

Zeeman Effect Experiment

Model SE-9654



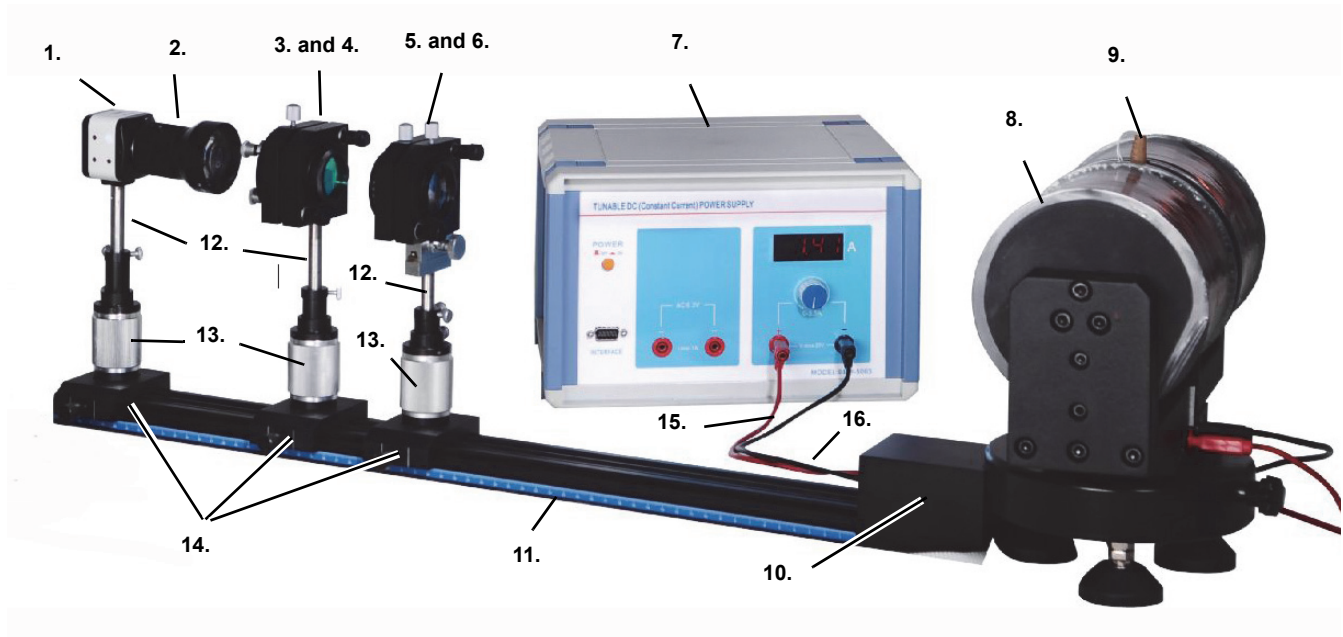
Brolight Technology Co., Ltd

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Zeeman Effect Experiment

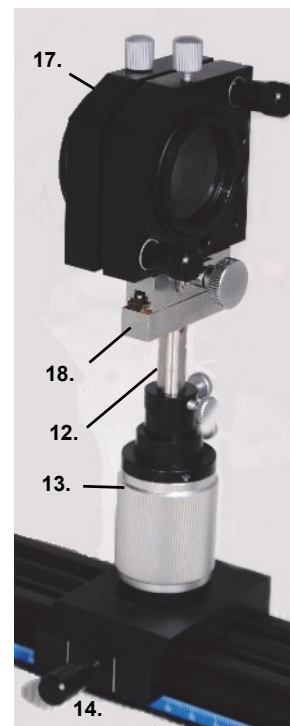
SE-9654



Equipment List

Included Items	Model	Quantity
Zeeman Effect Experiment	SE-9654	1
1. CMOS Camera		1
2. Camera Lens		1
3. Fabry-Perot Interferometer		1
4. Interference Filter		1
5. Polarizing Filter		1
6. Collimating Lens		1
7. Tunable DC (Constant Current) Power Supply	SE-9656	1
8. Electromagnet with Pole Shoes	SE-9655	1
9. Pen Type Mercury Lamp		1
10. Connection Block		1
11. Optical Track, 600 millimeters (mm)		1
12. Post		3
13. Adjustable Post Holder		3
14. Optical Carrier		3
15. Connection Cable, Red		1
16. Connection Cable, Black		1

Included Items	Quantity
17. Precision Kinematic Optical Mount	2
18. One-dimensional Horizontal Adjustable Holder	1
Power Cord (not shown)	1
USB Camera Cable (not shown)	1
Storage Case (not shown)	1
PASCO Capstone Software Single License (not shown)	1
Flash Drive labeled ZEEMAN EFFECT (not shown)	1
Zeeman Effect Experiment Information Sheet (not shown)	1



Included Items

Software Description

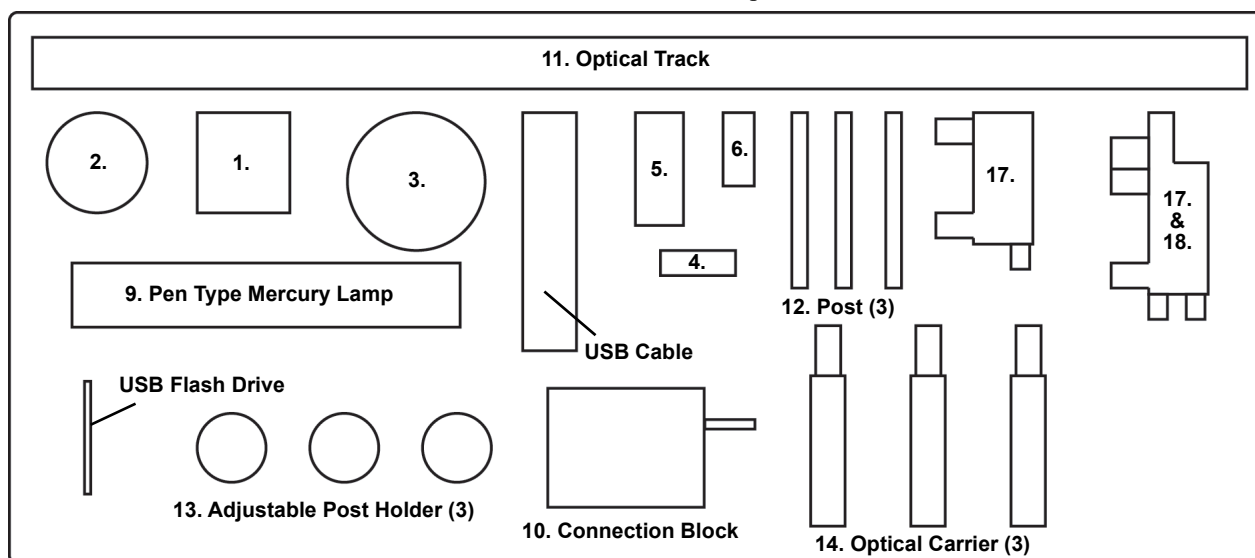
The PASCO Capstone Software (included) allows the user to record video of the Zeeman Effect interference patterns, and then play back the video frame-by-frame to measure the triplet rings in the patterns. The software also allows the user to apply calculations to the data and to display the results in tables.

PASCO Capstone Software supports any PASCO USB interface, PASPORT sensor, and Science-Workshop sensor. The software includes powerful measurement and analysis tools, a built-in calculator, and a variety of displays including graph, table, and video display. The video display will be used during the data recording and analysis. For more information about PASCO Capstone, interfaces and sensors, see the web site at: www.pasco.com.

The ZEEMAN EFFECT Flash Drive contains a Portable Document Format (PDF) file of this manual and three folders containing files for doing the experiment: Zeeman Capstone Files, Zeeman Graphics, and Zeeman Word Files.

Equipment Description

The Zeeman Effect Experiment arrives in three containers: storage case, power supply box, and electromagnet box. The storage case includes the USB flash drive that contains the Zeeman Effect Experiment Files and Manual.



Storage Case Layout

Storage Case

The Storage Case has cut-out areas for the various components of the Zeeman Effect Experiment. The Fabry-Perot Interferometer (3) is used with the interference filter (4), polarizing filter (5), and collimating lens (6) to view the interference pattern that results when the 546.1 nanometer (nm) “green” spectral line of the pen type mercury lamp (9) is immersed in a uniform magnetic field. The electromagnet powered by the tunable direct current (DC) supply produces a magnetic field that can be varied from zero to almost one tesla (T). The precision kinematic optical mounts (17), one-dimensional horizontal adjustable holder (18), posts (12), and adjustable post holders (13) allow the interferometer, filter, lens, polarizer, and camera to be precisely aligned. The connection block (10) and the optical carriers (14) fit firmly on the optical track (11) to reduce misalignment. The camera lens (2) attaches to the CMOS camera (1) and the USB cable (not shown) connects the camera to the USB port on a computer.

Power Supply

The Power Supply box contains the Tunable DC (Constant Current) Power Supply (7), the power cord (not shown), and the red and black connecting cables (15 & 16).

Electromagnet

IMPORTANT: The Electromagnet box includes a printed Test Report that has vital information. DO NOT discard the Test Report.

The electromagnet test report has three data tables: The Relation Between Intensity of Magnetic Induction and Intensity of Current, Sample Data, and Error Analysis. The report also lists the electromagnet’s Serial Number. The data on the report are specific to that electromagnet. It is recommended that a small label with the serial number be attached to the base of the electromagnet. Again, *do not discard the printed Test Report for the electromagnet.*

Limited Warranty and Limitation of Liability

This BroLight product is free from defects in material and workmanship for one year from the date of purchase. This warranty does not cover fuses, or damage from accident, neglect, misuse, alteration, contamination, or abnormal conditions of operation or handling. Resellers are not authorized to extend any other warranty on Brolight’s behalf. To obtain service during the warranty period, return the unit to point of purchase with a description of the problem. **THIS WARRANTY IS YOUR ONLY REMEDY. NO OTHER WARRANTIES, SUCH AS FITNESS FOR A PARTICULAR PURPOSE, ARE EXPRESSED OR IMPLIED. BROLIGHT IS NOT LIABLE FOR ANY SPECIAL, INDIRECT, INCIDENTAL OR CONSEQUENTIAL DAMAGES OR LOSSES, ARISING FROM ANY CAUSE OR THEORY.** Since some states or countries do not allow the exclusion or limitation of an implied warranty or of incidental or consequential damages, this limitation of liability may not apply to you.

Safety Information

















WARNING: To avoid possible electric shock or personal history, follow these guidelines.

