

Introduction

In 1896, the Dutch physicist Pieter Zeeman discovered that, in a magnetic field, the spectral lines of atoms split into a number of closely spaced lines. This is called the (anomalous) Zeeman Effect. The Zeeman Effect was very important in the development of quantum mechanics, and especially the development of quantum chemistry. It provides direct evidence that the orbital angular momentum of the atoms (the magnetic moment of atoms) is quantized. The number of lines that a single spectral line splits into allows the determination of the total angular momentum of the energy levels involved in the transition that produced the spectral line.



In this experiment, the student observes the interference pattern from a Fabry-Perot interferometer that results from the 546.1 nanometer (nm) spectral line of a mercury lamp that is immersed in a uniform magnetic field. The magnetic field is varied from zero to almost 1 tesla (T). Initially, the light is viewed along an axis perpendicular to the magnetic field axis. A polarizer is used to show the three lines due to light that is polarized parallel to the magnetic field axis and to show the six lines that are polarized perpendicular to the magnetic field axis. The interference pattern may also be observed along the magnetic field axis in the case where the light is circularly polarized. The included CMOS (complementary metal-oxide semiconductor) camera sends the interference pattern to a computer where the PASCO Capstone software (included) records and analyzes the pattern. Data from the pattern that is polarized perpendicular to the magnetic field axis is then used to calculate the Bohr magneton, the intrinsic magnetic dipole moment of an electron in the ground state. (All atomic magnetic moments are integral or half-integral multiples of the Bohr magneton.)

Background Information

Pieter Zeeman observed the “anomalous Zeeman Effect” in 1896 and shared the Nobel Prize in Physics in 1902 with his teacher, Hendrik Lorentz, who observed the “normal Zeeman Effect”.

In the Zeeman-Lorentz explanation, the electron moving in a magnetic field experiences a Lorentz force that slightly changes the orbit of the electron and hence its energy. The change in energy depends on the orientation of the orbit. If the plane of the orbit is perpendicular to the magnetic field, then the change in energy, ΔE , is either positive or negative depending upon whether the motion of the electron is clockwise or counter-clockwise. If the field lies in the plane of the orbit, the net Lorentz force is zero (averaged over one orbit) and the change in energy is zero. This reasoning thus predicts that the spectral emission line will split into three lines when a field is applied. More detailed arguments predict the same result for an arbitrary orientation of the plane of the orbit. A more modern argument, not using forces, can be made by noting that the orbital motion of the electron (angular momentum L) produces a magnetic moment.

The Zeeman Effect is very important in applications such as nuclear magnetic resonance spectroscopy, electron spin resonance spectroscopy, magnetic resonance imaging (MRI), and Mössbauer spectroscopy.

Theory

The 546.1 nm green spectral line in mercury is due to a transition of an electron from a $^3S_1(6s7s)$ energy level to a $^3P_2(6s6p)$ level as shown (see Figure 1). The $(6s7s)$ notation means that mercury has two valence electrons; one in a 6s orbital and one in a 7s orbital. The orbital angular momentum quantum number for an S state is $L = 0$ and for a P state is $L = 1$. Mercury has two valence electrons which couple here to give a spin quantum number $S = 1$ (called triplet states and annotated with the superscript 3). This results in total angular momentum quantum numbers for the states of $J = 1$ and $J = 2$ respectively. The J values are indicated by the subscripts. In the presence of a magnetic field, each level splits into $2J + 1$ closely spaced levels. NOTE:

Figure 1 is not to scale. The splitting between the $2J + 1$ levels is much less ($\sim 10^{-5}$) than the splitting between the original two levels.

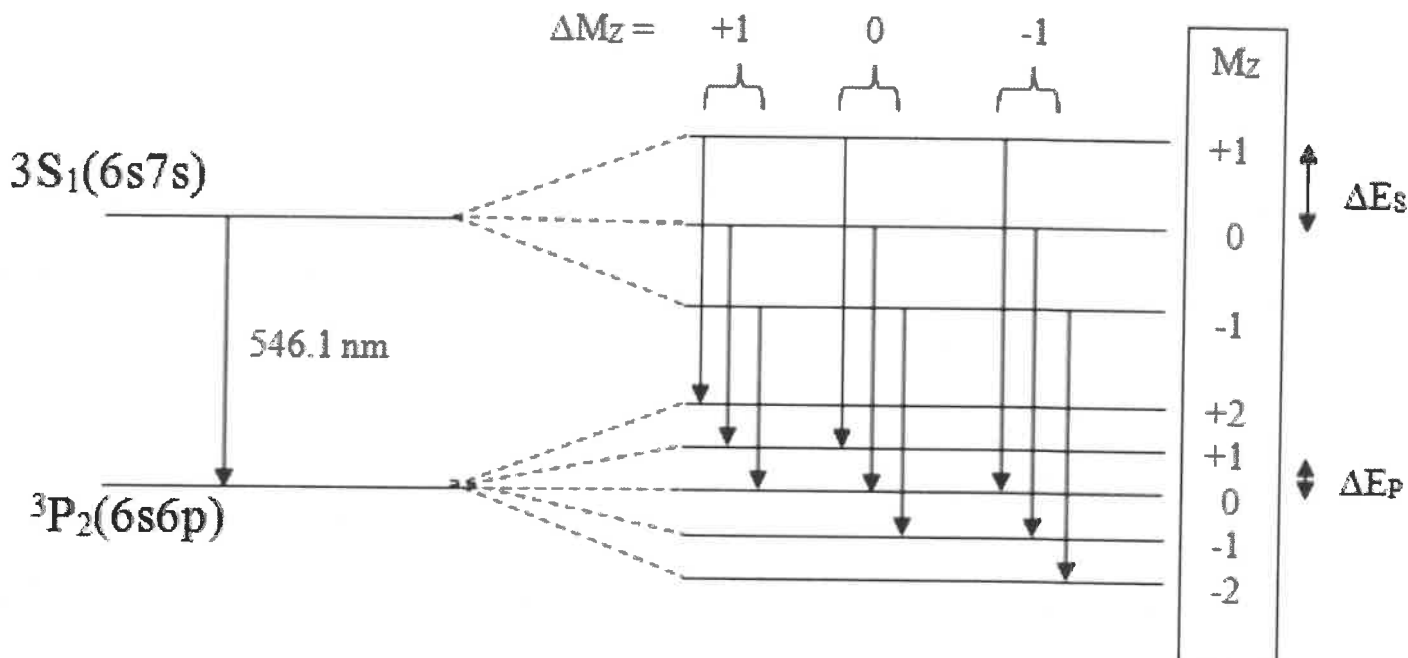


Figure 1: Energy Levels for 546.1 nm Mercury Spectral Line

In the diagram, M_Z is the projection of the orbital angular momentum on the z axis. Selection rules allow transitions between states where $\Delta M_Z = +1, 0, -1$. The transitions where $\Delta M_Z = 0$ produce photons that are polarized parallel to the magnetic field axis and the spectral lines are more intense. These are the lines that will be used for measurement. The $\Delta M_Z = +1, -1$ transitions produce photons polarized perpendicular to the field axis. Using a polarizer to eliminate the $\Delta M_Z = +1, -1$ lines makes it easier to do measurements.

Let E_S be the energy of the un-split ($B = 0$) 3S_1 state. This is exactly equal to the $M_Z = 0$ energy level when the field is not zero. Let ΔE_S be the shift in energy from the $M_Z = 0$ S state when $B \neq 0$. Similarly for E_P and ΔE_P . The energy shift is determined by the component of the magnetic moment of the atom along the magnetic field and is given by Equation 1:

$$\Delta E = M_Z g_L B \mu_B \quad \text{Eqn. 1}$$

where g_L is the Landé g factor and μ_B is the Bohr magneton. Recall that the Bohr magneton is the elemental unit of magnetic moment (analogous to electron charge, e , being the elemental unit of electric charge). All atomic magnetic moments are integer or half-integer multiples of μ_B , the Bohr magneton. The Bohr magneton is the classical magnetic moment that an electron in the first Bohr orbit of hydrogen would possess. Such an electron may be treated as a tiny current loop with current:

$$i = \frac{e}{T} = \frac{e}{\left(\frac{2\pi r_B}{v}\right)} = \frac{ev}{2\pi r_B} = \frac{e}{2\pi r_B} \left(\frac{h}{2\pi r_B m}\right) = \frac{eh}{m(2\pi r_B)^2}$$

where T is the time for one orbit of the electron, v is the speed of the electron in the first Bohr orbit, m is the electron mass, and r_B is the Bohr radius. The magnetic moment of a single current loop is given by Equation 2:

$$\mu_B = iA = \frac{\pi r_B^2 eh}{m(2\pi r_B)^2} = \frac{eh}{4\pi m} = 9.274 \times 10^{-24} \text{ (J/T)} \quad \text{Eqn. 2}$$

where A is the area of the current loop. Note that this derivation is not quantum mechanically correct and gives the wrong value for the first Bohr orbit of hydrogen, but the value for the Bohr magneton is correct.

The Landé g factor is:

$$g_L = 1 + \frac{J(J+1) + S(S+1) - L(L+1)}{2J(J+1)}$$

For both states, the two valence electrons couple to give $S = 1$. Then $L = 0$ for an S state and $L = 1$ for a P state. The total angular momentum is $J = 1$ for the S state and $J = 3$ for the P state. This gives:

$$g_S = 2 \text{ (for } ^3S_1 \text{) and } g_P = 3/2 \text{ (for } ^3P_2 \text{)}$$

Equation 1 then yields Equation 3:

$$\Delta E_S = 2B\mu_B \text{ and } \Delta E_P = (3/2)B\mu_B \quad \text{Eqn. 3}$$

where $M_Z = \pm 1$ for the states of interest.

Looking at the $\Delta M_Z = 0$ transitions, the $M_Z = 0$ to $M_Z = 0$ transition will result in the same $\lambda = 546.1$ nm wavelength as the $B = 0$ case. For the $M_Z = +1$ to $M_Z = +1$ transition,

$$h\nu_+ = (E_S + \Delta E_S) - (E_P + \Delta E_P) \quad \text{Eqn. 4}$$

For the $M_Z = -1$ to $M_Z = -1$ transition,

$$h\nu_- = (E_S - \Delta E_S) - (E_P - \Delta E_P) \quad \text{Eqn. 5}$$

Subtracting the two equations and using Equation 3 yields:

$$h(\nu_+ - \nu_-) = 2(\Delta E_S - \Delta E_P) = B\mu_B \quad \text{Eqn. 6}$$

Converting to wavelengths:

$$h \left(\frac{c}{\lambda_+} - \frac{c}{\lambda_-} \right) = \frac{hc(\lambda_- - \lambda_+)}{(\lambda_-)(\lambda_+)} = \frac{hc\Delta\lambda}{\lambda^2} = B\mu_B$$

$$\Delta\lambda = \frac{B\mu_B\lambda^2}{hc} \quad \text{Eqn. 7}$$

where $(\lambda_-)(\lambda_+) = \lambda^2$ to extremely good approximation.

Fabry-Perot Interferometer

The interferometer consists of two partially reflective optically flat plates of glass (called the elaton) that are parallel to a high degree of accuracy. The spacing between the plates of glass, d , is 1.995 millimeters (mm). The collimating lens causes rays of light that originate on the optical axis to come in parallel to the optical axis. However, the source is not a point source and rays that originate on the source at a position that is at a small angle, θ , from the optical axis seen from the collimating lens will reach the interferometer nearly parallel and at the same angle θ from the optical axis as shown in Figure 2.

