

Optical Polarization (Optics)

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November 16, 2011

Visible light is only a small fraction of the electromagnetic spectrum. In fact, light is composed of oscillating electric (**E**) and magnetic field (**B**) vectors. These vectors are mutually perpendicular as well as perpendicular to the direction of the propagation.

Light passing through vacuum is the simpler to understand, moving unperturbed with the speed $c \approx 3 \times 10^8$ m/s but in the present experiment we would like to understand the more complicated (and aesthetically assuring!) problem of how radiation interacts with matter. The simple experimental setup will help us appreciate one facet of light's wave nature itself, its polarization and how this polarization can rotate as it traverses an optically active liquid.

KEYWORDS

Polarization · Optical Activity · Chirality · Stereochemistry · Enantiomers · Laser · Photodetectors · Cathode Ray Oscilloscope

APPROXIMATE PERFORMANCE TIME 5 hours.

1 Conceptual Objectives

In this experiment, we will,

1. learn how to use lasers safely;
2. practice aligning of optical setups;
3. investigate the concept of standard errors in simple measurements;
4. identify regions where measurements yield the most precise results;
5. learn the use of cathode ray oscilloscopes (the work-horse of most science laboratories);
6. identify uncertainties in measurement of angular and linear scales;

7. correlate experimental data with mathematical expressions;
8. observe the difference between accurate and precise results;
9. learn that for wave motion, intensities are squares of amplitudes; and
10. reveal the inter-disciplinary character of experimental science, revisiting an experiment that is routinely performed in the chemistry laboratory.

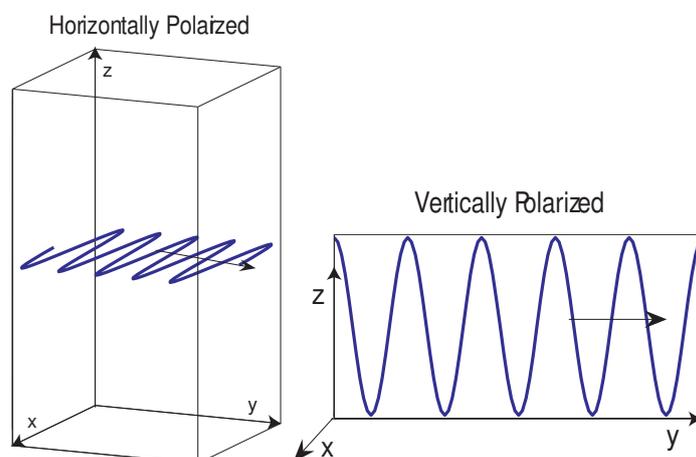
2 Experimental Objectives

The experiment manifests the wave nature of light through the concept of polarization. We will also find the optical activity of a commonly available compound showing how the plane of polarization can be rotated by certain molecules. Finally, we will demonstrate the concept of “optimal sampling”.

3 Theoretical Introduction

3.1 Polarization

Light is emitted by tiny atomic or molecular *emitters*. The electric field vector from a single emitter oscillates in a plane perpendicular to the direction of propagation.



The light is said to be *linearly polarized*. We may have horizontally (*H*) or vertically (*V*) polarized light, where the electric field vector vibrates in the horizontal or vertical planes, respectively. We may also have polarizations that are tilted with respect to these axes, 40° , 60° , 230° and so on.

Most objects we are familiar with, however, emit unpolarized light. The planes of polarization are oriented randomly in all possible directions. A *polarizer* picks up only plane of vibration from all these random orientations and produces *plane polarized* light. Materials that have this property are generally used in making polarized sunglasses.

