2/22/06

ZEEMAN EFFECT

<u>Fabry-Perot Spectroscopy:</u>
<u>Observation of the Anomalous Zeeman Effect in Mercury 5461Å Line</u>

Objective

This experiment employs a Fabry-Perot interferometer used as a high resolution spectrograph to observe the anomalous Zeeman splitting of the 5461Å line of the mercury spectrum. An electromagnet is provided to allow measurement of the effect at several different magnetic field values.

It should be noted that the 5461Å line of mercury will exhibit the anomalous, not the normal, Zeeman effect and will be split into nine, as opposed to three, components. A polarizer is provided to allow the isolation of either three $\Delta m = 0$ lines or six $\Delta m = \pm 1$ lines.

A linear correlation between the magnetic field strength and the width of the splitting should be found. An experimental value of μ_0/hc should also be determined.

The Appendix gives a brief introduction to the Fabry-Perot interferometer. For more details, refer to Chapter 7 in Melissinos I.

Experimental Procedure

All optical components are placed on a single rail, which should ease the alignment procedure. Figure 1 shows a diagram of the apparatus, and Fig. 2 shows a picture.

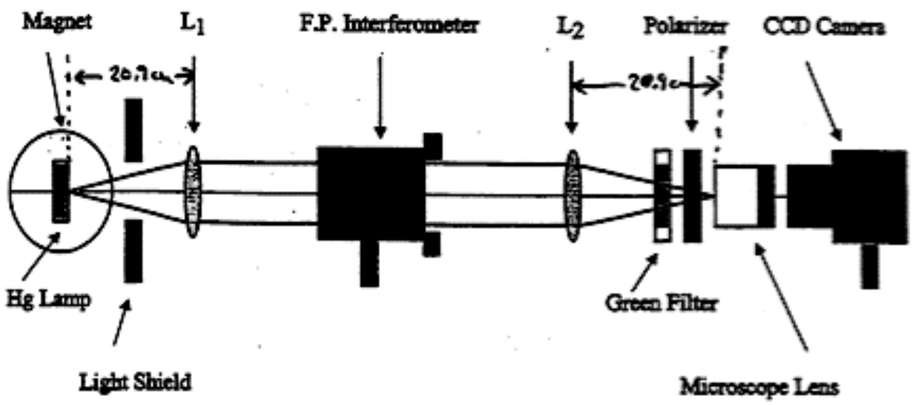


Figure 1: Suggested setup for the Zeeman effect lab. See page 5 for a photo.

1. The alignment of the apparatus is tricky. The setup should be pretty much ready to use. If not, ask for help. The magnet current should not exceed <u>5 amperes</u> or a voltage above <u>70 volts</u>, whichever comes first.
2. Position the discharge lamp in the center of the magnet gap. The lamp is excited by a 15 kV neon sign transformer. Use caution in adjusting the lamp while it is on, since the resulting voltage can give a very unpleasant, although not lethal, shock.
3. Place the light shield in front of the magnet. The green filter and polarizer can be mounted directly on the light shield as close as possible to the light source. On the rail, place L_1 and the Fabry-Perot interferometer. L_1 has a focal length of 209 mm. Place the lens around this distance away from the discharge tube and check that the aperture is

fully open. Turn on the lamp and look into the interferometer. A set of concentric rings should be visible.

