Light reveals the intimate structure of matter: its polarization records both the asymmetry of a medium and the geometry of an interface. — C. T. Dominguez, 2026. Free translation: Light reveals the intimate structure of matter: its polarization records both the asymmetry of a medium and the geometry of an interface.

Experimental Physics Examination†

Polarization of Light in Transparent Media

rotation of the polarization direction in a sugar solution and polarization by reflection from a glass plate

Examination topics: light polarization, optical rotation and the Brewster condition.
Suggested total score: 20 points.
Suggested examination time: 5 hours.
Permitted materials: pen, pencil, eraser, ruler, graph paper and a non-programmable scientific calculator.

General Instructions

1. Read the whole examination before measuring; divide your time between the two experimental parts.
2. Record all readings, units, instrument ranges, uncertainties and relevant qualitative observations.
3. Graphs must identify the axes, units and legend, and represent the experimental data appropriately.
4. Maintain the angular references defined in each part. Do not arbitrarily redefine zero during a measurement series.
5. Before and after each series, check that the beam is aligned with the centres of the optical elements and the photodetector. Do not directly compare currents obtained with different lengths or configurations.
6. **In both parts of the examination, always assemble the kit with the laser on the right** (the beam travelling from right to left), as viewed by the experimenter working in front of the laboratory bench. This arrangement reduces the risk of reflections reaching the experimenter, but does not remove the need to control reflected beams.
7. **Strictly follow the laser safety instructions and WEAR the protective goggles (PPE) supplied by the examination staff throughout assembly and data acquisition.**
8. Handle the sugar solution and glass plate carefully. Immediately dry any liquid spilled on the laboratory bench.

LASER SAFETY: wearing the protective goggles (PPE) supplied by the examination staff is MANDATORY. Keep the goggles correctly positioned during alignment and measurements. Even with PPE, NEVER look directly into the laser beam, DO NOT point it at other people, and avoid specular reflections at eye level. Goggles reduce the risk of accidental exposure, but do not make direct viewing of the beam safe.

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Aim and Background

Polarization describes the direction in which the electric field of a light wave oscillates. When polarized light interacts with matter, its polarization direction may change during propagation, or it may be reflected and transmitted differently at an interface. This examination investigates these two effects experimentally.

Examination structure. You are not expected to know all the concepts presented here beforehand. Each stage briefly introduces an idea, relates it to what you will observe on the laboratory bench, and sets a task. Read each guided explanation before taking the corresponding measurement: the examination is designed to assess, but also to teach and practise, experimental research procedures.

How your answers will be assessed. Marking is based exclusively on the answers submitted on paper. Assembly and adjustment instructions guide your work; carrying them out earns no points by itself. For each item, present the requested evidence: labelled diagrams, readings with units and uncertainties, tables, calculations, graphs or data-based justifications. Show numerical substitutions in calculations; for repeated operations, one complete example and a table of results suffice. Statements such as "I assembled the apparatus correctly" or "the alignment was good" do not replace this evidence. If you cannot obtain a measurement, record the difficulty and analyse the available data. Safety precautions remain mandatory throughout.

Part I studies **rotation of the plane of polarization in optically active media**: the ability of certain media to rotate the polarization direction as light propagates through them. This can occur in crystals, liquids and solutions with suitable microscopic structures. An aqueous sugar solution provides an accessible, safe example of an optically active medium. Sugar molecules are chiral: they cannot be superimposed on their mirror images.[1] The observed rotation can depend on the substance and its concentration, the light path length, wavelength and temperature.

Part II studies reflection of polarized light at an air–glass interface. Components polarized perpendicular and parallel to the plane of incidence have different reflection coefficients. For parallel polarization, there is an incidence angle at which reflection ideally vanishes: the Brewster angle. Measuring this angle experimentally allows the refractive index of glass to be estimated.[2]

Initial Background: Concepts Needed for the Experiment

This section contains only the relations needed to interpret the measurements in Q1 and Q2.

[1] A chiral molecule and its mirror image form distinct structures called enantiomers. A sample containing an excess of one enantiomer may exhibit net optical rotation.

[2] The refractive index of a medium is $n = c/v$, where c is the speed of light in vacuum and v is its phase velocity in the medium.

Polarization and Malus's Law

Light is a transverse wave: its electric field $\vec{E}$ oscillates perpendicular to the propagation direction $\vec{k}$. In linearly polarized light, $\vec{E}$ oscillates in a definite direction. A polarizer mainly transmits the component of $\vec{E}$ parallel to its transmission axis.

As the analyser rotates, the current measured by the photodiode follows a shifted Malus law:

$$i(\theta_A) = a + b\cos^2(\theta_A - \phi)\,.$$

Here, θ_A is the analyser angle reading; a is the minimum signal level, b its amplitude, and ϕ the angular position of the curve. The model repeats every 180°, so all comparisons must retain the same zero, angular direction and branch of the curve.

