Polarization of light

TWO WEIGHTS

RECOMENDED READINGS

1) G. King: Vibrations and Waves, Ch.5, pp. 109-112. Wiley, 2009.
2) E. Hecht: Optics, Ch.4 and Ch.8. Addison Wesley, 2002.
3) PASCO Instruction Manual and Experiment Guide for EX5543 and EX5544
   https://www.pasco.com/prodCatalog/EX/EX-5543_polarization-experiment/index.cfm
   https://www.pasco.com/prodCatalog/EX/EX-5544_brewsters-angle-experiment/index.cfm

INSTRUCTOR'S EXPECTATIONS

1. Before performing the lab, you should read the introduction to this manual and be able to define polarization, linearly polarized light, know the Fresnel formulas and definition of Brewster's angle. It would be very helpful if you read Chapter 8 of the 2nd source (see the list of Recommended Readings).
2. Before assembling the setup for each experiment exercise, get familiar with functions and basic principles of work of the components such as the laser, the slits, the acrylic D-lens etc. Ask your demonstrator for help.
3. Make most of each session by spending it entirely to acquire and analyze data, as well as to seek help from the demonstrator.
4. Your lab report should include the following sections:
   Introduction. Give the basic definitions. State the Malus' law. Describe the light analyzer using 3 polarizers. State the Fresnel formulas and include graphs for s- and p-polarizations vs angle of incidence. Define Brewster's angle.
   Procedure. Include diagrams or photos of the 3 setups with labelled components. Describe your steps in point form. Include all acquired graphs.
   Data analysis. For experiments 1 and 2, discuss how your data fit Eq. (1) and (3). For the experiment 3, state the obtained Brewster's angle, find the refractive index of acrylic and compare your value with any reported in the literature. Answer the questions from this manual for each experiment. Include discussion of uncertainties where applicable.
   Conclusion. Compare your results with your own expectation and conclude on the quality of your results.

INTRODUCTION

Light, viewed classically, is a transverse electromagnetic wave. Namely, the underlying oscillation (in this case oscillating electric and magnetic fields) is along directions perpendicular to the direction of propagation. This is in contrast to longitudinal waves, such as sound waves, in which the oscillation is confined to the direction of propagation.

Light is said to be linearly polarized if its oscillation is confined to one direction (the direction of the oscillation of the electric field is defined as the direction of polarization). Most light sources in nature emit unpolarized light i.e., light consists of many wave trains whose directions of oscillation are completely random.

Unpolarized light may become polarized after passing through a sheet of a commercial material called Polaroid, invented by E.H. Land in 1938. A sheet of Polaroid transmits only the component of light polarized along a particular direction and absorbs the component perpendicular to that direction.

Consider a light beam in the z direction incident on a Polaroid which has its transmission axis in the y direction. On the average, half of the incident light has its polarization axis in the y direction and half in the x direction. Thus, half the intensity is transmitted, and the transmitted light is linearly polarized in the y direction.

MALUS' LAW

Suppose we have two pieces of the Polaroid film that will perform as polarizers. When two polarizing elements are placed in succession in a beam of light as described here, the first is called **polarizer** and the second is called **analyzer**.

Let the transmission axes of the polarizer and the analyzer make an angle θ (see Fig. 1). After exiting from the polarizer, the initially unpolarized light has become linearly polarized in y-direction. The E-vector of the light between the polarizers can be resolved into two components: one parallel and one perpendicular to the transmission axis of the analyzer. If the direction of transmission of the analyzer is y', the components of the E-vector incident on the analyzer are $E_{x'} = E \sin\theta$ and $E_{y'} = E \cos\theta$. The latter is transmitted, while the first component is absorbed.

The intensity of light is proportional to the square of the electric field amplitude. Thus, the intensity transmitted by the system of the polarizer and the analyzer shown in Fig.1, can be expressed as:

$$I'(\theta) = const \cdot E_{y'}^2 = const \cdot E^2 \cos^2\theta = I\cos^2\theta$$

where I is the intensity of linearly polarized light between the two Polaroids, or

$$I'(\theta) = I\cos^2\theta \qquad (1)$$

This equation is known as Malus Law after its discoverer, E.L. Malus (1775-1812). It applies to any two polarizing elements whose transmission directions make an angle θ with each other. As you will see, no light reaches the photocell when the polarizer and analyzer are crossed (θ = 90°).

