electron orbital angular momentum. The Lande formula can be used to determine the Lande-g factors of the two states, often showing that those two factors are different. Now, we find that the Zeeman effect takes a single spectral line (at zero  $B$ ) and splits it into potentially many different lines (at non-zero  $B$ ). An example of the anomalous Zeeman effect is provided in Melissinos' text (Ref. 6); see specifically **Ch. 6.5: The Zeeman Effect of the Green Line of 198Hg**. There, Melissinos reviews the Zeeman effect on a transition from the  $^3S_1$  excited state to the  $^3P_2$  lower-energy state in mercury. These states have different Lande-g factors:  $g'_J = 2$  for the  $^3S_1$  state, and  $g_J = 3/2$  for the  $^3P_2$  state. The resulting Zeeman-shifted optical spectrum is somewhat complex: There are now observed *nine* spectral lines, three for each polarization. In a large-enough magnetic field, and with sufficient resolution, one can observe all nine of these lines. In a weaker magnetic field and with poor resolution, these many lines might not be resolved and the Zeeman spectrum would be observed just as single broadened line.

In this lab, you will observe examples of both the normal and the anomalous Zeeman spectrum by looking at the emission of atomic helium. Helium is a two-electron atom. Its atomic states can be divided between those with total electron spin  $S = 0$  (singlets, like the ground state) and those with total electron spin  $S = 1$  (triplets). While relativistic effects, and also nuclear-spin effects, can generally mix states with different total electron spin  $S$ , in helium these effects are very strongly suppressed. Electric dipole transitions result from the electric field of light exerting a force on electrons; this force does not affect the electron spin. For this reason, electric dipole transitions only occur between states with the same value of  $S$ . Thus, the spectrum of helium can be cleanly divided between two types: There are transitions between states with  $S = 0$  (known as the parahelium spectrum), and there are other transitions between states with  $S = 1$  (the orthohelium spectrum). The parahelium spectrum, with  $S = 0$ , exhibits only the normal Zeeman effect. The orthohelium spectrum, with  $S > 0$ , exhibits the anomalous Zeeman effect. You will look at one spectral line of each type: The "helium red line," at the wavelength of 6678 Å, is part of the singlet parahelium spectrum. The "helium yellow line," at the wavelength of 5875 Å, is part of the triplet orthohelium spectrum. You can identify the levels associated with these lines by referring to "**Atomic Energy Levels for Helium**".

## 6 Balmer Series Experiment

### 6.1 Equipment used in this experiment

You should locate all of the equipment before starting the experiment.

1. Safety Goggles (green)
2. **Acton Research Half-meter Monochromator: Full Manual** with PMT used, Operation, Gratings, and Circuit Diagram.
3. **Discharge Lamps:** filled with H, Hg, He (He is sandwiched between the magnet's coils)
4. Lens
5. **HP 3478A Multimeter: Full Manual**
6. **Tektronix 2225 Oscilloscope: Full Manual**
7. **Fluke 415B High Voltage Power Supply: Full Manual**
8. Equipment Rack (Note: In case anything needs to be added or removed: equipment is mounted using 10-32 screws)
9. **Gaussmeters: RFL 3265 or F.W. Bell 5180.** Along with **Calibration Magnet**. As of 8/26/25, use the RFL 3265.
10. Digilent **Analog Discovery Studio** or ADS (used for recording voltage data for spectra).

- **IMPORTANT NOTE:** The holes on the sides of the 20K Gauss Magnet are fixed at 10.5” from the table. All optics equipment are specifically measured and adjusted to this height (from the table). **DO NOT** adjust the heights of any of the optics equipment. The experiment is sensitive to even the smallest adjustments.

## 6.2 Preparation

1. Draw an energy-level diagram of hydrogen and show the Balmer series transitions with their corresponding wavelengths and energies. Show what the spectrum ought to look like. You can construct the principal levels from the simple expression of the energy levels for hydrogen which you learned in the quantum mechanics class, but other texts show more complete diagrams with the angular momentum states designated. References are books by Bashkin & Stoner, by Herzberg, by White, and the tabulation by Sitterly. Refer to the CRC Handbook for wavelengths and relative intensities. You may need to review the spectroscopic notation.
2. Draw an energy level diagram of mercury and show the transitions likely to be observable (yellow, green, blue, and violet lines). You could make a copy of all these diagrams out of books, but they have so much detail you would lose sight of only the few lines it is possible to observe in a simple experiment. Thus, keep your diagrams simple.
3. Read carefully the operating instructions for the monochromator in the [Appendix](#) (Complete manual found [here](#)). This is a *very* expensive piece of equipment, and the instructions are simple enough that there should be no reason for causing damage! Be sure to pay particular attention to the cautions listed. If you have to force something the slightest bit on this piece of equipment, something is not right. Ask someone how to turn a knob if it doesn't want to turn. Also note that our spectrometer has a grating of 300 grooves/mm. Multiply the counter reading by 6 to get the correct wavelength in Å (e.g. a reading of 01000 corresponds to 6000 Å, or 600 nm).
4. To manually scan place the speed knob in between any two speeds positions before turning the manual scan knob. To change the speed control knob, first pull it out and then turn it. **DO NOT FORCE IT** and **do not scan below** a counter reading of 00000 or above 08000.
5. Read about the function and operation of the photomultiplier tube (PMT) in any text on radiation detection and measurement. (For example: [Chapter 9](#) of Knoll's *Radiation Detection and Measurement*, or RCA's "[Photomultiplier Manual](#)").