Ray 1 is partially reflected at points A and B (the transmitted rays are not shown). It then interferes with Ray 2, since they both follow the same path after point B. Ray 1 travels along a path that is longer than Ray 2 by:

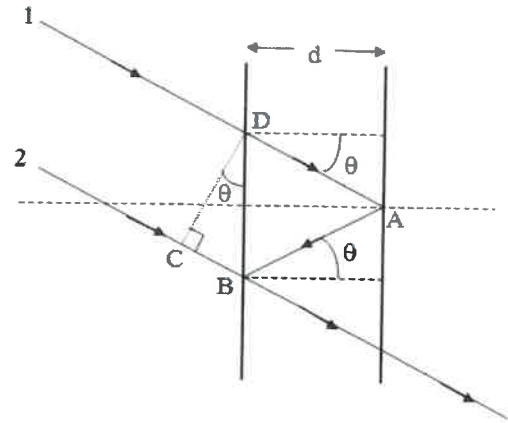


Figure 2: Fabry-Perot Geometry

$$\Delta l = DA + AB - CB = \frac{d}{\cos\theta} + \frac{d}{\cos\theta} - 2d(\sin\theta)\tan\theta = \frac{2d}{\cos\theta} - \frac{2d\sin^2\theta}{\cos\theta}$$

$$\Delta l = \frac{2d(1 - \sin^2\theta)}{\cos\theta} = 2d\cos\theta = 2d\left(1 - \frac{\theta^2}{2}\right) \quad \text{Eqn. 8}$$

where only two terms in the Taylor series expansion ($\cos\theta = 1 - \theta^2/2! + \dots$) are kept because θ is very small. The two rays will be in phase and produce an interference maximum if and only if the following:

$$\Delta l = (n + k)\lambda, \text{ where } k = 0, 1, 2, 3, \dots$$

and n is a large integer approximately equal to $2d/\lambda$. Equation 8 then yields:

$$2d\left(1 - \frac{\theta_k^2}{2}\right) = (n + k)\lambda \text{ where } k = 0, 1, 2, 3, \dots \quad \text{Eqn. 9}$$

where θ_k is the angle to the k th ring in the interference pattern (see Figure 3 where $k = 0$ for the innermost ring). Here the negative sign must be chosen for the $(n - k)$ term since as k increases, the left of Equation 9 decreases. Thus, the right hand side must decrease as k increases. Note that the Fabry-Perot interferometer can measure much smaller changes in λ because λ is multiplied by a large n resulting in a much larger change in θ . This increases its resolution by roughly $2d/\lambda \sim 10^4$.

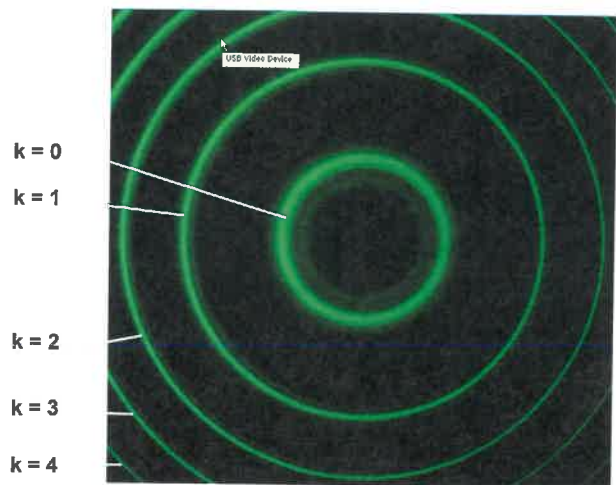


Figure 3: B = 0 Pattern

Final Theory

The camera has a focal length, f . Since the angle is small, $\theta_k = R_k/f$ to a very good approximation and Equation 9 becomes:

$$2d \left(1 - \frac{R_k^2}{2f^2} \right) = (n - k)\lambda \quad \text{Eqn. 10}$$

We do not know the effective focal length, f , but we can use the $B = 0$ pattern shown in Figure 3 to evaluate it. For the $k = 0$ ring, Equation 10 becomes:

$$2d \left(1 - \frac{R_0^2}{2f^2} \right) = n\lambda \quad \text{Eqn. 11}$$

Subtracting Equation 10 from Equation 11 gives:

$$\frac{d}{f^2} (R_k^2 - R_0^2) = k\lambda$$

$$\frac{d}{f^2} \lambda = C_0 = \frac{k}{(R_k^2 - R_0^2)} \quad \text{Eqn. 12}$$

By measuring the R values in the $B = 0$ pattern, the constant C_0 can be determined to better than 0.5%.

With an applied magnetic field, through a polarizer parallel to the magnetic field, the spectral lines each split into three lines. The center line in each triplet has the same wavelength as for the $B = 0$ case. The inner ring with radius R_{k-} has a slightly longer wavelength and the outer ring (R_{k+}) has a slightly shorter wavelength. Equation 10 is still valid and yields the following:

$$2d \left(1 - \frac{R_{k-}^2}{2f^2} \right) = (n - k)\lambda_- \quad \text{where } k = 0, 1, 2, 3, \dots$$

and

$$2d \left(1 - \frac{R_{k+}^2}{2f^2} \right) = (n - k)\lambda_+ \quad \text{where } k = 0, 1, 2, 3, \dots$$

Subtraction yields:

$$\left(\frac{d}{f^2} \right) (R_{k+}^2 - R_{k-}^2) = (n - k)(\lambda_- - \lambda_+) \quad \text{where } k = 0, 1, 2, 3, \dots$$

Using Equation 7 and the excellent approximation $(n - k)\lambda = n\lambda = 2d$ yields:

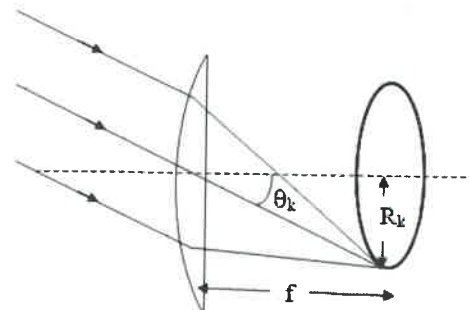


Figure 4: Camera Geometry

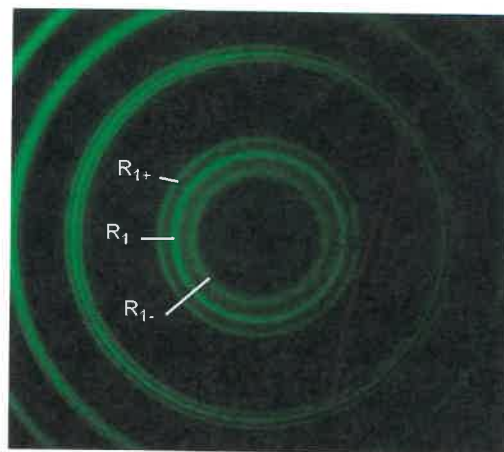


Figure 5: $B \neq 0$ Pattern, Triplets

$$\left(\frac{d}{f^2}\right)(R_{k+}^2 - R_{k-}^2) = (n - k) \left(\frac{B\mu_B \lambda^2}{hc}\right) = \frac{B\mu_B \lambda 2d}{hc}$$

where h is Planck's constant and c is the speed of light. Solving for the Bohr magneton, μ_B , yields:

$$\mu_B = \left(\frac{C_0 hc}{2dB}\right)(R_{k+}^2 - R_{k-}^2) \quad \text{where } k = 0, 1, 2, 3... \quad \text{Eqn. 13}$$

where C_0 is the constant determined previously (Equation 12) and $d = 1.995$ mm is given for the separation of the Fabry-Perot parallel plates (called the 'etalon').

Setup

CAUTION: Do not look with your naked eye at the pen type mercury lamp when it is lit. The mercury lamp has bright emission lines in the ultraviolet part of the spectrum which can damage your eyes permanently. Look at the lit mercury lamp through the Interferometer/Filter Assembly.

Position the Electromagnet

- NOTE: A spirit level ("bubble" level) and protractor are recommended for use when aligning the electromagnet.
1. Place the electromagnet in a convenient location on a level surface. NOTE: The electromagnet weighs 72.5 pounds! If possible, set aside a permanent place for the electromagnet in the laboratory so it will not need to be moved. Arrange the electromagnet so that the locking thumbscrew on the base points away from the direction where the track will be placed (see Figure 6).

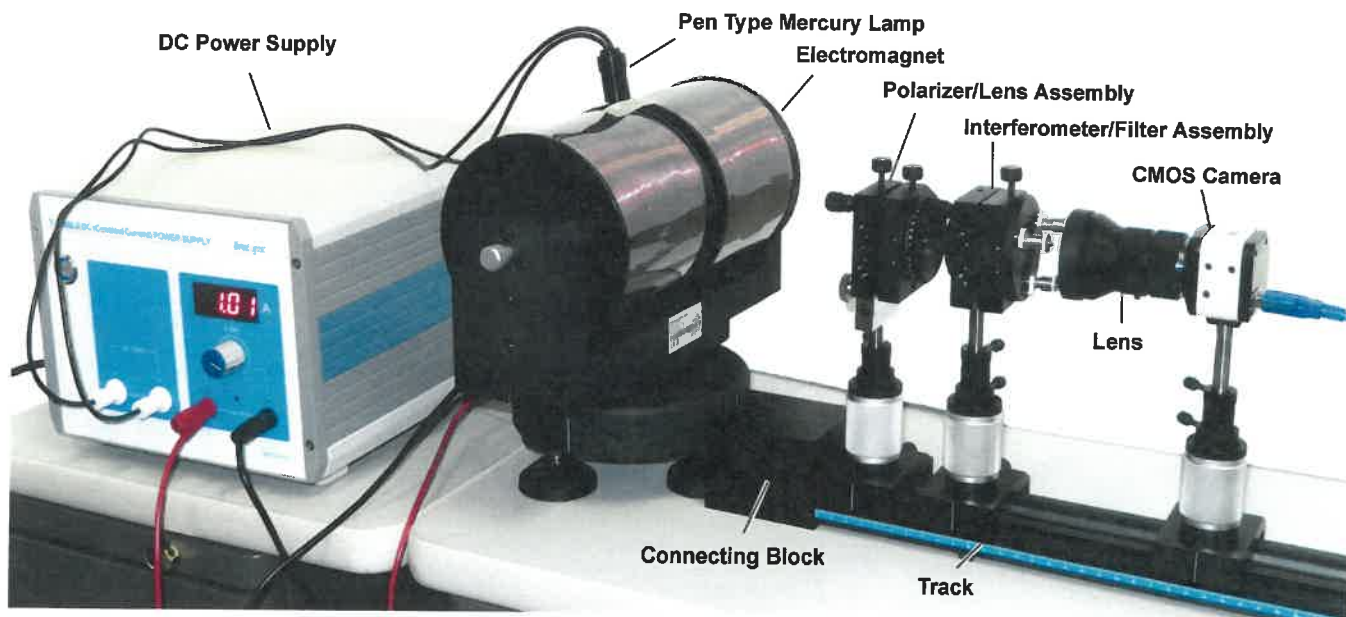


Figure 6: Setup

2. Place a level on the base of the electromagnet. If necessary, adjust the screw feet under the base. Turn the level ninety degrees and adjust the base again, if necessary.