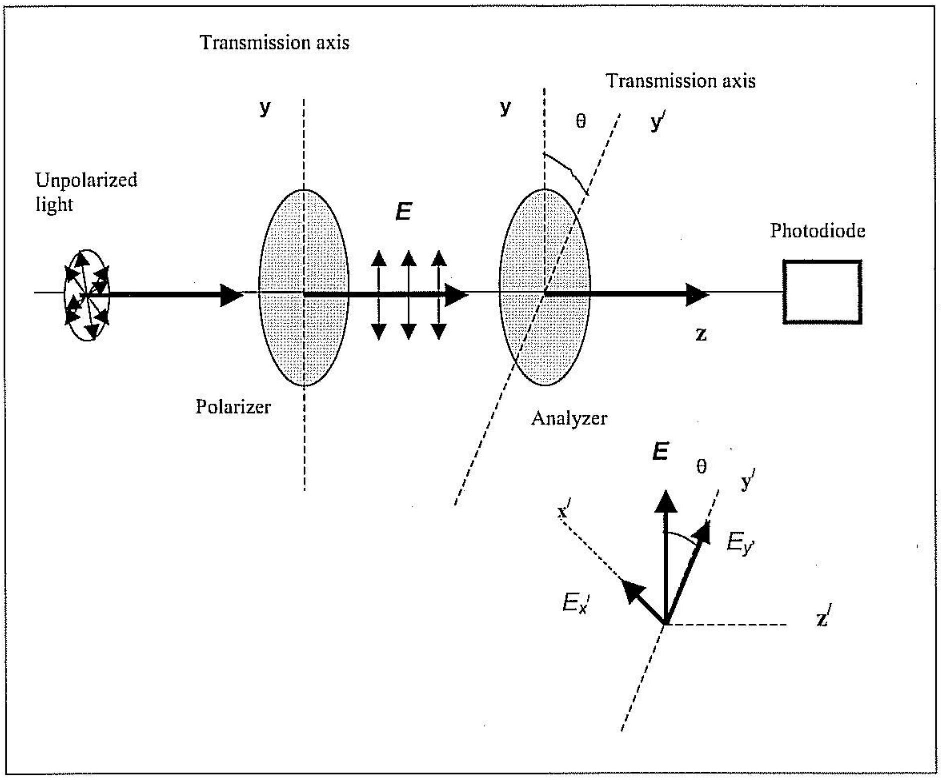

Fig. 1: Two Polaroids whose transmission directions make an angle θ with each other.

MALUS' LAW FOR A SYSTEM OF THREE POLARIZERS

Now, suppose that unpolarized light passes through 3 parallel successive polarizers with different direction of transmission as in Fig. 2.

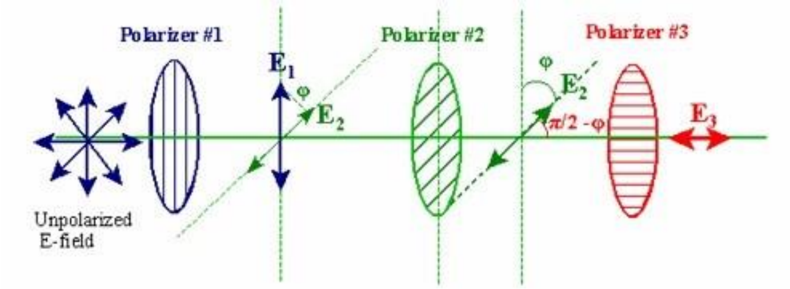

Figure 2: The electric field transmitted through three polarizers.

The first and last polarizers are oriented at 90° with respect to each other. The second polarizer has its polarization axis rotated an angle φ from the first polarizer. Therefore, the third polarizer is rotated an angle $\pi/2 - \varphi$ from the second polarizer. The intensity after passing through the first polarizer is I_1 and the intensity after passing through the second polarizer, I_2, is given by:

$$I_2 = I_1 \cos^2 \varphi$$

The intensity after the third polarizer, I_3, is given by:

$$I_3 = I_2 \cos^2\left(\frac{\pi}{2} - \varphi\right) = I_1 \cos^2 \varphi \cos^2\left(\frac{\pi}{2} - \varphi\right) \tag{2}$$

Rearranging Eq. (2), we obtain:

$$I_3 = \frac{I_1}{4} \sin^2(2\varphi) \tag{3}$$

Because the data acquisition begins when the transmitted intensity through Polarizer 3 is a maximum, the angle Θ measured in the experiment is zero when the second polarizer is 45° from the angle φ. Thus, the angle φ is related to the measured angle Θ by:

$$\varphi = 45^\circ + \Theta \tag{4}$$

REFLECTANCE/BREWSTER'S ANGLE

Consider unpolarized light incident on a surface separating air and glass or air and water. The plane containing the incident, reflected and refracted rays as well as the normal to the surface is defined as *the plane of incidence*.

