The Zeeman Effect

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Abstract

This report describes the experimental procedure we used to observe and quantify the Zeeman effect in a mercury atom i.e the splitting of a single spectral line of an atom into three distinct components when subject to a magnetic field. Results are shown and discussed for the the 5461A green line splitting and for the 4040A violet line splitting.

Introduction

Place an atom in a magnetic field, and as Pieter Zeeman dicovered (and got the Nobel Prize in 1902 for that discovery), its spectral lines will split.

For some atoms, they will split into three distinct spectral lines. This is called the normal Zeeman effect, and it is that effect that was initially discovered. But for other atoms, it turned out that the spectral lines were splitting into more than 3 lines. This couldn't be explained by the theory and so it was called the "anomalous" Zeeman effect.

The "anomaly" was solved when the concept of electron spin was fully understood and incorporated int he theory.
The green 5461Angstroms line of the mercury we are studying corresponds to the anomalous Zeeman effect ; it splits into 9 components :

*6 components for Δm=+/-1

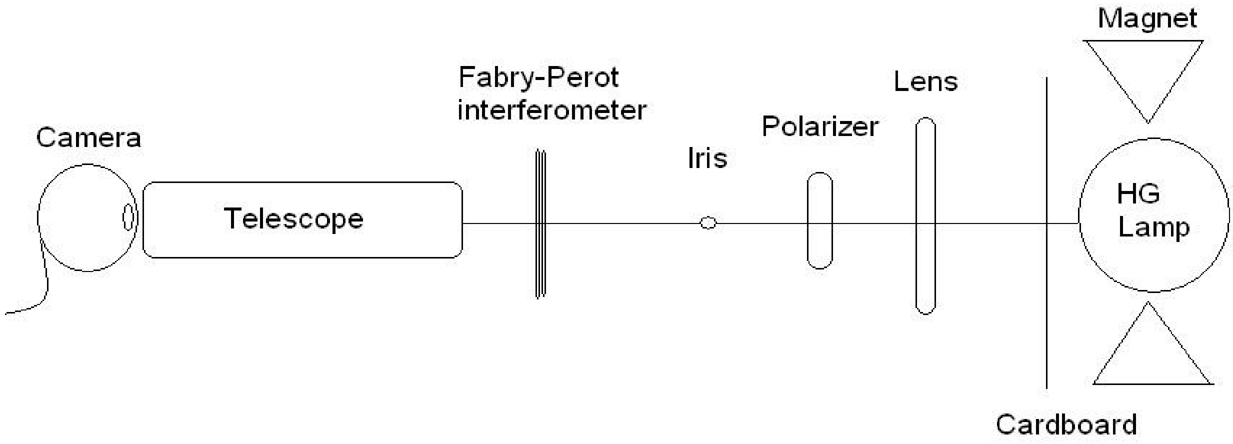
*3 components for Δm=0

We will use a polarizer to see only the three Δm=0 lines (which don't have the same polarization as the six Δm=+/-1 lines).