- Attach the connection block to the track and place the curved end of the connection block against the electromagnet base. Loosen the locking screw on the base of the electromagnet. From the end of the track away from the electromagnet, look along the center of the track at the electromagnet. Turn the electromagnet so that the gap in the electromagnet is parallel to the track. (In other words, the electromagnet will be perpendicular to the track.) NOTE: Use a protractor to check the alignment of the electromagnet with the white indicator mark on the connection block. Tighten the locking screw.

Setup the Power Supply

The SE-9656 TUNABLE DC (Constant Current) POWER SUPPLY supplies power to the pen-type mercury lamp and the electromagnet (SE-9655). The output for the mercury lamp is 1500 V (volts) AC (alternating current) with a maximum current of 145 mA (milliamperes). The output for the electromagnet is controlled by the Current Adjustment Knob and the maximum output is 36 V.

- NOTE: The electromagnet has a maximum input current of 6 A and a maximum magnetic intensity of 1.2 T (tesla).

- Check the LINE VOLTS setting on the back of the Power Supply. Select the right setting based on your AC voltage.
- Connect the power cord to the AC POWER CORD port. Plug the cord into a grounded AC electrical outlet.

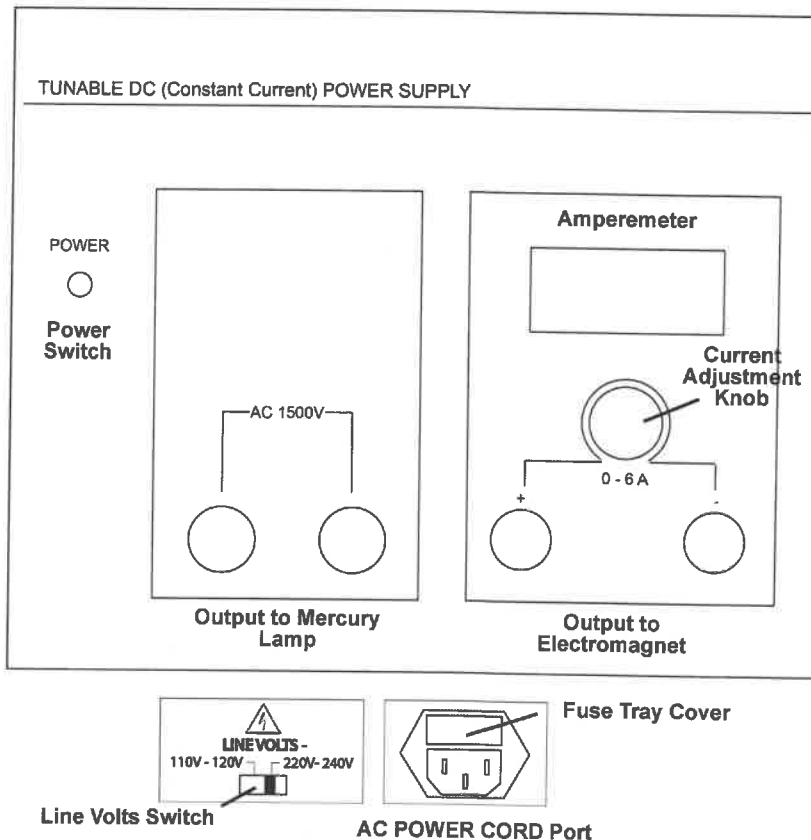
NOTE: The power supply fuse is located in a plastic tray in the top part of the AC POWER CORD port. The tray also holds a spare fuse. Before opening the fuse tray, disconnect the power cord. Always replace a fuse with a new fuse of the same type (Fuse Type 250 V T5A).

- Power Switch: Turns the power in the instrument ON or OFF.
- Current Adjustment Knob: Sets the current through the electromagnet.
- Amperemeter: Displays the current.

Insert the Mercury Lamp into the Electromagnet

CAUTION: The next step involves handling the pen type mercury lamp. Do not touch the glass envelope of the mercury lamp. Oil and moisture from your fingers will degrade the lamp's performance.

- Insert the pen type mercury lamp into the holder between the poles of the electromagnet. The glass envelope should be centered between the pole pieces.



NOTE: A good way to check that the mercury lamp is centered properly is to remove the axial iron core plug (with the knurled silver knob) from one end of the electromagnet. Next, shine a light-emitting diode (LED) flashlight through the hole and look between the poles of the electromagnet to see that the light is shining on the mercury lamp and that the lamp is centered. Remember to replace the axial iron core plug.

2. Measure the height of the center of the axial iron core plug as shown in Figure 7 and record the height.

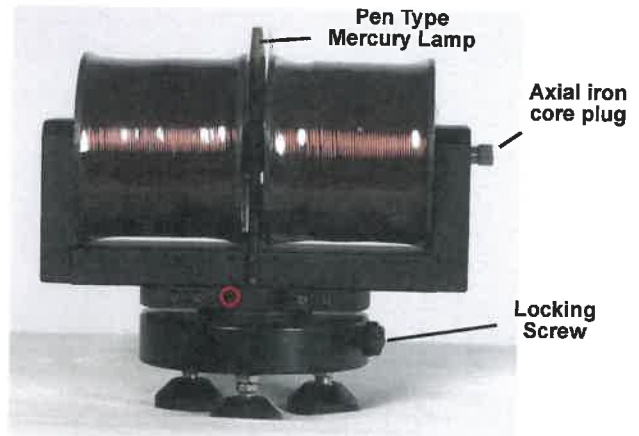
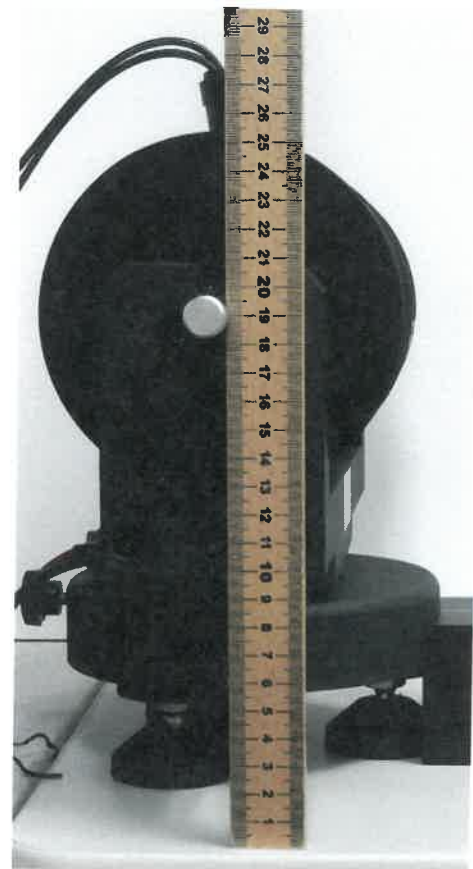


Figure 7: Electromagnet Setup



Measure the height of the axial iron core

Mount the Polarizing Filter and Collimating Lens

1. Assemble the polarizing filter and collimating lens on the precision kinematic optical mount that has the one-dimensional (horizontal) adjustable holder. Put the collimating lens on the side of the optical mount that has the X - Y Adjustment Screws
2. Tighten the set screw that holds the collimating lens, but leave the polarizer set screw loose so that the polarizer can be rotated.
3. Complete the assembly by fastening a post to the bottom of the horizontal adjustable holder, and then inserting the post into one of the adjustable post holders. Screw the adjustable post holder into one of the optical carriers.
4. Attach the optical carrier of the polarizer/lens assembly to the track so that the collimating lens faces the electromagnet (see Figure 8).

Align the Polarizer/Lens Assembly

5. The optical axis of the polarizer/lens should be aligned with the middle of the mercury lamp when it is mounted in the electromagnet. To align the assembly, first loosen the two thumbscrews on the adjustable post holder.
6. Hold a book vertically against the base of the optical carrier. Rotate the assembly so that both of the black X - Y adjustment screws on the collimating lens side of the assembly both touch the book. (see Figure 9).



Figure 9: Align the Assembly

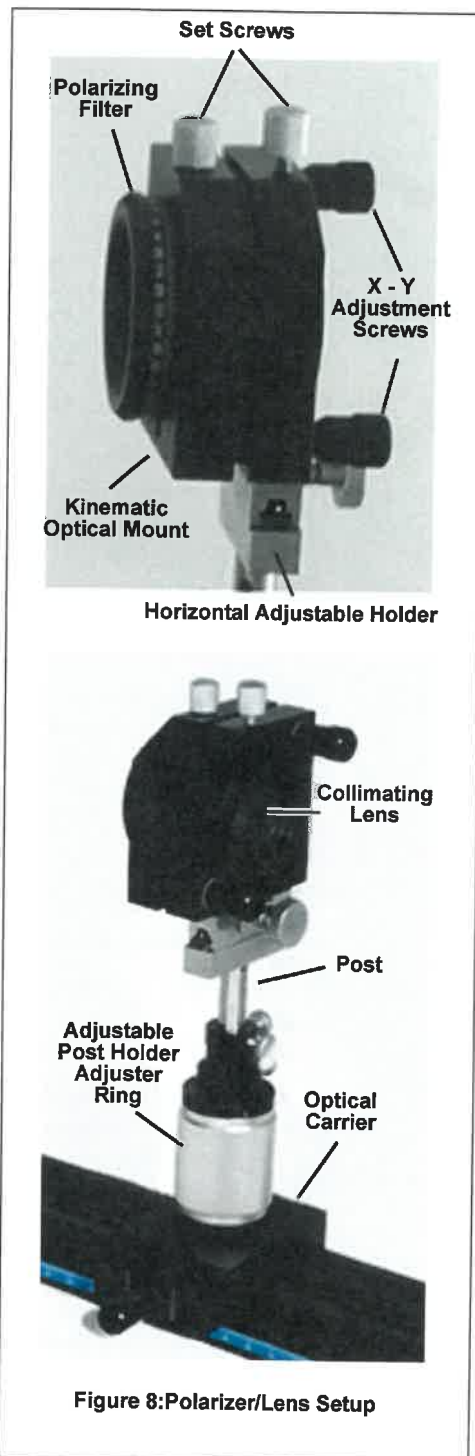


Figure 8: Polarizer/Lens Setup

7. Once the assembly is aligned, tighten the upper thumbscrew on the adjustable post holder.
8. Using the silver adjuster ring on the adjustable post holder, adjust the height of the polarizer/lens assembly until its center, indicated by the white horizontal mark on the polarizer side of the assembly, is at the height measured for the center of the axial iron core plug. Tighten the lower thumbscrew on the adjustable post holder.

9. Adjust the two black X - Y adjustment screws on the collimating lens side of the assembly so the polarizer is roughly parallel to the collimating lens plane. Do this by adjusting the gap between the collimating lens holder and the polarizer holder. (The polarizer is then roughly parallel to the axis of the electromagnet.)
10. Rotate the polarizer so that the 90 degree mark on the rim of the polarizer is aligned with the white indicator mark at the top of the assembly.
11. Position the polarizer/lens assembly at the 30 cm mark on the track.
12. The glass envelope of the pen-type mercury lamp has wires up two sides. Looking through the lens, rotate the mercury lamp in its holder until the wires are out of the line of sight. NOTE: It helps to back-light the mercury lamp with a flash-light (see Figure 10).