When light is reflected from a flat surface, the reflected light is partially polarized. This is due to the fact that the reflectance of light R = (Reflected Intensity)/(Incident Intensity) depends on the polarization itself. The degree of polarization depends on the angle of incidence and the indices of refraction of the two media. For reflection at an air-glass interface (indices of refraction n_1 for air and n_2 for glass), Fresnel equations give the reflection coefficients $r_{\|}$, $r_{\perp}$:

$$r_{\perp} = \frac{n_1 \cos\theta_1 - n_2 \cos\theta_2}{n_1 \cos\theta_1 + n_2 \cos\theta_2} \tag{5a}$$

$$r_{\|} = \frac{n_1 \cos\theta_2 - n_2 \cos\theta_1}{n_1 \cos\theta_2 + n_2 \cos\theta_1} \tag{5b}$$

where θ_1 is the angle of incidence, and θ_2 is the angle of refraction. [E. Hecht. Ch.4]

Above $r_{||}$ and $r_\perp$ refer to the reflection coefficients for polarized light whose direction of polarization lie in the plane of incidence and perpendicular to the plane of incidence, respectively.

Reflectance R (parallel or perpendicular) is defined as the square of the corresponding reflection coefficient: $R_{||} = r_{||}^2$, $R_\perp = r_\perp^2$

Note that θ_2 is not measured in this experiment and must be inferred from Snell's law of refraction:

$$\frac{\sin\theta_2}{\sin\theta_1} = \frac{n_1}{n_2} \qquad (6)$$

Figure 3 shows initially unpolarized light incident at the polarizing angle θ_p, for which the reflected light is completely polarized with its electric field vector perpendicular to the plane of incidence.

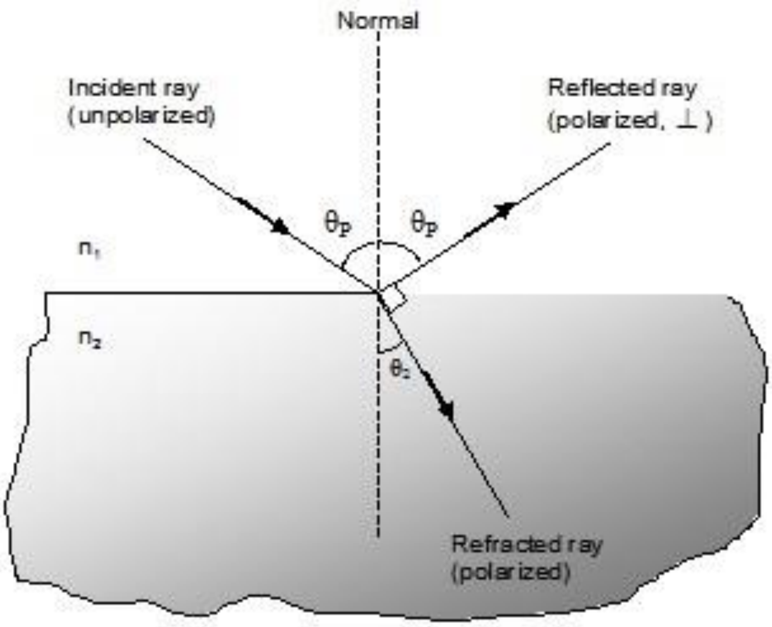

Fig. 3: Unpolarized light incident at the polarizing angle.

The electric field vector E of the incident wave can be resolved into two components: parallel to the plane of incidence and perpendicular to the plane of incidence.

Note that $R_{||} = 0$ when $n_1 \cos\theta_1 = n_2 \cos\theta_2$, which leads to the definition of the Brewster's angle:

$$\tan\theta_p = \frac{n_2}{n_1} \qquad (7)$$

Here θ_p is the angle of incidence of unpolarized light which makes the reflected light completely polarized in the perpendicular direction to the plane of incidence (Sir David Brewster, 1812). When the angle of incidence of the initially unpolarized light is θ_p, the reflected and refracted rays are perpendicular to each other.

