Atomic Physics Description (ATM)

1. Note that there is NO eating or drinking in the 111-Lab anywhere, except in rooms 282 & 286 LeConte on the bench with the BLUE stripe around it. Thank You the Staff.

Atomic spectroscopy was the proving ground for Quantum Mechanics. In this lab you will observe the emission lines of mercury and hydrogen over the range 250 to 750 nm, using a diffraction-grating spectrometer. You will identify and measure the Balmer series of spectral lines in hydrogen, and then use the results to determine the energy levels and the value of the Rydberg constant. Mercury lines are used to calibrate the wavelength scale of the spectrometer.

In 1896 Peter Zeeman observed the broadening and polarization of spectral lines of sodium when the source was placed in a magnetic field. Since that time both the changes in the energy levels of an individual atom and the splitting of spectral lines in a magnetic field have carried the name Zeeman Effect.

After observing the principal spectral lines in hydrogen, you will go on to measure the Zeeman effect in a single spectral line of helium. A high voltage discharge tube filled with helium is placed between the poles of an electromagnet. Light from the lamp is analyzed with a Fabry-Perot interferometer. From your data you will calculate the magnitude of the Bohr magneton.

In addition to atomic physics and quantum mechanics, this lab emphasizes optics.

You need to be present for all parts of the experiment. You can't leave while the data are being recorded. If you know what you are doing and don't make any mistake, you can complete the data-taking in 4 days.

You will need to review (perhaps see for the first time) optics at the sophomore and junior levels. You may have had very little in formal classroom work about mirrors, lenses, spectrometers, diffraction gratings, and Fabry-Perot interferometers. You will need to integrate practical knowledge about spectra, spectroscopic terminology, and energy level diagrams, with the more abstract quantum theory of atoms. None of the subjects is difficult, but each requires time. Your study will be a good review for parts of the advanced GRE.

1. Pre-requisites: Physics 137AB
2. Days Alloted for the Experiment: 7

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

Comments: E-mail Don Orlando

The Atomic Physics Experiment Photos

1. Balmer setup with the Computer
2. Zeeman setup with Camera and Prism
3. Monochromator
4. Grating, Entrance and Exit slit inside View
5. Inside View of Mirrors
6. Zeeman front view with Camera and Prism

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Before the 1st day of Lab

Complete the following before your Experiment’s scheduled start date

1. View the three videos Atomic Theory Only Video \[19\] (Great Introduction to ATM, 37 minutes long), Video on Balmer Series Part 1 \[20\] (20 minutes long), and the Video on Zeeman Effect Part 2 \[21\] (30 minutes long).
2. Complete the ATM Pre Lab and Evaluation \[22\] sheets. Print, fill out the answers, and turn in with your report. The Pre-Lab must be printed separately. Discuss the experiment and pre-lab questions and answers with any faculty member or GSI and get it signed off by that faculty member or GSI. Turn in the signed pre-lab sheet with your lab report.
3. View the optics tutorial article (7pps), a great review of the principles of optics, Optics Tutorial \[23\] and the Light and Optical Instruments Video \[24\] (Good introduction to light and optics, 50 minutes long), Light Sources and Detectors \[25\] (Good source for Light Sources & Detectors 37 minutes), Energy Levels (part 1) Video \[26\] (54 minutes long) and Energy Levels (part 2) Video \[27\] (33 minutes long).
4. Atomic Physics Reprints \[28\] Library site
5. Secure references located on the Physics 111 Library Site \[29\]
6. Research the following topics in the suggested readings below;

   - Diffraction Grating Information \[30\] Gratings \[31\]
   - Fabry Perot Fabry-Perot \[32\] (For an explanation of resolution, see Hecht-Zajac “Optics” Ch.9 pp. 307-310, Ch. 10: Diffraction \[33\])
   - Rydberg constant (See Gerhard Herzberg \[34\] below)
   - Balmer Series (See Gerhard Herzberg \[35\] below)
   - Zeeman Effect (See Gerhard Herzberg \[36\] below)
   - Bohr Theory for Balmer Series (See Gerhard Herzberg \[37\] below)
   - Energy Level Diagrams for Hydrogen and Helium and Mercury Spectral Tubes Energy Level Data \[38\]
   - Hyperfine Structure Ch. 18: Hyperfine Structure \[39\]

Last day of the experiment please fill out the Experiment Evaluation \[40\]

Suggested Reading:

2. Spectral Tubes Energy Level Data \[42\]

Experiments in Modern Physics, A. C. Melissinos and Jim Napolitan 2nd Edition:

2. Ch. 4:6. The Fabry-Perot Interferometer \[44\], 7pgs
3. Ch. 5:2:5:5. Various Information About Diffraction \[45\], 18pgs
4. Ch. 6:2: The Normal Zeeman Effect \[46\], 11pgs
5. Ch. 6:5: The Zeeman Effect of the Green Line of Hg \[47\], 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 add you when you write your report.