- Clean the equipment only with a soft, dry cloth.
- Before use, verify that the apparatus is not damaged.
- Do not defeat the power cord safety ground feature.
- Plug the power cord into a grounded (earthed) outlet.
- Do not use the product in any manner that is not specified by the manufacturer.
- Do not install substitute parts or perform any unauthorized modification to the product.
- Line and Current Protection Fuses: For continued protection against fire, replace the line fuse and the current-protection fuse only with fuses of the specified type and rating.
- Main Power and Test Input Disconnect: Unplug the instrument from the wall outlet, remove power cord, and remove all probes from all terminals before servicing. Only qualified, service-trained personnel should remove the cover from the instrument.
- Do not use the equipment if it is damaged. Before you use the equipment, inspect the case. Pay particular attention to the insulation surrounding the connectors.

- Do not use the equipment if it operates abnormally. Protection may be impaired. When in doubt, have the equipment serviced.
- Do not operate the equipment where explosive gas, vapor, or dust is present. Don't use it under wet conditions.
- Do not apply more than the rated voltage, as marked on the apparatus, between terminals or between any terminal and earth ground.
- When servicing the equipment, use only specified replacement parts.
- Use caution when working with voltages above 30 V AC rms, 42 V peak, or 60 V DC. Such voltages pose a shock hazard.
- To avoid electric shock, do not touch any bare conductor with hand or skin.
- Adhere to local and national safety codes. Individual protective equipment must be used to prevent shock and arc blast injury where hazardous live conductors are exposed.
- Special note: If a dangerous voltage is applied to an input terminal, then the same voltage may occur at all other terminals.

Electrical Symbols

	Alternating Current
	Direct Current
	Caution, risk of danger, refer to the operating manual before use.
	Caution, possibility of electric shock
	Earth (ground) Terminal
	Protective Conductor Terminal
	Chassis Ground
	Conforms to European Union directives.
	WEEE, waste electric and electronic equipment
	Fuse
	On (Power)
	Off (Power)
	In position of a bi-stable push control
	Out position of a bi-stable push control

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.

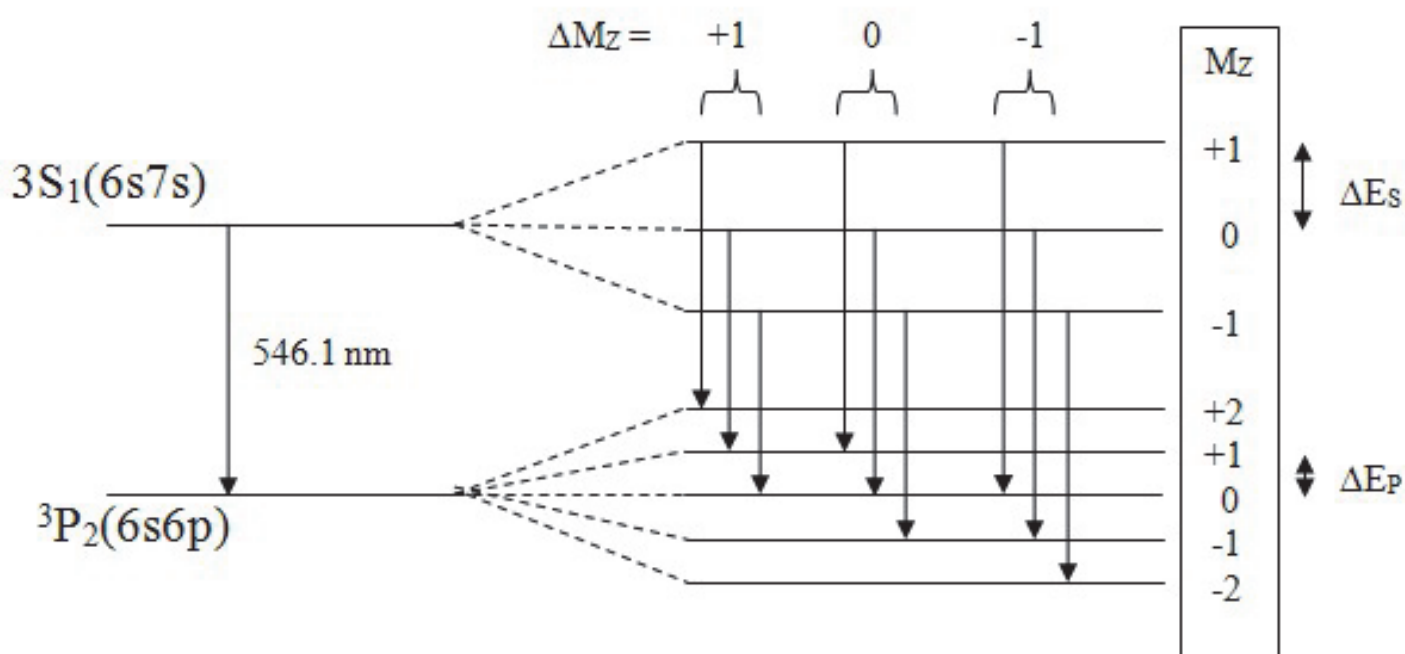


Figure 1: Energy Levels for 546.1 nm Mercury Spectral Line

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:

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

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:

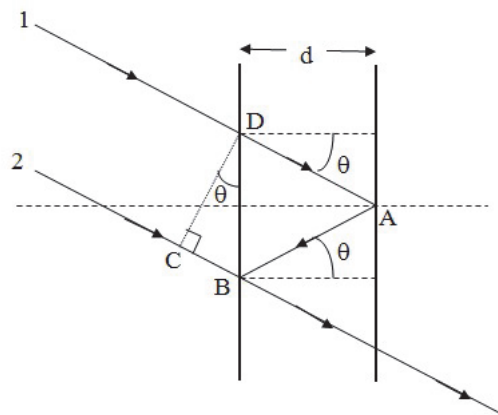


Figure 2: Fabry-Perot Geometry

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

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

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:

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

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 θ 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 $2d/\lambda \sim 10^4$.

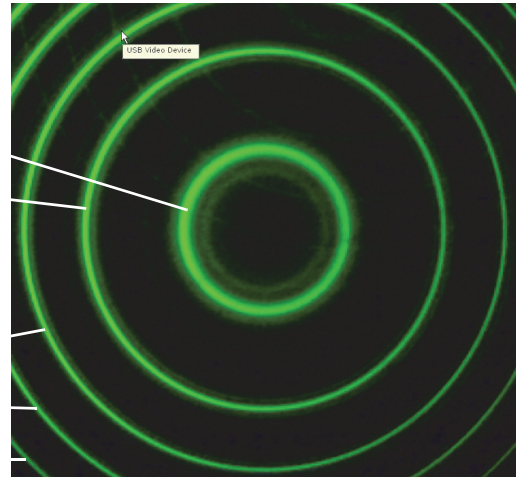


Figure 3: B = 0 Pattern

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:

$$2d\left(1 - \frac{R_k^2}{2f^2}\right) = (n - k)\lambda \text{ where } k = 1, 2, 3 \dots \quad \text{Eqn. 10}$$

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:

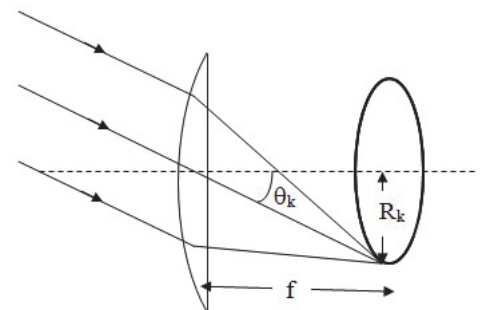


Figure 4: Camera Geometry

$$\frac{d}{f^2}(\mathbf{R}_k^2 - \mathbf{R}_0^2) = k\lambda$$

$$\frac{d}{f^2} \frac{1}{\lambda} = C_0 = \frac{k}{(\mathbf{R}_k^2 - \mathbf{R}_0^2)} \quad \text{Eqn. 12}$$

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:

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

and

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

Subtraction yields:

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

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

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

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

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

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').

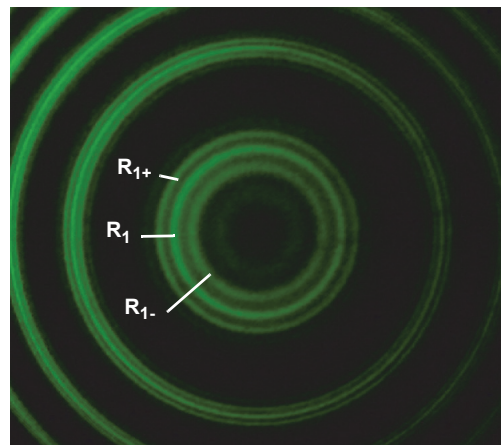


Figure 5: $B \neq 0$ Pattern, Triplets

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).

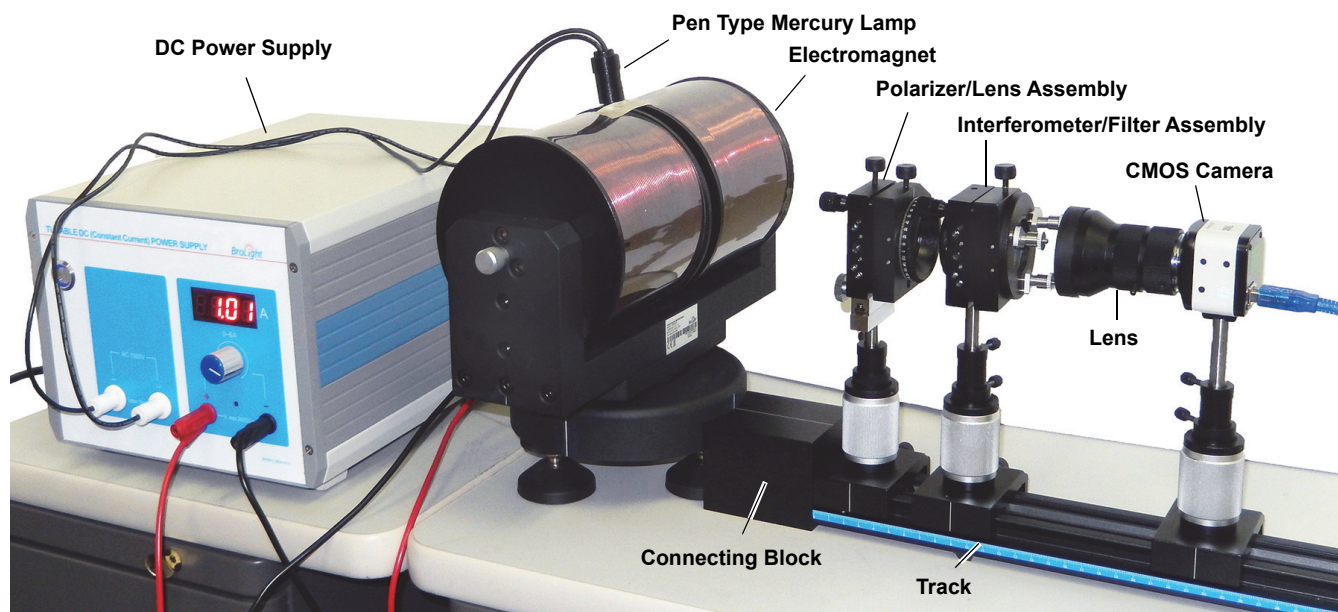


Figure 6: Setup

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.
3. 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).
1. Check the LINE VOLTS setting on the back of the Power Supply. Select the right setting based on your AC voltage.
 2. Connect the power cord to the AC POWER CORD port. Plug the cord into a grounded AC electrical outlet.