4. Place L_2 behind the interferometer. L_2 also has a focal length of 209 mm. Place the small microscope lens approximately one focal length away from L_2. Look into the microscope lens. A magnified image of the ring pattern should be visible. Adjust the microscope lens and/or L_2 positions to get the image in focus. This image needs to be properly focused; the CCD camera does not see the image any better than a naked eye can.
5. Ideally the lamp should be at the focal point of L_1 so that the light rays go through the interferometer roughly parallel to its axis. However, this arrangement give a narrow vertical image of the discharge tube. It is therefore better to place L_1 either closer or farther. Suggested positions relative to the discharge tube are 30 cm for L_1, 49 cm for L_2, 76 cm for the microscope with the camera lens just behind it.
6. Adjust the position and orientation of the lenses to center the pattern over the rail. If necessary, move the rail to maximize the intensity. If major alignment is necessary, it is best to start without the green filter. Make sure the lenses are perpendicular to the beam axis. The interferometer can be rotated about a vertical axis to center the rings. A vertical tilt can be made using a thumbscrew.
7. If the interferometer is correctly aligned, you should see a sharp, symmetrical pattern of concentric rings. The quality of data depends mostly on the sharpness of the ring pattern. ***Do not attempt to adjust the thumb screws that adjust the spacing of the interferometer plates without first consulting with an instructor!*** While making adjustments to the interferometer, it will not be necessary to turn any of the three screws more than one-eighth turn in either direction. As you turn the screw, the image will contract or expand. First, adjust the two screws on the bottom of the interferometer so that the ring pattern neither expands nor contracts with any horizontal movement of the eye. A slight distortion can be expected near the edge of the plates, but otherwise the pattern should remain constant. Now, adjust the third screw so that the pattern remains constant with any vertical movement of the eye. Check the horizontal adjustment again and readjust if necessary. Continue the adjustment until the ring pattern is constant with any movement of the eye.
8. Once the image is clear in the microscope lens. Place the CCD camera behind the microscope lens. Open the aperture to maximum and set the focus to infinity.
9. Power up the computer, log in, and open the kSA400 program for CCD image acquisition. A "Help" menu is available. Click on the camera icon. Go to "Properties" under the Edit menu. Choose "Video Setting". Under "Filter", choose "Maximize Contrast". Under "General" you can set the Exposure Time. For tuning up, 2 sec. is convenient with Sum(# frames) set at 1. You will have to turn off the room lights and work in the dark to reduce background light. You should see an image similar to Fig. 3(a) but with considerably more noise. Now you can carefully adjust the positions of the lenses, microscope and camera to maximize brightness, center the rings in the field of view, and get the sharpest possible rings. Once you have a sharp, well-centered image, you can mount the green filter.

Once a satisfactory image is obtained with no magnetic field, turn up the magnet current. As you do, you will notice that the rings split. Arrange the polarizer so that only the 3 $\Delta m = 0$ lines are visible, which should occur with the polarizer axis parallel to the magnetic field. You should do some fine tuning of the positions and orientations to get the sharpest possible rings.

Now you are ready to acquire the images. Set the Sum(#frames) to 40 or so to get a long exposure time and adequate signal/noise. [You may have to hit Enter or restart the program to coax it to do something.] If you are satisfied with the image, go to Single Image Acquisition mode and acquire and save your image. You can try the Line Profile tool to get line profiles such as those in Fig. 3.

Obtain images at least four different magnet currents between 0 and 5 A. Make sure the splitting is clearly visible for analysis.

Use a Hall probe to measure the magnetic field *vs*. current. Make sure to first calibrate the probe using a reference magnet. Plot the magnet calibration data (magnetic field strength *vs.* applied voltage). Is there a linear relationship between the magnet current and the field strength?

Data Analysis

For a more detailed explanation and procedure for data analysis, refer to Chapter 7, Sections 5 & 6 in Melissinos I.

1. Use the kSA software Line Profile tool to get ring profiles. Make sure to take measurements along the diameter of the ring.
2. Correct analysis of the data requires the determination of the relative radius of each ring. On the Line Profile tool, extend the analysis line vertically from the center. Using the Data Cursor, read the column numbers of all visible and identifiable rings. It is useful to shrink the analysis line to isolate each set of rings. Make sure the analysis line remains vertical along the center of the rings.
3. Repeat steps 2 and 3 for all images.
4. Determining the fractional order at the center:
   a) Just as the first ring is labeled as first order, an order is assigned to the center of the rings and this value is called the fractional order at the center. It is fractional since the interference order at the center is in general not an integer. (Hence there is no bright interference pattern at the center.)
   b) The fractional order at the center is used to compare the overall shifting of the ring pattern. By comparing the fractional order at different magnetic field strengths, the effect of a magnetic field application to the ring pattern can be determined.
   c) The fractional order at the center is determined as the intercept on the ring order axis on the plot of the ring order *vs*. relative radii squared.
   d) Determine the radius of each ring by using the column value of each ring as determined in step 3 and of the center as determined in step 2. Tabulate the radius squared *vs.* the ring order.