**Checkpoint Preparation:**<sup>†</sup> Point out the location of the diffraction grating inside of the monochromator. Disengage the speed knob. Scan automatically and manually. Within what values must the wavelength reading remain? Show your drawings of the Hydrogen and Mercury spectra and point out the relevant transitions.

## 6.3 Procedure

It's time to get started. Pro-tip: check out the photos at the beginning of the lab to get an idea of what is inside the monochromator.

1. Setting up the electronics: there should be a T with two BNCs hooked up to the PMT output. One BNC should take the signal to the scope. The signal sits on 120Hz line noise, so choose an appropriate time scale for the scope. The other heads to the DMM. The DMM needs to have a banana plug in the input (make sure the little notch goes into the LO input). A T should go into the banana plug, which allows you to hook up the PMT to one of the ports, and a little gadget with a resistor onto the other port (Why? It is because the PMT voltage is big and the DMM has a limit. Voltage divider makes sure that the output doesn't exceed the limit). Make sure that the little button labeled "Terminals" is extended (otherwise it displays the input from the back of the box). It should be set to read volts DC.

2. Aligning the mercury lamp. Objective: get the lamp's light focused on the slit. First, make sure the opening in the lamp is aligned with the slit of the monochromator. There ought to be a lens attached to a rail, in between the lamp and the slit. By loosening the bottom screw, you can adjust its position on the rail. In order to gauge how well focused the light is, hold up a piece of paper close to the slit. By moving around the lamp, the light should change its focus on the paper. Try and line it up with the slit opening. You can also slide around the lens in order to obtain sharper focus. Use the thin lens equation to get a good idea of where to position the lens and the source with respect to the slit. The end result should be a well-focused slit of light, aligned with the slit of the monochromator.
3. Checking out the spectrum: Make sure that the knob on the corner of the top of the monochromator is switched into the "o position." This turns the mirror so that the light will be reflected out of the slit on the side of the monochromator. You can stick your eye up to the slit. Before turning the wave knob, you must **DISENGAGE THE SPEED KNOB**. To do this, pull it out a little and turn it so that it rests between two numbers. You will notice that it stays out. Now, by cranking the wave knob you can adjust the color that is being displayed. **IMPORTANT:** the wave knob suffers from **backlash**, so it may be moved in one direction without applying appreciable force or motion right away. Thus, in order to set the wave number, you must approach it from the left (smaller value). Also remember that the wave number on the display must be multiplied by 6 to correspond to an actual wavelength in angstroms. Hint: there's a big blue peak in the mercury spectrum at *around* 4400 angstroms (check out the figure below of the intensity of different peaks): divide that by 6. You should see a bright blue line, oriented vertically on the mirror. If you don't, you need to go back to step 2. If you do, and the line is well resolved, you can move on.
4. Optimizing the mercury lamp: now that we've checked out that the line is decently focused, we're going to use the electronics to optimize it. Switch the PMT knob to the "o position." This sends the light into the PMT. Check to make sure that the power supply of the PMT must be at the **NEGATIVE** polarity and the set voltage must be less than 2000 V. By twisting around the wave knob, you should be able to find a peak on the spectrum (it will register on the scope). Now wiggle around the mercury lamp, trying to get the signal on the scope bigger. Now that you have managed to get peaks, you need to narrow the peak. Adjust the appropriate parameters until the peak's signal is sharply peaked (i.e. we the signal to die off quickly for nearby wavelengths).

**Checkpoint Peak Finding:**<sup>↑</sup> **Manually scan and find a peak. Show the width of the peak by scanning the nearby wavelengths (remember backlash!). What steps have you taken to get a sharp peak?**

5. The PMT is already connected to both the multimeter and the ADS. (Double check that the ADS is on.) Open WaveForms, and then the Scope. Set the mode to 'Record' (see Figure 9). We'll use this to scan over the different frequencies and measure the results. The monochromator has a mechanical scanning capability, but WaveForms can't control it. Thus, you have to sync up the monochromator's scanning with the program. Start at a wavelength below the bright blue line that you know and love. Set the speed control knob to a value of your choosing (not too fast, not too slow). Make sure you note this value down, as you'll need it to reprocess the data! Also make sure to note down the counter value at which you start (note that if you start on an earlier peak, it may take a moment to trigger, so make sure to keep an eye on when the program actually starts recording data, and record the counter value at this point). Then hit 'Rec.' on the top left to select the sampling frequency and the length of the recording (see Figure 9). Make sure you record the sampling frequency; you'll need to use it to recalibrate the x-axis. Choose based on how many wavelengths you want to observe and the settings you set on the speed knob (how do these affect the time and the sampling frequency, respectively? choose carefully or your data file will be massive). Change the type of file saved to .csv and the format to 64 bit float. Now you must start recording (using the 'Start' button in the 'Rec.' settings panel - not the main record button) at the same time that you snap the monochromator's automated scanning on. WaveForms will save the voltage data (the same data that you see on the multimeter), and the index of this data will be the sample number - you'll have to recalibrate this. That way the values of the program are coordinated with the actual machine. After the program runs, plot the .csv file, recalibrating the time axis into wavelength based on the sampling frequency (to get

from sample number to time), speed control knob value you set (to get from time to wavelength), and the counter value you started at (to account for the offset). You should be able to see distinct peaks at the appropriate frequencies (check the Spectrum of Mercury, below). We want a narrow linewidth. I got mine to be around 5 angstroms for the 443nm line. If they're too wide, play around with the setup and try and improve the reading. You may also need to smooth your data in post-processing - you may be interested in the Savitzky-Golay filter.

