UCI **ZEEMAN EFFECT**

OBJECTIVES

Observe the fine structure lines of mercury and the Zeeman splitting of one or more of these lines as a function of magnetic field.

Compare the observed splitting with theoretical splitting.

REFERENCES

Tipler, section on Zeeman effect.
Melissinos, sections on Mercury in Chap. 2 and Chap. 7.
Vaughn, "The Fabry Perot Interferometer".
Born and Wolf, "Principles of Optics".
Hernandez, "Fabry-Perot Interferometers"
(The last four may be checked out from Jim Kelley)

ZEEMAN EFFECT

The observation of spectral line splitting when an atom is placed in an external magnetic field --known as the Zeeman effect--was first explored by Faraday. However, because of the low resolution of his instrument, he was unable to detect any spectral line splitting. It was later successfully observed by Zeeman, for whom the effect was named.

This advanced laboratory employs a Fabry-Perot interferometer, a high-resolution spectroscopic instrument. It produces a fringe pattern when a light beam hits and transmits through and/or reflects off its mirrors causing interference. Use the refrence texts listed above to understand interferometer basics. It can be seen that when a discharge lamp is placed in a magnetic field, each interference fringe is split into two or more fringes. One can analyze such an effect in light of quantum mechanics as well as classical mechanics.

GENERAL ARRANGEMENT

The apparatus, as shown in Fig. 1, consists of six main parts: (1) a laser and a beam steering mirror for rough adjustments, (2) a discharge lamp placed in an electrically powered magnet, (3) a condensing lens assembly, (4) a collimating lens assembly, (5) a linear polarizer, (6) a Fabry-Perot interferometer, and (7) a photomultiplier (PMT) detector unit. Students are expected to be able to set up the apparatus by following the procedures below and by experimenting with other arrangements.

ALIGNMENT OBJECTIVES - GENERAL

1. Insure that angle of incidence of light is completely normal to the front surfaces of the interferometer mirrors,

2. incident light is perfectly collimated (parallel), and

3. interferometer mirrors are perfectly parallel.

The procedures outlined below are suggested methods to help you achieve these objectives. You will probably discover better ways.

<u>Laser Alignment</u>

The laser is used in this experiment simply as an alignment tool to aid in the adjustment of your optical components. First, adjust the height of the laser so that the beam is at the same height as the center of the interferometer mirrors (it should also pass directly through the center of the magnet pole pieces). Place the laser straight to the beam steering mirror, which faces the laser at 45^0 in order to project the laser beam along the length of the table. Adjust the two knobs of the mirror so that the laser beam is parallel to the table top (height adjustment) and aligned with a line of screw holes (side adjustment) all the way along the top of the table. Use the glass rulers to measure the horizontal and vertical displacement of the laser path. One knob of the mirror controls the deflection horizontally and the other vertically. Concentrate at first on making the beam parallel to one of the rows of screw holes, because once it is straightened horizontally, the whole path can be shifted laterally by adjusting the translator <u>stand</u> of the mirror (not the angle of the mirror).

<u>About Lenses</u>

Referring to the figure, there are two lenses, 1 and 2, in the condensing unit and one, lens 3, in the collimating unit. Light rays from the light source are divergent. When Lens 1 is focussed on the light source, it generates nearly parallel light for better focusing by lens 2. Besides making light nearly parallel, lens 1 can provide fine adjustments of the light path along the x- and y- directions. Assumptions here are (1), that light between lens 1 and lens 2 does not have to be parallel for the rays emerging out of lens 3 to be parallel and (2), that the x- and y-adjustments of lens 1 do not prevent the final rays from being parallel. What is meant by x- and y-adjustments is that as you move lens 1 around using the two thumb screws on the condensor, the image of light projected on the pinhole aperture of the collimating unit also moves around. Next, focusing of light on the aperture is done by lens 2. The aperture acts as a point source. Lens 3 is focussed on the light rays from the point source and is adjustable along the z-axis to make them parallel.