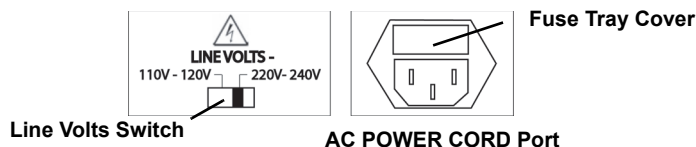
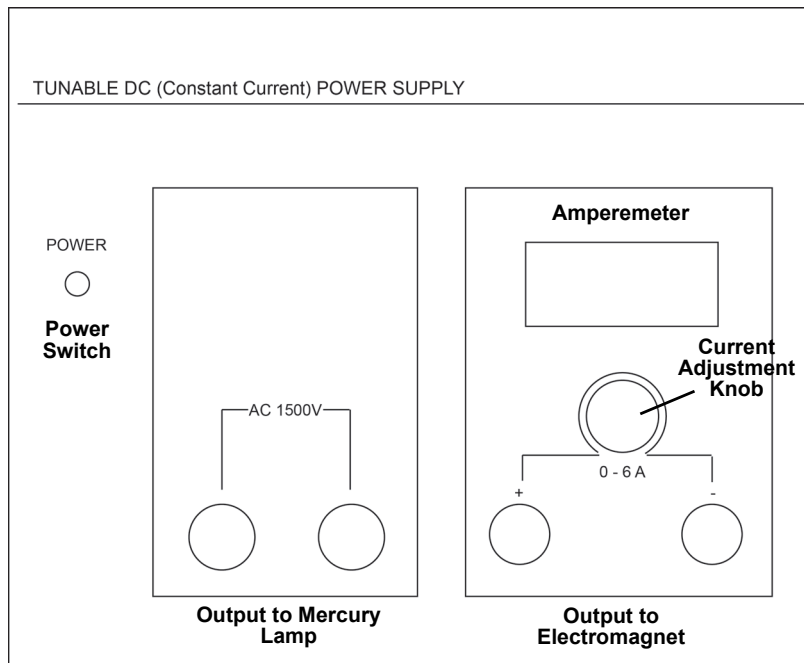
NOTE: The power supply fuse is located in a plastic tray in the top part of the AC POWER CORD port. The tray also holds a spare fuse. Before opening the fuse tray, disconnect the power cord. Always replace a fuse with a new fuse of the same type (Fuse Type 250 V T5A).

- 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.

1. 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.

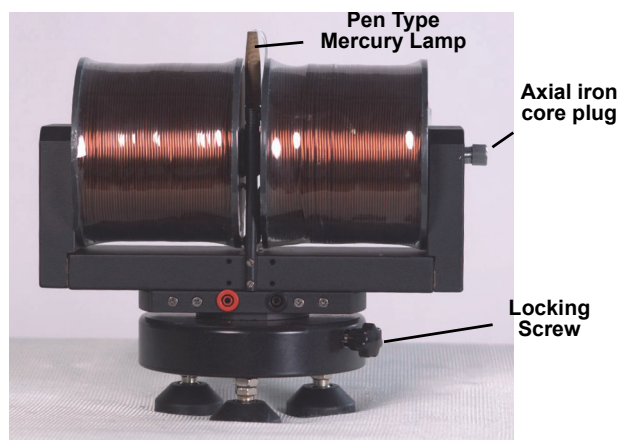
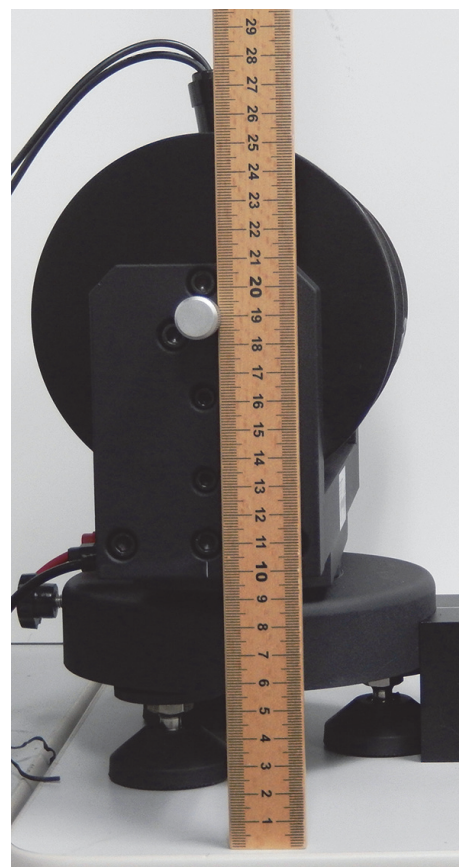


Figure 7: Electromagnet Setup



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).

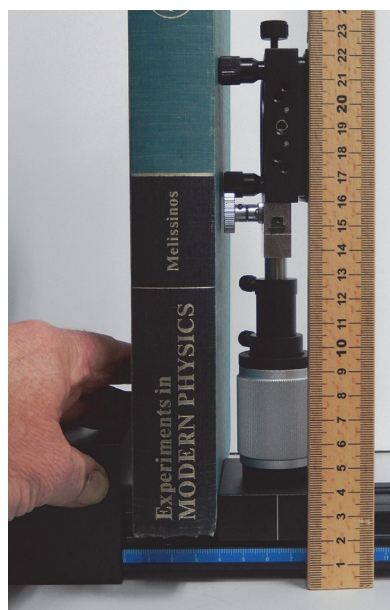


Figure 9: Align the Assembly

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.

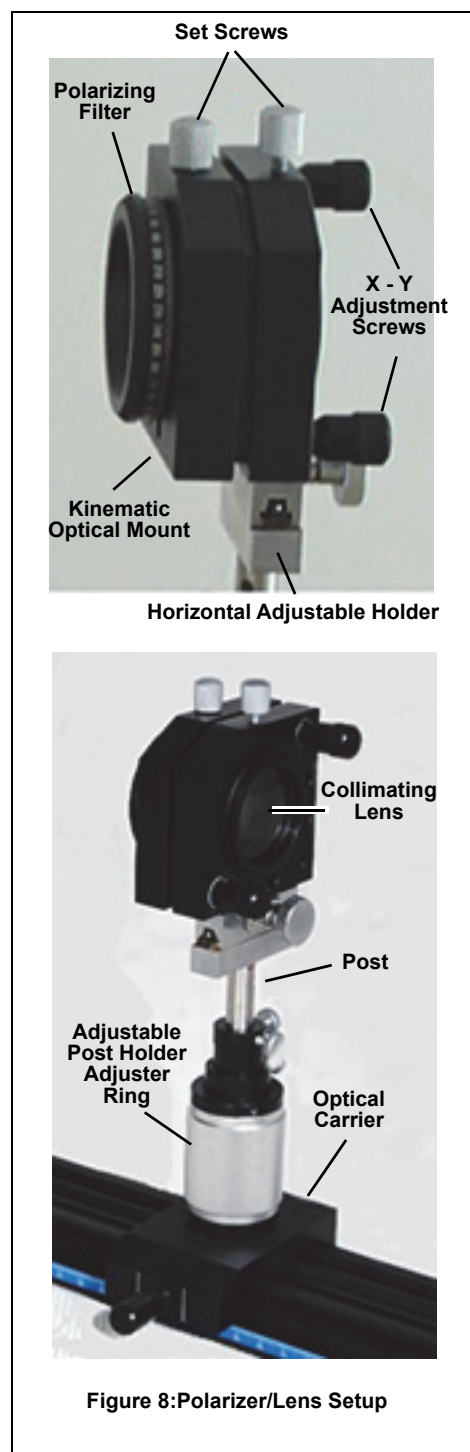


Figure 8: Polarizer/Lens Setup

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 flashlight (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.

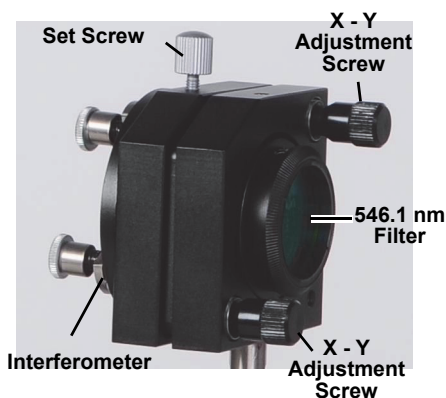


Figure 10: Interferometer/Filter Assembly

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

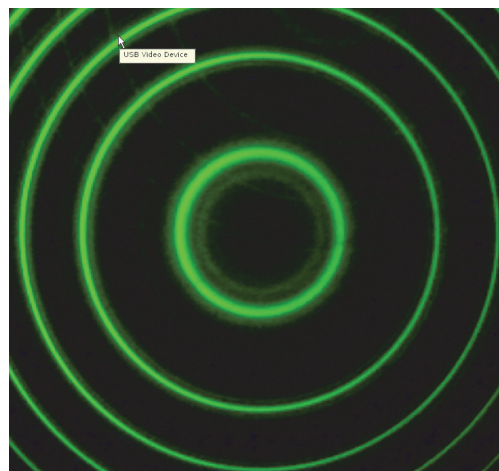


Figure 11: “Bulls-eye” Image

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.

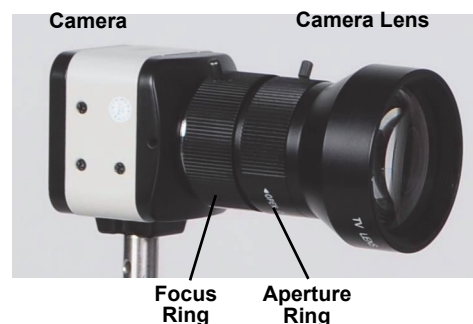


Figure 12: Camera/Lens Assembly

- 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.

