

Optical Activity

Introduction

The electric (**E**) and magnetic (**B**) vectors in a traveling electromagnetic wave (such as light for example) oscillate in directions perpendicular to each other and to the direction of travel of the beam. In general, if the light is traveling in the positive z-direction, the **E** and **B** vectors oscillate in random directions in the x-y plane, but are perpendicular to each other at any point in space and time.

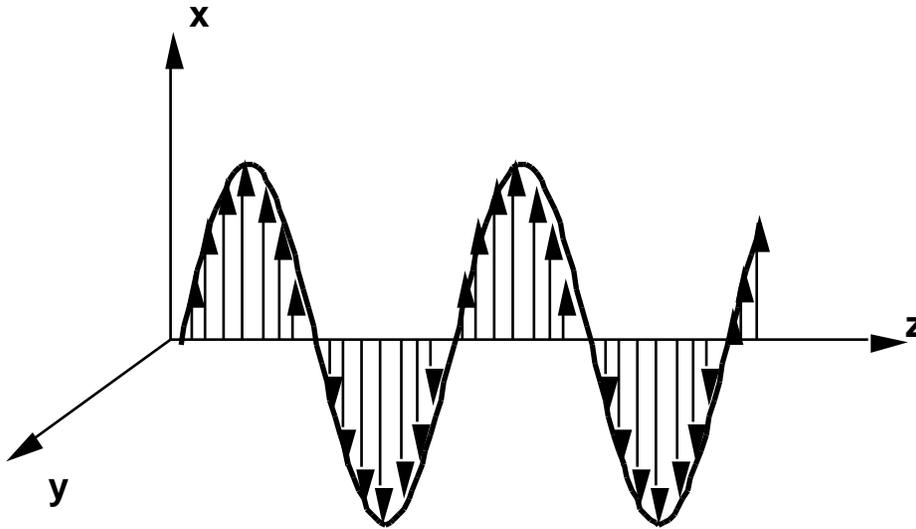


Fig. 1: The electric field vector **E** in a plane-polarized light beam.

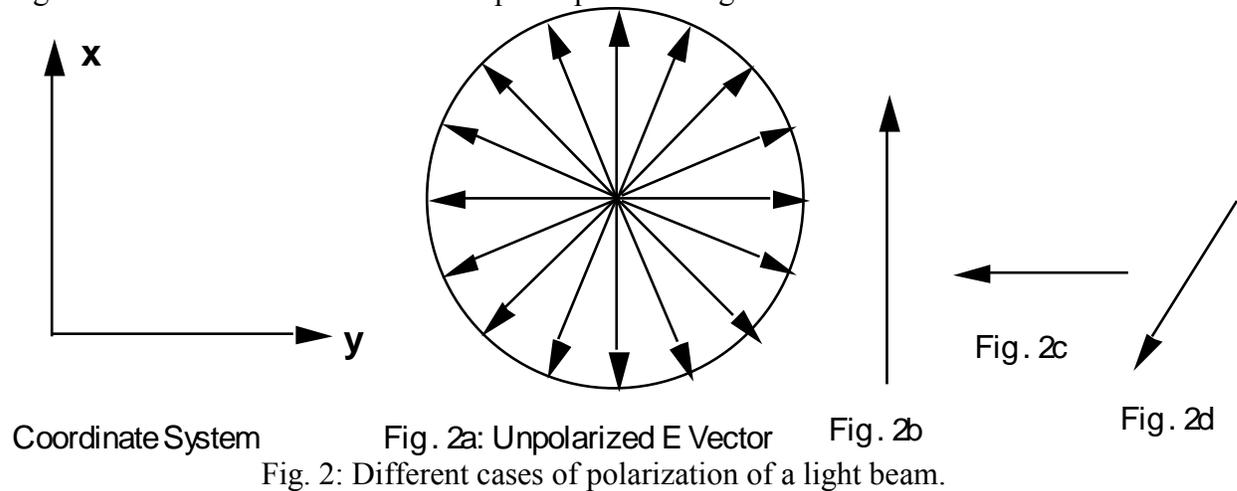


Figure 2a shows the unpolarized case. The axis of oscillation of the **E** vector is in the x-y plane but, at random direction with respect to any of the two axes. Figure 2b shows polarization along the x direction. The **E** vector oscillates only in the x-direction. Figure 2c

shows polarization along the y-direction and Figure 2d shows polarization along some arbitrary direction in the x-y plane.

Since it is the electric field vector \mathbf{E} that defines the direction of polarization, we shall, without loss of generality, omit further mention of the \mathbf{B} field. A beam of light in which the direction of \mathbf{E} is random in the x-y plane (see Fig. 2a) is called unpolarized. However, if the electric vectors are pointing in only one direction, e.g. parallel to the x-axis (see Fig. 2b) then the beam is said to be plane-polarized. With \mathbf{E} parallel to the x-axis as shown in Figure 1, the beam is said to be polarized in the x-direction in the plane of the page.