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Objectives

- Learn what real experimental physics is about
- Learn the synergy between experimental and theoretical work
- Learn to use pieces of equipment that are commonly used in research
- Learn how measurements are performed, analyzed, and interpreted.
- Learn how to present your work and results
- Learn problem solving strategies
- Learn how to manage and organize your time

Introduction

Atomic spectroscopy is the field of physics that was the proving ground for the quantum mechanics of atoms and their energy level structures. In this experiment we observe the atomic spectra of hydrogen, helium, and mercury, and correlate the data with known energy levels. You also will calculate the Rydberg constant. The apparatus used is a 0.5 meter monochromator Appendix I: ARC Model AM-505 Atmospheric Monochromator \[48\] Action model AM-505 with photomultiplier tube. The data is collected with a LabView Program.

It is important that you become familiar with light sources, geometrical optics (how to get light into the spectrometer), learn a little about diffraction, actually see what the spectra look like, and record each spectrum photoelectrically. See Optics Tutorial \[49\].

Your report, written or oral, should include enough physics to make the experiment understandable to one of your classmates who has not done the experiment, and enough experimental details to show that you have done all the right things. Include diagrams, plots, and whatever else is needed for clarity and completeness. Your written report should include answers to all the Pre-Lab questions and answers with any faculty member or GSI and get it signed off by that faculty member or GSI. Turn in the signed pre-lab sheet with your lab report.

Spectroscopy predates quantum theory, so some of the diagrams you see in early texts are not labeled correctly. Look for simplicity and correctness which you can check with current quantum mechanics books.

We think of an isolated atom as having an energy level structure described by the quantized energies that its outermost or optical electron can assume. When this electron is excited by collisions or by electromagnetic radiation, the atom emits radiation of characteristic wavelengths when the electron returns to its unexcited state. These characteristic wavelengths are called spectral lines, because they appear as sharp lines when the radiation is examined with a spectrometer. In principle we can use quantum mechanics to calculate these energy levels if we can write down the proper Hamiltonian.

When the atom is placed in a magnetic field a new term is added to the Hamiltonian. It is a perturbation which splits each energy level into several levels, called Zeeman levels after a Dutch physicist.

The optical electron circulating around the nucleus is like a magnetic dipole in a magnetic field, and the energy added by an external magnetic field is therefore \( - \vec{J} \cdot \vec{B} \). A classical description would have a continuous distribution of orientations, but a quantum mechanical description allows only a finite number of possible orientations. Each different orientation results in a different energy, and a single level is split into as many levels as there are orientations of the dipole in the field. This splitting of spectral lines in a magnetic field is called the Zeeman effect. The splitting energy is much less than the energy difference between the two energy levels which produce a spectrum line.

The reduction of these lines is elliptically polarized. When the radiation is viewed perpendicularly to the magnetic field, the lines are linearly polarized parallel to the field direction, and the others perpendicularly to the field direction. When viewed parallel to the field, some lines are right circularly polarized, the others left circularly polarized, and some are missing entirely. Linear and circular polarizations are special cases of elliptical polarization.

From your experience with quantum mechanics you will note that perturbations are only approximately linear, and are not always simply calculable as implied above, especially when the perturbation energy becomes comparable to other energies in the Hamiltonian. We will only work with the linear Zeeman effect here. Also, in the early days of the Zeeman effect, the terms “normal” and “anomalous” were used, but not any longer in an historical approach in physics texts.