Note: If the incident light has no component of E perpendicular to the plane of incidence, there is no reflected light.

APPARATUS, EXPERIMENT AND PROCEDURE

Malus' Law: Apparatus Notes

- Be careful not to leave your fingerprints on optical surfaces.
- Rotate the aperture disk so the translucent mask covers the opening to the light sensor.
- Verify that the Rotary motion sensor is mounted on the polarizer bracket and connected to the polarizer pulley with the plastic belt.
- Place all the components on the Malus Law Optics Track in the order shown in Fig. 4.
- Space components apart along the optics track (largest distance should be between the detector and the polarizer).

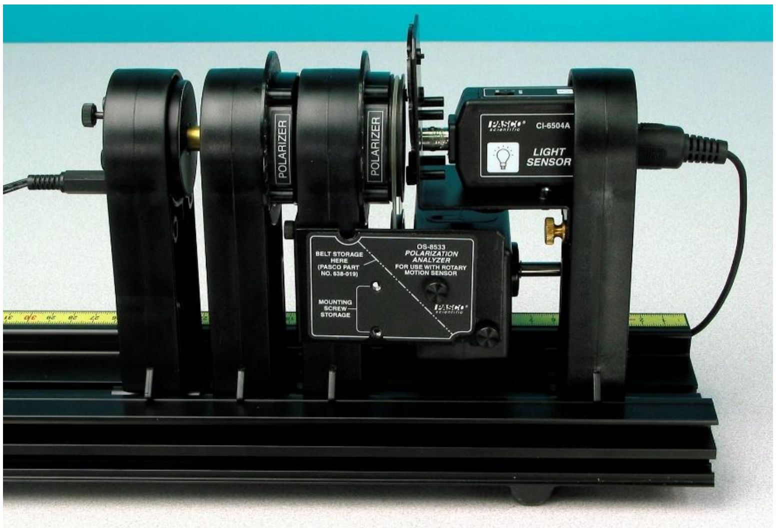

Fig. 4: Experiment Components.

- To open up the software necessary for this part of the experiment, click on the desktop shortcut Polarization of Light.
- Click on the little arrow located in the upper left corner of the screen to start the acquisition. The program is self-explanatory.

Exercise 1: Two Polarizers, verify Malus' law

Begin with aligning the polarizers to allow the maximum amount of light through. Since the laser electromagnetic wave is already polarized, the first polarizer must be aligned with the polarization axis of light.

Remove the holder with the polarizer and Rotary motion sensor from the track. Slide all the other components on the track close together and dim the room lights. Click ON/OFF and manually rotate the polarizer that does not have the Rotary motion sensor until the light intensity on the graph is at its maximum, but *keep in mind that the detector should NOT be saturated*. An intensity level of ≈ 3.5-4 V is acceptable.

To allow the maximum intensity of light through both polarizers, bring back the holder with the polarizer and Rotary motion sensor on the track, and rotate the polarizer until light intensity on the graph is at its maximum (take the same precaution as before). Before you begin a new scan, you may clear previous data. *Note: If the maximum exceeds* 4.5 *V, decrease the gain on the light sensor. If the maximum is less than* 0.5 *V, increase it.*

To scan the light intensity versus angle, press ON/OFF and rotate the polarizer which has the Rotary motion sensor through 180 degrees. Rotation should be constant. Do not rotate back! Acquisition stops by itself at the end of 180 degrees. Practise until you get the best (smooth) recording of Intensity of light vs. angle.

Required analysis to include into the report

Export data, draw diagrams and analyze functions: Intensity vs. cosθ, and Intensity vs. $\cos^2\theta$ You have to include experimental errors for both light intensity and angle readings. The dataset includes about 300 values (Intensity, θ). Compare with Malus Law prediction of Eq. (1).

Exercise 2: Three Polarizers

Repeat the experiment with 3 polarizers (see setup in Fig. 5).

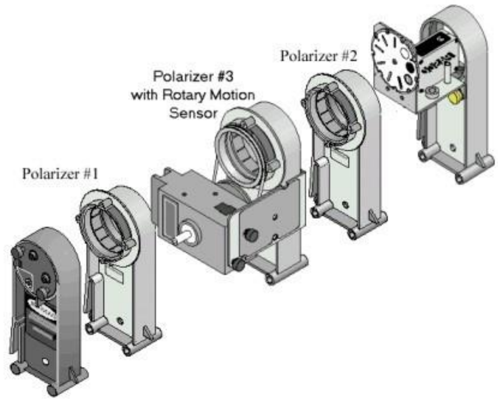

Fig. 5: Experiment components for the three polarizers in the

- Remove the rotary motion sensor from the track, insert Polarizer 1 and rotate it until the transmitted light is a maximum.
- Insert Polarizer 2 and rotate it until the transmitted light is a minimum.
- Place the rotary motion sensor between the two polarizers and collect data through 360^o. Try the qualitative fitter from the LabView application.
- Export data and find the best fit matching Eq. (3). Include experimental errors.

