PHYSICS 18L Lab 3: Fun with Polarization of Light

Scarlett Yu
Lab Partner: Janice Nguyen
Professor: Huan Huang
TA: 赵长玲 Section B
University of California, Los Angeles
(Dated: January 26, 2019)

Abstract. In this lab, we investigate the Malus' law by building a polariscope with a polarizer and an analyzer. We experimentally verified the Malus' law with measurements of transmitted light intensity displaying a sinusoidal relationship with the relative angle of the two polarizers. In addition, we measured using the Snell's law and Brewster angle the index of refraction of lucite to be $n_{\text{lucite}=}1.55 \pm 0.01$. Finally, to study the optical activity of chiral molecules in sucrose solution, we built a saccharimeter to measure the specific rotation of the sucrose fluid. Finally we determine the density of sucrose in the mystery tube to be 650$\pm$ g/m^3.

I. INTRODUCTION AND OBJECTIVES OF THE EXPERIMENT

The wave nature of photons refers to the fact that light is propagating electromagnetic oscillations. The directions of electric field oscillation, magnetic field oscillation, and the propagation of light ray are mutually orthogonal. Conventionally, we set the electric field vector $\bar{E}$ to be the polarization direction. In this lab, we measure and verify the Malus' law which governs how light emerges from polarizers, the Snell's law and the Brewster's angle of a certain medium, as well as using polarization to test the specific rotation of chiral molecular fluid.

A. The Malus' Law

A beam of unpolarized light where directions of electric field of individual ray are pointing in random orientation can be filtered and turned into linearly polarized light by using a polaroid. A polariscope consists of two polaroids, with the first polaroid the incident beam hits is called the "polarizer" and the second one "analyzer". Consider a polarizer with a transmission axis $\bar{P_1}$, and an analyzer with transmission axis $\bar{P_2}$, where the angle between the two axes is α. When an incident light with an electric-field $\bar{E_0}$ and intensity of $I = {E_0}^2$ emerges from the polarizer, the amplitude of the transmitted light $\bar{E_1}$ is:

$$\bar{E_1} = \bar{E_0}\cos\theta \tag{1}$$

where θ is the angle between $\bar{E_0}$ and $\bar{P_1}$. The intensity of the transmitted light from the first polarizer can be calculated by averaging over all angles for unpolarized rays that make up the incident beam:

$$I_2 = \langle \bar{E_1}^2 \rangle = \bar{E_0}^2 \frac{1}{2\pi}\int_0^{2\pi}\cos^2\theta d\theta = \frac{1}{2}\bar{E_0}^2 = \frac{1}{2}I_0 \tag{2}$$

If the transmitted light subsequently emerges after the analyzer $\bar{P_2}$, the transmitted intensity I_2 is given by Equation (3):

$$I_2 = I_t\cos^2\alpha \tag{3}$$

where I_t is the transmitted intensity emerging from the analyzer when $\bar{P_1}$ is parallel to $\bar{P_2}$ ($\alpha = 0$). In the most ideal case, for an initially unpolarized beam, $I_t = \frac{1}{2}I_0 = I_1$. In the first part of our experiment, we verify the Malus' law by measuring the intensity of the transmitted light.

B. Verification of Snell's Law

The fundamental constant of speed of light in vacuum c relative to the speed of light traveling in a medium v defines a "refrative index" of the transmission medium: $n \equiv \frac{c}{v}$. The famous Snell's Law in Equation (4) relates the refractive index of incident light's medium n_i and incident angle θ_i with the refractive index of transmitted light's medium n_t and the refraction angle θ_t:

$$n_i\sin\theta_i = n_t\sin\theta_R \tag{4}$$

In our experiment, given that light beam incidents from air $n_{air} \approx 1.003$, we measure the angles θ_i and θ_i to calculate n_t.

C. Measurement of Brewster's angle

When light impinges on a surface, part of it is reflected and part of it refracted. One can view an unpolarized incident beam as having two orthogonal components: P and S, where P-polarized light is when $\bar{E_0}$ (the direction of electric-field oscillation) is perpendicular to the plane of incidence, and S-polarized light is when $\bar{E_0}$ is parallel to plane of incidence. The incident light can drive the dipole oscillation of electrons in the surface and thus induces a new oscillating electric field that is strongest perpendicular to the oscillation. At a certain incident angle, called the "Brewster angle" θ_B, only the S-polarized light is reflected and only P-polarized light transmitted:

$$\tan\theta_B = \frac{n_t}{n_i} \tag{5}$$

D. Specific rotation of chiral molecules using Saccharimeter

Molecules possessing chirality show optical activity. Specifically, when linearly-polarized light passes through the substances containing chiral molecules, it gets rotated about the beam axis. The change in rotation $\Delta\theta$ is proportional to the density of the molecular solution C and length the beam's traversed path L:

$$\Delta\theta = \alpha C L \tag{6}$$

where the proportionality α is called the specific rotation. Using the relationship in Eqn 5, we use polarizers to measure the change in rotation when a beam passes through a fluid with known density in order to calculate the specific rotation of the fluid.