The key to the explanation of the Zeeman effect lies in how the magnetic moment of the atomic electron is related to its mechanical angular momentum. Qualitatively, the magnetic moment is given by \( \vec{m} = \frac{e}{2m} \vec{J} \) where \( \vec{J} \) is the total angular momentum and \( \mu \) is the Lande g-factor which relates the magnetic moment to the angular momentum. The energy levels are then split into as many levels as the quantum mechanical scalar product \( \vec{J} \cdot \vec{B} \) can have. The product looks like \( \mu J_m \beta J \) where \( J_m \equiv \frac{1}{2} \beta J_m \). The symbol \( m \) represents the magnetic quantum number, and has half-integral values between \( -J \) and \( +J \). The extra energy resulting from the magnetic field is \( \Delta E = \mu J_m \beta J \).

Many atoms, such as helium, have more than one optical electron, in which case the angular momentum symbol is an upper case \( J \), and the quantum number \( M_J \) can be integral or half-integral, depending upon whether the number of optical electrons is even or odd.

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Equipment in this experiment

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

1. Safety Goggles (green)
2. 0.5 meter Monochrometer, or Full Manual; PMT used, Operation, Gratings, and Circuit Diagram.
3. Discharge lamps filled with H, He, Hg.
4. Lamps
5. HP3478A-DVM
6. Tektronix 2225 scope Tek 2225 Manual
7. Fluke 4118 High Voltage power supply
8. Rack of the equipment; note that in the Rack it uses 10-32 screws to mount the equipment. They are spaced 3/4 inch apart.
9. Gaussmeter PFL 3265 or P.W. Bell 5190 and 5180 Interactive Manual Calibration Magnets
10. CCD Camera Lens mounted to CCD camera on Track using a firewire 1394 card and cable.
11. Fabry Perot Article
12. Magnet Coils and Magnet Power Supply
13. GPIB card by National Instruments in the computer
14. Prism Monochrometer

**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.

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**Preparation: Balmer Series**

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 levels 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 Baehr & Stoller, by Herzberg [4], by White, and the tabulation by Sitterly (see Reading Materials). Refer to the CRC Handbook for wavelengths and relative intensities. You may need to review the spectrophotometric 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 Appendix I. 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 gratin of 300 grooves/mm. Multiply the dial number by 6 to get the correct wavelength.
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 0000 or above 8000.
5. Read about the function and operation of the photomultiplier tube (PMT) in any text on radiation detection and measurement. (See, for example, Kroll Chapter 9 [2] and RCA PMT Manual [42].)

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**Procedure: Balmer Series**

Here we will use the known Mercury lines to find a conversion from the number shown on the monochromator to wavelength.