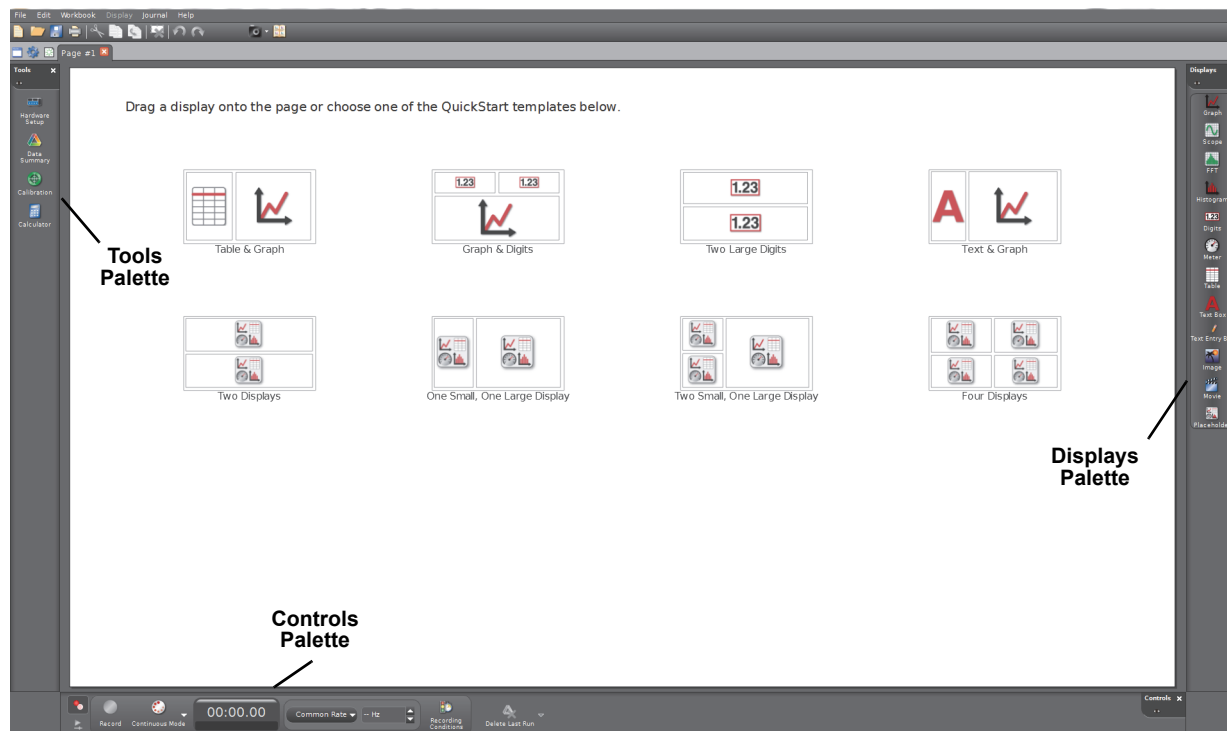



Figure 13: PASCO Capstone

- 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.

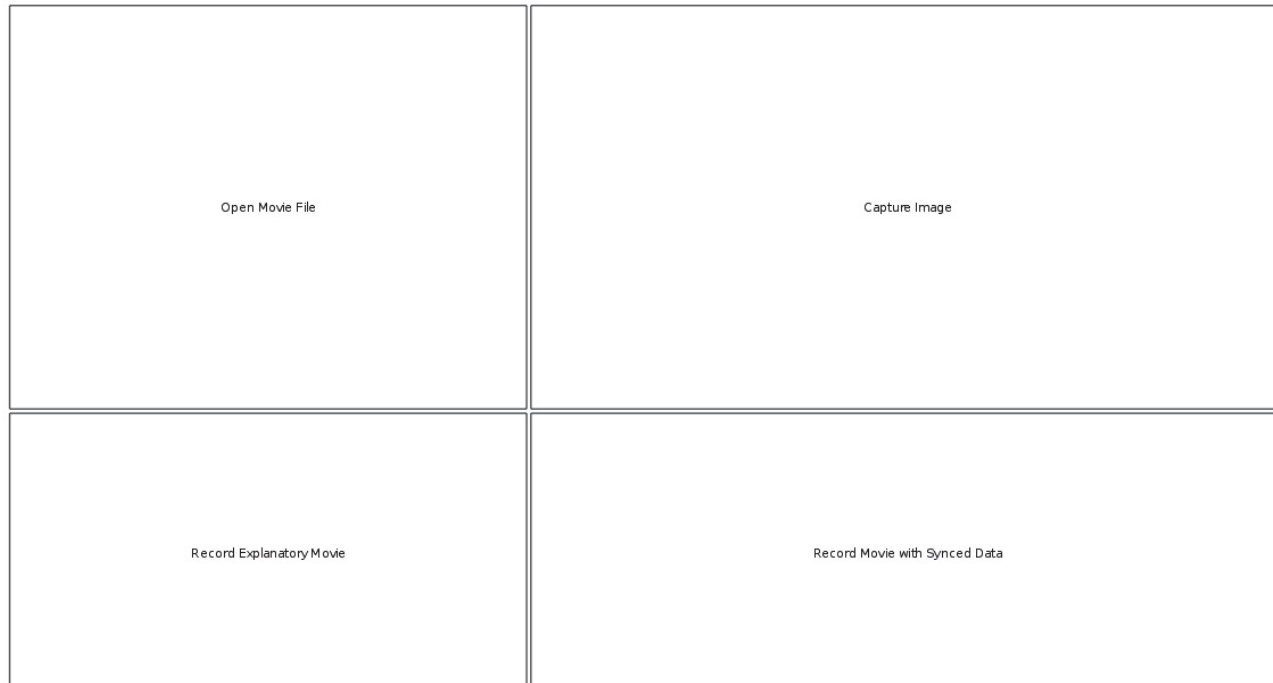


Figure 14: PASCO Capstone Movie Display

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.

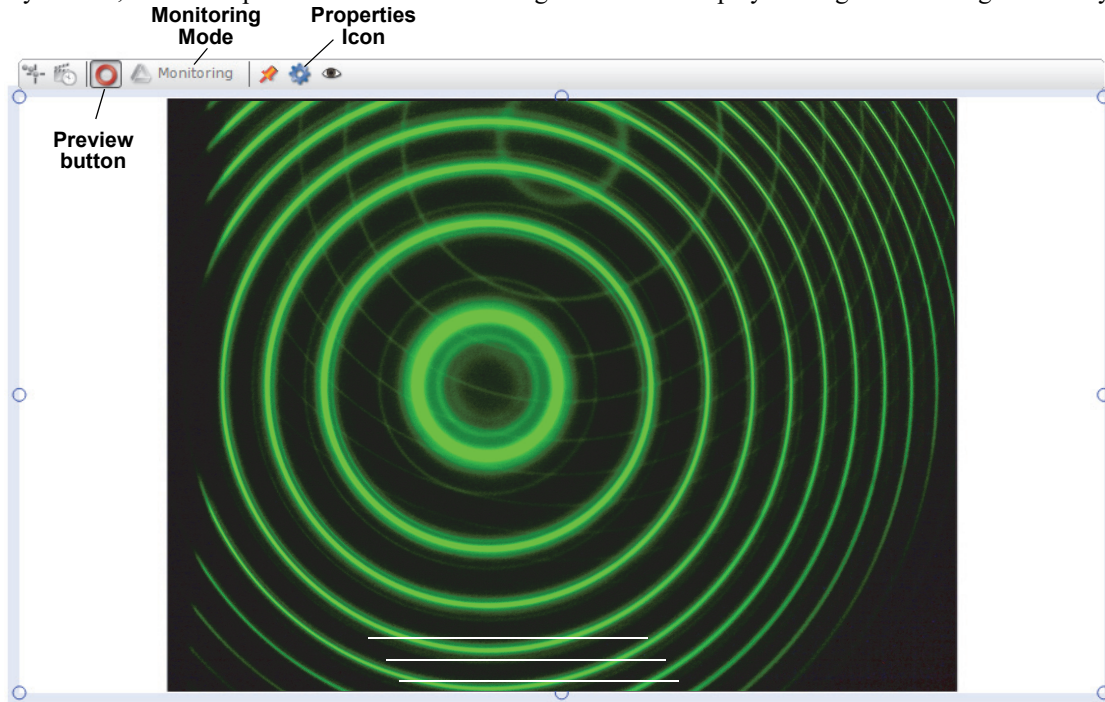


Figure 15: Interference Pattern Example

- 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”.

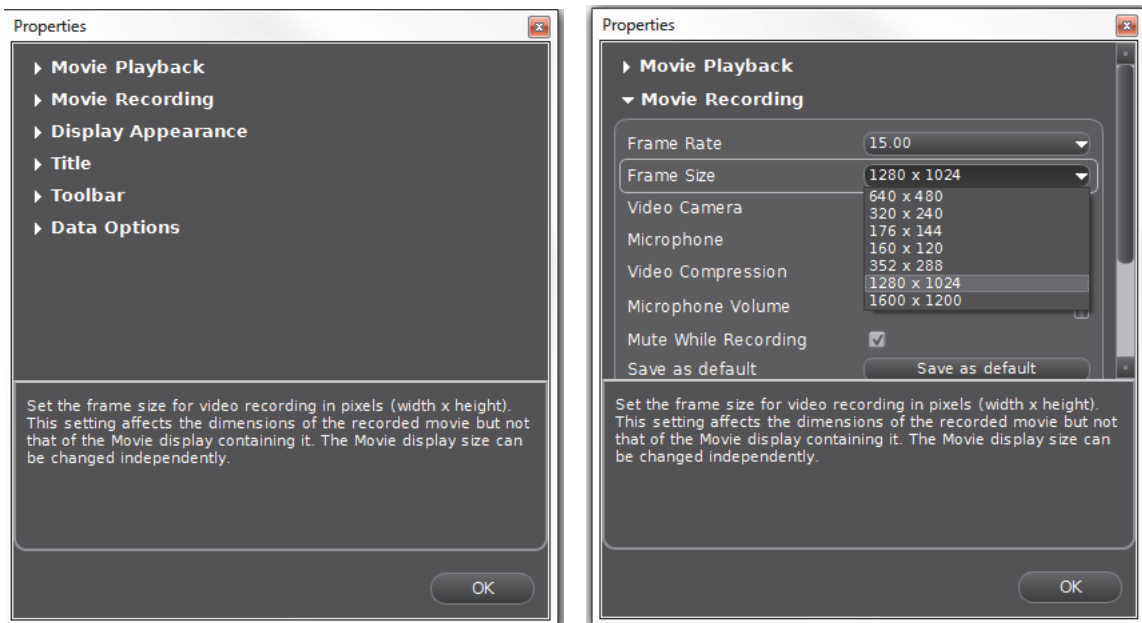


Figure 16: Movie Display Properties

- 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-

- 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.
- If the pattern is not uniformly illuminated (as in Figure 17, use the knob on the horizontal adjustable holder of the polarizer/lens assembly to adjust the horizontal position of the polarizer/lens assembly.
- 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 18. The rings should be sharply defined all the way around.