Mount the Interferometer and Filter

1. Screw the 546.1 nm (nanometer) filter onto one end of the interferometer. Put the interferometer/filter assembly into the second precision kinematic optical mount (see Figure 11).
2. Complete the assembly by fastening a post to the bottom of the kinematic optical holder, and then inserting the post into a second adjustable post holder. Screw the adjustable post holder into one of the optical carriers.
3. Mount the optical carrier of the interferometer assembly in the middle the track so that the three adjustment screws on the interferometer face away from the electromagnet.
4. Adjust the interferometer assembly in a manner similar to adjusting the polarizer/lens assembly. First, loosen the two thumbscrews on the adjustable post holder. Raise the interferometer assembly so it is approximately at the same height as the lens assembly.
5. Hold a book vertically against the base of the optical carrier. Rotate the assembly so that both of the black X - Y adjustment screws on the filter side of the assembly touch the book as shown before. Tighten the upper thumbscrew.
6. Position the interferometer assembly on the track so that the white indicator mark on the optical carrier is at 40 cm on the track scale.
7. Using the silver adjuster ring on the adjustable post holder, adjust the height of the assembly until its center (as indicated by the horizontal white mark on the kinematic optical holder) is at the height of the axial iron core plug measured before. Tighten the lower thumbscrew.
8. Adjust the two black X - Y adjustment screws on the filter side of the assembly so that the interferometer is roughly parallel to the filter. Do this by adjusting the gap between the interferometer part of the holder and the filter part of the holder.

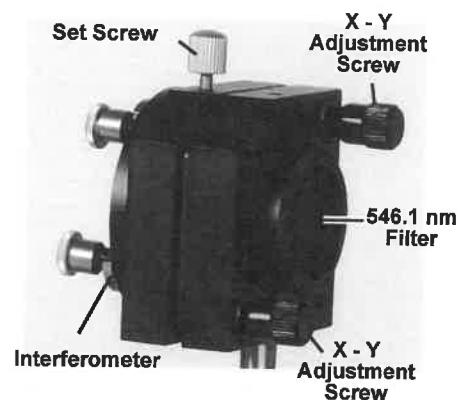


Figure 10: Interferometer/Filter Assembly

Connect Power to the Mercury Lamp and the Electromagnet

1. Plug the white plugs from the mercury lamp into the 1500 V outputs on the DC power supply.
2. Plug the red and black connecting cords between the red and black jacks on the electromagnet and the red and black output ports on the power supply. (The next step is to turn on the power supply.)

CAUTION: Do not run the power supply at 3 A for more than 30 minutes or at 4 A for more than two minutes. Heat generated by the electromagnet will cause a built-in thermal switch to open, which will turn off

the electromagnet. If the switch opens, it will be necessary to wait for it to reset by itself before proceeding.

- Turn on the power supply and adjust the current to 0.00 A. Allow the mercury lamp to warm up for a few minutes until it reaches full brightness.

Check the Alignment

NOTE: Because the filter blocks all but the 546.1 nm spectral line, there is no ultraviolet light that passes through the interferometer/filter assembly. Therefore, it is safe to look through the interferometer at the mercury lamp while it is on.

- Look through the interferometer at the mercury lamp. You should see a green “bull’s-eye” that is centered in the interferometer circle (see Figure 12).
- If the image is not centered, use the knob on the horizontal adjustable holder of the lens assembly to move the assembly left or right, or use the silver adjuster ring to adjust the vertical height of the interferometer to move it up or down.

- NOTE:** The background of the “bull’s-eye” interference pattern viewed through the interferometer may not be black due to scattered light. The best solution to this problem is to dim the room lights

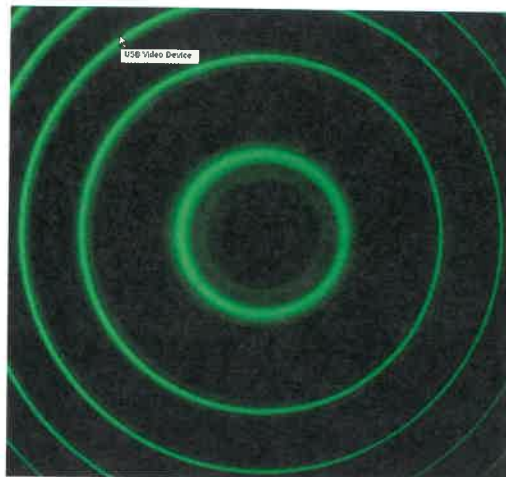


Figure 11: “Bull’s-eye” Image

CMOS Camera and Lens

- Carefully screw the 50 mm (millimeter) camera lens to the front of the CMOS camera (see Figure 13). Thread the remaining post into the bottom of the camera. Mount the post in the remaining adjustable post holder. Screw the adjustable post holder onto the third optical carrier.
- Mount the camera/lens assembly on the track. Position the optical carrier at the end of the track so that the white indicator mark on the carrier is near the 57 cm on the track.
- Adjust the camera/lens so that it is parallel to the track and the center of the camera lens is at the same height as the other two assemblies.

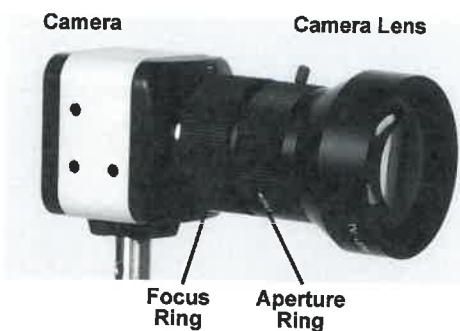


Figure 12: Camera/Lens Assembly

- NOTE:** If the background of the “bull’s-eye” interference pattern viewed through the interferometer is not black due to scattered light, the camera can be moved closer to the interferometer. However, this may cause the illumination of the pattern viewed through the camera to be non-uniform. A better solution is to dim the room lights and keep the camera optical carrier at the 57 cm mark.

Experiment Procedure

Use the Included PASCO Capstone Workbook File or the Microsoft Word File...

NOTE: The SE-9654 Zeeman Effect Experiment includes the ZEEMAN EFFECT Flash Drive that contains three folders: Zeeman Capstone Files, Zeeman Graphics, and Zeeman Word Files. One of the Zeeman Capstone files (Zeeman Effect.cap) is already configured for use in the Zeeman Effect experiment. The setup of the software has been done. Follow the instructions on each page of the Capstone workbook in order to record, measure, and analyze the data.

... or, Setup the Experiment in the PASCO Capstone Software Program

NOTE: The following pages describe the step-by-step process for configuring a PASCO Capstone workbook file for the Zeeman Effect Experiment, including the setup of displays, calculations, and data tables. Use these pages if you want to learn more about the setup of the Capstone software and the creation of the calculations used to analyze the data.

1. Open the PASCO Capstone program.

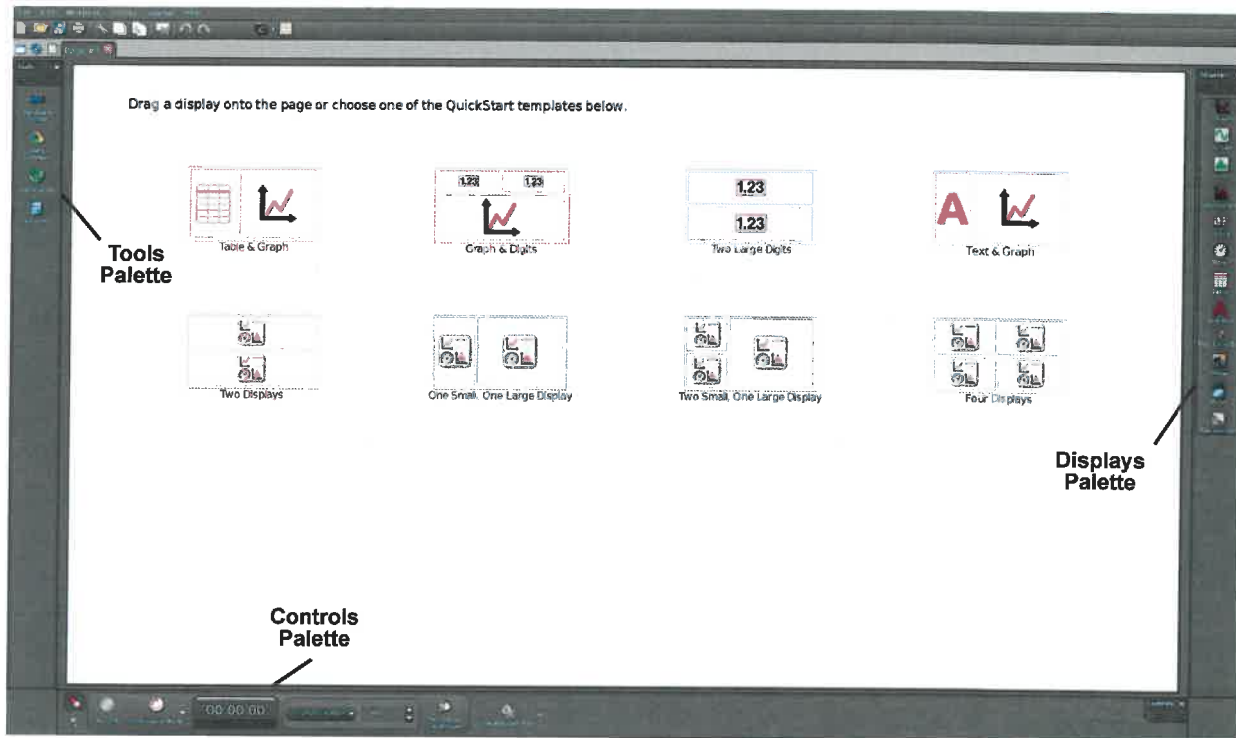


Figure 13: PASCO Capstone

- The workbook page has a Tools Palette to the left side, a Displays Palette to the right side, and a Controls Palette on the bottom.
2. Plug the USB connector cable from the camera into a USB port on the computer.

Zeeman Effect Experiment ... or, Setup the Experiment in the PASCO Cap-

3. Double click the Movie icon () on the Displays Palette at the right side of the workbook to open a four-part Movie display.