6. Finally, do a nice, slow, high-resolution scan of the spectrum. Note the wavelength corresponding to the peaks on your scan and compare it to the true location of the peaks, as per the Bureau of Standards. This allows us to calibrate the instrument. Do you notice anything weird about the height of the different peaks? How do they compare to the intensity values listed in the article “[The Band Spectrum of HgIn](#)”? How can you account for this? Remember the pre-lab...

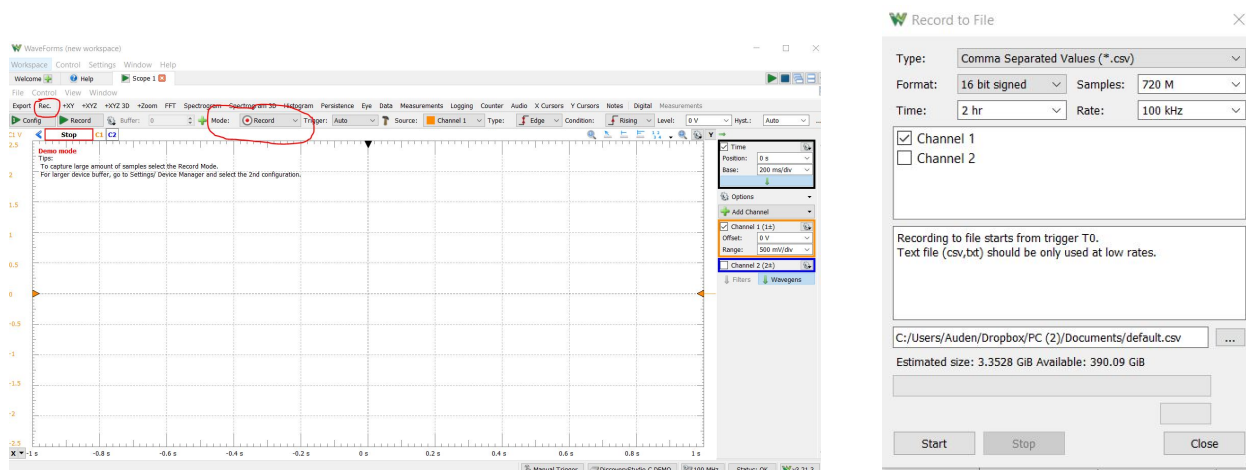


Figure 9: Left: Record mode on WaveForms. Right: Example record options. Format should be 64 bit float, type should be .csv as shown. To take the measurement, hit ‘Start’ in the right panel. You should set your own time and sampling frequency based on what type of measurement you are setting up. Make sure you record your selections!

## 6.4 Wavelength Calibration

The wavelength scale of the spectrometer is only good to a few nanometers at best. Here, we pretend that the mercury spectrum is absolutely known, use that spectrum to calibrate the wavelength scale of the spectrometer, and then use that calibration to measure the “unknown” Balmer spectrum. Your procedure will be to set up the mercury lamp; get a strong mercury line and adjust the scale of the spectrometer until the line is centered in the exit slit; the signal displayed on the oscilloscope will be a maximum. Record the scale reading, and compare with the wavelengths given below. Repeat for the other mercury lines.

When you study the Balmer lines of hydrogen, set the dial until each one in turn yields a maximum amplitude on the oscilloscope. You can also look at the output from the computer, and calibrate it. This method is probably better for the very weak lines.

Traditionally, wavelengths are measured in air. To compare with the predicted wavelengths of the Balmer series, you must convert the wavelengths you measure into wavelengths in vacuum. You can do this by using the index of refraction of air, given by

$$n = 1 + 6432.8 \times 10^{-8} + \frac{2949810}{146 \times 10^8 - \sigma^2} + \frac{25540}{41 \times 10^8 - \sigma^2} \quad (5)$$

where  $\sigma$  is the reciprocal of the wavelength in vacuum, called the wavenumber, in units of  $\text{cm}^{-1}$ .

Color/name	Wavelength (Å)	Wavenumbers (cm <sup>-1</sup> )
<b>Mercury</b>		
Red	7081.90	14120.50
Yellow	5790.66	17264.401
Yellow	5769.60	17327.439
Green	5460.74	18307.479
Blue	4358.33	22938.156
Blue-violet	4046.56	24705.376
<b>Hydrogen</b>		
alpha	6562.72	15233.377
beta	4861.33	20564.758
gamma	4340.47	23032.505
delta	4101.74	24373.020
epsilon	3970.072	25181.336
zeta	3889.049	25705.931
eta	3835.384	26065.615
<b>Helium</b>		
Red	6678.15	14970.074
Yellow	5875.62	17013.752

Table 1: Wavelengths and wavenumbers of a number of transitions relevant to this laboratory: Hg transitions that you consider as absolutely known and use to calibrate the spectrometer, H transitions belonging to the Balmer series whose wavelengths/wavenumbers you will be measuring in the first part of this lab, and two He transitions that you examine to study and explain the Zeeman effect.