Positioning Elements

Place all the elements (condenser, collimator, etc.) one at a time, so that their optical axis is at the same height as the interferometer. Start with the condensing lens. The focal length of lens 1 in the condensing unit is 12.5cm, so the discharge lamp should be positioned so that it is 12.5cm from the condensing lens. Remove the filter from the condensing unit, and make sure the shutter is open. Adjust the position of the holder and the lens so that beam is directed along the optical axis (parallel to the table top, and directly above the holes).

Now put the collimating lens assembly unit in place, and adjust its height and angle so that the laser beam passes through the pinhole aperture and emerges from the collimater lens without diverging from the optical axis (this can be tedious!).

Next, check the alignment of the Fabry-Perot interferometer. Set the spearation between plates to .5 cm. To make sure the beam incident on the interferometer is perpendicular to its mirrors, insert a microscope slide into the light path between the collimating unit and the interferometer. Adjust the tilt and azimuth angle of the interferometer baseplate so that the incident and reflected beams coincide on the same spot. Look at the projection of the interferometer on the wall. If you see a series of red dots trailing off one way or another, use the micrometer adjustments on the interferometer to bring them into coincidence.

You should now be able to produce interference fringes. In order to see them more easily, put a piece of frosted glass in front of the interferometer, and project the output onto a piece of white paper. Carefully make fine micrometer adjustments to center the bullseye pattern. Try to get just a few broad fringes rather than many narrow fringes. The fewer you have, the more parallel the interferometer plates.

Parallelism will be observed by positioning the center of the fringe pattern bull's eye in the center of the field of view. Slowly move the micrometer adjustments, alternating from one to the other, causing the fringes to become farther and farther apart until a bull's eye emerges. This will take time. To make sure it is the bull's eye, turn on the high voltage supply which is connected to the interferometer. The high voltage controls the length of the piezoelectric material on which one of the mirrors is mounted. This effectively adjusts the separation between the two mirrors on the order of wavelengths. You should be able to see the fringes move as you adjust the high voltage. CAUTION: Do not exceed 400V on the high voltage. When you are satisfied with your alignment, turn off the laser and place the mercury lamp between the poles of the magnet. Install the large plano-convex lens at the output side of the interferometer, 125mm from the PMT translating stage assembly. (The curved side of the lens should face toward the interferometer.)

From now on you will use the discharge lamp as the light source. Use the clamp to position the light source between the poles of the magnet, and turn on the light. (It will take a few minutes before the light intensity reaches maximum.) Turn off the lights and you will see the image of the light on the pinhole aperture plate. Adjust the focus of lens 2 by moving the focus pin of the condensing unit back and forth until the image is sharpest. Project the light from the collimator onto a piece of white paper. Make fine adjustments to the position of the lamp until you can see a nice round blue spot on the paper. Adjust the position of the lens 3 focus pin so that the size of the aperture image remains the same all the way along the optical path.

Insert the green interference filter into the condensing unit. Get a flashlight, and turn off the room lights. Locate the image with your eye (the light will be too dim to project). It will appear as a green spot or band. Use the H.V. supply to move the interferometer plate and verify that you are observing fringes. Repeat the procedure above by making fine adjustments to the micrometers. You must have no more than one fringe in the field of view at a time. The other two channels of the H.V. supply can be used to fine adjust mirror tilt. This is highly recommended! Your objective is to zero in on the bullseye of the concentric ring pattern. As you sweep to voltage to the piezo you will see a single fringe emerge from the center, expand outward, and then disappear before the next fringe emerges.

Our detector (a photo-multiplier tube) integrates all the light picked up by it's photocathode, but cannot resolve the spacial features of a concentric ring pattern. In this case, with 1.) perfectly parallel light impinging upon 2.) perfectly parallel mirrors at 3.) an angle precisely normal to the surface, the path length for every reflection of light across the surface of the interferometer mirrors is identical. Instead of generating a pattern of concentric rings, the entire field of view is uniformly illuminated with either constructive or destructive interference. Each "fringe" is then easily discernable by the PMT. With diligence and attention to the three conditions outlined above, this circumstance is approachable.