1. Look over the equipment and locate the spectrometer, light sources, photomultiplier tube (PMT), power supply, and digital multimeter. The spectrometer disperses the incident light into various colors depending on the characteristic of the light source and forms an image of the entrance slit. The spectrometer has two sets of optics: one sets forms images, and the other disperses the light - spreads it out with each color of light traveling in a different direction from all the others. The dispersing element in our spectrometer is a diffraction grating. The image forming optics are two concave mirrors. Light from the entrance slit which acts as the source of light is collimated by the first mirror (the slit is at the focal plane of the mirror) and directed toward the grating. The grating disperses the light and reflects it back to the second mirror, which in turn focuses the light on the exit slit at the photomultiplier detector or into the viewing window, depending on which way the plane mirror is positioned.
2. Do not remove the top of the spectrometer. The top needs to remain on - your breath is full of noxious chemicals which stick to glass and aluminum surfaces and make them cloudy. Locate the entrance and exit slits, collimating and camera mirrors, and grating. Observe how the grating turns as the wavelength is changed by turning the black knob (the other black dial, Speed Control Knob, must be disengaged by pulling and turned to a position between any two settings). See the manual for diagram of inside elements. It may help to draw a sketch to see just where the light is going, and why.
3. Turn on the oscilloscope that is set up to monitor the output of the photomultiplier tube (PMT). On the Power Supply make sure that the HIGH VOLTAGE switch is on STDBY, that the POLARITY switch is set to NEGATIVE, and that the voltage is set to 1000 volts. You may have to change this voltage later, but do not exceed 1500 volts! Turn on the Power Supply, and when the STDBY/RESET light comes up, switch the voltage on.
4. Wear the plastic safety goggles for the UV light. Turn on the mercury lamp and place it about 30 cm from the slit. Pull up a lens with a focal length of 10 cm between the source and the slit to focus the light from the source on the slit.
5. To find the first mercury line adjust the monochrometer knob until you see a bright blue line on the camera port. (Remember that in order to change the wavelength setting manually, you must set the SPEED CONTROL KNOB between any two settings.)
6. Set the diverter mirror to the film holder position “S” (to the right) and look at the diffraction light. You may have to move your head around in front of the window in order to bring the line into view. You should see a blue line at the center of the window (change the grating angle if it is not);
7. Position the light source on the spectrometer axis by moving it sideways until the blue line is in the center of the diffraction grating. If it is not enough light to see the grating outline, take off the spectrometer cover;
8. To see a spectrum line, you must move your eye back away from the film holder until you can focus on the position where the film will be. Or, you can use another lens as a magnifier by placing it between your eye and the film holder. It may help to draw a picture of the optics, to be sure you understand what is happening.
9. Observe the effect of varying the entrance slit width by using the micrometer on the top of the entrance housing, but don't worry about setting it for now.
10. Switch the diverter mirror to the PMT position “O” (to the left), and look at the output of the PMT. The source lamps run on AC, and therefore the light output is modulated at 120 Hz; we can see the output of the PMT modulated as well.
11. You may have to decrease the wavelength setting slightly to get the light into the PMT. What does this tell you about the calibration of the spectrometer? Observe the effects of varying the position of the light source, lens, slit width, and high voltage (not exceeding 1500V). Everything is positioned properly when your output is a maximum, but is not "clipped."
12. Switch the diverter mirror back to the film holder position, and increase the wavelength setting until you see sharp lines in the visible spectrum of mercury corresponding to first order diffraction. The counter should read about 610. Now choose the proper slit width. There is a way to calculate it on the basis of theory, but in practice you simply want narrow yet bright lines. Too large a slit gives bright lines that have a rectangular profile, while too narrow gives the proper line shape (Gaussian) but with reduced intensity. Observe the effects of a slit width that is too narrow or too wide, but end up with a choice that will give you good pictures. Once you have made a choice, you should set the micro mesh on the PMT housing to the same width.

**Wavelength Calibration**

The wavelength scale of the spectrometer is only good to a few nanometers at best. You can use the mercury emission lines to correct for the scale errors. 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
\[ n = 1 + \frac{6328 \times 10^{-8}}{\lambda^2} + \frac{23.48 \times 10^{-16}}{\lambda^4 \sigma^2} \]
where \( \sigma \) is the reciprocal of the wavelength in vacuum, called the wavenumber, in units of cm\(^{-1}\).

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.

<table>
<thead>
<tr>
<th></th>
<th>Wavelength (A)</th>
<th>Wavenumbers (cm(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mercury</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Red</td>
<td>6149.50</td>
<td>16 256.986</td>
</tr>
<tr>
<td>Yellow</td>
<td>5790.66</td>
<td>17 264.401</td>
</tr>
<tr>
<td>Yellow</td>
<td>5769.60</td>
<td>17 327.439</td>
</tr>
<tr>
<td>Green</td>
<td>5460.74</td>
<td>18 307.479</td>
</tr>
<tr>
<td>Blue</td>
<td>4358.33</td>
<td>22 938.156</td>
</tr>
<tr>
<td>Blue-violet</td>
<td>4046.56</td>
<td>24 705.376</td>
</tr>
<tr>
<td><strong>Helium</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Red</td>
<td>6678.15</td>
<td>14 970.074</td>
</tr>
<tr>
<td>Yellow</td>
<td>5875.62</td>
<td>17 013.752</td>
</tr>
<tr>
<td><strong>Hydrogen</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>alpha</td>
<td>6562.72</td>
<td>15 233.377</td>
</tr>
<tr>
<td>beta</td>
<td>4861.33</td>
<td>20 564.758</td>
</tr>
<tr>
<td>gamma</td>
<td>4340.47</td>
<td>23 032.505</td>
</tr>
<tr>
<td>delta</td>
<td>4101.74</td>
<td>24 373.020</td>
</tr>
<tr>
<td>epsilon</td>
<td>3970.072</td>
<td>25 181.336</td>
</tr>
<tr>
<td></td>
<td>3889.049</td>
<td>25 705.931</td>
</tr>
<tr>
<td></td>
<td>3835.384</td>
<td>26 065.615</td>
</tr>
</tbody>
</table>

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 \( \frac{1}{\lambda} \) vs. \( \frac{1}{\sigma} \). Fit the data points to a line. Determine the Rydberg constant and the series limit, and estimate their errors. Follow the example given in Section 2.9, page 63, of Lyons. Do not neglect this error analysis of your data.