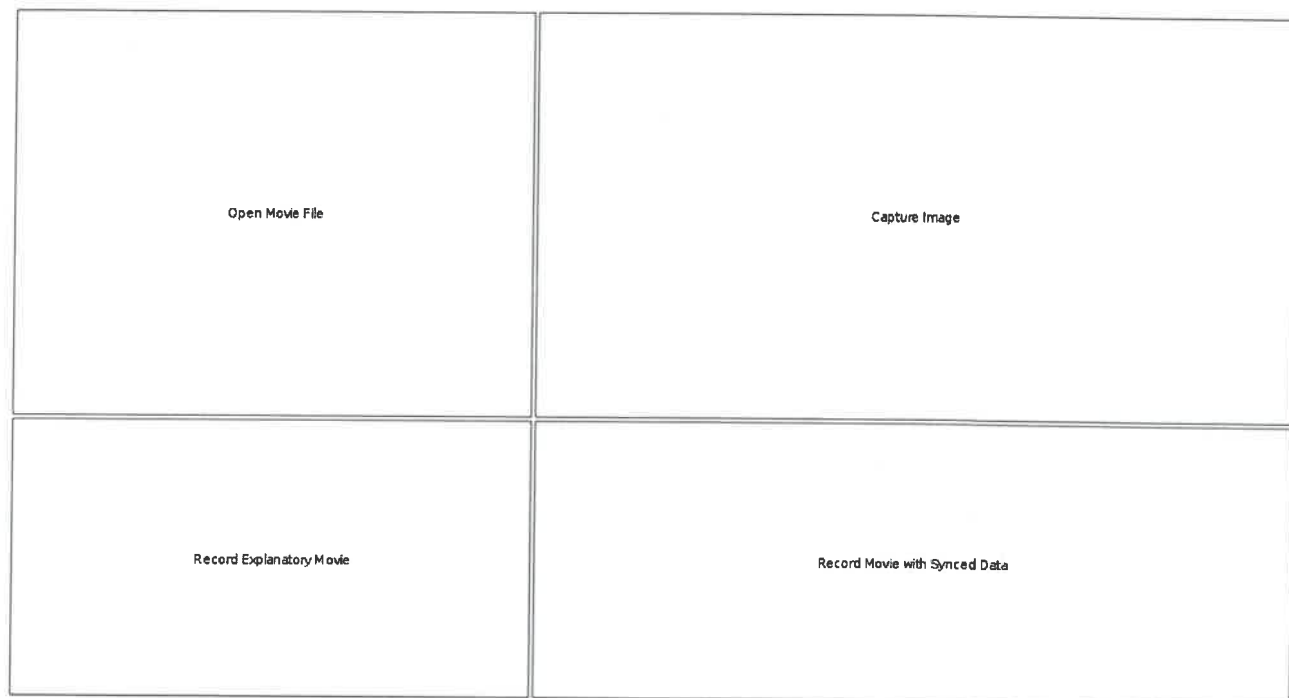


Figure 14: PASCO Capstone Movie Display

4. In the Movie display, click “Record Movie with Synced Data” in the lower right-hand box.
- NOTE: If the “Choose Video Camera” window opens, pick “USB Video Device” and click “OK”. The display changes to show the movie panel.

- By default, the movie panel will be in “Monitoring” mode. The displayed image is not being recorded yet.

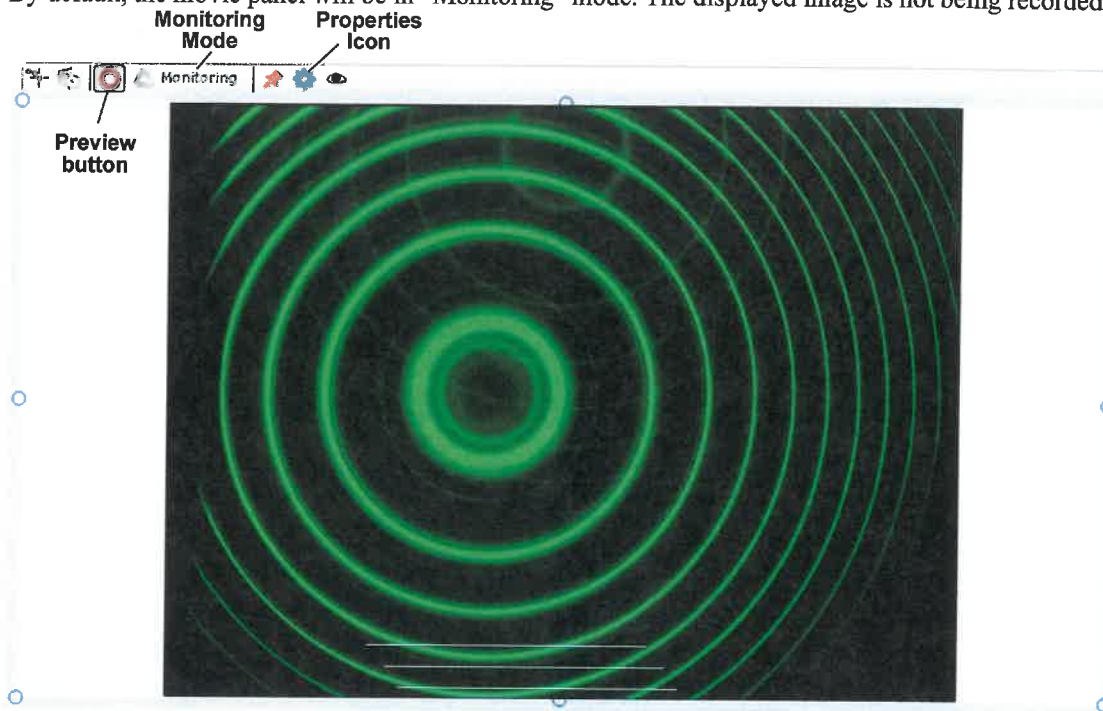


Figure 15: Interference Pattern Example

- The interference pattern should appear. See Figure 16.
- Click the gear-shaped Properties icon (⚙️) in the toolbar of the movie panel to open the Properties dialog window. Click “Movie Recording”, and then select the “Frame Size” as 1280x1024. Click “OK”.

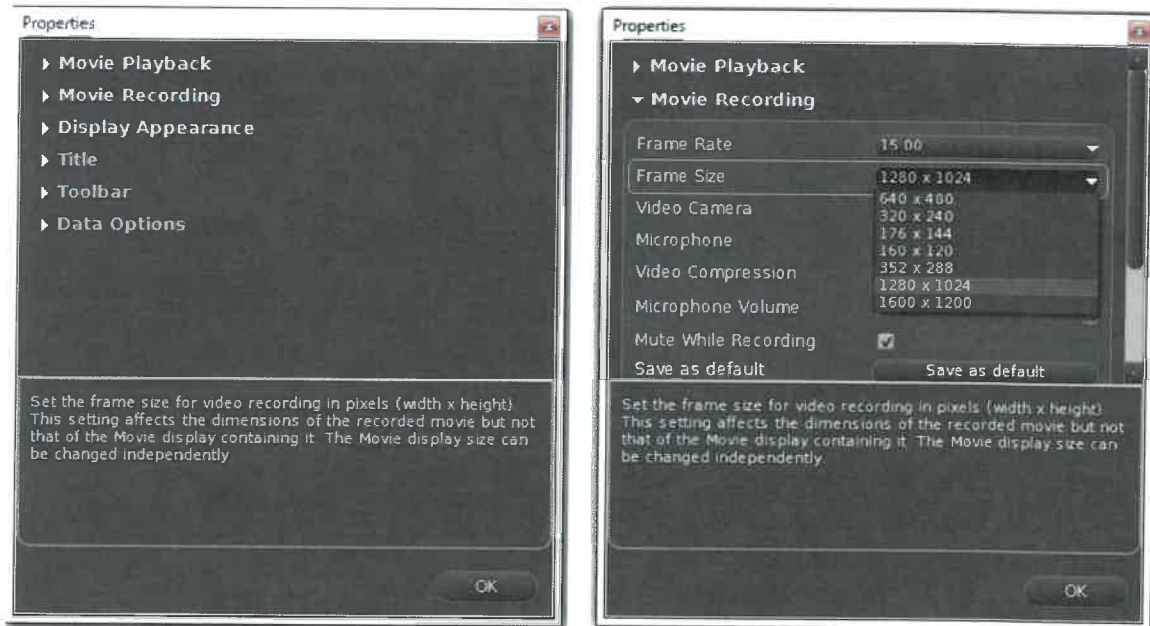


Figure 16: Movie Display Properties

- Adjust the aperture on the CMOS camera (front ring) to get a nice intensity (bright enough to see, but not burning out). Adjust the back ring on the camera to focus the image.

Zeeman Effect Experiment ... or, Setup the Experiment in the PASCO Cap-

7. Center the pattern horizontally approximately by moving the camera. To do this, hold the camera, loosen the upper screw on the adjustable post holder, and rotate the camera left or right. Tighten the upper screw. Then use the black X - Y adjustment knobs on the interferometer assembly to adjust the vertical position and fine tune the horizontal position.
8. If the pattern is not uniformly illuminated (as in Figure 18, use the knob on the horizontal adjustable holder of the polarizer/lens assembly to adjust the horizontal position of the polarizer/lens assembly.
9. Increase the power supply current to 3.0 A.
 - With the electromagnet on at 3.0 A, the rings should split into triplets as shown in Figure 19. The rings should be sharply defined all the way around.

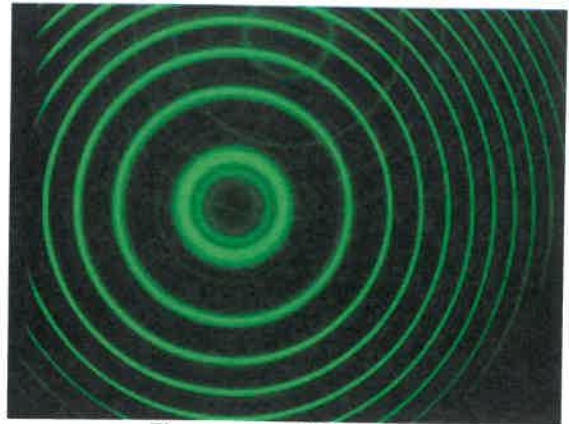
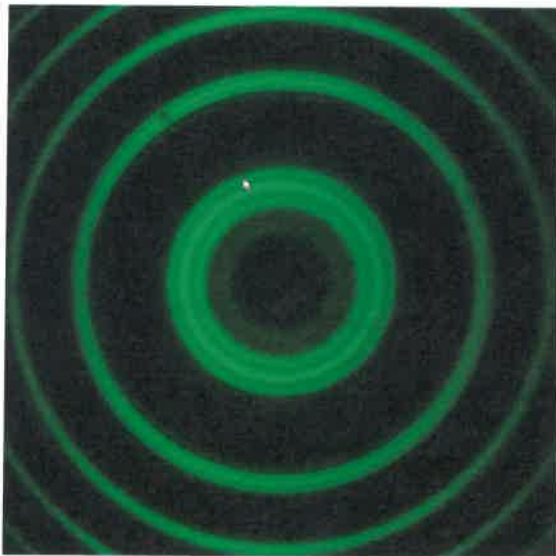


Figure 17: $B = 0$ Pattern



Rings split
into triplets

Figure 18: Well Aligned Pattern

- If the pattern is like Figure 20, the two plates of the interferometer are not sufficiently parallel. The plates are adjusted using the three silver knobs on the interferometer. You may also need to adjust the camera aperture and focus.
 - NOTE: This adjustment is a challenge. It is a good idea to put a pencil mark on each of the silver knobs to mark the initial vertical position and keep track of how far you have turned them clockwise or counterclockwise. That way you can always start over.
 - CAUTION: If you go too far the knob will pop off.
 - NOTE: This adjustment is critical for obtaining good results!
10. After completing the adjustments, reduce the power supply output to 0.00 A.