EXPERIMENTAL PROCEDURES

Every time you come into the lab, probably the first thing you want to do is check the interference pattern, assuming that everything else remains properly set up. Once the bull's eye is obtained, place the photomultiplier tube (PMT) behind lens 4 in such a way that light focuses a little in front of the PMT aperture plate. The image should be somewhat larger than the PMT aperture. You do not want the image too small because the PMT will not be able to resolve individual fringes. Remove the filter from the condensing unit, get a flashlight, and turn off the room lights. You will just barely be able to see the image of light (a tiny spot) on the aperture plate of the PMT. Adjust the vertical and horizontal position of the PMT so that the spot falls into the aperture of the PMT. To make certain that light is going into the PMT, turn on the discriminator and the photon counter. Adjust the high voltage to the interferometer through a range of about 50 volts and find the fringe peak by watching the count rate. The schematic diagram of the detector unit is as shown in Fig. 2.

The high voltage power supply for the PMT is in the photon counter. Note: Do not turn on the Photon Counter (and PMT) when the room lights are on. Use the single counter mode on the discriminator, and set the discriminator level high enough to avoid an excessive count rate which would overload the discriminator. While moving the PMT slowly, maximize the counter rates to locate the optimum position of PMT. Find the maximum for both x and y axes. Insert the filter back into the condensing unit. Place the polarizer angle at 0^0. (Verify its orientation.) Now the experiment is ready to start. Lower the discriminator level and adjust the integration time interval until you have a count rate with a good signal to background ratio. Turn on the interferometer high voltage ramp generator. Set the duration to 10 sec, and adjust the amplitude to a level of about 500 Volts. The interferometer will sweep through about 4 peaks corresponding to 4 orders. Important: Do not exceed the maximum rating for the Burleigh piezo elements. Refer to the Burleigh manual.

For each trial you should always start taking data with the X-Y plotter at the beginning of a ramp cycle. Continue the plot until the beginning of the next ramp cycle. First, with the magnetic field off, take data for one sweep. Then open the water line of the magnet, and turn on its DC power supply. Up to a limit, the magnetic field strength is directly proportional to the DC current, as shown in the graph on the DC power supply. For more accurate current readings use a DMM in series with the power supply and magnet, and calibrate B vs. I using the gaussmeter.

Do trials for different field strengths. Change the polarizer angle (to say 90^0) and repeat.

After you are done, make sure that the following items are turned off.

1) water
2) DC power supply (magnet)
3) light source
4) high voltage power supply
5) frequency generator
6) photon counting electronics
7) X-Y plotter

Zeeman Effect Data Analysis

References: Max Born and Emil Wolf, *Principles of Optics* (Pergamon Press, Oxford, 1984)
JM Vaughan, *The Fabry-Perot Interferometer* (Adam Hilger, Bristol and Philadelphia, 1989)
G. Hernandez, *Fabry-Perot Interferometers* (Cambridge University Press, 1986)

This experiment studies the effect of a magnetic field on the green light emitted by hot Hg atoms. In the absence of a magnetic field the green light comes out in a narrow range of wavelengths centered at 546.1 nm. A narrow band of wavelengths emitted by an atom is called a spectral line. When the same atom is placed in a magnetic field the situation changes. Instead of consisting of one spectral line, the green light from the atom is made up of several spectral lines with wavelengths that depend on the size of the field. The object of the experiment is to measure the differences between each spectral line in the field and the single spectral line in zero field. These differences in wavelength are called Zeeman splittings. The tool in the Advanced Lab that allows the Zeeman splittings to be measured is a Fabry-Perot interferometer, or F-P for short. The polarization of the spectral lines in the field are also studied.