II. EXPERIMENTAL PROCEDURE

A. Verifying of the Malus' Law

The light source we use in the experiment is a side-projector with a collimator, and the intensity of light is measured by the Pasco 0S-8020 Photometer with a fiber-optic cable. We first align the projector, two polaroids (polarizer A, analyzer B), and the photometer on an optical track such they are co-linear, as illustrated in FIG 1. To verify the Malus law, we change the angle α of the analyzer relative to the polarizer from 0° to 360° at an increment of 10°, and record the intensity measured by photomer. According to Eqn 3, the dependence of I_t on α should be periodic in form of cosine. We first measure the stability of the light source and the photometer by recording how much the light intensity varies over a five-minute period as detected by the photometer.

`malus_setup.png`

FIG. 1. Experimental set up for verifying the Malus law, where a light source passes through a pair of polarizers to reach the photometer which measures the transmitted light's intensity.

B. Measuring Snell's Law and Brewster Angle

We perform precision measurement of the refraction index of a lucite block by shining a laser source through the lucite, as shown in FIG 2 and measuring the θ_i and θ_R in Eqn4. The Brewster angle of the lucite block is measured by rotating the polarizer as well as the incident angle until the reflected beam is minimum.

`lucite_setup.png`

FIG. 2. Experimental set up for measuring the incident and refracted angles

C. Specific rotation of chiral molecules using Saccharimeter

To investigate the optical activity in sucrose fluids, we assemble a saccharimeter as shown in Figure 3. We first set the polarizer to zero degree, and then for each of the red, blue, and green filter, we minimize the transmission of light without any fluid and record down the angle that gives minimum transmission. These angles measured with the filters but without the fluids are the reference angles.
For each filter, we install a sucrose fluid in the sacchimeter, and rotate the analyzer again we find a new minimum and record down the marking on the analyzer as our "measured angle". Using the difference of the measured and the referenced angles, we calculate α the specific rotation using Eqn 6. We repeat the angle measurements for three different fluids in the long tube, short tube, and the mysterious tube.

`chiral_setup.png`

FIG. 3. Experimental set up for testing the optical activity in sucrose fluid containing chiral molecules.

III. MEASUREMENT DATA AND ANALYSIS

A. Malus' Law Verification

Before making any measurements, we calibrate the photometer by covering it with a black cloth and setting the reading to zero on th most sensitive scale (0.1). The background ambient light is measured to be 1.55 ± 0.06 lux. We then observe the stability of light source and photometer by recording the measured intensities, as shown in Table 1 (Note that measured light here has been transmitted through a polarizer). We install a single polarizer and rotate it to see the transmitted light. Because the mirror in the projector is slightly polarized, we find two minima at $(135 \pm 0.5)°$ and $(96 \pm 0.6)°$ degrees, two maxima at $(315 \pm 0.5)°$ and $(358 \pm 0.5)°$. To verify the Malus' law, we measure the intensity of light I_t emerging after the two polariods as a function of relative angle α between the polarizer and analyzer. The recorded intensities are shown in Table 2 and the data points are plotted in FIG 4.The well fitted cosine function in FIG 4 confirms that the intensity does have a cosine dependence on α, as stated in by Malus' Law in Eqn 3.

Time Elapsed [Min]	Relative Intensity [Lux]
1	18.48 ± 0.05
2	18.72 ± 0.03
3	18.00 ± 0.02
4	17.95 ± 0.03
5	17.96 ± 0.02

TABLE 1. Intensity of light source as measured by the photometer

α [Deg]	Measured I_2 [Lux]	α [Deg]	Measured I_2 [Lux]
0	36.40		
10	34.90	190	36.70
20	32.50	200	34.00
30	27.50	210	28.00
40	21.00	220	21.90
50	14.20	230	12.10
60	9.00	240	8.23
70	4.00	250	4.10
80	0.12	260	0.80
90	0.00	270	0.00
100	0.70	280	1.02
110	3.10	290	3.77
120	7.50	300	9.60
130	13.50	310	16.10
140	20.40	320	24.00
150	26.80	330	30.10
160	32.23	340	36.20
170	36.00	350	39.60
180	38.00	360/0	41.00