Another way is to use a table converting wavelengths in air to wavenumbers in vacuum. (Reference: Table of Wavenumbers, Volume 1, NBS Monograph 3, May 2, 1960.)

Think before you do anything, because some errors are so small that they are insignificant.

## 6.5 Data Collection

1. Set up the hydrogen lamp. Record the lines in the spectrum, and measure their wavelengths by using the spectrometer readout calibrated as mentioned above. You should be able to see at least SIX lines in the Balmer series. Check with an instructor if you cannot.
2. Identify the lines of the Balmer series and make a plot of  $1/\lambda$  vs.  $1/n^2$ . Fit the data points to a line. Determine the Rydberg constant and the series limit.
3. Error analysis: In this lab, you need to consider carefully both the sources and impacts of statistical errors and also of systematic errors. Recall, systematic errors are errors that have independent values for every repeated measurement, and have the property that the more measurements you make, the smaller the overall statistical error becomes. Your texts on data analysis (for example, Section 2.9, page 63, of Lyons) explain how to propagate statistical errors in linear regression to the slope and offset determined from that regression. Systematic errors are errors that persist no matter how many times you repeat your measurement. Such errors can affect your entire dataset in a common way, for example, in a case of linear regression, shifting all your points up/down on a graph or shifting so as to make a slope systematically larger or smaller. There are important sources of systematic error in the measurement you just made. Stop, think, talk it out with your lab partner, and figure out what

those sources are. Then, think of ways to estimate those errors and to figure out how they affect the outcome of your data analysis.

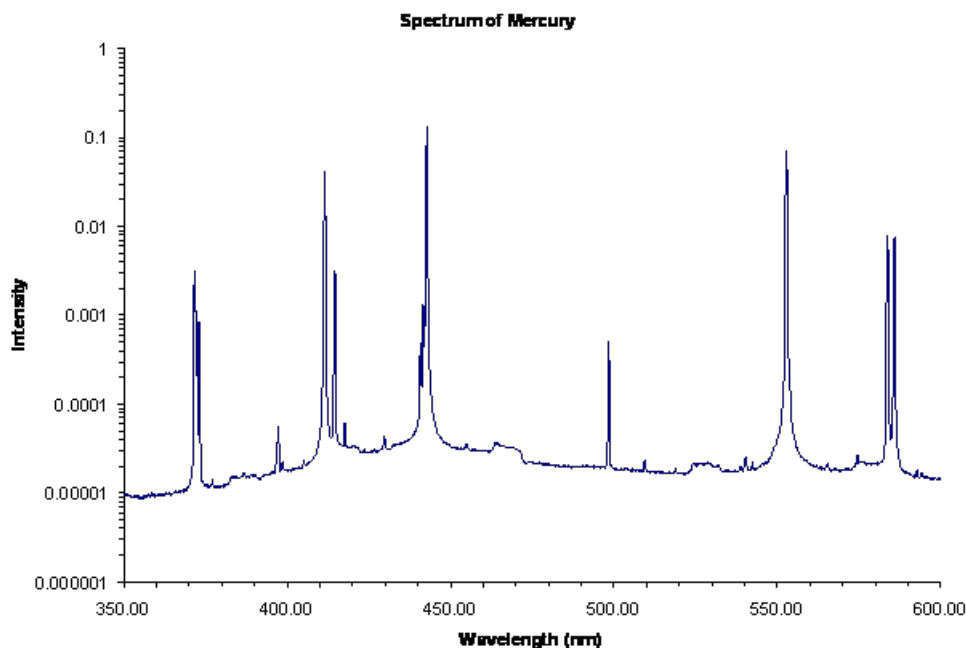


Figure 10: Spectrum of Mercury

## 6.6 Additional Questions: Balmer Series

**Checkpoint** Additional Questions:<sup>†</sup> Discuss the following questions and answers with a GSI:

1. What elements in the equipment set the upper and lower limits in the wavelengths that can be observed? What are these limits?
2. Calculate the dispersion and resolution of the spectrometer when it is used to observe the first order at a wavelength of 5461 Å (mercury green line). The parameters of the spectrometer are given in the manufacturer's manual. Compare the calculated values with what you obtain experimentally.

## 7 Zeeman Effect Experiment

### 7.1 Equipment used in this experiment

You should locate all of the equipment before starting the experiment.

1. Safety Goggles (green)
2. **He Discharge Lamp:** sandwiched between the magnet's coils
3. Lens
4. **Fluke 415B High Voltage Power Supply:** [Full Manual](#)

5. Equipment Rack (Note: In case anything needs to be added or removed: equipment is mounted using 10-32 screws)
6. **Gaussmeters: RFL 3265 or F.W. Bell 5180.** Along with **Calibration Magnet.** As of 8/26/25, use the RFL 3265.
7. CCD-Camera Lens mounted to CCD camera on Track using a fire-wire 1394 card and cable,
8. **Magnet Coils** and **Magnet Power Supply**
9. **Prism Monochromator**

## 7.2 A word of warning

In principle, this part of the lab is remarkably simple and should not take you very much time. In reality, we find students get to this part of the lab very late in the time they have been allotted for the overall experiment. This leaves students having to rush, leaving calculations and estimations to the last minute, and not taking the time to understand what they're doing. So we recommend strongly that you stay on top of things. Be sure you prepare thoroughly for this part of the lab before starting the experimental procedure. Aim to start here no later than the 4th day of the 6 days you have to work on this experiment.