An unpolarized light beam can be plane-polarized by passing it through a sheet of Polaroid material. The Polaroid sheet (referred to as the "polarizer") transmits only the components of \mathbf{E} oscillating parallel to its "axis" and absorbs those that oscillate perpendicular to its "axis". The polarizing direction of the sheet is established during its manufacture when long chain molecules are embedded and the sheet is subsequently stretched so that the molecules are aligned parallel to one another. Ideally, 50% of the light intensity is transmitted and is plane-polarized parallel to the axis of the Polaroid (see Fig. 3). If a second Polaroid (the "analyzer") is placed in the path of a polarized beam then the amount of light transmitted depends on the orientation of the axis of the second Polaroid relative to the first. If the axes are parallel, then the beam passes through the second Polaroid, in the ideal case without further loss in intensity. If the axes are perpendicular as in Fig. 3, then there will be 100% loss in the second Polaroid: no light will pass through.

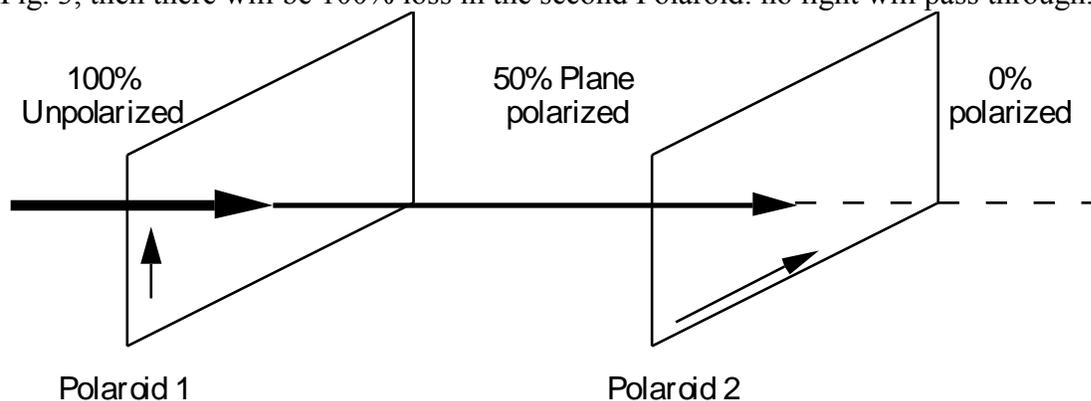


Fig. 3: Light intensities and polarization.

It was discovered, originally by accident (serendipity), that if a transparent container, containing certain naturally-occurring organic fluids, is placed between crossed Polaroids, then the light is no longer completely eliminated by the second Polaroid.

The explanation of this surprising phenomenon is that certain organic liquids have the ability to rotate the plane of polarization of polarized light (see Fig. 4). Such liquids are said to be optically active. The amount of rotation is directly proportional to the path-length of the beam in the liquid and to the concentration of organic compound in the liquid.

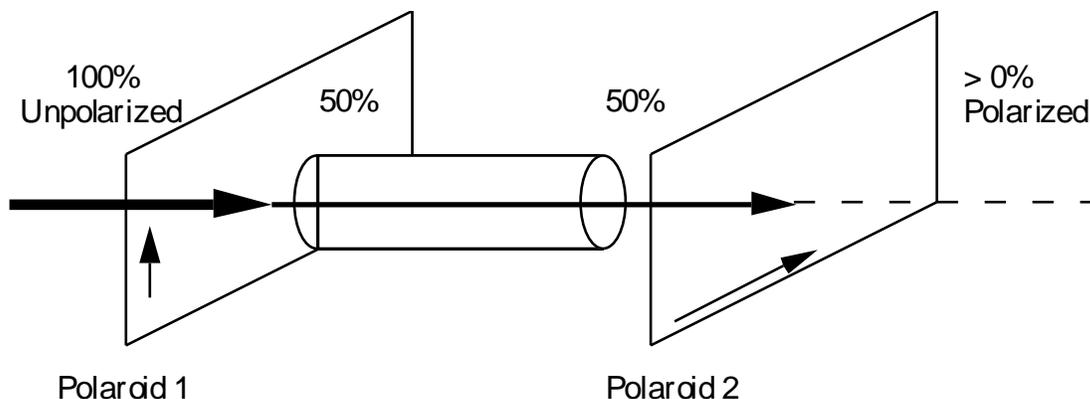


Fig. 4: Light intensities and polarization with rotation of \mathbf{E} vector by medium.