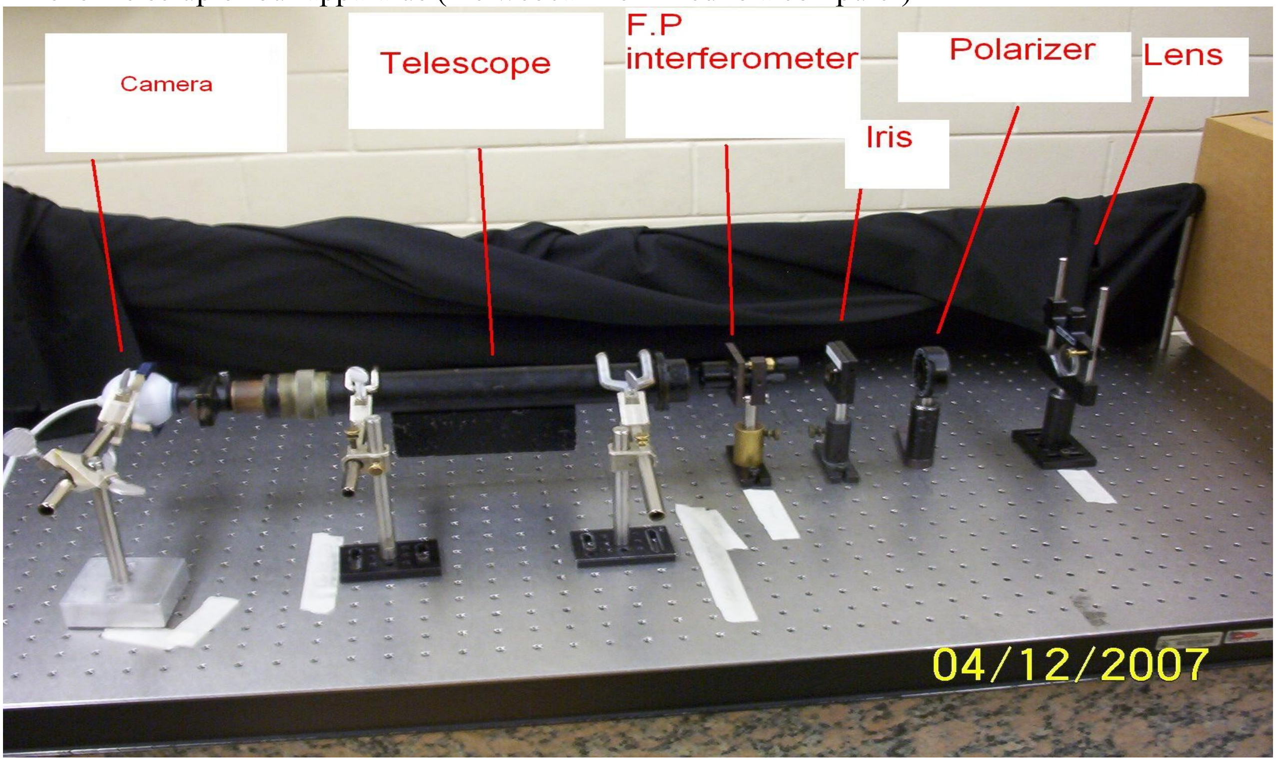
In our experiment, we observed the Zeeman effect for the 5461A Hg energy level.
Our first goal was to calibrate the electromagnet so that we could know to what magnetic fild corresponds a given amperage.
Our second goal was to measure the rate of change of the separation of the lines. As 1 line splits into 3, we will have an inner, a central and an outer ring. We wanted to see how they were moving apart as B was increased.
Our third goal was to check that the rate at which the lines moves apart from each other agrees with the theory : if the theory is correct, we should find that 2times the slope gives μ0/hc=4.67*10^-5 cm^-1/Gauss