The direction of the plane of polarization emerging from the polarizer depends on its *optical axis*. We use a polarizer in which the direction of polarization is marked by two diametrically opposed green spots. (However, you cannot see them because the lab demonstrators have already fitted the polarizers into their mounts). Suppose we orient the optical axis so that we obtain vertically polarized light. The electric field vector is always pointing along the vertical ($\pm\hat{z}$) direction while the light moves forward in the horizontal \hat{y} direction. For such an arrangement, the electric field is,

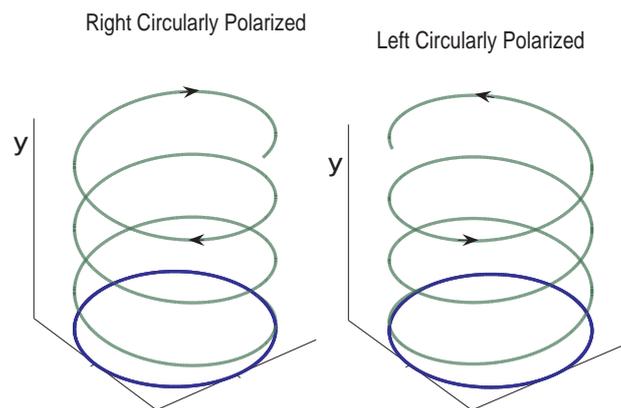
$$E_0 \cos(ky - \omega t + \phi) \hat{z}, \quad (1)$$

where E_0 is the amplitude, $\omega = 2\pi f$ is the frequency, $k = 2\pi/\lambda$ is the wave number and ϕ is the phase of the wave. Make sure you understand these terms [1].

On the other hand, if the optical axis were horizontal (along the \hat{x} axis), we would obtain horizontally polarized light,

$$E_0 \cos(ky - \omega t + \phi) \hat{x}. \quad (2)$$

The direction in which light propagates is still along the \hat{y} axis. Note that the unit vector written in bold denotes the *direction of the plane of polarization*, whereas the variable y next to k denotes the *direction of propagation*.



We can also get *circularly polarized* light. In this case, the field vector rotates along a helix just like a screw. When viewed from the end, the vector is in fact moving in a circle. This happens when you add or subtract two components that are 90° out of phase, a sine and a cosine. This circularity can be right or left depending on how you add or subtract the components,

$$E_0[\cos(ky - \omega t + \phi_0) \hat{z} - \sin(ky - \omega t + \phi_0) \hat{x}], \quad (3)$$

$$E_0[\cos(ky - \omega t + \phi_0) \hat{z} + \sin(ky - \omega t + \phi_0) \hat{x}]. \quad (4)$$

The tip of the electric field vector rotates clockwise or anticlockwise for circularly polarized light, but the important thing to remember is that the phase (ϕ_0) is the same for both the components. The accompanying Figures may help you perceive this concept better.

Q 1. Write down the mathematical expression for the electric field for light that is linearly polarized with a plane of polarization making an angle of 45° with the \hat{x} and \hat{z} axes? In which direction is the light propagating?

3.2 Malus's Principle

In our experiment randomly polarized light from a laser (633nm) passes through two polarizers labelled A and B as shown in Figure 1. The field emerging from A is given by the expression (1). The field emerging from B is determined by the relative orientations of the optical axes of A and B. The polarizer B used in this way is called an *analyzer*.

If the relative orientation between A and B is θ , then the emergent electric field after passing through B becomes,

$$E_0 \cos \theta \cos (ky - \omega t + \phi) \hat{z}. \quad (5)$$

This represents a *decrease* in the amplitude by a factor of $\cos \theta$. But experimentally, we measure the intensity, not the electric field. As the intensity is proportional to the amplitude squared, it reduces by a factor of $\cos^2 \theta$. This statement is the Malus's principle, mathematically captured as,

$$I_B = I_A \cos^2 \theta. \quad (6)$$

We will measure intensities using a silicon photodetector. Remember that I_A and I_B are the intensities of the radiation emerging from the polarizers A and B. The arrangement is depicted in Figure 2.

Q 2. A third polarizer C is placed between A and B. The relative orientation between A and B is unchanged at the value θ . The inclination between A and C is β . What relationship must the angles satisfy to ensure that $I_B = I_A$?