TABLE 2. Verifying Malus law by measuring the light intensity after analyzer as the angle between the polarizer and analyzer changes. The uncertainty on all the intensity data is 0.03

B. Snell's Law and Brewster Angle

We make two measurements of the θ_i, θ_R by tracing the laser beam path through the lucite block and using protractor to measure the angles. The results are shown in Table 3 with corresponding calculated value of refraction index using Eqn 4, with $n_{\text{air}} \approx 1.003$ and the error propagation from the angle to index of refraction following: $\sqrt{(\frac{\cos(\theta_i)\Delta\theta_i}{\theta_i})^2 + (\frac{\cos(\theta_R)\Delta\theta_R}{\theta_R})^2}$. We then make two measurement of the Brewster angle, both of which are $52.0°$. The index of refraction is calculated using the measured Brewster angle and Eqn 5 is 1.300 ± 0.0006.

`malusplot.png`

FIG. 4. Dependence of transmitted intensity after the analyzer on the relative angle between the two polaroids, fitted to a cosine function.

Measurement	θ_i [deg]	θ_R [deg]	Calculated n_t
1	34.5 ± 0.2	21.0 ± 0.2	1.50 ± 0.01
2	24.7 ± 0.2	16.0 ± 0.2	1.60 ± 0.01

TABLE 3. Measurements of incident and refracted angles used to calculate index of refraction using Snell's Law

C. Measuring Specific Rotation of Sucrose

Tables 4 and 7 show the measured reference angles and new minimum angles for each of the red, green and blue filter, repeated for two fluids in the long and short tubes. The specific rotation for each fluid with each color filter is calculated using Eqn 6, with error propagated from L and $\Delta\Theta$. For the mystery tube In Table 5, we average the specific rotations of each color filter found in Table 4 and 5 to calculate the density, with error propagated from L, $\Delta\Theta$ and α. The average of the three calculated density values is 650 ± 2 g/m^3. By plotting the data in Table 4

TABLE 4. Fluid 1. Long tube with measured length $L = 0.32 \pm 0.02$ m and given density $C = 500$ g/m^2:

Filter	Reference [Deg]	Measured [Deg]	$\Delta\theta$	Calculated α
Red	272.5 ± 0.5	199.0 ± 0.5	73	0.5 ± 0.1
Green	272.0 ± 0.5	351.0 ± 0.5	79	0.5 ± 0.1
Blue	270.0 ± 0.5	322.0 ± 0.5	52	0.3 ± 0.1

TABLE 5. Fluid 2. Short tube with measured length $L = 0.153 \pm 0.02$ m and given density $= C = 500$ g/m^2:

Filter	Reference [Deg]	Measured [Deg]	$\Delta\theta$	Calculated α
Red	272.5 ± 0.5	287.0 ± 0.5	14.5	0.2 ± 0.2
Green	272.0 ± 0.5	293.0 ± 0.5	21	0.3 ± 0.1
Blue	270.0 ± 0.5	300.0 ± 0.5	30	0.4 ± 0.1

TABLE 6. Fluid 3. Mystery sucrose tube with measured length $L = 0.101 \pm 0.03$ m:

Filter	Reference [Deg]	Measured [Deg]	$\Delta\theta$	Calculated C
Red	272.5 ± 0.5	289.0 ± 0.5	14.5	503.5 ± 0.8
Green	272.0 ± 0.5	296.0 ± 0.5	21	618.6 ± 0.6
Blue	270.0 ± 0.5	302.0 ± 0.5	30	883.6 ± 0.6

and 5, we attempt to establish a dependence of specific rotation on wavelength of the incident light as shown in FIG 5. While for the measurements done on the short tube suggests a trend that specific rotation decreases as the wavelength increases, the measurements of the long tube suggest otherwise. Based on the limited number of data points, we reserve to conclude any clear dependence between λ and α.

`wavelength_dependence.png`

FIG. 5. Wavelength-dependence of specific rotation using two sets of measurements done on the long and short tubes from Table 4 and 5.

IV. CONCLUSION AND OUTLOOK

We experimentally verified the Malus' law with measurements of transmitted light intensity displaying a sinusoidal relationship with the relative angle of the two polarizers. In addition, we measured using the Snell's law and Brewster angle the index of refraction of lucite to be 1.55 ± 0.01. Finally, we determined the density of sucrose in the mystery tube to be $650\pm$ g/m^3. The wavelength-dependence of specific rotation can be better supported with more data points on different fluids.

V. REFERENCES

[1] Huang, H. *Modern Physics Lab Manual*. January, 2019.