## 7.3 Apparatus

1. To observe the Zeeman effect we must put a light source in a magnetic field and observe the radiation with a spectrometer capable of resolving the Zeeman lines. We are going to use a discharge tube, an ordinary electromagnet with iron pole pieces, a lens, a Fabry-Perot interferometer, and a digital camera, arranged in a configuration as shown in Figure 11.

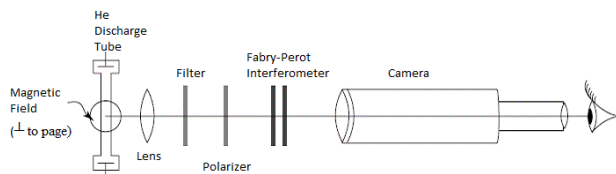


Figure 11: Apparatus

The lens is present merely to get light into the interferometer; it plays no part in resolving the spectrum lines. The interferometer forms fringes at infinity, as will be discussed below, and the camera is used to magnify and view these fringes. It is possible to dispense with the camera if you can focus your eyes at infinity but the fringes will look smaller and be harder to see.

2. The Fabry-Perot interferometer (see Jenkins & White **“Ch. 14: Interference Involving Multiple Reflections”**; also look at **Video Optical Instruments**) works on the principle of multiple amplitude division of a wavefront and recombination of these wavefronts, each of which has traveled a different optical path length. We can represent these wavefronts by rays, as shown in Figure 12.

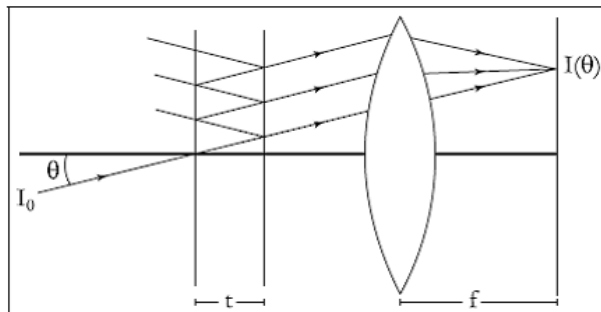


Figure 12: Fabry-Perot Interferometer

The interferometer itself is nothing but two plane parallel partially-reflecting films. In our case they are multi-layer dielectric coated mirrors supported on two flat quartz discs, called plates, or substrates. The optical path difference between two adjacent rays is  $\sigma = (2t) \cos \theta$ , and the order of interference  $n$  is this path difference divided by the wavelength. When all the rays are added together, the intensity distribution is

$$\frac{I_0}{1 + \frac{4R}{(1-R)^2} \sin^2 \frac{\delta}{2}}, \text{ where } \delta = 2\pi \frac{2t \cos \theta}{\lambda}$$

is the phase difference between adjacent rays, and  $R$  is the reflectance of a single coating. The interference fringes are circles. The smallest wavenumber difference (energy) that can be resolved is given by

$$\delta\sigma = \frac{1}{2tN_R}, \text{ where } N_R = \pi \frac{\sqrt{R}}{1-R}$$

There is also a wavenumber interval called the **free spectral range**, the difference in wavenumber of two spectral lines that will give a ring of exactly the same radius (fringes at the same angle  $\theta$ , but differing in order by 1). It is also approximately the reciprocal of the path difference between adjacent fringes of the same wavelength. The F-P interferometer used in this experiment is a very precise and expensive piece of equipment. Do not touch its optical surfaces or attempt to clean it-if you think it's dirty, ask the staff for assistance. The only adjustments you need make are its horizontal and vertical orientations, controlled by the two large graticulated knobs. Its spacing  $t$  is 8.11 mm, and its reflectance  $R$  is 0.90.

## 7.4 Procedure

1. Before you turn on the helium lamp, turn on the cooling air. If the lamp gets too hot it breaks. The air valve is located above the top shelf on the right side of the ATM bench-it should be adjusted so that the indicator ball is between 40 and 50 on the scale.
2. Make sure that the black transformer is set to zero, and then turn it on.
3. Then turn on the box marked "HIGH VOLTAGE".
4. Increase the voltage on the transformer until the He tube begins to glow brightly.
5. The **Fabry-Perot** interferometer should already be adjusted. The plates are flat and parallel to a fraction of a wavelength. Also see **Beam Shaping**
6. See how to set up the CCD camera below so that you can use the camera's image to adjust the setup in the next step.
7. Set up the optical system shown above on the rail closest to the edge of the table, leaving out the red filter for now. Adjust the lens until you get a crisp image from the camera. Make sure that the lamp

cooling air is on and watch the lamp carefully; if it gets too hot, it will melt. The image might be very dim, as well as blocked by the magnets. Move the lens wherever you need to to get as much light as possible going through the interferometer.