Experimental Procedure

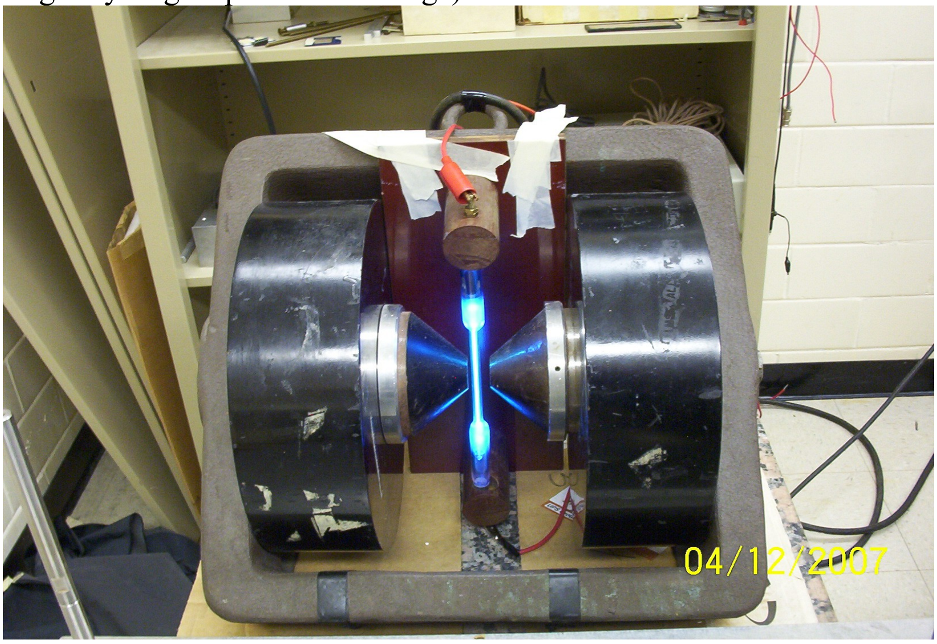
A schematic of our experiment :
The alignment is tricky, so we used a laser to make sure that everything was at the same height and properly aligned.
The light from the Hg lamp goes through the lens, which focalizes it on the Fabry-Perot interferometer. The Fabry-Perot sharpens the image and makes it circular, then it goes in the telescope, that we use to magnify the image. Due to a broken eyepiece, we are using a lens right in front of the camera instead of the original eypiece of the telescope.
This technique works perfectly, and, as we will see later, allowed us to view the whole image of the rings (more than 7rings at B=0) with a very good quality.
As in the experiment we are only concerned with the first ring (measurments could be done on the others but the splitting is more difficult to measure), to "zoom in" you just have to change the lens to another one.
It turned out that a converging lenses with a focal length between 200mm and 1000mm wer very good to get a whole image ; lenses with a shorter focal length (~10-50mm) were used to get a better view of the central rings and to make the measurments.



This is the setup of our apparatus (the webcam is linked to a computer)



The cardboard on the right is used to avoid any reflection : we only want the light directly produced by the Hg lamp to be sent on the lens.
A sheet was also used to cover the whole apparatus. As we saw on the images, it could greatly reduce reflections (especially reflection from external on the telescope bouncing back on the camera that were creating very bright spots on the image).



The mercury lamp and the electromagnet

The electromagnet ranges from 0 to 10 Amps, which turnd out to be between 0 and 15kGauss approximately.

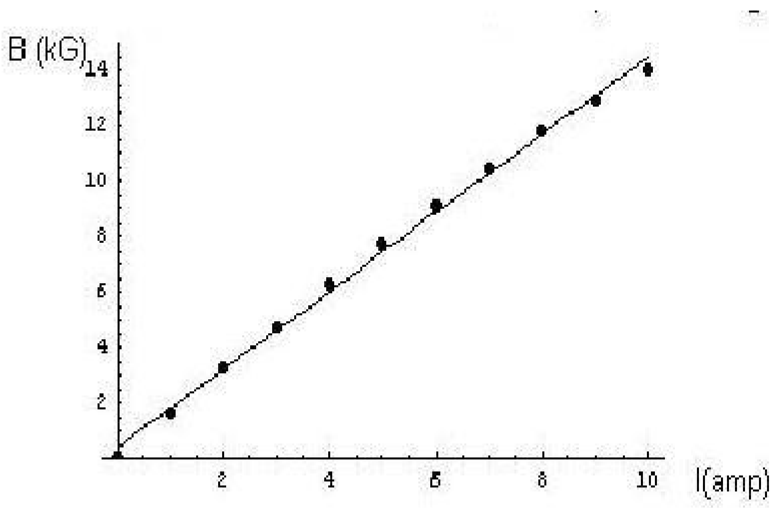
We are using a polarizer to select the spectral lines we want to see. As already explained in the introduction, we are selecting the 3 $\Delta m=0$ splitting. As it is not possible to see if the polarizer is in the good position when B=0 (rays are not polarized), you have to turn on the magnet to a few amps to be able to see some splitting, and then turn the polarizer to see clearly the 3 distinct lines.
That's one of the reason why using a webcam instead of a camera was very convenient : we were able to see very clearly on a computer screen what was going on, to tune perfectly the polarizer to get the 3 lines,... Being able to see every conscequence of what you are doing in live on a computer definitely turned out to be very convenient !