   e) Plot the ring order *vs.* radius squared. Fit a linear line and determine the intercept on the ring order axis. This is fractional order at the center.
   f) Repeat the procedure for all other images. For images with an applied magnetic field, use only the central component ('b').
5. Determining the Zeeman splitting:
   a) The Zeeman splitting data will be analyzed using square array reduction method as described in Melissinos I.
   b) For images with the applied magnetic field, set up the square array as Table 7.4 described on page 319 of Melissinos I.
   c) After tallying the data in the array, determine $<\Delta>$, $<\delta_{ab}>$ and $<\delta_{bc}>$. Remember to take every other column of Δ to determine $<\Delta>$. If there are any Δ, δ_{ab} and/or δ_{bc} with significant deviation from other values, they can be discarded.
   d) The wave number separation, $\Delta\nu$, is calculated as:

$$\Delta\nu_{ab} = <\delta_{ab}> / 2t <\Delta>$$

   where t is the Fabry-Perot interferometer spacing. (The Fabry-Perot interferometer has a spacer of width 0.28 ± 0.02 cm).
   e) Plot the wave number separation against applied magnetic field values. To produce a chart similar to Melissinos I, it may be necessary to label 'bc splitting' value as negative. Fit a linear curve with the intercept at 0 to determine $\Delta\nu/B$ values for both 'ab' and 'bc' splitting. Take the average of 'ab' and 'bc' splitting to get the central line.
6. Determining the experimental value of μ_0/hc:
   a) Once $\Delta\nu/B$ values for both 'ab' and 'bc' splitting are determined, take the average. This is the experimental $\Delta\nu/B$ value.
   b) Since $\Delta\nu = \mu_0 B / 2hc$ (Equation 6.2, page 326 in Melissinos I), the experimental value of μ_0/hc can be determined. [Don't forget (0,0) is a point!]
   c) Compare your value of μ_0/hc with the accepted value, 4.669×10^{-5} cm^{-1}/gauss

If this is a 3-week experiment, you should also study the six $\Delta m = \pm 1$ green lines or the yellow doublet lines of mercury.

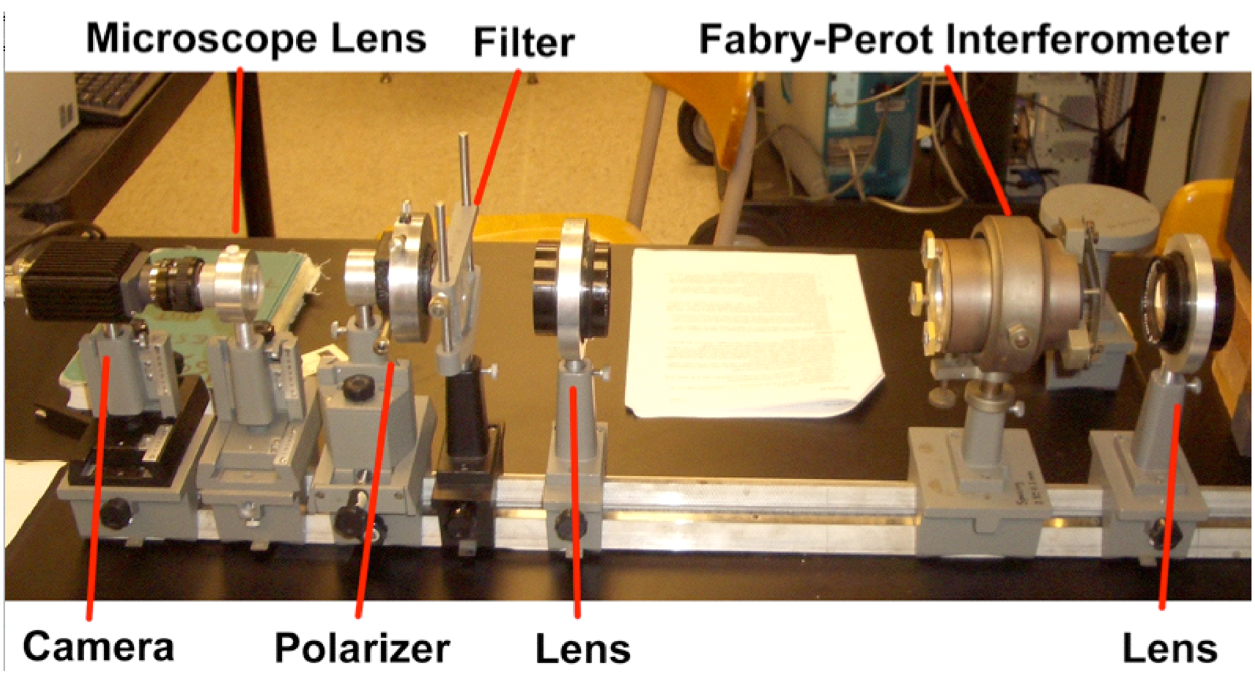
To observe the mercury yellow lines remove the green interference filter from the optical path and insert the yellow interference filter. Note that there will now be two sets of interference rings present since the filter passes both of the yellow lines. With luck the two sets of rings may be conveniently spaced so that their Zeeman patterns do not overlap at moderate fields.