**Checkpoint Zeeman Picture:**<sup>†</sup> Show the produced image to a GSI

8. Observe, record, and explain what happens when you do the following, using your eye instead of the camera image: move the position of the lens; tilt the F-P plates; raise and lower the interferometer. Now with the camera in place: change the position of the camera; shift the camera sideways.
9. Put in the red glass filter; adjust the system until the fringes are sharp. Turn on the magnetic field. To control it, use the LAMBDA DC POWER SUPPLY. Turn the OUTPUT VOLTAGE VDC knob to zero, and the CURRENT LIMITER IDC knob to 2 Amps. Turn on the power supply. Increase the VDC control until you see the fringes start to split. If the lamp flickers or goes out, increase the voltage on the transformer. Can you explain why this happens? The lamp is just a tube filled with He gas, and electrons are accelerated through the tube by an electric field from the high voltage. As they travel through the tube, they collide with He atoms, and excite them. When these de-excite, they emit the characteristic He lines. Now what happens when we add a transverse magnetic field? Rotate the polarizer and note the behavior of the lines. Don't be discouraged if you see fuzzy fringes and bizarre behavior. With a little experience your skill will improve until you can produce and see the proper Zeeman effects.

**Checkpoint Zeeman Splitting:**<sup>†</sup> Produce Zeeman splitting by varying the field strength. Explain why the lamp dies when a high enough field is applied. Rotate the polarizer until only the sigma components are observed; increase the field strength until the fringes show equal spacings between the rings. What fraction of an order did the magnetic field shift the frequencies of the Zeeman components of the line? [1/2, 1/3, 1/4, or ?. We take one order to be the spacing between two unsplit lines – no magnetic field.] Repeat several times, so you can make some estimate of the error in your measurements. Measure the magnetic field strength with the Universal Gaussmeter 3265. The He discharge tube is mounted on a track so that you can slide it back out of the center region of the magnet and position the meter probe where the tube usually sits.

- *Before taking any readings with the 3265 gaussmeter,*
  - 1st = Select Auto Zero. To select AUTO ZERO operation, press the ZERO pushbutton. Unit automatically returns to normal operation.
  - 2nd = Select Auto Range. To select AUTO RANGE operation, press the SHIFT pushbutton followed by the RANGE pushbutton. Press the SHIFT pushbutton followed by the RANGE pushbutton to exit Auto Range mode. Manual Range.
  - Also; To select MANUAL RANGE operation, press the RANGE pushbutton. Press the UP (5) and DOWN (6) arrow pushbuttons to select ranges. Press the RANGE pushbutton to return to normal operation.
  - For the complete FWBell 5180 manual, see ([FWBell 5180 Manual](#)). For the interactive version of the manual, see ([5180 Manual.exe](#)).
  - Zero the gaussmeter by using the Zero Gauss Chamber located in the unit, and the Zero Adjust and Differential Zero Balance knobs, and then calibrate it using the 1000 gauss Probe Reference Magnet and the Calibrate and Differential Zero Balance knobs. Note that the top most scale on the 3265 is in kiloGauss. You may have to repeat both steps several times in order to have the meter both zeroed and calibrated correctly. Make sure that you calibrate the meter on the scale that you will use to make your measurements.
    - (a) Turn the magnet through 90 degrees, and look at the lamp through the hole in the pole piece. What is the effect of removing the polarizer?
    - (b) **Setup the Camera:** After you have the Zeeman apparatus set up, you can get an even better view of the fringes (and take some snapshots for your write-up) by using the zoom lens and video camera. Attach the camera to the USB Micro B cable and run IDS Peak Cockpit on the PC from the Desktop shortcut. If prompted, select “I

want to use settings like auto exposure, auto gain, etc. to easily get appealing images.” You may find a screenshot with the following settings under Fig.13. The camera should automatically initialize. If it does not, select “Open Camera Manager” at the top left corner and under the drop down select “U3-304xCP-M 4110022145.” Once the camera is ready, select “Start/stop continuous acquisition.” Zoom out all the way and set the focus to infinity on the camera lens. You may also use the micrometer adjustment knobs on the Fabry-Perot mount to center the fringes in the field of the camera. Once you are done using the camera, close by right-clicking on the camera name under the camera manager, and unplug the Micro B USB cord.

\* To take a snapshot, de-select Start/stop continuous acquisition - Select Single frame acquisition -> Save image -> Save As -> \*.png , and choose an appropriate location.