The F-P consists of two partially reflecting parallel mirrors separated by a distance d. The mirrors are on the two inside surfaces of the substantial looking glass plates you can just barely see when you look into the F-P from the top. (Y*ou must be careful to never touch those surfaces or allow them to touch each other. Nasty chemicals on your skin or mechanical abrasion will ruin the reflectivity of the mirrors.*) The layer of air between the mirrors acts like a thin film interference medium. Most of the alignment procedure in the earlier part of this manual is designed to turn light from the Hg lamp into plane waves incident normally on the mirrors and air gap. Please refer to your P7E textbook to review thin film interference at normal incidence if you don't remember how all of that goes. Imagine monochromatic, plane wave light with wavelength λ at normal incidence on the reflecting surfaces. You may recall, or your P7E text will tell you, that the transmitted intensity will be a maximum when

$$\delta \equiv \frac{4\pi}{\lambda} d = 2\pi m. \tag{1}$$

The formula in your text book will have an n in the numerator of the middle expression. Because our film is made of air, n = 1 in this experiment. δ is the phase difference between light that goes directly through both mirrors and light that goes through the first mirror, reflects from the second mirror, reflects again from the first mirror, and finally goes through the second mirror. In Eq. (1) m is a positive integer. This equation can be simplified to

$$2d = m\lambda \tag{2}$$

In Eq. (2) d is something you measure and λ you already know. In the experiment d will be about 0.5 cm, so when bright green light is coming through the F-P, m will be about 20,000. Please notice that if d is set so that the light transmitted through the F-P is a maximum, it will be a maximum again when d changes (either way) by $\lambda/2$. When Eq. (2) is obeyed the transmitted intensity is said to be at an mth order transmission maximum.

Now suppose that d is set so that Eq. (2) is obeyed, but light with a wavelength of $\lambda + \Delta\lambda$ is sent through the interferometer. $\Delta\lambda$ is small. How must d change so that the transmitted intensity is again at an mth order maximum? Call the new mirror spacing $d + \Delta d$ and use Eq. (2) to get,

$$2(d + \Delta d) = m(\lambda + \Delta\lambda) \tag{3}$$

Using Eq. (2) once more to cancel 2d and mλ, and yet again to eliminate m, Eq. (3) becomes

$$\Delta d = d\frac{\Delta\lambda}{\lambda} \tag{4}$$

Eq. (4) implies that if the wavelength of 500 nm light changes by 0.1 nm, Δd will be $1\mu m$, a distance that can be controllably moved with the piezoelectric devices on the F-P that move one of the mirrors.

In your experiment, you will want to measure $\Delta\lambda$ for the lines in the field from the $\lambda = 546.1\ nm$ spectral line. So you will want to rewrite Eq. (4) as

$$\boxed{\Delta\lambda = \lambda\frac{\Delta d}{d}} \tag{5}$$

Eq. (5) is the key to extracting wavelength shifts from your data. Please note that Δd is varied by applying a voltage to piezoelectric elements in the F-P that move one of the mirrors. You must measure the dependence of Δd on V_{piezo}. Bear in mind that the transmitted intensity moves from maximum to maximum every time d increases by $\lambda/2$. To zeroth order Δd is linear in V_{piezo}. But be careful. Nothing is linear forever and piezos can be hysteretic. Arrange your data so that measuring V_{piezo} allows you to extract values of Δd to use in Eq. (5).

You must bear in mind that in your experiment you will have several spectral lines shifted by different amounts from the zero field line, not just one line as discussed above. You must use your head to keep straight which line is which. If you watch what happens as you increase the field in reasonably sized steps, you'll be able to do this and apply Eq. (5) to each line.