Experimental results & analysis

In this part are shown and discussed our experimental results.
Our first task was to calibrate the electromagnet, as everything is indicated in Amps and we want our data to be in Gauss (to be able to compare it with theory easily).

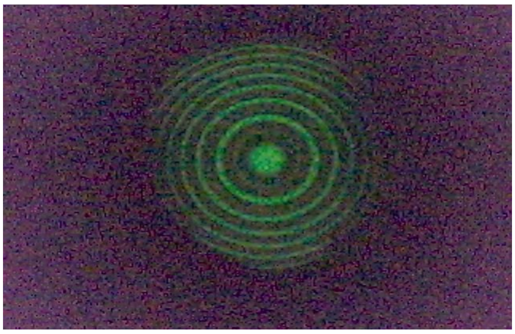
A/ Calibration of the electromagnet

Using a magnetic probe (which works using the Hall effect), we were able to measure the magnetic field between the two magnets (i.e. where the Hg lamp).



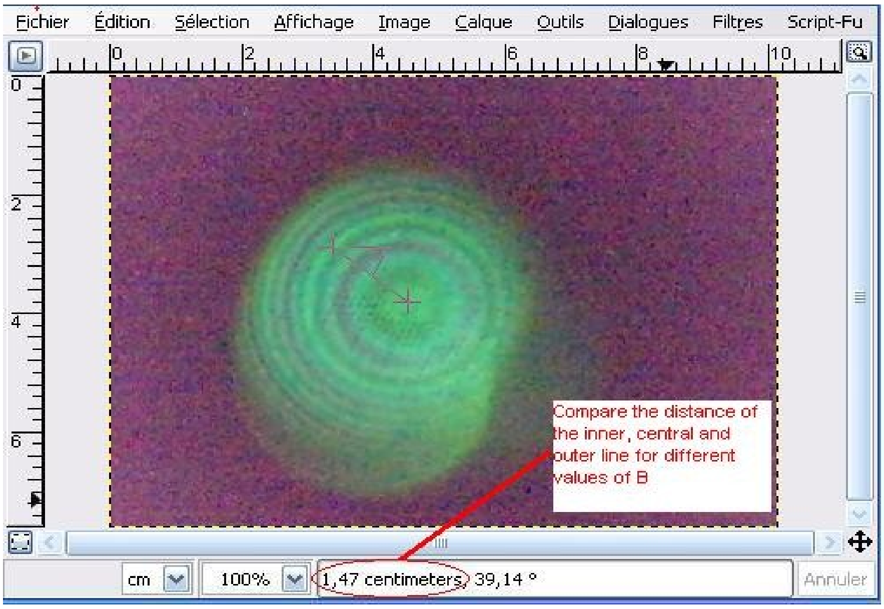
The relation turns out to be linear (as expected) : **B=1.41*I.** Our values seem higher than the ones from precedent results. It seems that they had not been using the probe properly and didn't put its surface perpendicular to the filed (B_measured is proportional to the flux going through the surface of the probe, therefore if the probe is parallel to B, B_measured will be 0).

B/ Observing the full rings splitting
Our next task was to observe the splitting. As indicated in the progress report, we had lots of troubles getting full images of the rings. We finally found out that replacing the eyepiece by an external lens, we could get really good images really easily. Our first images only show the first 2 rings, and barely the 3rd one. We are now able to get the 6 first rings perfectly and almost all the 7th one, which is a very good improvment (I don't think it is possible to see any more rings simply because of the size of the Fabry-Perot).