Optically active organic molecules have a spiral structure like a right-handed or left-handed screw. It is this spiral nature of the molecule, which rotates the plane of polarization of light passing through it. Right-handed molecules will rotate the plane of polarization clockwise as viewed in the direction of the beam, while left-handed molecules rotate the plane in a counterclockwise direction. If right-handed and left-handed species of a given molecule occurred with equal abundance, then there would be no net effect on the polarization of light passing through. However, naturally occurring biological molecules of a given species are always either purely right-handed or purely left-handed. Probably at the time of origin of life, organic molecules corresponding to both right and left-handed forms were produced. Laboratory synthesis always produces both types. However, in the first living systems on earth, left or right-handed activity could have been adopted purely as a matter of chance and, once a particular asymmetry was established, it maintained itself. This conjecture implies that optical activity is probably a feature of life on any planet and also that the chances should be equal for finding a given terrestrial organic molecule or its mirror image in extraterrestrial life forms, if any exist.

Optically active organic compounds are classified as d (dextro-) when right-handed and l (lev-) when left-handed. For instance, the most common sugar is dextrose or d-glucose ($C_6H_{12}O_6$) which is right-handed. There is also l-glucose (levulose), called invert sugar of fructose (fruit sugar). Sucrose ($C_{12}H_{22}O_{11}$), cane sugar, is right-handed. Most organic acids are optically active, including all amino acids. Specific rotation (also called rotary power) is defined to be the actual rotation per unit concentration and per unit length for solutions of the pure material. Specific rotations are published for many optically active substances at various temperatures and wavelengths of light. Quantitative and qualitative analyses of organic substances by measurements of specific rotations of the plane of polarization, are very important tools in biochemical analysis. One reason that optical activity is so important in the identification of organic molecules is that they are often so similar in other properties.

For this experiment, we are using sugar solutions to provide the optical rotation. Since we are running the experiment over the course of a week, we want concentrations to be stable during the entire week. But bacteria are evolutionarily tuned to feed on sugars, and it is hard to mix solutions without admitting some bacteria. To prevent bacteria from changing the concentrations, we sterilize the sealed samples with strong UV light, killing all bacteria. This has removed problems we used to see with concentrations changing with time.

Theory

Specific rotary power (α) is the quantity, which indicates the degree of optical activity of substances in solution. Its magnitude and sign depend on the detailed structure of the molecule and they generally vary for a given substance with the wavelength of light used in performing the measurement and also to some extent with the concentration of the solution. Neglecting small variations of α with concentration, the angle of rotation is given by:

$$\theta = \alpha LC \quad (1)$$

where θ (degrees) is the angle through which the plane of polarization is rotated by a solution with concentration C (g/cm^3) and length L (cm). The specific rotary power, α ($\text{degrees}/(\text{g}/\text{cm}^2)$), is the characteristic of a particular substance at the wavelength of light used for the measurements.

Equation (1) says that a measurement of θ vs. L for a solution of 'unknown' concentration should yield a linear graph with slope equal to αC ($\text{degrees}/\text{cm}$). Also, measurements of θ vs. C at constant L , should yield a linear graph with slope αL ($\text{degrees}/(\text{g}/\text{cm}^3)$). In this case L is easily measured and α can be determined. Hence the unknown concentration can be determined using the α determined from the known concentrations.

Method

In this experiment we wish to verify the two important relationships mentioned above: 1) that the amount of rotation of the plane of polarization is directly proportional to the path length of the light in the optically active medium, and 2) that the amount of rotation is proportional to the concentration of the sample. Concentration, sometimes measured in moles per liter of solution, is usually given in grams of the substance per ml of solution when specific rotary power is tabulated.

The apparatus consists of a standard Ne-He laser, sample cells, and rotating Polaroid analyzer. These components are arranged on an optical bench as shown in Figure 5.

Question 1: Is the output of the laser naturally polarized?

If the laser already emits plane polarized light use it as it is; otherwise mount the Polaroid polarizer in front of it in order to create a beam of plane polarized light for use in the experiment. Your instructor will give you a sealed cell filled with an unknown (to you) concentration of l-glucose. The cell has six windows, one in the center of each of the six sides of the cell. This configuration allows three different path lengths through the cell. There is also a cell with four windows at each end. This cell is filled with various concentrations of a sample in order to determine the relationship between rotation and concentration.