Questions to be answered in the report:

1) Select your data from 2 polarizers and from 3 polarizers. What two things are different for the Intensity vs. Angle graph for 3 polarizers compared to 2 polarizers?
2) For 3 polarizers, what is the angle between the middle polarizer and the first polarizer to get the maximum transmission through all 3 polarizers? Remember: in the experiment, the angle of the middle polarizer automatically reads zero when you start taking data but that doesn't mean the middle polarizer is aligned with the first polarizer
3) For 3 polarizers, what is the angle between the middle polarizer and the first polarizer to get the minimum transmission through all 3 polarizers?

Brewster's Angle: Apparatus Notes

Light from a diode laser (1) is reflected off the flat side of an acrylic semi-circular lens (2) (Fig.6). The reflected light passes through a square polarizer (3) and is detected by a light sensor (4). The angle of reflection is measured by a rotary motion sensor (5) mounted on the spectrophotometer table. The apparatus plots intensity of the reflected polarized light versus reflected angle to determine the angle at which the light intensity is a minimum. This happens at the Brewster's Angle, which is used to calculate the index of refraction of acrylic according to Eq. (7).

You will use this apparatus to measure the intensity of the parallel and the perpendicular polarization components of reflected light at a range of incident angles. The first steps are:

- Move the diode laser to the optics bench marked Brewster's angle,
- Attach 2 polarizers to the same holder, and place the collimating slits on the track as shown in Fig. 6. Make sure the rotary motion sensor is mounted on the spectrophotometer table with the bigger diameter of spindle against the table (see Fig. 6).

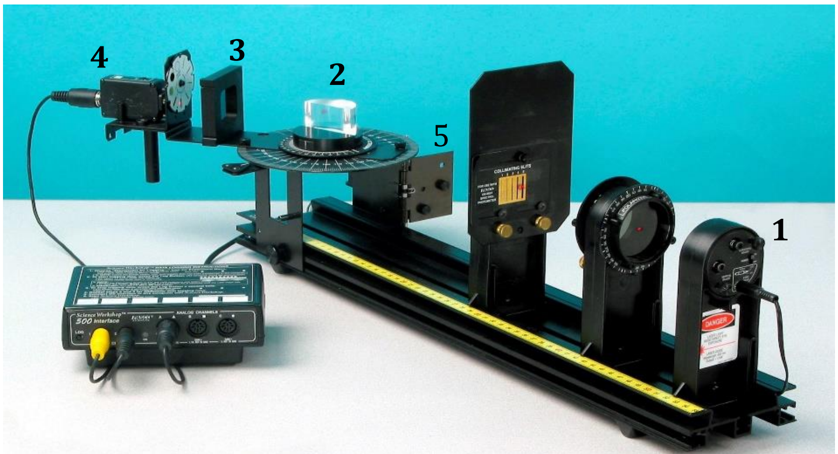

Fig. 6: Complete setup for Exercise 3.

- Note that the computer interface is different in your experiment.
- Open the LabView application, Brewster's Angle tab.
- Remove the analyzing (square) polarizer and the D-lens and rotate the sensor arm to 180^{o}, in-line with the light source.
- Use the $x - y$ adjustment screws on the back of the laser diode to align the beam onto the light sensor.
- Rotate polarizer 1 until a maximum signal is measured by the light sensor (without saturating it).
- Replace the D-lens and the square polarizer.
- Rotate the second polarizer (second from laser diode) to 225^{o} and lock it in place by tightening the brass screw. (In reality, this is a 45-degree polarizer, used to solve the problem that the laser light is already polarized). The first polarizer (closest to the laser diode) is used throughout the experiment to adjust the light level.

The square analyzing polarizer (Fig. 7) has its transmission axis marked, and will be used to select the horizontal or vertical polarization component of the reflected light.