	B = 0 kGauss No lines split
	B = 6 kGauss Lines are starting to split

C/ Extracting the results

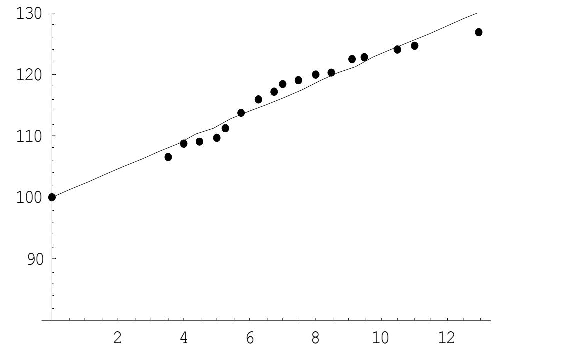
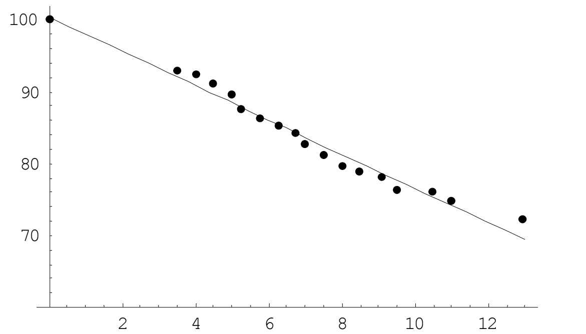
Our next task was of course to extract some results from those pictures.
This was done using gimp, as shown below :



First, you have to open the image using gimp.
Then, select the tool to measure 'angle and distances' and use it to measure the distance from the center of the rings to the inner one.
Repeat that for every image (i.e for different values of B) ; as the ring splits, you get 3 measurments for each image (for each value of B) : the radius of the inner ring, of the outer ring, and of the central ring.

Those two tables show our results, first a table to show the values, and then a plot showin very clearly the percentage of increase or decrease in the distance (the initial value being 100) as a function of the magnetic field B (in kGauss) :

B (kgauss)	Inner ring (% of initial distance)	Outer ring (% of initial distance)
3.50	93	106.6
4	92.4	108.9
4.50	91.1	109.1
5	89.6	109.7
5.25	87.5	111.2
5.75	86.3	113.9
6.28	85.2	116
6.75	84.2	117.1
7	82.8	118.3
7.5	81.1	119.1
8	79.7	120.1
8.5	78.9	120.3
9.1	78.1	122.4
9.5	76.2	122.9
10.46	76	124.2
11	74.7	124.7
12.96	72.2	127

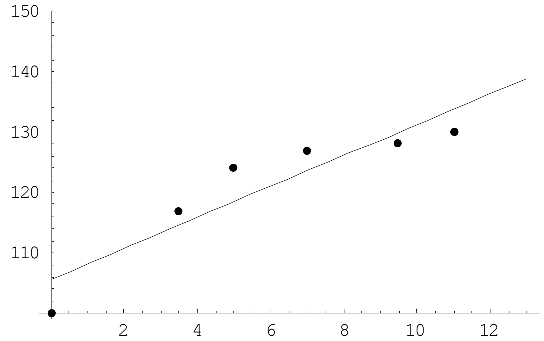
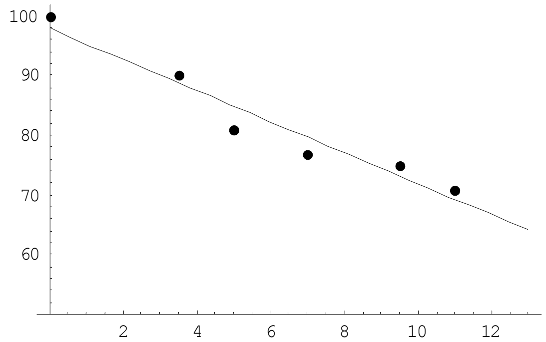
<table>
<tr><td>Outer ring</td><td>
</td><td>Best fit : 2.37721x+100</td></tr>
<tr><td>Central ring</td><td>-no graph-
Oscillates between 97.3 and 102.1.</td><td>As it should be constant, we get very quickly an idea of our experimental uncertainty (~2.8%)</td></tr>
<tr><td>Inner ring</td><td>
</td><td>Best fit : -2.31773x+100</td></tr>
</table>

Theory tells us that the two slopes, in absolute value, should add up tu 4.67*10^-5 cm^-1/Gauss.
The slopes here are percentage and in kGauss^-1, so :
(2.3772%+2.317%)*10^-3 = **4.70* 10^-5 cm^-1/Gauss** with a 2.8% uncertainty on that result.