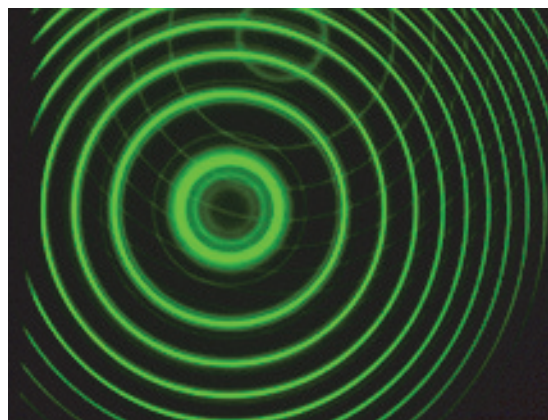
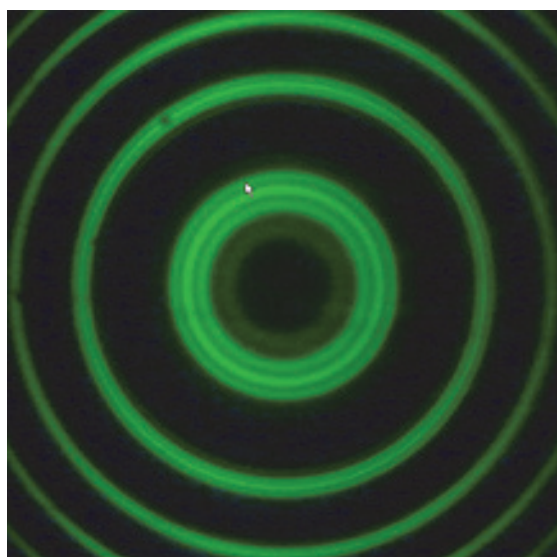


Figure 17: B = 0 Pattern



Rings split
into triplets

Figure 18: Well Aligned Pattern

- If the pattern is like Figure 19, 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!
- After completing the adjustments, reduce the power supply output to 0.00 A.

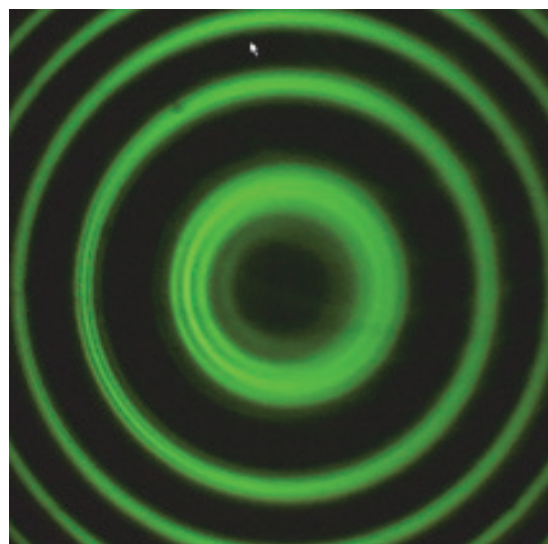




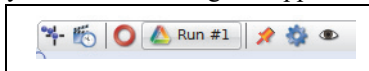
Figure 19: Poorly Aligned Pattern

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

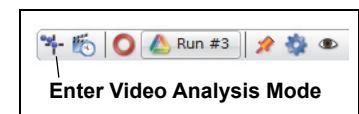
2. Check that the polarizer is still set at 90° and the power is at 5 A. Click **Record**. After a few seconds, *rotate the polarizer to 0°*. Wait a few more seconds and then *remove the polarizer*. After a few more seconds, click **Stop**.
- This is Run #2.
3. Replace the polarizer.

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

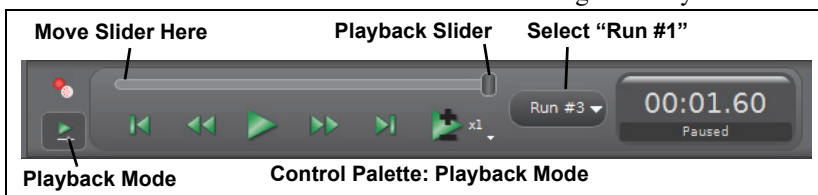
4. Remove the axial iron core plug (silver knob) from the electromagnet. (It just slides out, but is a tight fit so it is probably easier to rotate it as you pull out). Rotate the electromagnet by 90° on its base so the axial hole is toward the camera.
5. Click the **Preview** button in the movie toolbar (). 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

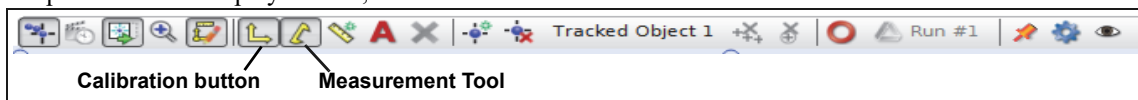
1. Click the “Enter Video Analysis Mode” button at the left end of the movie toolbar to expand the movie display toolbar.



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



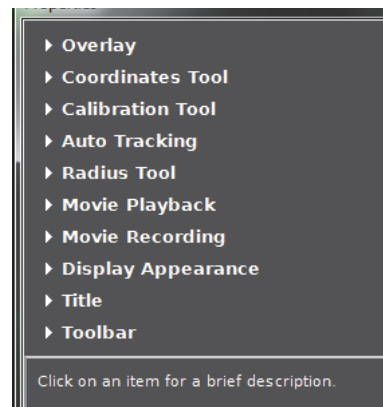
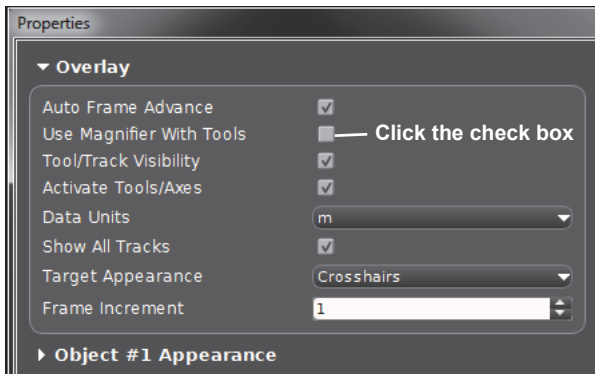
2. Select “Run #1” from the menu in the Control Palette. Move the playback slider to the *beginning* ($B = 0$ at that point).
3. In the expanded movie display toolbar, click the “Calibration” button to turn off Calibration.


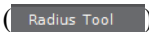


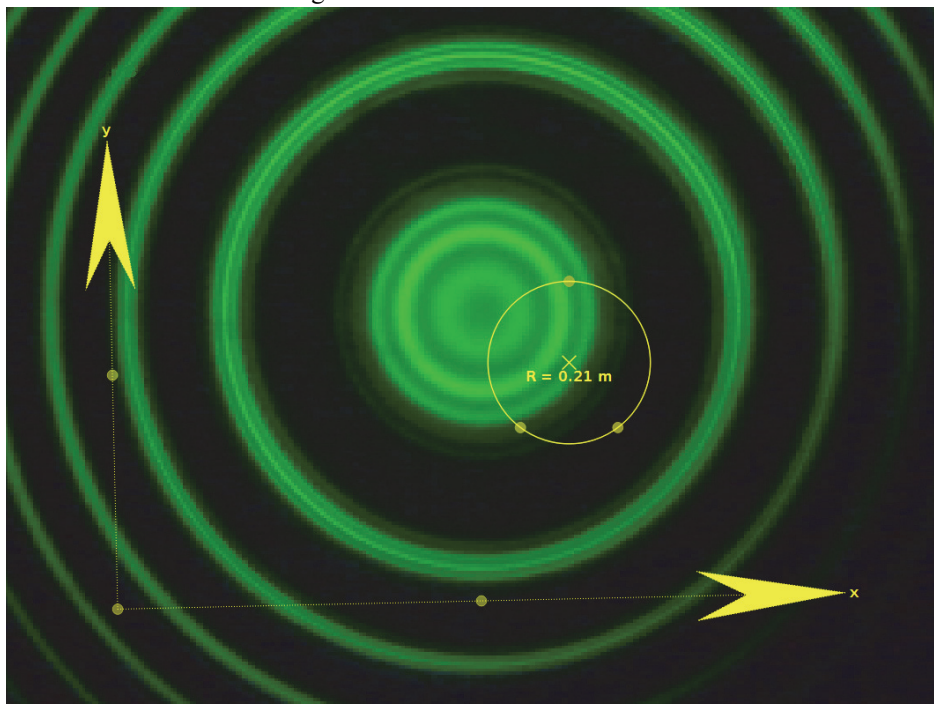
- NOTE: This means that the radius tool will not be calibrated. This will affect the value of C_0 , but it will not affect the final result. An examination of Equations 12 and 13 shows that the radii are squared in both the denominator and the numerator, so any scale factor cancels out.