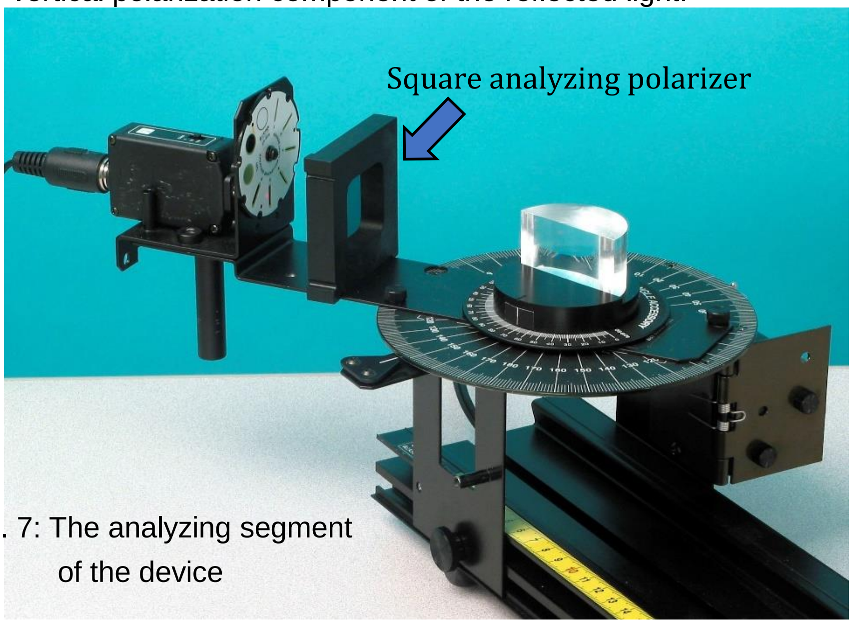

Fig. 7: The analyzing segment of the device

Note about reflection angle measurements: The angle is calculated by dividing the actual angle (recorded by the computer) by two, with a correction with respect to the spindle diameter. The markings on Brewster's disk are there only for convenience (in this experiment) and are not used directly. To get the laser beam exactly on to the slit, you must make fine adjustments while watching the digits display on computer for the maximum light intensity. You can adjust either the Brewster's disk or the spectrophotometer arm until the intensity is maximized.

Exercise 3: Polarization by Reflection and Brewster's angle

Dim the room lights. With the Brewster's Angle application open and the unobstructed opening on the light sensor, rotate the D-lens (together with the Brewster's disk) so that the incident and reflected beams make an angle of 180°. The flat side of the D-lens must now be parallel to the laser beam.

Start the acquisition and, while watching the digits display of light intensity, rotate the spectrophotometer arm to get the beam onto the light sensor. Rotate the first polarizer (nearest to the laser) to adjust the intensity level to be as high as possible. You may adjust the tip and tilt nobs on the laser for this measurement and each later point of acquisition to maximize the sensor signal. The light sensor should be on gain of 1 or 10. This will set up the starting point of the rotational motion sensor.

Start the acquisition without the square polarizer: slowly rotate the spectrophotometer arm clockwise (**decrease the angle of incidence**), while **at the same time** rotating the Brewster's disk to keep the reflected beam aligned with the opening at the Light Sensor. Use the cursors to read the intensity I_0 and the angle values of the graph maxima.

Place the square analyzing polarizer (axis horizontal) on the spectrophotometer arm as in Fig. 7. Do an acquisition with horizontal axis polarizer using the same procedure as before.
Read intensity I and the angle values of the graph maxima.

Repeat with the vertical axis polarizer.

Required analysis to include into the report

- Plot $I_{||}$ and $I_{\perp}$ versus angle. Include uncertainties in reading intensity and angle. Determine the Brewster's angle.
- Use Brewster's angle to calculate the index of refraction of acrylic using Eq. (7). Use $n_1 = 1$.
- Calculate the values of parallel and perpendicular reflectance using Fresnel equations (5a) and (5b).

Questions to be answered in the report:

1) Would the Brewster's angle be more or less if acrylic is replaced by water?
2) How would the data look like for an arrangement with a vertical square polarizer?
3) How do polarized sunglasses reduce glare? Which direction is the axis of polarization in a pair of polarized sunglasses? How could you check this?

Created by Ruxandra Serbanescu with notes from Kyle Manchee. The acquisition DAQ board was built and programmed by Larry Avramidis.

Significantly revised by PhD student Ms. Elena Renzhiglova for PHY293/PHY294 Lab course in 2017.