D/ Violet lines

Using another filter, it is possible to make measurments for other rings than the green one :

B (kgauss)	Inner ring (% of initial distance)	Outer ring (% of initial distance)
3.50	90	117
5	81	124
7	77	127
9.5	75	128
11	71	130

<table>
<tr><td>Outer ring</td><td></td><td>Best fit : 2.5582x+100</td></tr>
<tr><td>Central ring</td><td>-no graph-
Oscillates between 94 and 106.4.</td><td>As it should be constant, we get very quickly an idea of our experimental uncertainty (~7%)</td></tr>
<tr><td>Inner ring</td><td></td><td>Best fit : -2.5909x+100</td></tr>
</table>

The slopes here are percentage and in kGauss^-1, so :
(2.59%+2.55%)*10^-3 = **5.14* 10^-5 cm^-1/Gauss** with a 7% uncertainty on that result.
We should find 4.67, which is at the limit of our experimental error.

Summary and Conclusion

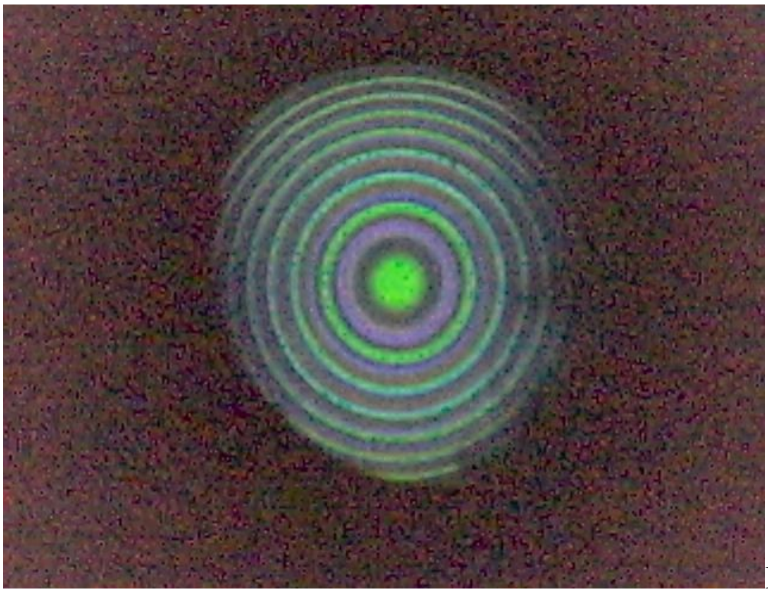
In the progress report, I had listed the major problems we had :
*The rings are still too dim
*Our optical setup doesn't seem to be very good if we want a full picture of the diffraction patter.
*We have troubles fixing the senior lab camera on the telescope, therefore the webcam is really convenient to have immediate images and datapoints.

We greatly improved the brightness of the image and its size (seeing all the rings) by changing the eyepiece and putting an external lens directly in front of the camera.

The accuracy of our measurments was of 5% and it is now of 2.8% (by taking more datapoints and making sharper images allows us to make better measurments on gimp) on the green rings. Our measurments were in very good agreement with the theory.

What we wanted to do, but turned out to be more diffuclt than expected, was to make intensity measurments ; as gimp didn't seem to work very well on that (the results I got did not make any sense ; it seems that it depends more on which pixel you selected that the actual evolution of intensity that you can measure...), we decided to make distance measurments on other rings : violet rings.
It turned out to be a difficult task : the background noise is stronger than for the green lines, and they are dimmer ; however, our results were still in agreement with theory.

More pictures


Full fings with no filter ; B=0


Blue rings ; B=0


Blue rings ; B=8kGauss

References

* http://en.wikipedia.org/wiki/Zeeman_effect

* http://galileo.phys.virginia.edu/classes/317/zeeman/zeeman.html

* Introduction to Quantum Mechanics - David J. Griffiths

* Previous lab reports