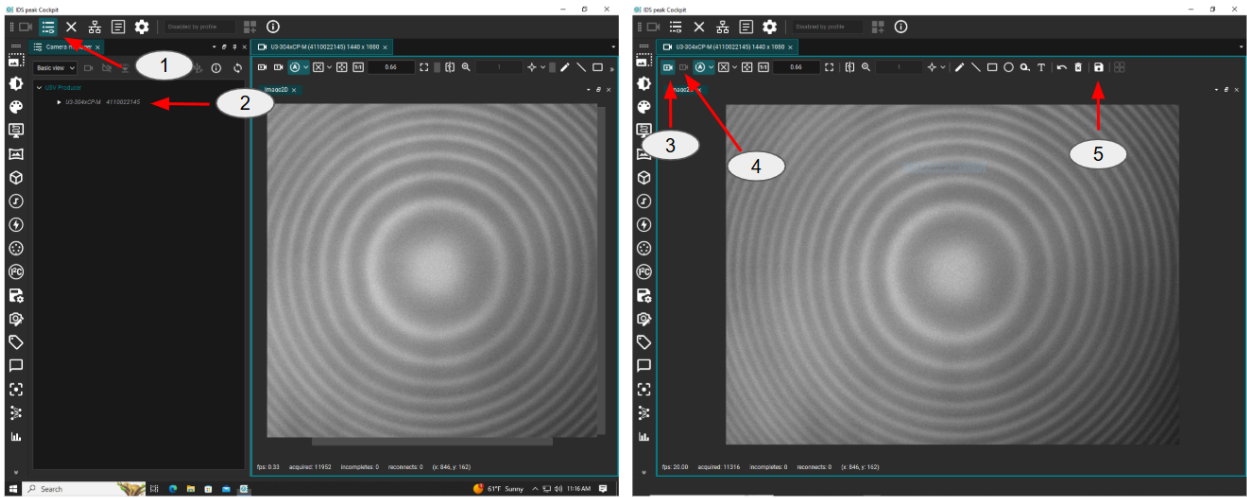


Figure 13: IDS Peak Cockpit Camera Software Control. 1. Open Camera Manager. 2. Selection for camera U3-304xCP-M. 3. Start/Stop Continuous Acquisition. 4. Single Frame Acquisition. 5. Save Image.

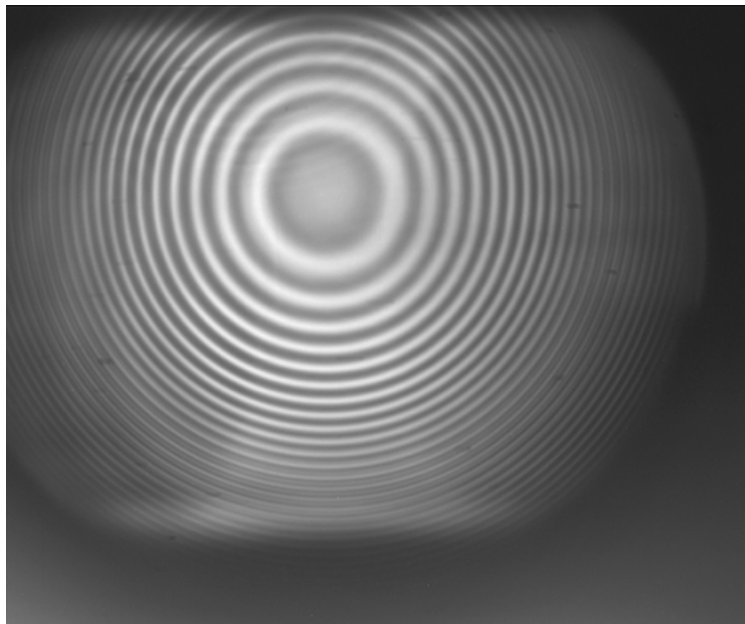


Figure 14: Captured image from Fabry-Perot interferometer

10. **Something more complex and interesting:** Use the spectrometer to see what lines are actually present in helium. Set up the system to use the prism spectrometer as a filter to isolate the red, yellow, and blue lines, and observe the splitting with the interferometer. The trick here is to focus the light from the lamp on the slit of the prism spectrometer and open the slit up all the way to let in as much light as possible. Then closing it down to see the yellow line in the center of the eyepiece. Ensure that the lens focuses a sharp line of light onto the slit. The optical equipment should already be aligned for this, just move the lens along the track until the line is sharp. When using the camera, try using the Live Control Settings found under “Brightness/frame rate” section on the left hand vertical panel. Turn off the auto-exposure, play around with the gain, brightness, zoom, and camera focal length set to infinity.