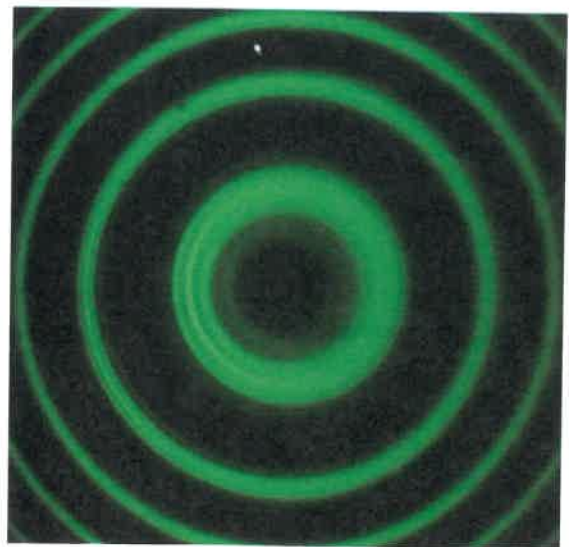




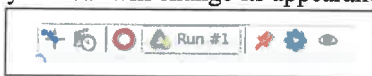
Figure 19: Poorly Aligned Pattern

Data Recording

NOTE: Three runs of data will be recorded, but only the first run of data, Run #1, will be used for measuring and analysis.

Run #1: Power at 0 A and then Power at 5 A - Polarizer at 90°,


1. Check that the polarizer is set to 90° and the power is set at 0 A. Click **Record** () at the bottom left corner of the screen. After a few seconds, increase the power supply output to 3.00 A. After about 5 seconds click **Stop** ().
- This is Run #1. NOTE: The movie display toolbar will change its appearance to show that Run #1 was recorded.



Run #2: Rotate Polarizer from 90° to 0°, and then remove Polarizer - Power at 5 A

2. Check that the polarizer is still set at 90° and the power is at 5 A. Click **Record**. After a few seconds, *rotate the polarizer to 0°*. Wait a few more seconds and then *remove the polarizer*. After a few more seconds, click **Stop**.
- This is Run #2.
3. Replace the polarizer.

Run #3: Axial Magnetic Field, Rotate Polarizer through 90°- Power at 5 A

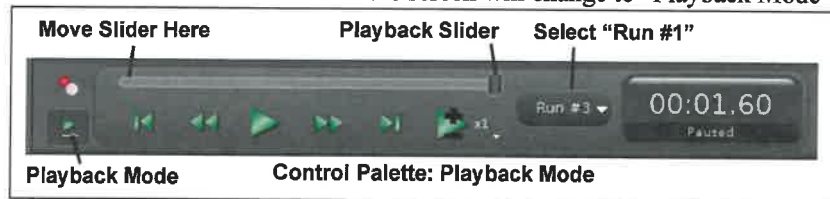
4. Remove the axial iron core plug (silver knob) from the electromagnet. (It just slides out, but is a tight fit so it is probably easier to rotate it as you pull out). Rotate the electromagnet by 90° on its base so the axial hole is toward the camera.
5. Click the **Preview** button in the movie toolbar (). If necessary, adjust the position of the electromagnet and/or mercury lamp to give a bright image. You will probably need to open the aperture on the camera.
6. Click **Record**. *Slowly rotate the polarizer through 90°*. Click **Stop**.
- This is Run #3.
7. Decrease the power supply to 0 A. Turn the power supply off.

Measuring

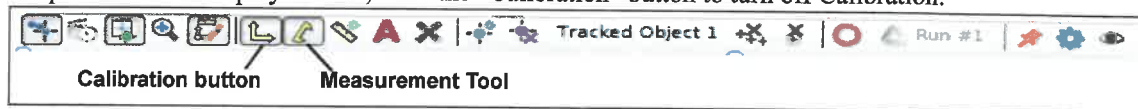
1. Click the “Enter Video Analysis Mode” button at the left end of the movie toolbar to expand the movie display toolbar.



- The Control Palette at the bottom of the screen will change to “Playback Mode”.



2. Select “Run #1” from the menu in the Control Palette. Move the playback slider to the *beginning* (B = 0 at that point).
3. In the expanded movie display toolbar, click the “Calibration” button to turn off Calibration.





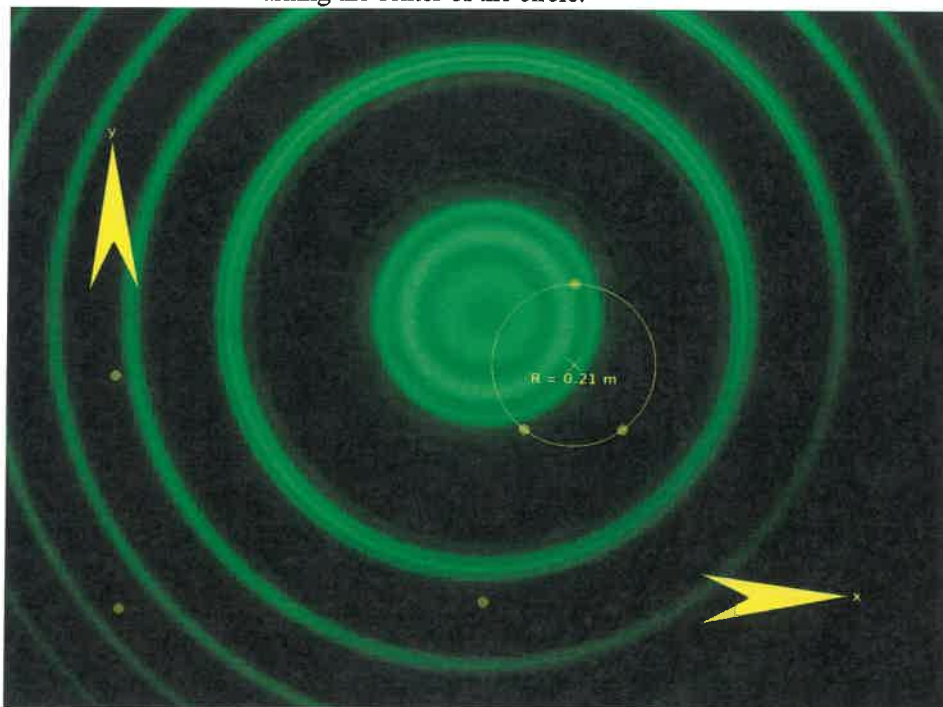
- NOTE: This means that the radius tool will not be calibrated. This will affect the value of C_0 , but it will not affect the final result. An examination of Equations 12 and 13 shows that the radii are squared in both the denominator and the numerator, so any scale factor cancels out.

For Run #1, Measure the Radius of the Rings for $B = 0$

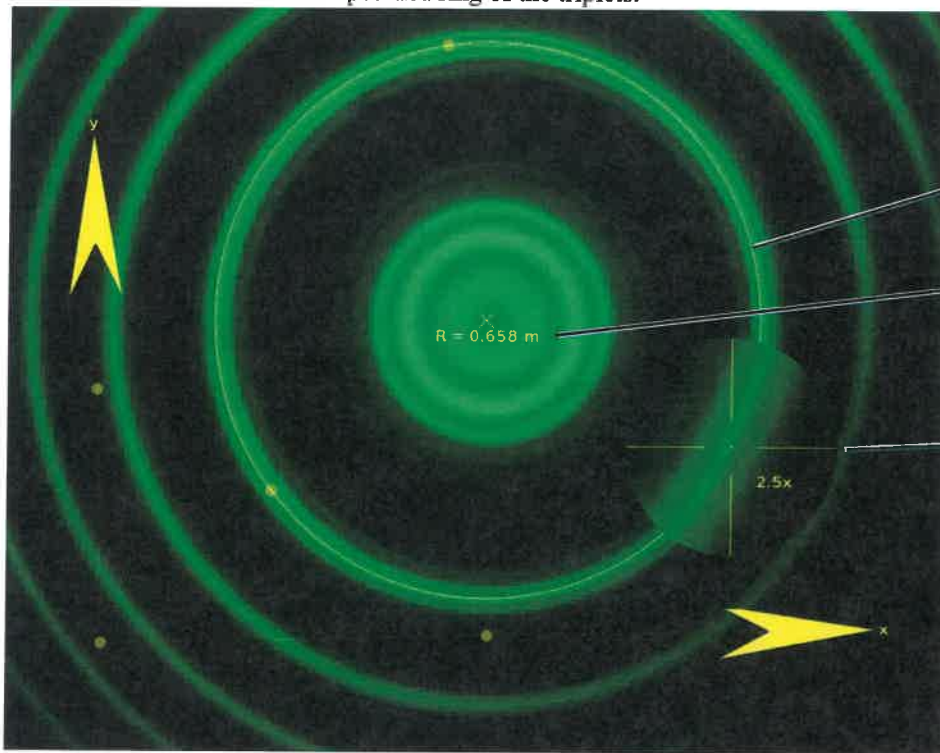
Click the Properties icon (shaped like a gear) at the right-hand end of the movie display toolbar to open the Properties window. In the window, click “Overlay”. Click the check box to select “Use Magnifier With Tools” from the list of choices under “Overlay”.



- In the movie display toolbar, click the “Measurement Tool” button () and select Radius Tool () from the drop-down menu.
- A circle with three circular handles opens in the movie display. A value for the radius, R , appears in the circle. There is also a small “X” marking the center of the circle.



5. Farther down in the Properties window, click “Radius Tool” to open the Radius Tool choices. Set the “Number of Decimal Places” to 3. Click “OK” to close the Properties window.
6. One at a time, drag the three circular handles on the Radius tool until they are all on the $k = 4$ ring and the handles are about 120 degrees apart. The outer rings may partially be off the screen. (Recall that the innermost ring is $k = 0$). Check the fit of the circle to the ring with your eye. If $k = 4$ is not clear enough, start with $k = 3$.
7. NOTE: Because “Use Magnifier With Tools” was selected earlier, the image is magnified when you click and hold the mouse on a point, such as one of the circular handles. The default magnification is 2X, and the magnification can be adjusted using the scroll-wheel on the mouse. The magnified image makes it easier to position the Radius Tool circle on the specified ring of the triplets.



Radius Tool circle on a triplet ring

Radius value

Magnifier (at 2.5x)

8. Record the value for the radius, R , to three decimal places in Table 1 below (where k is the ring number).
 9. Move the X-Y Axes so the origin is at the point marking the center of the circle.
 10. Using the same Radius Tool circle, repeat the measurement process for the $k = 3$, $k = 2$, $k = 1$, and $k = 0$ circles (if possible).
- NOTE: Don't define a new Radius Tool since they would be on top of each other. All of the circles should have their centers at the same point.

For Run #1, Measure the Radius of the Triplets for $B \neq 0$ and $k = 1$

11. Slide the playback slider back all the way to the right to show the image of the $B \neq 0$ data for which each line has become a triplet (and B is at its maximum value).
12. Adjust the Radius tool to measure the radius of the triplets of the $k = 1$ ring. Record the measurements in Table 2 below. For the outer triplet ring, record the radius as R^+ . For the inner triplet ring, record the radius as R^- .

13. Repeat the previous step two more times (for a total of three trials) to help estimate the uncertainty.

For Run #1, Measure the Radius of the Triplets for $B \neq 0$ and $k = 0$

14. Adjust the Radius tool to measure the radius of the triplets of the $k = 0$ ring. Record the measurements in Table 3 below. For the outer triplet ring, record the radius as R plus. For the inner triplet ring, record the radius as R minus.

15. Repeat the previous step two more times (for a total of three trials) to help estimate the uncertainty.

Data Tables:

| k | Radius (m) |
|---|------------|
| 4 | |
| 3 | |
| 2 | |
| 1 | |
| 0 | |

| Trial | R+ (m) | R- (m) |
|-------|--------|--------|
| 1 | | |
| 2 | | |
| 3 | | |

| Trial | R plus (m) | R minus (m) |
|-------|------------|-------------|
| | | |
| | | |
| | | |

Setup the Data Displays in Capstone

1. Create a new page in PASCO Capstone by clicking the Add Page button to the left of the first tab (Page#1). Label it **Data Analysis**.
2. Click the Four Displays icon at the lower right of the workbook.