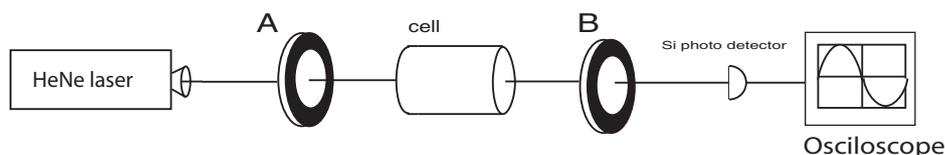


Figure 1: Schematic sketch of the experimental setup.

Our polarizers act as “projectors”—they project a vector onto a certain axis. It is also possible to do something more complicated, *i.e.*, to physically *rotate* the plane of polarization. This is achieved through optical components called *wave plates* or *retarders*. In our experiment we will achieve the same effect using certain chemical substances that are called *optically active* substances. What are the basic properties of optically active substances and why are they important? This question requires a foray into the area of stereochemistry.

3.3 Chirality and Enantiomers

Try to recall what you saw when you were combing your hair in the morning or brushing your teeth for that matter. What did you see? ‘Your image!’ That is such a trivial question. But what if you are asked to place your image on top of your original self. Will they coincide or not? The answer is ‘No! They will not’. This ‘placing on top’ is called *superposing*. If you have parted your hair on the right, your image has parted them on the left. Try shaking hands with your mirror image. You will be confounded. Similarly there is no painless way of wearing your left shoe on your right foot.

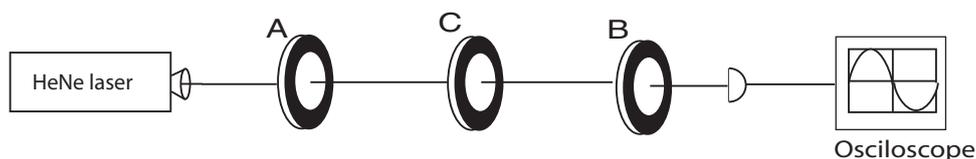


Figure 2: Schematic for Q2.

With this background, consider a molecule, a network of atoms arranged in three dimensional space. Two molecules may have an identical composition of atoms and the same bonding network, however they may still differ in their detailed three dimensional arrangement. Surprisingly, these variants of molecules can have totally different physical and even chemical properties.

For example, consider bromochlorofluoromethane. Its structure is shown in Figure 3. Now place a mirror next to the molecule and observe the image. The mirror image has a distinct configurational arrangement and **cannot** be superposed onto the original molecule (without of course, reflection through the mirror plane). The molecule and its non-superposable mirror image are *enantiomers* of each other and the corresponding property is called *chirality*. Only chiral molecules are optically active.

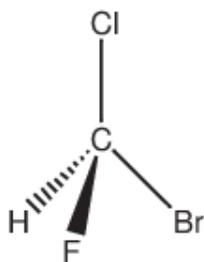


Figure 3: (a) Structure of fluoromethane and (b) its ball-and-stick model shown along with the mirror image. The wedge shaped arrows in (a) represent chemical bonds pointing out or into the plane of the paper.

Q 3. Identify the chiral molecules: (a) 3-methylhexane (b) 3-methylpentane (c) the amino acid glycine and (d) dibromochlorofluoromethane. The structures are shown in Figure 4.

Chirality is seen throughout the biological world. With the exception of inorganic salts and a few low molecular weight organic substances, molecules in living systems, both plant and animal are generally chiral. For example, only one of the stereoisomers called (*S*)-alanine occurs naturally. Enzymes that catalyze biochemical reactions are also highly stereoselective, i.e., they will speed up reactions only with one enantiomer of the chiral pair. Chymotrypsin, a chiral intestinal enzyme will break down only the corresponding peptide enantiomer during digestion. This 'chiral favouritism' in nature is one of the open questions in the life sciences. Researchers have even linked this with the similar question in cosmology of why the universe is made up of matter and not of antimatter!

In the chemical industry too, there is a drive towards synthesizing chiral catalysts for developing stereoselective reactions.