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

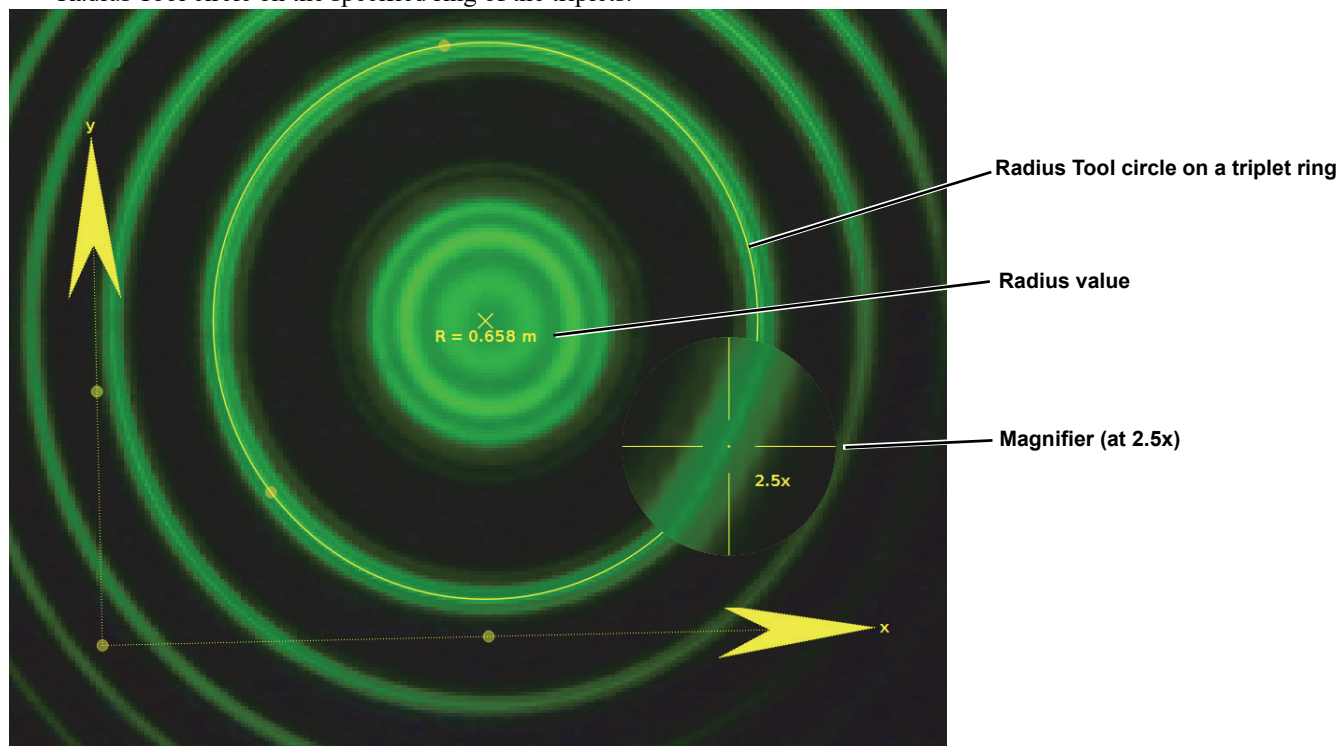
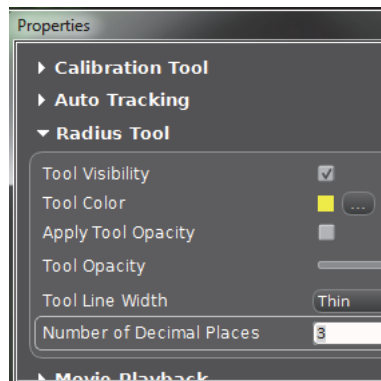
Click the Properties icon (shaped like a gear) at the right-hand end of the movie display toolbar to open the Properties window. In the window, click "Overlay". Click the check box to select "Use Magnifier With Tools" from the list of choices under "Overlay".



- 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.



- 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.
- 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 $k = 3$.
- 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.



- Record the value for the radius, R , to three decimal places in Table 1 below (where k is the ring number).
 - Move the X-Y Axes so the origin is at the point marking the center of the circle.
 - 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 $k = 1$

- 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).
- 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:

Table 1: Run #1, B = 0	
k	Radius (m)
4	
3	
2	
1	
0	

Table 2: Run #1, B \neq 0, k = 1		
Trial	R+ (m)	R- (m)
1		
2		
3		

Table 3: Run #1, B \neq 0, k = 0		
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.

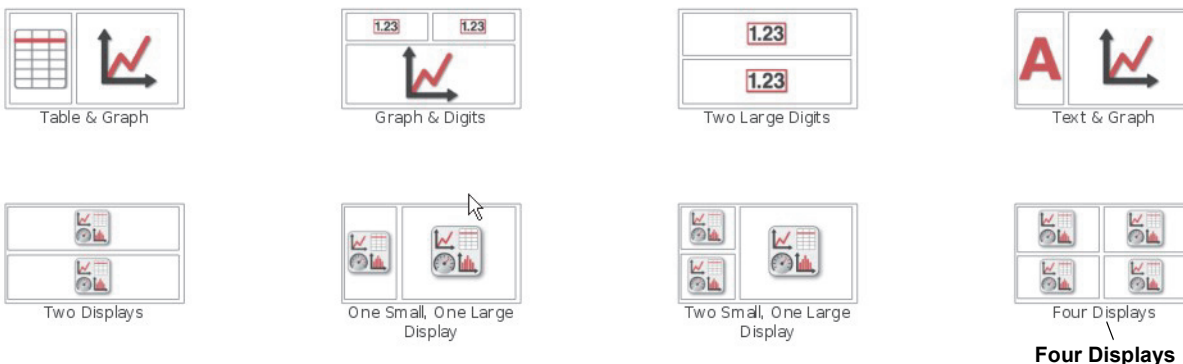


Figure 20: Click the Four Displays Icon

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

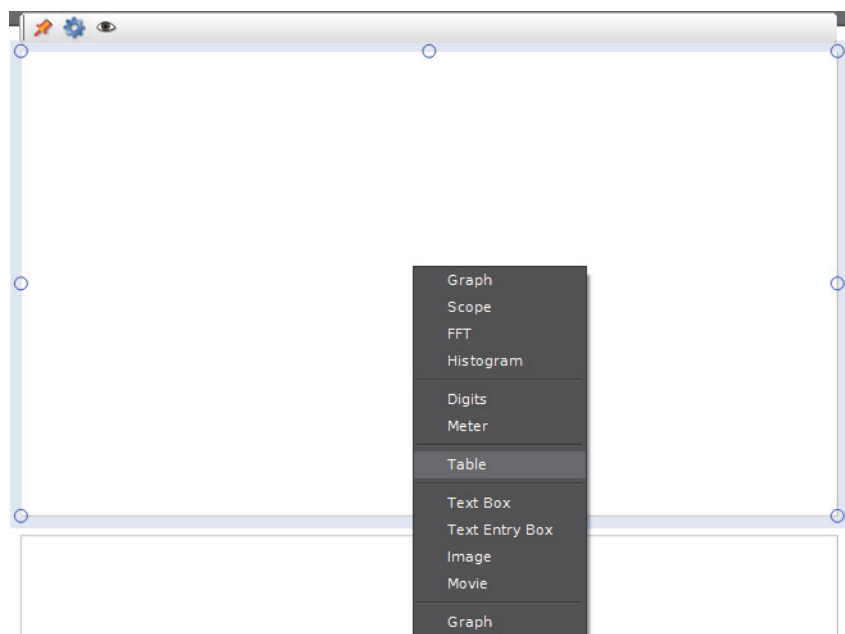


Figure 21: Select Table from the menu

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.

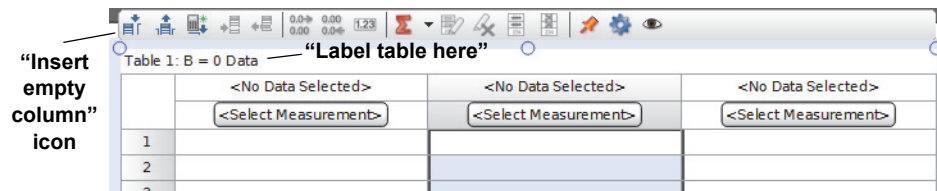


Figure 22: Label the Table and add a Column

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

- 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.

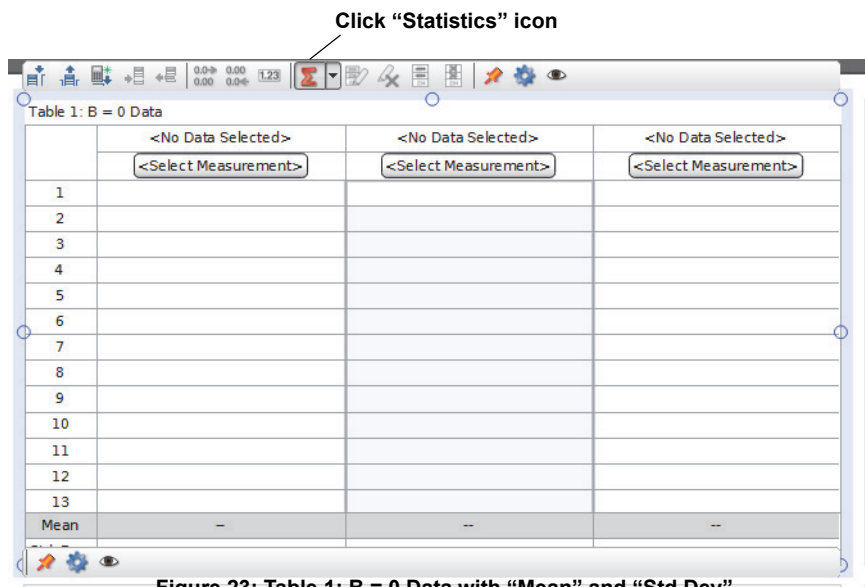


Figure 23: Table 1: B = 0 Data with “Mean” and “Std Dev”

Setup Table 2

- 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

- 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.

The screenshot shows a spreadsheet with three tables. Table 1 is titled 'Table 1: B=0 Data' and has 11 rows (1-10) and 4 columns. The first column is labeled '1', and the other three are labeled '<No Data Selected>'. Each of these three columns has a '<Select Measurement>' button at the top. Summary rows for Mean and Std. Dev. are at the bottom, showing '--'. Table 2 is titled 'Table 2: B=0, k=0' and has 10 rows (1-9) and 4 columns. The first column is labeled '1', and the other three are labeled '<No Data Selected>'. Each of these three columns has a '<Select Measurement>' button at the top. Summary rows for Mean and Std. Dev. are at the bottom, showing '--'. Table 3 is titled 'Table 3: B=0, k=1' and has 11 rows (1-10) and 4 columns. The first column is labeled '1', and the other three are labeled '<No Data Selected>'. Each of these three columns has a '<Select Measurement>' button at the top. Summary rows for Mean and Std. Dev. are at the bottom, showing '--'. The spreadsheet interface includes a toolbar at the top with various icons and a status bar at the bottom.

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.

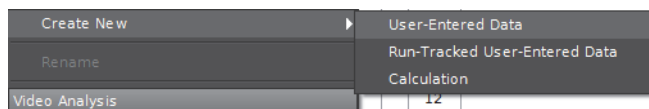


Figure 25: Select “User-Entered Data”

- “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.