Measure the structure and splitting of both components of the mercury yellow doublet. This will require special care because of possible overlapping of the two interference patterns at high field values. Note the slight difference in the Zeeman patterns of the 5769.6 Å and 5461 Å lines. How do they differ and why?

Additional Questions

1. Present a <u>classical</u> reason why the triple splitting of the spectrum (*i.e.*, the normal Zeeman effect) occurs. Why would the three split components be polarized the way they are? Why would the central component be missing if viewed along the pole of the magnet? (Hint: Try to imagine a randomly orbiting, photon-emitting electron under a magnetic field.)
2. Did you confirm that the central component of concentric rings remain stable with the application of magnetic fields?
3. Did you observe a linear relationship between the splitting strength and the applied magnetic field value?
4. Did you obtain an acceptable experimental value for μ_0/hc?
5. Why is the lamp ideally placed at the focal plane of the first lens?
6. Construct energy level diagrams of the mercury transitions and identify the observed Zeeman component frequencies with the various allowed transitions between the magnetic substates.

Figure 2: Picture of the apparatus, compliments of Joseph Westlake. The mercury lamp and magnet are off the picture to the right. See text for suggested positions of the elements.



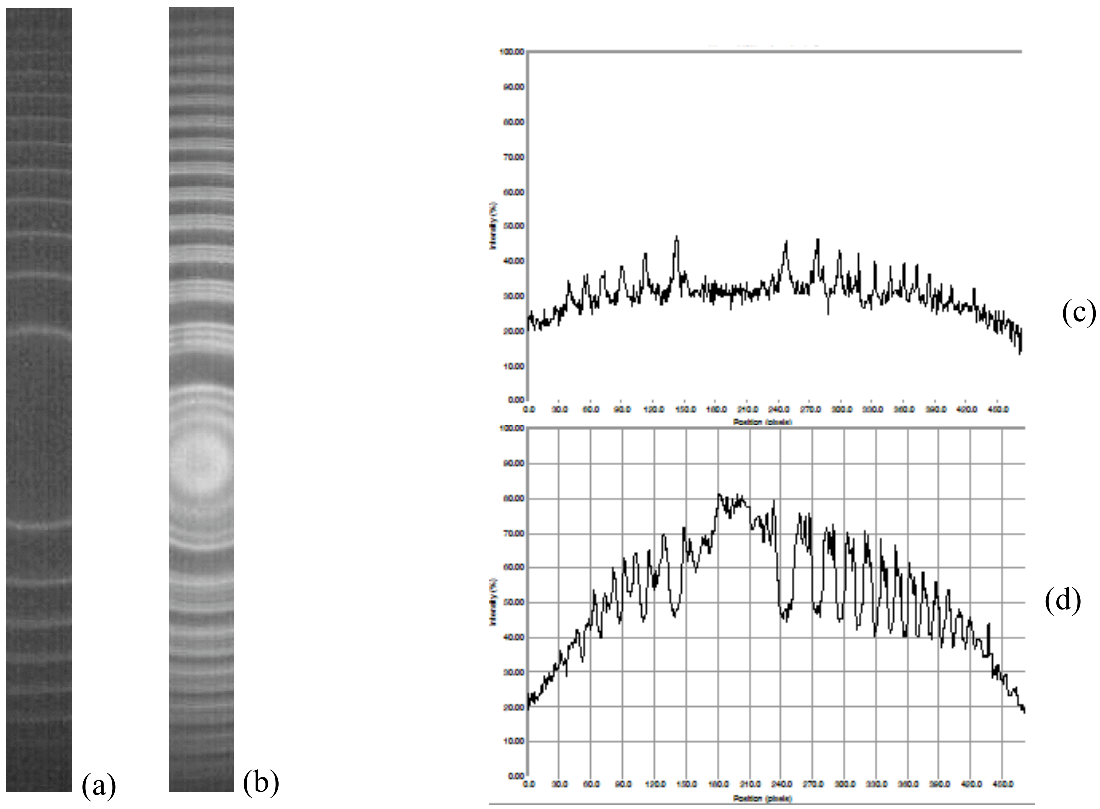


Figure 3: (a) Vertical slice of image with B=0. (b) Image with B near maximum (Polarizer @ 90°)

(c) Line profile through image in (a). (d) Line profile through (b).

APPENDIX A: THEORY OF THE FABRY-PEROT INTERFEROMETER