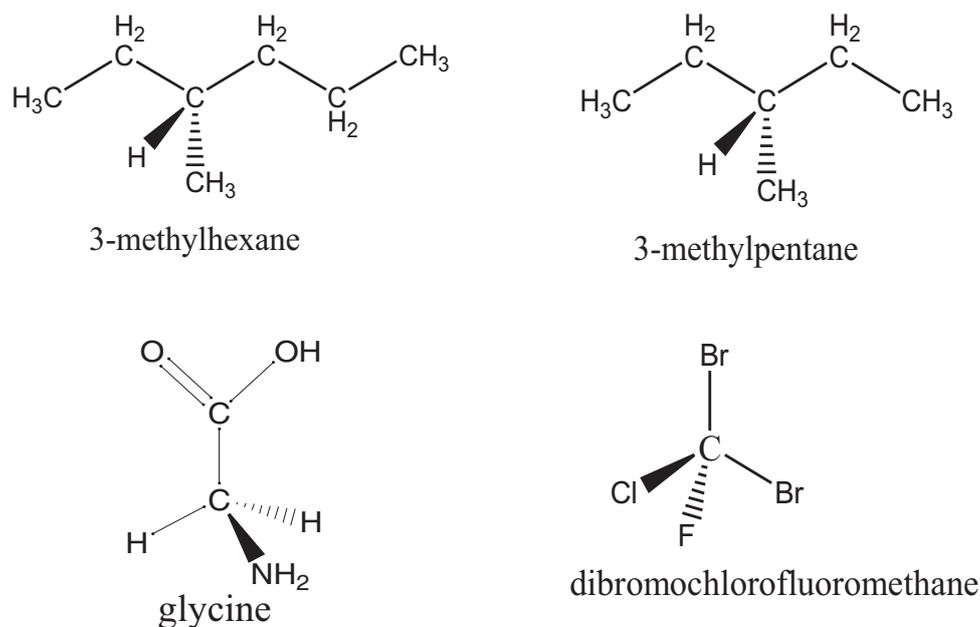


Figure 4: Chemical structures for the molecules named in Q3.

Chirality is also an important factor in drug efficacy and design. Drugs that are packaged as *racemic* mixtures, comprise equal amounts of the two enantiomers. However in most cases, only one of these molecules is biologically active. For example in *Ibuprofen*, sold as an analgesic in Pakistan in the racemic form, only the (*S*)-enantiomer is active [6]. Chiral drugs have now become a focus of most pharmaceutical companies. For example *Naproxen* available in this country is a chiral molecule and is sold in the enantiomerically pure form. Statistics show that about 56 percent of the drugs in present use are chiral molecules [7].

3.4 Light as a Chiral Probe

The human foot is a chiral entity. That is why a right shoe cannot fit on the left foot and a left shoe cannot fit on the right foot. However, the traditional footwear, the *khussa* can—it cannot distinguish between “leftness” and “rightness”. The shoe is a chiral probe whereas the *khussa* is an achiral entity.

Analogously, it is impossible to physically distinguish between two enantiomers using unpolarized light. One needs plane polarized light to test chirality.

The experiment that performs this probing is in fact, very simple. Shine polarized light onto an optically active substance. The plane of polarization rotates in one direction or the other. (We cannot tell before hand, the direction of physical rotation. This has to be determined from experiment.) For example, the chiral molecule *d*-glucose bends light to the right (when viewed along the direction of propagation) and this is experimentally determined. The prefixes *d* and *l* signify ‘dextro’ (right) and ‘levo’ (left) physical rotations.

Q 4. Why is plane polarized light chiral? Why is randomly polarized light achiral? *HINT:* Draw a one-sided arrow pointing upwards representing plane polarized light and reflect it across a plane perpendicular to the arrow.