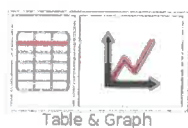


Figure 20: Click the Four Displays Icon

3. Click the icon (📄) in the center of the upper left display and select “Table” from the pop-up.

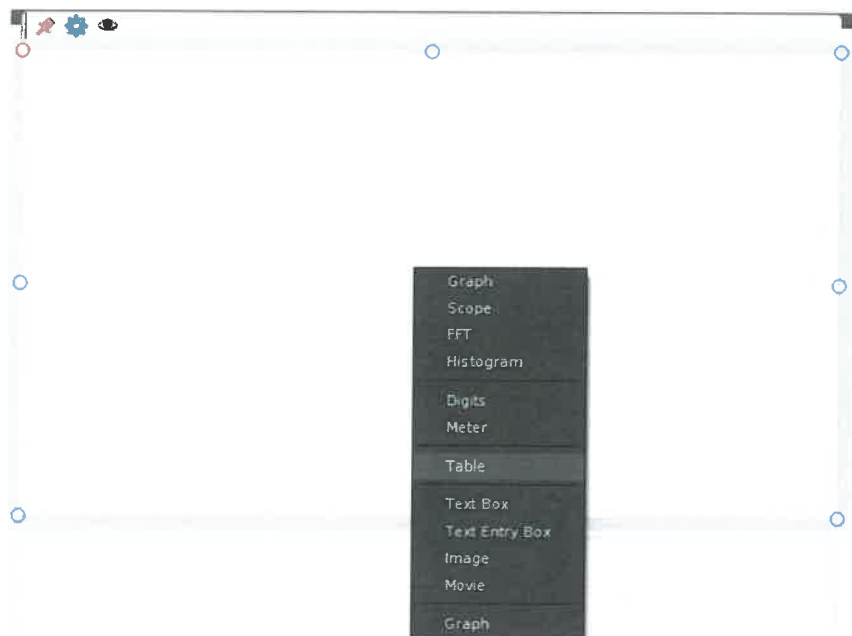


Figure 21: Select Table from the menu

Setup Table 1

4. Click the Table display where it says “Table title here” and label this table: “Table 1: B = 0 Data”. Add a third column to the table by clicking the “Insert empty column to the right” icon (📄) at the left end of the table toolbar one time.

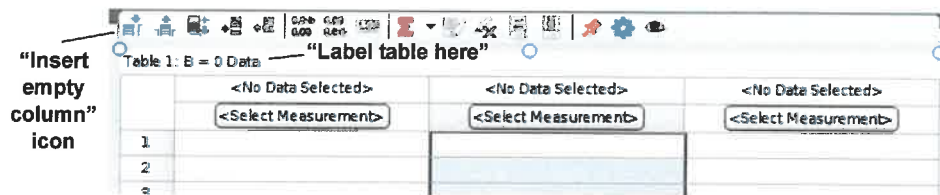


Figure 22: Label the Table and add a Column

- NOTE: Table 1 is where the ring numbers will be listed and the measured values of R will be entered.

5. Click the black triangle button (▼) next to the Statistics icon (a capital sigma Σ) and deselect “Minimum” and “Maximum”. Next, click the Statistics icon to display “Mean” and “Std. Dev.” at the bottom of the table.

Click “Statistics” icon

| | <No Data Selected> | <No Data Selected> | <No Data Selected> |
|------|----------------------|----------------------|----------------------|
| | <Select Measurement> | <Select Measurement> | <Select Measurement> |
| 1 | | | |
| 2 | | | |
| 3 | | | |
| 4 | | | |
| 5 | | | |
| 6 | | | |
| 7 | | | |
| 8 | | | |
| 9 | | | |
| 10 | | | |
| 11 | | | |
| 12 | | | |
| 13 | | | |
| Mean | - | - | - |

Figure 23: Table 1: B = 0 Data with “Mean” and “Std Dev”

Setup Table 2

6. Repeat the setup procedure for the display at the lower left. Click “Table title here”. Label it: “Table 2: $B \neq 0$, $k = 0$ ”. (NOTE: To get the inequality sign, right click the mouse and select the inequality from the Insert Special Character pop-up.) Add two columns for a total of four columns. Click “Statistics” to set up “Mean” and “Std Dev” at the bottom of the table.

Setup Table 3

7. Repeat the setup procedure for the display at the upper right. Click “Table title here”. Label it: “Table 3: $B \neq 0$, $k = 1$ ”. Add two columns for a total of four. Click “Statistics” to set up “Mean” and “Std Dev” at the bottom of the table.

- The workbook page with three table displays should appear as below.

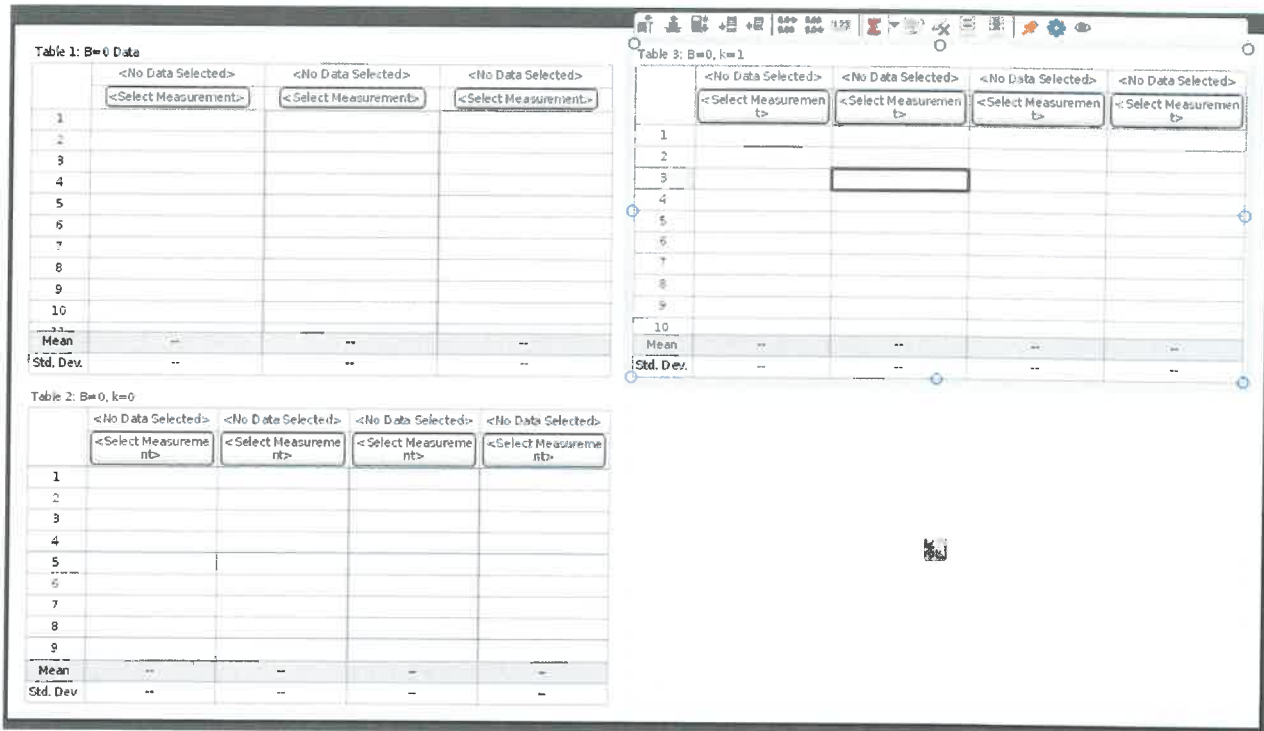


Figure 24: Workbook page with three table displays

Label the First Two Columns of Each Table

- Click “Select Measurement” at the top of column 1 in Table 1. Click “Create New” and select “User-Entered Data” from the menu.



Figure 25: Select “User-Entered Data”

- “User Data 1” will appear highlighted at the top of column 1.
- Type “k” and press Enter. The term “units” is now highlighted. Since “k” is unit less, press Delete or Backspace. If you make a mistake in the label, click on it and select Rename. In the cells below the column heading, type in the values for k for the circles you measured with B = 0. For example 4, 3, 2 and 1.)
 - Click “Select Measurement” at the top of column 2 in Table 1. Click “Create New” and select “User-Entered Data” from the menu.
- “User Data 2” will appear highlighted at the top of column 2.
- Type “Radius” and press Enter. The term “units” is now highlighted. Type “m”.
 - DO NOT do column 3 yet!
 - Use the same procedure to label the first two columns in Table 2 as “R+” and “R-”, with the units “m”, and the first two columns in Table 3 as “R plus” and “R minus” with the units “m”.

- The workbook page should appear as below.

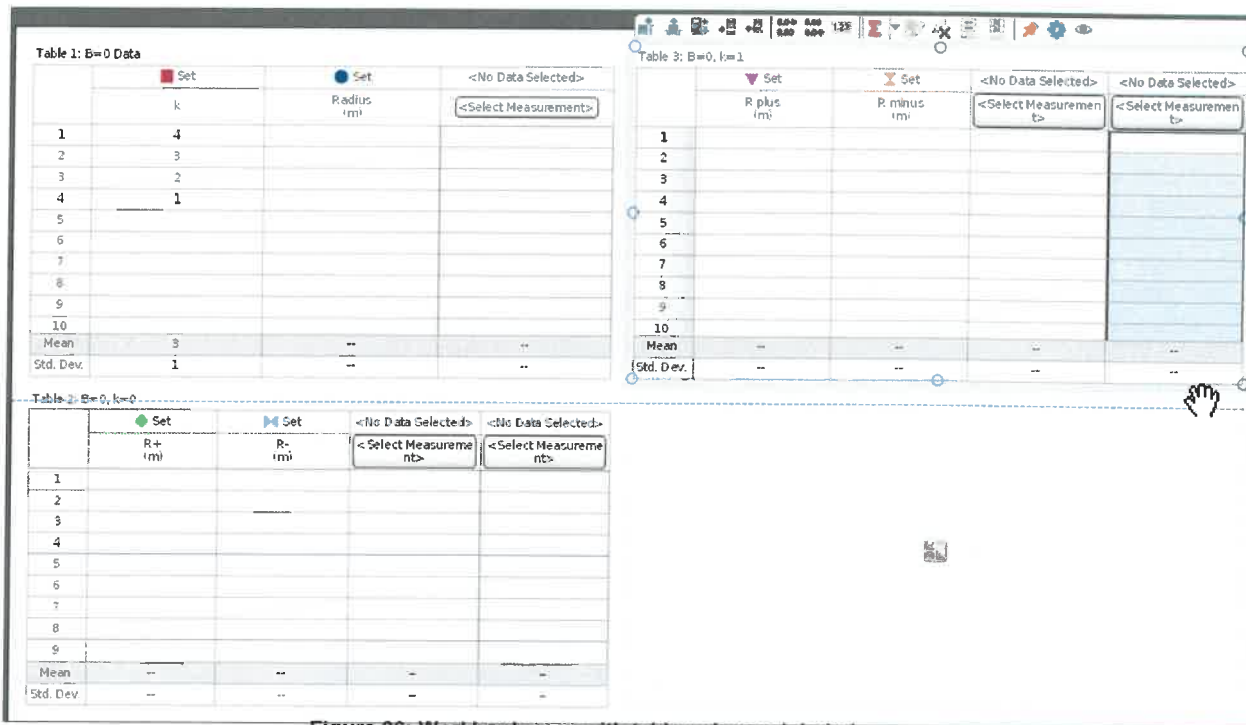


Figure 26: Workbook page with table columns labeled

Setup the Calculations

- Click the “Calculator” button () on the left Tools palette to open the Calculator window.
- Type in rows 1, 2, 3 and 5 exactly as shown below. Subscripts (or superscripts) are done by right clicking (or control-click) the mouse and using the “Insert Subscript” pop-up. NOTE: You can also get Greek characters this way.

| | Calculations | Units |
|---|--|---------|
| 1 | $d = 0.001995$ | m |
| 2 | $B = 0.934$ | T |
| 3 | $R_n = 0.199$ | m |
| 4 | $C = [k]/([Radius (m)]^2 - [R_n (m)]^2)$ | $1/m^2$ |
| 5 | $C_n = 2.567$ | $1/m^2$ |

Figure 27: Calculations 1 through 5

- Type in row 4. Note that instead of typing in the quantities as shown in the square brackets, you must *select* them from the “Calculator” list that pops up when you click the multi-colored triangle () below the calculator to the left.
 - The [k] and [Radius] are under “User-Entered Data” in the Calculator list.
 - The term $[R_0]$ is under “Constants” and then “User-Defined Constants”.
 - You may type the exponents or use the x^2 button in the Scientific keypad.