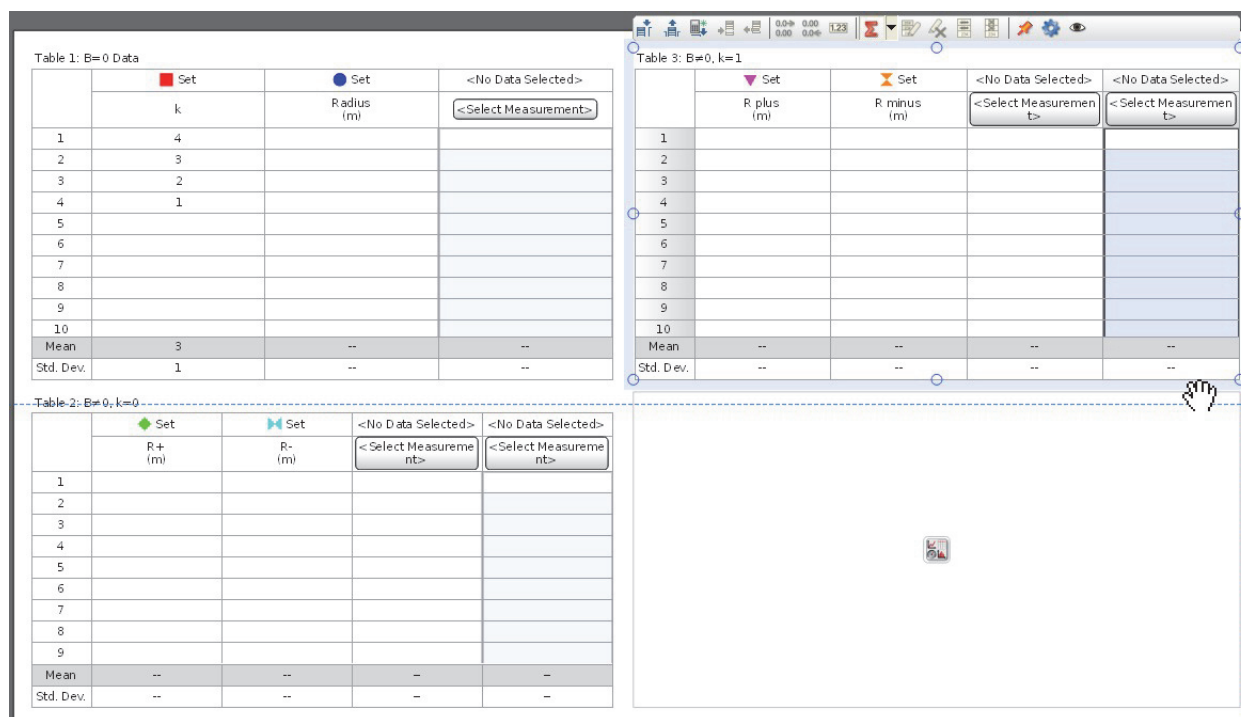




Figure 26: Workbook page with table columns labeled

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	$R_0 = 0.199$	m
4	$C = [k]/([Radius (m)]^2 - [R_0 (m)]^2)$	$1/m^2$
5	$C_0 = 2.567$	$1/m^2$

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 [R₀] is under “Constants” and then “User-Defined Constants”.
- You may type the exponents or use the x² button in the Scientific keypad.

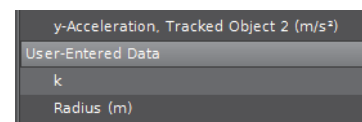



Figure 28: User-Defined Data


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, [Planck’s constant (J •s)], and the third term [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”.

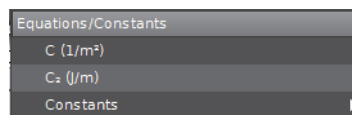





Figure 30: Equations/Constants

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.

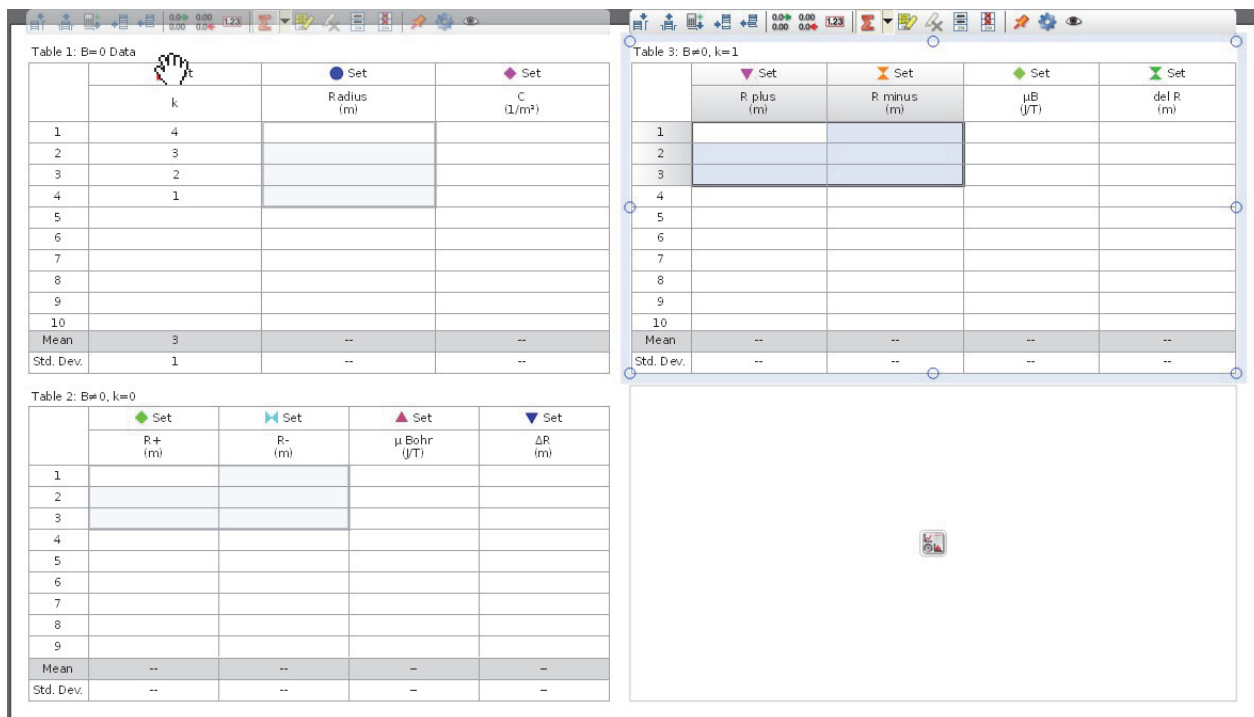


Figure 31: Finished Workbook Page of Tables 1, 2, and 3

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

1. Do the mean values for the Bohr magneton from Table 2 and Table 3 agree with theory (9.27×10^{-24} 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?

Appendix A: Intensity of Current (A) and Intensity of Magnetic Induction (T)

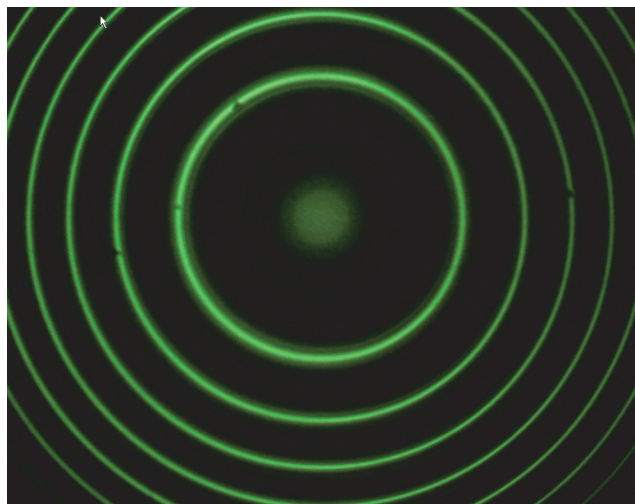
The following is an example of the TEST REPORT that is included with the Electromagnet. Each electromagnet should have its own unique TEST REPORT. Note the **Serial No.** on the **TEST REPORT** This number is also found on one side of the bracket that supports the electromagnet's coils.

TEST REPORT																							
Product: Zeeman Effect with an Electromagnet Model: BEX-8501 Batch No: 000101-130827-02&130914-01 Serial No: BEX-8501-0085	Tested by: <u>ZL Zou</u> Checked by: <u>Nan Shu</u> Date: <u>2013.11.20</u>																						
Experimental data:																							
The Relation Between Intensity of Magnetic Induction and Intensity of Current																							
<table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="text-align: center;">Intensity of Current (A)</th> <th style="text-align: center;">Intensity of Magnetic Induction (T)</th> </tr> </thead> <tbody> <tr><td style="text-align: center;">0.5</td><td style="text-align: center;">0.250</td></tr> <tr><td style="text-align: center;">1.0</td><td style="text-align: center;">0.486</td></tr> <tr><td style="text-align: center;">1.5</td><td style="text-align: center;">0.682</td></tr> <tr><td style="text-align: center;">2.0</td><td style="text-align: center;">0.792</td></tr> <tr><td style="text-align: center;">2.5</td><td style="text-align: center;">0.872</td></tr> <tr><td style="text-align: center;">3.0</td><td style="text-align: center;">0.934</td></tr> <tr><td style="text-align: center;">3.5</td><td style="text-align: center;">0.986</td></tr> <tr><td style="text-align: center;">4.0</td><td style="text-align: center;">1.031</td></tr> <tr><td style="text-align: center;">4.5</td><td style="text-align: center;">1.070</td></tr> <tr><td style="text-align: center;">5.0</td><td style="text-align: center;">1.105</td></tr> </tbody> </table>	Intensity of Current (A)	Intensity of Magnetic Induction (T)	0.5	0.250	1.0	0.486	1.5	0.682	2.0	0.792	2.5	0.872	3.0	0.934	3.5	0.986	4.0	1.031	4.5	1.070	5.0	1.105	
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<i>Note: The exact data obey this data testing report</i>																							
Sample Data																							
<table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="text-align: center;">No.</th> <th style="text-align: center;">e/m($\times 10^{11}$ C/Kg)</th> </tr> </thead> <tbody> <tr><td style="text-align: center;">1</td><td style="text-align: center;">1.746</td></tr> <tr><td style="text-align: center;">2</td><td style="text-align: center;">1.720</td></tr> <tr><td style="text-align: center;">3</td><td style="text-align: center;">1.794</td></tr> <tr><td style="text-align: center;">4</td><td style="text-align: center;">1.735</td></tr> <tr><td style="text-align: center;">5</td><td style="text-align: center;">1.726</td></tr> </tbody> </table>	No.	e/m($\times 10^{11}$ C/Kg)	1	1.746	2	1.720	3	1.794	4	1.735	5	1.726											
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1	1.746																						
2	1.720																						
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5	1.726																						
Error Analysis																							
<table border="1" style="width: 100%; border-collapse: collapse;"> <tbody> <tr> <td style="padding: 2px;">Average value($\times 10^{11}$ C/Kg)</td> <td style="text-align: center; padding: 2px;">1.744</td> </tr> <tr> <td style="padding: 2px;">Standard value($\times 10^{11}$ C/Kg)</td> <td style="text-align: center; padding: 2px;">1.759</td> </tr> <tr> <td style="padding: 2px;">Relative error</td> <td style="text-align: center; padding: 2px;">-0.841%</td> </tr> </tbody> </table>	Average value($\times 10^{11}$ C/Kg)	1.744	Standard value($\times 10^{11}$ C/Kg)	1.759	Relative error	-0.841%																	
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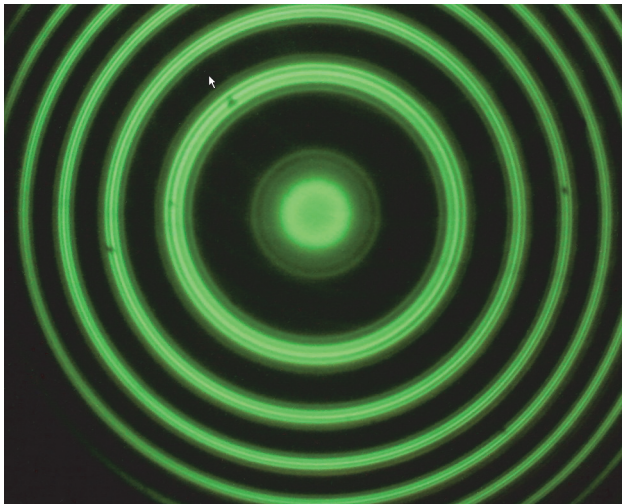
Appendix B: Teacher's Notes