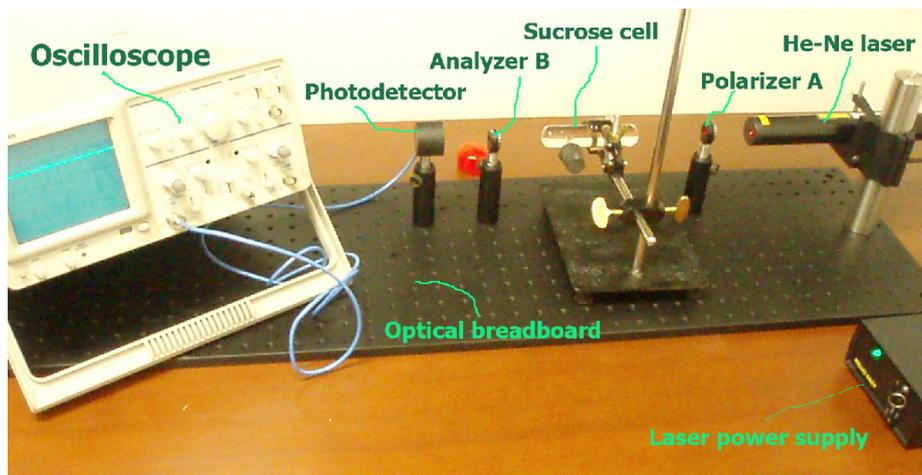


Figure 5: Photograph of the experimental setup. Refer to the Section on Apparatus for a description of the components.

Q 5. Polarized light is shone through a racemic mixture of glucose. In which direction will the plane of polarization rotate?

Q 6. A mixture of *l*-2-butanol and *d*-2-butanol rotates the polarization plane in the left direction through 10° . If pure *l*-2-butanol has a rotation of 13.5° in the same direction, determine the composition of the mixture.

Q 7. A liquid is made up of molecules randomly jostling in all directions. Investigate why this randomly oriented jumble-up can, in fact, rotate light so coherently in one direction.

In a chiral medium, each molecule contributes to the optical rotation. More molecules would imply stronger rotation. So a longer path length and a more concentrated solution would result in greater rotation angles. For comparison, we often normalize with respect to the length of the sample and concentration, resulting in the *specific optical activity*,

$$[\theta] = \frac{\theta}{c l} \quad (7)$$

where c is the concentration and l is the path length. It is also important to mention the temperature and wavelength of the light used.

Q 8. A sample of an optically pure enantiomer yields an optical rotation of about 180° . How will you determine whether it is dextrorotatory or levorotatory?

Q 9. What are the units of $[\theta]$?

4 Apparatus

The schematic of the experimental setup is shown in Figure 1 and a digital photograph in Figure 5.

1. **Laser** The source of light in the experiment is a continuous-wave He-Ne laser (*Melles-Griot 25-LHR-073* or *Thorlabs HRR020*) with a wavelength of 633 nm (red) and output power of 2 mW. The output from the laser is randomly polarized. The laser is mounted on a V-shaped housing (*Thorlabs*) attached to a mounting post (*Thorlabs*).

Lasers can be very dangerous if mishandled or if sufficient safety procedures are not followed. Always contact the lab staff if you have any doubt. In all cases, it is incumbent that you always abide by these **safety precautions** for our Class-IIIa laser.

- **Never look directly into the laser beam or direct the beam to anyone else or to an area where people are present. This may result in serious bodily damage.**
- Wear the properly rated safety glasses (*Thorlabs*) while performing the experiment.
- Do not scoop down to the level of the table or bring the laser to the level of the eye.
- Do not disconnect or connect the laser head from its high voltage power supply. The demonstrators have already completed this step for you.
- Do not remove the laser head from its housing.