Some fine points you should pay attention to if you are actually a Physics Major:

At first sight Eq. (5) implies that to get the best resolution you should make d (and therefore m) as big as possible. But there is another consideration. Things get ambiguous if $\Delta\lambda$ gets too large. The problem is that if $\Delta\lambda$ gets big enough, the (m - 1)th order transmission maximum for wavelength $\lambda + \Delta\lambda$ has the same d as the mth order maximum for wavelength λ. The value of $\Delta\lambda$ that does this is called the "free spectral range." It can be calculated from Eq. (2) and the result is

$$\Delta\lambda_{fsr} = \frac{\lambda}{m-1} \approx \frac{\lambda}{m} = \frac{\lambda^2}{2d} \tag{6}$$

Of course if $\Delta\lambda$ is even bigger than $\Delta\lambda_{fsr}$, the (m-1)th order transmission maximum for $\lambda + \Delta\lambda$ will be at a bigger d than the mth order maximum of wavelength λ. When this happens you can no longer be sure which maximum of the $\lambda + \Delta\lambda$ wavelength light is the mth order maximum. Then you won't be able to figure out what to use for Δd in Eq. (5) and you've had it as far as measuring $\Delta\lambda$ goes. So in most circumstances, the range of wavelength shifts that can be unambiguously measured is a free spectral range. Making d large increases the resolution according to Eq.(5), but only at the cost of restricting the range of shifts that can be measured, according to Eq. (6). Fortunately, this is not too big a problem in the Zeeman experiment because the shifts are not large and the lines can be followed as the field is gradually increased.

Finally, how can you estimate how much wavelength resolution to expect from the F-P? The intensity maximums that are described by Eqs. (1) and (2) are not infinitely narrow. The transmitted intensity as a function of d is a series of symmetrical peaks with finite widths. Eqs. (1) and (2) locate the central, highest point on each peak. Obviously the success you will have using the equations in this section to find $\Delta\lambda$ will be limited by how well you can experimentally determine the values of Δd (or really its surrogate, V_{piezo}) at which the peaks occur. You can do a better job finding the highest point of a skinny needle-like peak than you can the center of a broad, haystack of a peak. This is particularly true in the inevitable presence of noise. So F-P's are made to give narrow peaks. This is done by making the reflectivity of the mirrors large. (Obviously you can't make it infinite or no light ever gets into the air gap. In that case nothing interferes and the game is over.) The details are given in Section 7.6 of the book by Born and Wolf. It's well worth reading.

The high points of that discussion are as follows. It turns out that the intensity pattern is given as a function of δ by

$$I = I_0 \frac{1}{1 + F(\sin(\delta/2))^2}, \tag{7}$$

where δ is defined in Eq. (1) and I_0 is the intensity of the plane waves incident on the first mirror. In Eq. (7) F is defined by

$$F \equiv \frac{4R}{(1-R)^2}. \tag{8}$$

In Eq. (8) R is the intensity reflection coefficient (not the amplitude reflection coefficient) of the mirrors. Both mirrors have the same R. According to Eq. (7) if F is large (which according to Eq. (8) happens when R is large) I will be small except when $\delta/2 \approx m\pi$ When $\delta/2 = m\pi$, the transmission I_0, a maximum consistent with Eq. (1).

To illustrate the effect of the reflectivity, Fig. 1 shows the result of using Eq. (7) to calculate the transmitted intensity through the F-P as a function of the phase difference for two different reflectivities of the mirrors. The upper, smooth curve is for 4% reflectivity (F = 0.174), which is typical of a glass-air interface. The curve with the sharp peaks is for 80% reflective surfaces (F = 80).:

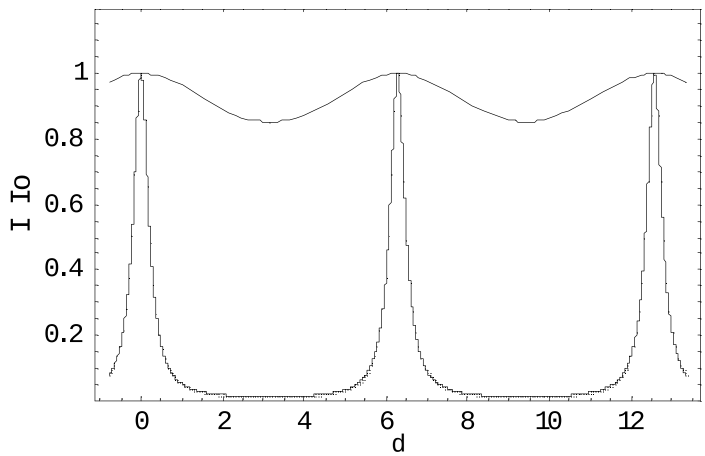

Figure 1. The relative intensity transmitted through an F-P as a function of the phase for two different mirror reflectivities. The upper curve is for R = 0.04 and the lower for R = 0.80.

It is obviously going to be easier to find the peaks for an F-P with 80% reflective surfaces, especially in the presence of noise.

How wide are the transmission peaks of the F-P? If you go back to Eq. (7) and assume that F is large compared to 1, you can calculate how far the phase, δ must be shifted from $2m\pi$ to make the relative intensity 1/2. Calling this additional phase shift ε, Eq. (7) leads to

$$\frac{1}{2} = \frac{1}{1 + F\left(\frac{\varepsilon}{2}\right)^2} \tag{9}$$

Solving Eq. (9) for ε gives

$$\varepsilon = \frac{2}{\sqrt{F}} \tag{10}$$

So the width, in phase, of the whole peak is just twice this, or $4/\sqrt{F}$

A common sense estimate of the precision achievable in measuring $\Delta\lambda$ with the F-P can be made based on ε. The significance of ε is that it is roughly the smallest phase shift that can be resolved.(If a peak shifts by a tiny fraction of its width, no one can tell it moved at all.) Because of Eq. (1) a smallest measurable phase shift implies that there is a smallest Δd you can hope to measure given by

$$\varepsilon = \frac{4\pi\Delta d_{min}}{\lambda} \tag{11}$$

This of course leads to

$$\Delta d_{min} = \frac{\lambda\varepsilon}{4\pi} \tag{12}$$

From this, Eq. (5) says that the minimum $\Delta\lambda$ that the F-P can resolve must be

$$\Delta\lambda_{min} = \lambda\frac{\Delta d_{min}}{d} = \lambda\frac{2\Delta d_{min}}{m\lambda} = \lambda\frac{\varepsilon}{2m\pi} = \frac{2\lambda}{m\pi\sqrt{F}} \tag{13}$$

Eqs. (1) and (12) and the result at the top of the page ($\varepsilon = 4/\sqrt{F}$) have also gotten into the act in the string of substitutions in Eq. (13). Finally the sensitivity of an interferometer or spectrometer is usually parameterized by its resolving power. The resolving power is the ratio of the wavelength to the smallest shift in that wavelength that can be detected,

$$\Re \equiv \frac{\lambda}{\Delta\lambda_{min}} = m\frac{\pi\sqrt{F}}{2} \equiv m\Im. \tag{14}$$

$\Im$, which is defined implicitly by Eq. (14) as $\pi\sqrt{F}/2$, is called the “finesse” of the interferometer.Since F is determined by R, the resolving power is determined by the reflectivity of the mirrors and the order, m, in which the instrument is used.

A fancier calculation (See Born & Wolf’s Section 7.6, again.) of the resolving power based on Rayleigh’s criterion, which is probably defined in your good old P7E text, leads to

$$\Re = 0.97m\Im \tag{15}$$

Of course the results for $\Re$ given here assume that the light hitting the F-P is absolutely monchromatic. Due to isotope effects, inhomogeneous $\vec{B}$ fields, thermal and pressure broadening in the lamp, etc., the light in your experiment is not absolutely monochromatic. So Eqs. (14) and (15) are a upper bound on how well you can do with the equipment in the lab.

Also note that all of the equations derived here are good for light near the center of the usual F-P “bulls-eye”, even if the collimation is imperfect.