A Fabry-Perot interferometer consists of two precisely parallel glass plates with optically flat and highly reflective surfaces facing one another, as illustrated in Figure 6. To use it as a spectrometer one must have, in addition, a lens to focus parallel rays to a point in its image plane and a magnifying eyepiece for examining the intensity pattern of light in the focal plane, i.e. a telescope.

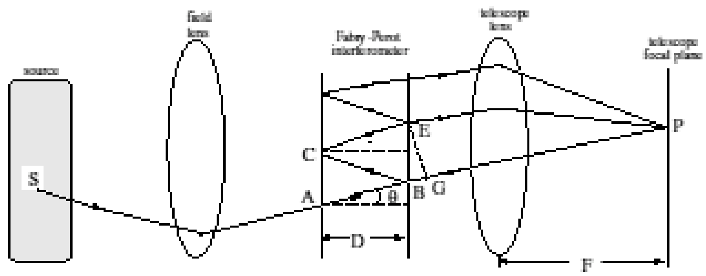


FIG. 6: Geometrical optics of the Fabry-Perot interferometer. Only one of many multiply reflected paths is shown.

Consider a ray of light of wavelength λ emitted by an excited mercury atom at S and making an angle θ with the axis, is incident on the Fabry-Perot from the left at the point A. It will be partially transmitted at each of the two Fabry-Perot mirror surfaces, and will arrive at P after passing through the telescope lens. The portion of the ray reflected at B will be reflected again at C and partially transmitted at E. It will enter the telescope lens parallel to the original ray and will be focussed to the same point P after having traversed an additional distance $2Dcos\theta$. If this additional distance is an integer number of wavelengths, i.e.,

$$2Dcos\theta = m\lambda \tag{7}$$

then the two rays (and all the additional multiply reflected rays) will interfere constructively when brought to the focus at P. Constructive interference among all the multiply reflected rays passing through the interferometer at an angle θ to the axis will produce a circle of interference maxima in the focal plane, i.e., a bright ring of the mth order of interference. If the separation of the plates is increased, then the angular radius of the mth order ring will expand so that the decrease in $cos\theta$ compensates for the increase in D.