2. **Polarizers and rotation mounts** The experiment uses two polarizers (*Thorlabs LPVIS050*) at the positions A and B in the experiment. These polarizers are mounted and retained in rotation mounts (*Thorlabs RSP05/M*). Be careful not to touch the surface of the polarizer. This will scratch the surface resulting in permanent damage. The rotation mount can be locked and unlocked with a hex key that is provided with the setup. The rotation mount is provided with an angular scale, that keeps track of the polarizer orientations.
3. **Optical activity cell** This is a cylindrical glass cell that has been designed in-house and manufactured by the glass-blowers (*Marghoob Scientific Store, Lahore*) in the market. The cell is supported by two crescent-shaped holders and posts manufactured locally (*Crown Engineering Works, Lahore*). The cell is fitted with inlet and outlet ports. When you start the experiment, the demonstrator will have already filled up the cell for you.
4. **Silicon photodetector** The Si photodetector (*Newport 818-SL*) converts incident light intensity into current. Ensure that the light falls in the central region of the photodetector. This is where the *sensitivity* (output current divided by the incident intensity) is flat and maximum. The output current is fed into an oscilloscope where it is converted into voltage.
5. **Cathode ray oscilloscope** The cathode ray oscilloscope (*GW-Instek GOS-635G*) is a ubiquitous tool used in most science laboratories, especially in physics and electrical engineering. A familiarity with this instrument is crucial, as it is likely to remain attached to your academic life at the SSE. In the present experiment, we will use the oscilloscope to measure voltages and your demonstrator will get you started in its use.

5 Experimental Method

5.1 Preparation

The laser has already been turned on by the demonstrators. Note that each time the laser is switched on, it takes about 15 minutes to warm up and reach a stable intensity.

★ **Q 10.** The demonstrator has already closed the shutter of the laser. Now connect the detector to the oscilloscope. Turn the input mode to GND. You should see a straight line. Turn the vertical positioning knob of the channel to place the line on the middle of the screen. Change the input mode to DC. Does the vertical position of the line shift? If yes, how much? This is background reading from ambient light? Turn the vertical positioning knob so that the background level is at the datum. All intensity readings will now be referenced to the background.

★ **Q 11.** Ask the demonstrator to open the laserhead shutter. Align the detector so that the laser spot falls on the approximate middle of the detector. What is the reading on the oscilloscope? Call it I_0 .

★ **Q 12.** What is the voltage sensitivity setting on the scope? Consequently, what are the units of I_0 ?

★ **Q 13.** Place the polarizer A near the output of the laser. Adjust its height and orientation and align the polarizer in the path of the optical beam.

★ **Q 14.** Call the intensity measurement with A as I_A ? Why is $I_A < I_0$?

★ **Q 15.** Unscrew the lock on the top of A using the hex key provided. Now rotate the optical axis of the polarizer through large angles on both sides. Does the reading I_A vary? Describe your observation.

★ **Q 16.** Now place the second polarizer B in front of the detector. The intensity recorded on the scope will change to I_B ? How does I_B compare with I_A ?

★ **Q 17.** Unscrew the lock on top of B. What happens to I_B as you rotate B through large angles?

5.2 Malus's principle

★ **Q 18.** Note the reading on the rotation mount A. Call it α . What is the uncertainty in α ?

★ **Q 19.** Slowly rotate B so that the intensity is maximized? Note down the value of the angular position of B, calling it β . Note down the corresponding intensity I_B .

★ **Q 20.** Rotate β in steps of 20° , keeping all rotations clockwise or anti-clockwise. Take approximately 20 readings. At each step, record I_B . Keep α fixed throughout.

★ **Q 21.** Plot the values of I_B versus β .

★ **Q 22.** Fit your data to a suitable function and type the following command in which you will enter guess values of amplitude, angular frequency and phase from your experimental data, also add your defined x and y -axis variables in the same sequence as mentioned,

≫ **lsqcurvefit(@cosq, [amplitude frequency phase], x-axis variable, y-axis variable)**

Fit the plot using resultant outcomes. Also plot the error bars.

What is the goodness of the fit? Describe your observations in light of Malus's principle.

5.3 Determination of the optical activity

★ **Q 23.** Note down the value of α , the reading on the polarizer A.

★ **Q 24.** Adjust β on the polarizer B such that the intensity is maximized. Call this intensity I_{max} . Note down the value I_{max} as well as the value of the corresponding β , calling it β_{max} .