Figure 28: User-Defined Data

17. Similarly, create lines 6-10.

| | | |
|----|--|-----|
| 6 | $C_2 = [C_0 (1/m^2)] * [\text{Planck's constant } (J \cdot s)] * [\text{Speed of light } (m/s)]$ | N |
| 7 | $\mu \text{ Bohr} = [C_2 (N)] * ([R_+ (m)]^2 - [R_- (m)]^2) / (2 * [d (m)] * [B (T)])$ | J/T |
| 8 | $\mu B = [C_2 (N)] * ([R \text{ plus } (m)]^2 - [R \text{ minus } (m)]^2) / (2 * [d (m)] * [B (T)])$ | J/T |
| 9 | $\Delta R = [R_+ (m)] - [R_- (m)]$ | m |
| 10 | $\text{del } R = [R \text{ plus } (m)] - [R \text{ minus } (m)]$ | m |

Figure 29: Calculations 6 through 10

18. Create line 6, C_2 , with terms from the Calculator list (click the multi-colored triangle (▲)) and with icons from the Calculator keypad.

- The first term in brackets, $[C_0 (1/m^2)]$, is under “User Defined Constants”.
- The next term, $[\text{Planck's constant } (J \cdot s)]$, and the third term $[\text{Speed of light } (m/s)]$ are both under “Constants”.

19. Line 7, $\mu \text{ Bohr}$, is also made up from terms in the Calculator list (click the icon (▲)).

- The first term, $[C_2 (J/m)]$ is the equation from line 6 and it is found under “Equations/Constants”.
- The next term, $[R_+ (m)]$, and the third term in brackets, $[R_- (m)]$, are both under “User Defined Data”.
- The fourth term, $[d (m)]$, and the fifth term, $[B (T)]$, are both under “User Defined Constants”.



Figure 30: Equations/Constants

20. Line 8, μB , is also made from terms in the Calculator list (click the icon (▲)).

- The first term, $[C_2 (J/m)]$, is under “Equations/Constants”.
- The second term, $[R \text{ plus } (m)]$, and the third term, $[R \text{ minus } (m)]$, are both found under “User Defined Data”.
- The fourth term, $[d (m)]$, and the fifth term, $[B (T)]$, are both under “User Defined Constants”.

21. Line 9, ΔR is also made from terms in the Calculator list (click the icon (▲)).

- The two terms in brackets, $[R_+ (m)]$, and $[R_- (m)]$ are both under “User Defined Data”.

22. Line 10, $\text{del } R$, is also made from terms in the Calculator list (click the icon (▲)).

- The two terms in brackets, $[R \text{ plus } (m)]$, and $[R \text{ minus } (m)]$ are both under “User Defined Data”.

Label the Other Columns of the Tables

23. Click “Select Measurement” in the third column of Table 1. Select “C” from the “Equations/Constants” choices in the Calculator list (click the icon (▲)).

24. Similarly, define the third and fourth columns of Table 2 to be “ $\mu \text{ Bohr}$ ” and “ ΔR ”

25. Define the third and fourth columns of Table 3 to be “ μB ” and “ $\text{del } R$ ”.

- The finished workbook page should look like the one below.

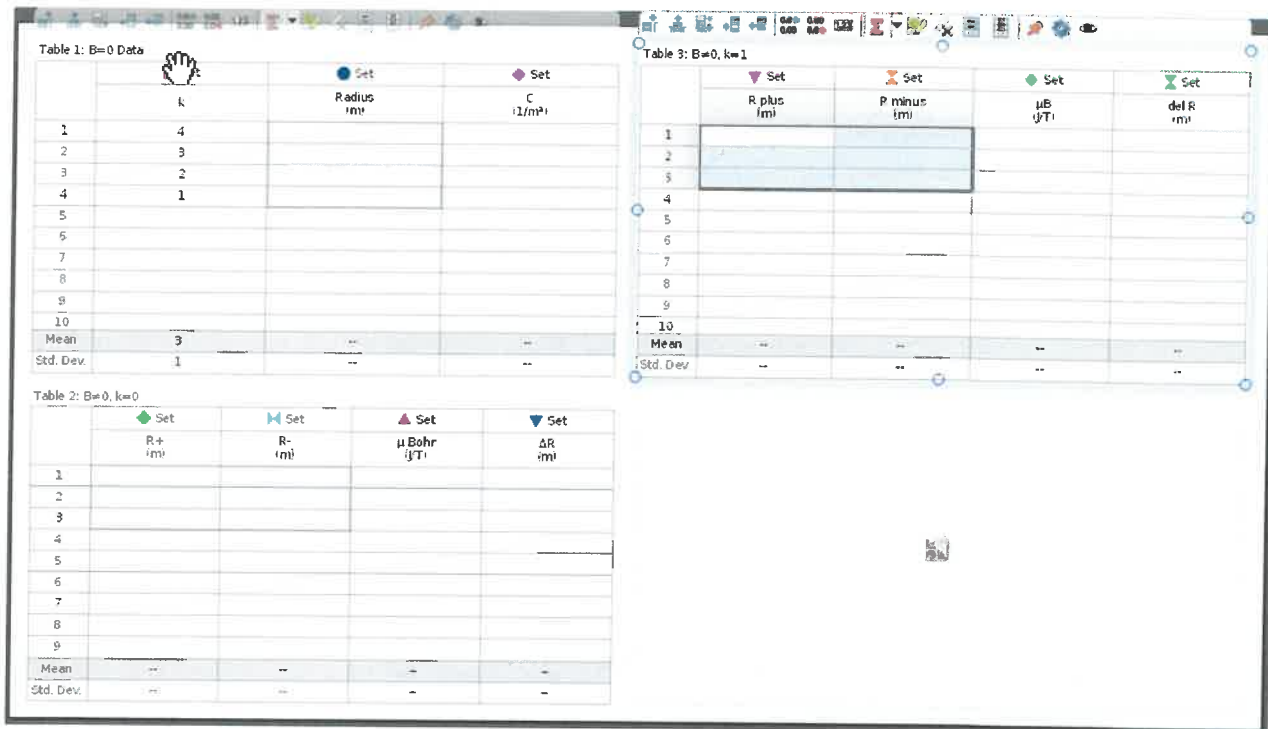


Figure 31: Finished Workbook Page of Tables 1, 2, and 3

Enter Data into the Tables

- Type in the measured values for R into the cells in the Capstone “Table 1: B = 0” for the k = 4 to k = 1 rings.
- Type in the measured values for R+ and R- into the cells in the Capstone “Table 2: B ≠ 0, k = 1”.
 - Recall that R+ is the radius of the outer ring and R- is the radius of the inner ring. You should have measured the radii three times and the values should go in the first three rows.
- Type in the measure values for R_{plus} and R_{minus} into the cells in the Capstone “Table 3: B ≠ 0, k = 1”.
 - Recall that R_{plus} is the radius of the outer ring and R_{minus} is the radius of the inner ring.
- Click open the Calculator at the left of the screen. In line 2, the default value is 0.934 T. Type in the actual value for B (replace the 0.934 T) of the magnetic field strength for your electromagnet at the current you used (probably 3.00 A).
 - NOTE: This value is given on the Test Report that came with the electromagnet. It is close to 0.93 T at 3.00 A but varies a few percent from unit to unit. If there is more than one electromagnet in the lab, note that there is a serial number on the electromagnet (silver label) that matches the serial number on the Test Sheet.
- In line 3 of the Calculator, type in the value for radius of the k = 0 circle when the magnetic field was off (B = 0). Replace the 0.199 m value with your value.
- In line 5 of the Calculator, replace the value 2.567 with the mean value of C from Table 1: B = 0.
- Verify that line 4 in the Calculator is the same as Equation 12 from the Final Theory page and that lines 6, 7, and 8 are the same as Equation 13.

Conclusions

1. If you wish to enter your answers using Capstone, create a new workbook page and label it "Conclusions".
- Double click the icon at the right that says "Text Entry Box" to open an empty text area.
- Type in your answers to the following questions.

Questions

→ Save all the data/data-files in a pen drive
 → Type answers to the following question in your lab report

1. Do the mean values for the Bohr magneton from Table 2 and Table 3 agree with theory ($9.27 \times 10^{-24} \text{ J/T}$) Discuss fully.
2. When the current was on, was the center Radius Tool circle in the triplet the same as the Radius Tool circle for the $B = 0$ field? What does this show?
 - On the "Data Analysis" workbook page, select Run #2 at the bottom of the page. Move the playback slider to the beginning of the run (all the way to the left). Using the "Create Measurement Tool" button, create three Radius Tools. Adjust one of the circles so it is just outside of the outer $k = 1$ triplet. Adjust a second circle to just inside the inner $k = 1$ triplet. Adjust the third circle to just outside the $k = 0$ triplet. Move the slider until the $k = 1$ triplet disappears.
 - NOTE: The triplet disappears when the polarizer has been rotated by 90° so you are seeing the light polarized perpendicular to the magnetic field axis. You may need to move the three circles slightly because rotating the polarizer may move the image slightly.
3. How many energy levels (separate circles) do you see now for the $k = 1$ band of circles? Does this agree with the discussion in the theory section?
 - NOTE: It may help to use the magnifier. The outside bands are more clear with the $k = 0$ band, but the $k = 0$ inside bands may not show if the $k = 0$ band is too close to the center.
 - Now move the playback slider to the end of Run #2 where the polarizer was removed.
4. Can you see all the bands without the polarizer? How many are there? Does it match theory?
 - Now select Run #3 at the bottom showing the interference pattern for the axial magnetic field (when the electromagnet was parallel to the track). Start with the slider at the beginning and move it to the end. Recall that you rotated the polarizer through 90° as you took the movie.
5. Do you see any change in the pattern? What does this tell you?
6. Why is all of this important?