Additional Questions: Balmer Series

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 546.1 nm (mercury green line). The parameters of the spectrometer are given in the manufacturer's manual. Compare the calculated values with what you obtain experimentally.

Preparation: Zeeman Effect

Let us take a specific example of the Zeeman effect. We will draw an energy level diagram, show the splittings of the levels, show the spectral lines emitted and their polarizations when viewed perpendicular to the magnetic field. Refer to figure 1 on the following page.

At this point we need to get an idea of the magnitude of the Zeeman effect. It is derived from the following: \( \psi \lambda = c \) energy \( E = \hbar \xi = \frac{\pi}{\sigma} = \hbar \sigma \) where \( \sigma = \frac{1}{\lambda} \) is called the wavenumber, given in reciprocal centimeters, \( 1/\sigma \) or cm\(^{-1}\). Because \( E \propto \sigma \), it is an accepted practice to use cm\(^{-1}\) as the unit of energy. An increment of energy is then \( \Delta \sigma \), and the energy of Zeeman splittings is \( \Delta \sigma = g_m \xi \lambda B \). Here \( L \) is called the Lorentz unit and is approximately \( 5 \times 10^{-4} \) cm\(^{-1}\). One electron volt is approximately \( 8000 \) cm\(^{-1}\). [Look up all the exact numbers before you make any calculations.]

For example, if we have a field of one tesla, a g-factor of 1.5, and a J-value of 2, we have a level split into 5 components, each one 0.05 cm\(^{-1}\) from its neighbor. For practice, compute the separations of the Zeeman lines shown in the Figure below. You will see that the field separations are less than the level separations, because it is the difference in g-factors that is important.
The mercury green line at 546.1 nm is an example of such a transition. [after Melissinos, p. 294]

Can we observe the Zeeman lines, in a practical case? Yes, if the lines are separated by more than their widths, and if we have a spectrometer of high enough resolution. A spectrum line has finite width (a frequency spread) because the energy levels are not infinitesimally sharp (natural width) and because the atoms are in thermal motion (Doppler width). The Doppler width is by far the larger in ordinary light sources, and has an approximate magnitude of \( 7 \times 10^{-7} \sqrt{T} \text{ cm}^{-1} \) where \( T \) is the absolute temperature and \( M \) is the gram atomic weight. For example, the green line of mercury at 546.1 nm in a discharge tube at room temperature has a Doppler width of \( 0.006 \text{ cm}^{-1} \). (Run through this calculation yourself— it will give you good practice in juggling units).

Your goals for this lab are to see the Zeeman effect in action and to learn something about the Fabry-Perot interferometer. Experimentally this is one of the easiest labs to perform, but treat it as an opportunity to learn more about the realities of quantum physics. Take the time to do a good job and to understand fully what is going on. And don’t leave your calculations and write-up until the last minute just because you think they will be easy: many students err here and receive poor grades on this easy lab just because they are rushed at the end. The same applies to presenting your oral report. There are lots of good quantum questions that can be asked.

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**Apparatus: Zeeman Effect**

1. To observe the Zeeman effect we must put a light source in a magnetic field and observe the radiation with a spectrometer which will resolve 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 2.

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 3.

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 \( \sigma = 2\pi n R \sin \frac{\theta}{2} \) 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

\[
I_I = \frac{I_0}{1 + \frac{R}{(1-R^2)} \sin^2 \frac{\theta}{2}}
\]

where \( \delta = 2\pi n R \sin \frac{\theta}{2} \) 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

\[
\delta \sigma = \frac{1}{2nR}
\]

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.

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**Procedure: Zeeman Effect**

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." Increase the voltage on the transformer until the He tube begins to glow brightly.

4. The Fabry-Perot interferometer is already adjusted. The plates are flat and parallel to a fraction of a wavelength. Also see Beam Shaping.

5. Set up the optical system with the helium lamp as shown above, but without the red filter, and adjust the position of the lens until you see sharp circular fringes in the camera. Make sure that the lamp cooling air is on and watch the lamp carefully; if it gets too hot, it will melt.