★ **Q 25.** Now rotate β such that the intensity is minimized. The minimum intensity is called I_{min} and the corresponding angle is β_{min} . What is the angular difference between β_{max} and β_{min} ? Note down the values of I_{min} and β_{min} .

★ **Q 26.** Calculate the intensity half way between I_{max} and I_{min} ,

$$I_{1/2} = I_{min} + \frac{I_{max} - I_{min}}{2} = \frac{I_{max} + I_{min}}{2}. \quad (8)$$

Adjust β to locate the point where the intensity equals $I_{1/2}$. Call this angle $\beta_{1/2}$. Note down the values of $I_{1/2}$ and $\beta_{1/2}$.

★ **Q 27.** Now vary the angle α by some fixed amount, say 20° and repeat the procedure of finding the maximum, minimum and average intensities, noting down the intensities and corresponding angles. Take approximately ten readings, tabulating your results in the suggested format (Table 1).

Sr.No.	α (deg.)	β_{max} (deg.)	I_{max} (V)	β_{min} (deg.)	I_{min} (V)	$\beta_{1/2}$ (deg.)	$I_{1/2}$ (V)
1.	0	76	0.22	166	0	122	0.11
2.	20						

Table 1: Suggested format for tabulating the experimental results.

★ **Q 28.** The demonstrators have already prepared a sucrose solution of a known concentration and filled it into a glass cell. Perch this cell on the posts and place it in between the polarizers A and B. The laser light must enter and emerge from approximately the middle of the side ends of the cell.

★ **Q 29.** Construct another table similar to the one above. This time find the maximum, minimum and average intensities and the corresponding angles with the optical cell in place.

★ **Q 30.** Once you have finished taking all the necessary readings, the demonstrator will switch off the laser power supply.

5.4 Data analysis for determination of the optical activity

All the remaining steps can be performed on paper or on the PC. From the available data, you are required to determine the optical activity of the solution.

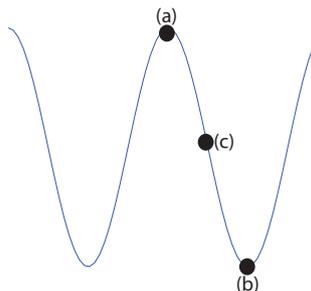
★ **Q 31.** What is the optical activity based on the maxima of the intensity? (Hint: Take difference of angles).

★ **Q 32.** What is the standard error in the measurement? (Hint: Use matlab command **std (vector name)**).

★ **Q 33.** What is the optical activity based on the minima of the intensity? What is the standard error in the measurement?

★ **Q 34.** Are the two results statistically different or the same? Justify your answer.

★ **Q 35.** Suppose you are given data that resembles the square of a cosine curve, as in (1). You measure the data along the curve. In which of the regions would one expect to get more precise results? Considering the accompanying Figure, would it be near the peak (a), the trough (b) or half way in between (c)? *HINT*: Think in terms of the slope of the cosine squared curve.



★ **Q 36.** Finally, determine the optical activity based on the intensities that are the average of the minima and maxima? The concentration of the sucrose solution is 0.2g/mL and $l = 1.12$ dm. What is the standard error in the measurement? Is this a more accurate result? Is this a more precise result?

★ **Q 37.** What are the main results of this experiment?

6 Experience Questions

1. Does the sun emit polarized light?
2. Can a star emit polarized light? If yes / no, what consequences could be seen in nature?
3. Is the light from the sky polarized?
4. A small radio receiver is placed near a radio transmitter. What is the optimum orientation between the transmitter and the receiver that maximizes the reception?

5. At the time of dusk, the atmosphere appears somber blue but looking directly at the sun, it has an orange or pinkish tinge. Reason why.

7 Idea Experiments

1. Find the optical activity of kerosene or octane.
2. Does the intensity of light change the measurement of optical activity?
3. Measure the birefringence of liquid crystals [9].

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