Sample Data

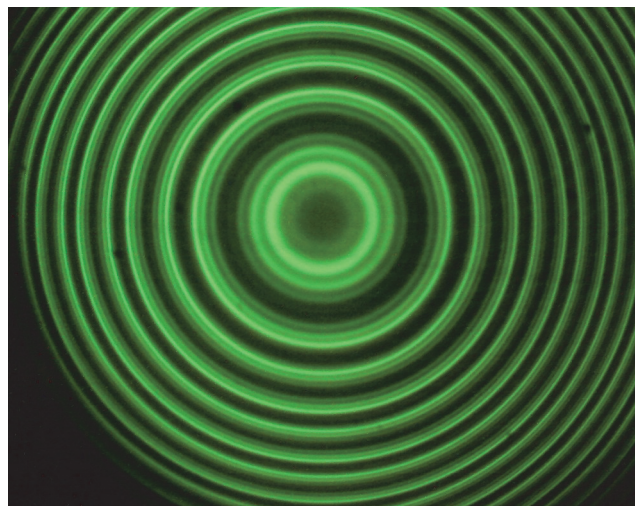
Images: Run #1 and Run #2



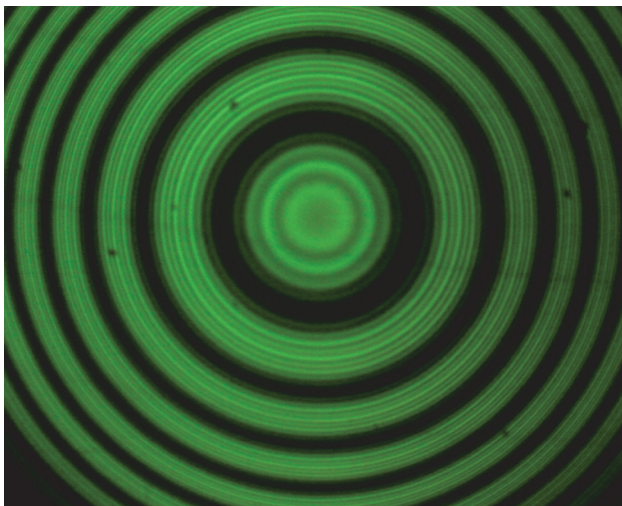
Run #1: $B = 0$, Polarizer at 90°



Run #1: $B \neq 0$, Polarizer at 90° (3.50 A)



Run #2: $B \neq 0$, Polarizer at 0° (3.50 A)



Run #2: $B \neq 0$, No Polarizer (3.50 A)

Radius Measurements: Run #1

Table 1: Run #1, $B = 0$	
k	Radius (m)
4	1.267
3	1.099
2	0.906
1	0.653
0	

Trial	R+ (m)	R- (m)
1	0.274	0.097
2	0.274	0.095
3	0.275	0.100

Trial	R plus (m)	R minus (m)
1	0.680	0.630
2	0.685	0.633
3	0.681	0.631

Calculation Results: Run #1

Table 1: $B=0$ Data

	k	Radius (m)	C ($1/m^2$)
	4	1.267	2.555
	3	1.099	2.568
	2	0.906	2.560
	1	0.653	2.585
Mean	3	0.981	2.567
Std. Dev.	1	0.264	0.013

Calculation Results: Run #1

Table 2: $B \neq 0$ $K=0$ data

	R+ (m)	R- (m)	μ Bohr (JT)	ΔR (m)
1	0.274	0.097	8.99E-24	0.177
2	0.274	0.095	9.04E-24	0.179
3	0.275	0.100	8.98E-24	0.175
Mean	0.274	0.097	9.00×10^{-24}	0.177
Std. Dev.	5.774×10^{-4}	0.003	3.21×10^{-26}	0.002

Table 3: $B \neq 0$ $K=1$ Data

	R plus (m)	R minus (m)	μB (JT)	del R (m)
1	0.680	0.630	8.96E-24	0.050
2	0.685	0.633	9.38E-24	0.052
3	0.681	0.631	8.98E-24	0.050
Mean	0.682	0.631	9.11×10^{-24}	0.051
Std. Dev.	0.003	0.002	2.36×10^{-25}	0.001

Questions:

1. Do the “Mean” values for the Bohr magneton, μ_{Bohr} and μ_B , from Table 2 and Table 3 agree with theory (9.27×10^{-24} J/T)? Discuss fully.

The values are close. The $k = 0$ mean value is about 3% low and the $k = 1$ mean value is about 2% low. Based on the standard deviation of the three runs, the precision is about 2.5% for the $k = 1$ values but less than 0.5% for the $k = 0$ values. This is probably optimistic for the $k = 0$ data since the calculation is based on $(R_+^2 - R_-^2) = (R_+ - R_-)(R_+ + R_-) \times \Delta R$. Note that ΔR is about $\pm 2\%$ for the $k = 1$ case in good agreement with our result, but ΔR is about $\pm 1\%$ for the $k = 0$ case so the uncertainty in μ_{Bohr} cannot be less than 1% and there was some luck involved in getting three values that agree within 0.4%. Thus, the $k = 0$ and $k = 1$ values agree with each other. However, since the $k = 0$ value has an uncertainty that is about 2.5 times smaller, when we average the values, we should weight the $k = 0$ value $2.5^2 = 6$ times heavier. So we have $\mu_{\text{Bohr}} = 9.02(10) \times 10^{-24}$ J/T. This does not quite agree with the theory value and we note that almost all the values are low. This implies a small systematic error. Direct measurement shows that the field in the gap between the poles is somewhat low in the region near where the axial hole was drilled, even with the plug in place. This would explain our slightly low result. Nevertheless, the results are impressive.

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?

Yes, the center circle of the triplet was the same as $B = 0$ line. This means that the energy of the center line does not shift.

- 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.
3. How many energy levels do you see now for the $k = 1$ band of circles? Does this agree with the discussion in the theory section?

With the polarizer perpendicular to the field axis, there are three levels above where the triplet levels were and three levels below. This is exactly what was predicted.

- Now move the playback slider to the end of Run #2 where the polarizer was removed.
4. Can you see all the bands? How many are there? Does it match theory?

Now nine levels show. This agrees with prediction.

- 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?

Rotating the polarizer has no effect on the pattern. This shows that the light is either unpolarized or circularly polarized. (It is actually circularly polarized.) With circular polarization, the axis of polarization rotates. This means that every half cycle the light gets through independent of the polarizer's orientation. Since the rotation is very fast, we see only the average which is independent of polarizer orientation.

6. Why is all of this important?

This is direct evidence that the magnetic moment of atoms is quantized both in magnitude and (more surprisingly) in direction. Although most students have accepted this by believing in the quantum numbers taught in a basic chemistry class to explain the atomic table (which they do quite well), here we see direct evidence of the quantization. To classical physicists educated before 1920, this idea was astonishing!

Appendix C: Maintenance and Storage

- The Zeeman Effect Apparatus should be used in a dry clean room with good ventilation.
- Lubricate the surface of the optical track periodically to prevent it from rusting.
- When not in use, the Fabry-Perot interferometer should be stored in a sealed container with a desiccator (drying agent). Replace the desiccator periodically to prevent mold formation.
- Do not touch any optical part with your fingers. To remove dust or dirt, use a photographic lens brush, or blow the dust off with “canned air”. Do not use compressed air from an air line as this frequently contains oil droplets, which will contaminate the surface of the optical parts.
- Stubborn dirt may be removed by gently cleaning the surface with a cotton ball soaked in a 1:1 mixture of denatured alcohol and ether.
- To prolong the life of the mercury lamp, avoid turning it on and off frequently.
- When applying the magnetic field, increase the current slowly and avoid using a maximum current for long periods. This will avoid excessive heat generation in the electromagnet coils.

Appendix D: Technical Support, Copyright, Warranty

For assistance with the equipment or any other PASCO products, contact PASCO as follows:

Address: PASCO scientific
10101 Foothills Blvd.
Roseville, CA 95747-7100

Web: www.pasco.com

Phone: +1 916 462 8384 (worldwide)
800-772-8700 (U.S.)

Email support@pasco.com

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Warranty

For a description of the product warranty, see the PASCO catalog.

Appendix E: Product End of Life Disposal Instructions

Product End of Life Disposal Instructions:

This electronic product is subject to disposal and recycling regulations that vary by country and region. It is your responsibility to recycle your electronic equipment per your local environmental laws and regulations to ensure that it will be recycled in a manner that protects human health and the environment. To find out where you can drop off your waste equipment for recycling, please contact your local waste recycle/disposal service, or the place where you purchased the product.



The European Union WEEE (Waste Electronic and Electrical Equipment) symbol (above) and on the product or on its packaging indicates that this product must not be disposed of in a standard waste container.

Mercury Lamp Disposal Instructions:

Mercury Lamps contain chemicals that, if released, may affect the environment and human health. Mercury Lamps should be collected separately for recycling, and recycled at a local hazardous material disposal location adhering to your country and local government regulations. To find out where you can drop off your waste Mercury Lamps for recycling, please contact your local waste disposal service, or the place where you purchased the product.