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Fig 1: Structure of the Zeeman multiplet arising in a transition from a \( ^3S_1 \) to a \( ^3P_2 \) level.

Fig 2: Apparatus

Fig 3: Fabry-Perot interferometer

"Ch. 14: Interference Involving Multiple Reflections"
6. Observe, record, and explain what happens when you do the following, using your eye without the camera; move the position of the lens; tilt the F-P plates; raise and lower the interferometer. With the camera in place, position the camera; shift the camera sideways.

7. 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.

8. 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 gaussmeter. 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 5180 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 (↑) and DOWN (↓) arrow pushbuttons to select ranges. Press the RANGE pushbutton to return to normal operation.
   - For a complete 5180 Manual See [5180Manual.exe](5180Manual.exe)
   For an Interactive Manual see [5180Manual.exe](5180Manual.exe)

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.

10. Before taking any readings with the 5180 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 (↑) and DOWN (↓) arrow pushbuttons to select ranges. Press the RANGE pushbutton to return to normal operation.
   - For a complete 5180 Manual See [5180Manual.exe](5180Manual.exe)
   For an Interactive Manual see [5180Manual.exe](5180Manual.exe)

11. 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?

12. **Setup the CCD 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 FireWire cable and run FireView on the PC from the Desktop. Use the drop down menu to select the Ohcilynx card. A Prosilica Digital Camera node should appear. Select the Prosilica camera and click Connect. Click OK, then click on View and then Start Acquisition. The camera should now be showing images, though they may be dark. If you need to change the brightness of the image, click on Others->Live Control, and you may change the gain and exposure from here. Temporarily remove the filter, lens, polarizer, and interferometer and line the camera up on the window in the center of the electromagnet. Then put all of the other optics back in place and align each component vertically with the aid of the camera. Zoom out all the way and set the focus to infinity. You can use the micrometer adjustment knobs on the Fabry-Perot mount to center the fringes in the field of the camera.
   - To take a snapshot, select Disk->Save Bitmap, and choose an appropriate location.

   ![Fig 4: Captured Image From Fabry Perot Interferometer](Fig4.png)

   **1. Something more complex and interesting (and yes, a required part of this lab):** 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 opening 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: Auto-Exposure 0, Gain 8, Shutter 425, Brightness 90, camera focal length set to infinity and zoom set to 80. If you go to edit the live controls and they are not having an effect, try restarting the computer or adjusting the lamp voltage until the rings are brighter.
APPENDIX I

Acton 0.5 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 step 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 99990 (equivalent to -10), or above a counter reading of 8000.

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 and to scan toward higher wavelengths move to the "H" position. Scans should be made to higher wavelengths for maximum reproducibility and accuracy. A knob on the top of the instrument indexes the moveable 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 on the 111-Lab Physics Library Site at [Monochromator Manual](#). Last day of the experiment please fill out the [Experiment Evaluation](#).

References

1. 2.Herzberg, Gerhard, *Atomic Spectra & Atomic Structure*, Dower Publisher, 1944, New York. Preface pg. 1-257. #QC451.H43 (this is an old text, but gives a good perspective on how the theory developed.)
2. 2.Knohl Ch.9: Photomultiplier Tubes Ch.8

Other References:

1. Introduction to Atomic Spectra, H. E. White: (This classic text was written by one of our own faculty members, and is still useful after 65 years.)
   a. Ch. 1: Early Historical Developments in Atomic Spectra
   b. Ch. 7: Penetrating and Non-Penetrating Orbits in the Alkali Metals
   c. Ch. 8: Doublet Fine Structure and the Spinning Electron
   d. Ch. 9: Hydrogen Fine Spectra and the Dirac Electron
   e. Ch. 10: The Zeeman Effect and the Paschen-Back Effect
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   g. Ch. 18: Hyperfine Structure
9. Optica, Hecht and A. Zajac
   a. Ch. 4: The Propagation of Light
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   c. Ch. 6: More Geometrical Optics
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10. Atomic Energy Levels and Grotrian Diagrams, Bashkin and J. M. Stoner: *Hydrogen*, *Helium*, *Potassium*, *Potassium*, *Potassium*, *Potassium*, *Potassium*, *Easiest place to find exact values of energy levels and transition energies for the red and yellow lines of helium.*