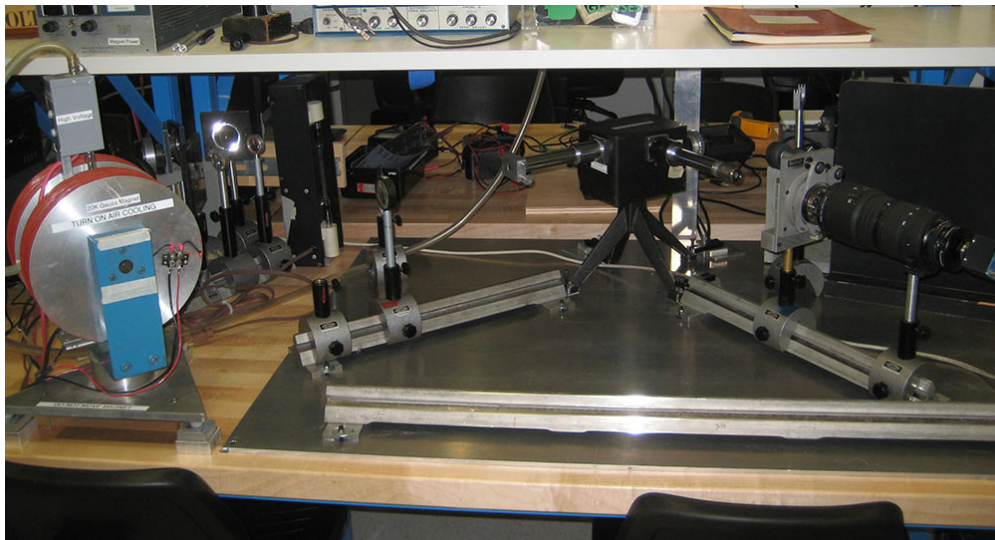


Figure 15: Setup Using the Prism Spectrometer

Find the levels which give rise to the  $5875.6 \text{ \AA}$  lines of helium. Work out the Zeeman pattern thoroughly enough to show you understand the problems. You will need to check out the magnitudes of the triplet splittings. Use the spectrometer together with the interferometer to observe the Zeeman effect in this line, and compare to the calculated pattern. Why don't you see a clear pattern? Can you still see polarization effects? Originally Zeeman did not have enough resolution or magnetic field to see components clearly, but only slight polarization effects in the wings of the line.

## 7.5 Calculations

1. Using your observations, calculate the ratio of energy level splitting to magnetic field, expressed in  $\text{cm}^{-1}/\text{gauss}$ . Always use these units. While others such as joules/gauss are correct, they are never used by practicing spectroscopists. Compare to the value of the Bohr magneton based on universal constants ( $m$ ,  $e$ ,  $h$ , etc.).

## 8 Appendix

### 8.1 Acton Research Corp Half-Meter Monochromator

Sections of the Operating Instructions ARC Model AM-505 Atmospheric Monochromator

SECTION III: OPERATION

Bilateral Slit Assemblies: Slit Width: The slit width of each bilateral slit assembly is adjustable from 0.005 mm to 3 mm (5 to 3,000 microns), by a micrometer knob located on the slit housing. The knob is graduated in 0.01 millimeter (10 micron) increments. One counterclockwise revolution of the micrometer knob increases the slit width 0.25 mm (250 microns). For maximum reproducibility the slit width should be set in a counterclockwise direction (increasing slit widths) each time it is changed. The micrometer knob should not be rotated below a reading of 0.05 or above a reading of 3.00. A micrometer setting of less than 0.005 mm (5 microns) should not be used, because a stop is provided to prevent the jaws from touching each other.

Wavelength Indicator: A five-digit mechanical counter is mounted on the side of the instrument housing, and indicates the wavelength at the exit slit in Angstrom units when a 1800 G/mm grating is used. For other grating groove spacings, simply factor the counter reading in an inverse proportion to the change in groove spacing. For example, if a 300 G/mm grating is installed, the counter reading must be multiplied by six to obtain the correct wavelength at the exit slit. [\*\*\*Note: the grating installed in the monochromator in 111-Lab has 300 G/mm.\*\*\*].

Manual Scanning Drive: A manual scanning knob is located in the side of the instrument housing, adjacent to the Wavelength Indicator. One revolution of this knob changes the wavelength by 20 Angstroms when a 1800 G/mm grating is installed. NOTE: The speed control knob must be disengaged - placed between any two speed positions - before turning the manual scan knob. To change the speed control knob, first pull it out and then turn it. CAUTION: Do not force Manual Scanning Knob. Do not scan below a counter reading of 00000 or above 08000.

Synchronous Motor Scanning Drive: A synchronous motor with a ten-speed transmission provides scanning speeds from 1 to 1000 Angstroms/minute. The various speeds are controlled by a speed control knob located on the side of the instrument housing. The speed control knob is labeled with the scanning speed directly in Angstroms per minute with a 1800 G/mm grating installed. For other grating groove spacings, factor the speeds in the same manner as the wavelength counter. To set the desired speed knob position, pull the speed control knob out and rotate until the desired position is in line with the dot on the instrument housing; release the knob to engage the transmission. To scan manually, set the speed control knob between any two speed positions. A scan power and direction switch is also located on the side of the instrument housing. The switch is labeled "H" (higher), "OFF" and "L" (lower). To scan to lower wavelengths move the scan switch to the "L" position, and to scan toward higher wavelengths move to the "H" position. Scans should be made to higher wavelengths for maximum reproducibility and accuracy.

Moveable Diverter Mirror: A moveable diverter mirror directs the beam either straight through, "O" position, to the PMT, or to the side slit in the "S" position. A knob on the top of the instrument indexes the mirror to either the "O" or "S" position. To change the mirror position, gently rotate the knob to the desired "S" or "O" position; a click will be heard and felt when the mirror indexes into position.

- FOR FURTHER INFORMATION, SEE THE [COMPLETE MANUAL](#)
- Last day of the experiment please fill out the [Experiment Evaluation](#)

## 9 References

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  - (d) [Ch. 9: Hydrogen Fine Spectra and the Dirac Electron](#)
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    - (b) [Ch. 5: Geometric Optics - Paraxial Theory](#)
    - (c) [Ch. 6: More Geometrical Optics](#)
    - (d) [Ch. 8: Polarization](#)
    - (e) [Ch. 9: Interference](#)
    - (f) [Ch. 10: Diffraction](#)
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  16. [Appendix I: ARC Model AM-505 Atmospheric Monochromator](#)
  17. [Additional Reference Index with Links](#)
  18. [Equipment Index with Links](#)