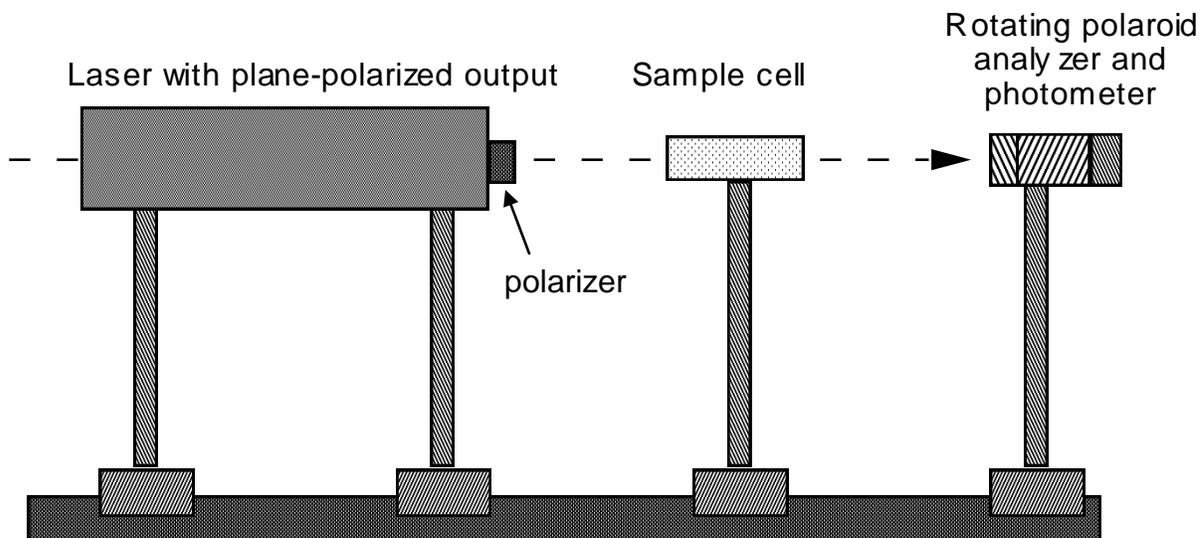


Fig. 5: Experimental setup for measurement of optical activity.

Procedure

With the laser turned on without the polarizer and no sample on the sample table you should observe a bright red spot on the window at the rear of the analyzer. Align the laser so the red dot is at the center of the analyzer. Check to see if the laser output is perfectly plane-polarized. By rotating the analyzer, points of minimum intensity can be found. Most likely, you will not be able to determine the minimum to the precision of the Vernier scale of the analyzer.

Place (screw in) the polarizer on the laser head to set the polarization of the laser output. Then turn the Polarizer analyzer until the transmission vanishes. Record the values of the angles where minimum intensity can be found.

Question 2: How many points of minimum intensity do you expect and what is the angular difference between them? The fact that the intensity is not quite zero at the minimum may mean that the laser light is not quite 100% plane-polarized. Verify your answers by rotating the analyzer through 360 degrees, and record the angle reading for all minima.

Question 3: What is the angle between the plane of polarization of the laser beam and the analyzer at the intensity minima?

Either one of these angles, where a minimum is observed, should be recorded as the zero rotation angle. With the analyzer set to a minimum (zero rotation), place the sealed cell (unknown concentration) in the beam path so that the beam enters and leaves the cell through the glass windows. You should now observe a bright spot at the analyzer window. Rotating the analyzer clockwise should bring back the minimum. The amount of rotation necessary to regain the minimum intensity at the analyzer window is the amount of rotation of the plane of polarization by the sample. Try to determine the uncertainty of your angles based on how precisely you can watch the intensity diminishing and return.

Question 4: Look carefully from above and to the side to be sure you are not running the laser beam through bubbles in the liquid (why?).

1. For four different known concentrations of KARO syrup (pure l-glucose) and distilled water, labeled A, B, C, D, measure the angular rotation of the plane of polarization of the beam. See hints below!
2. *Hints:*
 - a. It is clearest to proceed from lowest to highest known concentration samples, and for the unknown to start from the shortest path.
 - b. Find the polarization angle rotation by rotating both to the left and to the right, and average. In each case, you are looking for the smallest rotation angle between the reference minimum without the sample, and with the sample. The left and right reference minima differ by 180 degrees, but the magnitudes of the rotations should be equal.
3. Plot this data as a function of concentration in order to verify that angular rotation is proportional to concentration. (Your data for this part should include the path-length of the cell). Determine the slope of the graph and the specific rotary power of l-glucose (including errors!).

Question 5: Can you use the origin as an additional constraint in determining the slope?

4. Using the sealed cell which contains an "unknown" concentration of l-glucose, measure the angular rotation of the plane of polarization as a function of path length and estimate your uncertainties. Do this for each of the three different paths through the cell. Plot this data with Kgraph to determine the relationship between rotation and path-length for this sample.

Question 6: Can a straight line pass through the three data points and the origin? Answer using your graph, fit, and uncertainties.

5. Using the data from Parts 1 and 2, and the method explained in the theory section, determine the concentration of the sample in the sealed cell and its uncertainty. The sealed cells are numbered; record the number for your write-up.