Optical Rotation

An optically active solution rotates the polarization direction. Experimentally, this appears as a horizontal shift of the Malus curve. If ϕ_{ref} corresponds to the empty cell and ϕ_L to a solution length L, the rotation is

$$\Delta\phi(L) = \phi_L - \phi_{\text{ref}}.$$

Amplitudes need not be compared: the relevant quantity is the angular shift between the curves, with its sign and uncertainty.

This examination tests the model

$$\Delta\phi(L) = \alpha(\lambda, T)\, L^n C,$$

where C is the concentration, n the length exponent, and $\alpha(\lambda, T)$ characterizes the medium at the wavelength and temperature used. During the measurements, C, λ and T must remain constant.

Reflection and the Brewster Condition

The incident ray and surface normal define the plane of incidence. In s polarization, the electric field is perpendicular to this plane; in p polarization it is parallel.

The reflected currents i_s and i_p depend on the incidence angle θ_i. Near the Brewster angle, reflection of the p component reaches a minimum. The ratio

$$q(\theta_i) = \frac{i_s}{i_p}$$

increases in this region, but should be calculated only when i_p is positive and distinguishable from zero within its uncertainty. Determine θ_B by comparing the minimum of i_p with the region of the largest reliable ratio.

For incidence from air into glass,

$$\tan\theta_B = \frac{n_{\text{vidrio}}}{n_{\text{aire}}}, \qquad n_{\text{vidrio}} = n_{\text{aire}}\tan\theta_B.$$

Angles are measured from the normal. In this examination, use $n_{\text{aire}} = 1{,}000$ and obtain the index uncertainty by evaluating the expression at $\theta_B - u_\theta$ and $\theta_B + u_\theta$.

Instrumental Error Limit of the Multimeter

For current measurements in Q1 and Q2, use the **DT8380B** multimeter specifications in section 3.2 of the manufacturer's manual. The table below gives the **DC current** ranges used in this examination, originally in Portuguese.

Range	**Resolution D**	**Specified accuracy**
200 µA	100 nA	±(1,0 % of reading + 2D)
2000 µA	1 µA	±(1,0 % of reading + 2D)
20 mA	10 µA	±(1,0 % of reading + 2D)
200 mA	100 µA	±(1,2 % of reading + 2D)

The parameter D is the resolution of the selected range.[3] The manual's term +2 means two counts of the least significant displayed digit, i.e. $2D$, not two percent of the reading. For an indicated current i, calculate the instrumental limit from

$$\Delta i_{\text{inst}} = a_{\text{inst}}\,|i| + 2D, \qquad a_{\text{inst}} = \begin{cases} 0{,}010, & \text{in ranges 200 µA, 2000 µA and 20 mA;} \\ 0{,}012, & \text{in range 200 mA.} \end{cases}$$

The coefficient a_{inst} is the percentage in the table expressed as a decimal. Use the same unit for i and D; in the lowest range, $D = 100\,\text{nA} = 0{,}1\,\mu\text{A}$. Here, Δi_{inst} is the error limit specified by the manual's accuracy specification, not the standard deviation of repeated readings.[4]

Example for the DT8380B. For a reading of 4,58 mA in the 20 mA range, we have $a_{\text{inst}} = 0{,}010$, $D = 0{,}01\,\text{mA}$ and

$$\begin{aligned} \Delta i_{\text{inst}} &= 0{,}010 \times 4{,}58\,\text{mA} + 2 \times 0{,}01\,\text{mA} \\ &= 0{,}0458\,\text{mA} + 0{,}0200\,\text{mA} = 0{,}0658\,\text{mA}. \end{aligned}$$

Rounding this limit upward to the decimal place of the resolution, the reading may be reported as

$$i = (4{,}58 \pm 0{,}07)\,\text{mA},$$

considering only the **instrumental contribution**.

For N repeated readings x_k, the **sample standard deviation** s and the **standard deviation of the mean** $s_{\bar{x}}$, also used here as the statistical uncertainty of the mean u_{estat}, are given by

$$\bar{x} = \frac{1}{N}\sum_{k=1}^{N} x_k, \qquad s = \sqrt{\frac{1}{N-1}\sum_{k=1}^{N}(x_k - \bar{x})^2}, \qquad s_{\bar{x}} = u_{\text{estat}} = \frac{s}{\sqrt{N}}.$$

Application to repeated measurements. In Q1–A.1 and Q2–A.1, calculate Δi_{inst} for every reading using a_{inst} and D for its range. Report the mean, sample standard deviation and standard deviation of the mean separately for each set of three measurements; in this case, $N = 3$ and $u_{\text{estat}} = s/\sqrt{3}$.
Do not divide Δi_{inst} by $\sqrt{3}$: repeated readings do not automatically reduce the instrumental error limit. Even when the display reads zero, the expression gives $\Delta i_{\text{inst}} = 2D$.

[3] Resolution is the smallest distinguishable change in a reading; for a digital multimeter it is the last displayed digit's step in the selected range. Resolution alone does not represent the entire specified error limit.

[4] An error limit bounds the error interval permitted by the specification. It is not, by itself, a statistical uncertainty of the mean or a standard uncertainty equivalent to one standard deviation.

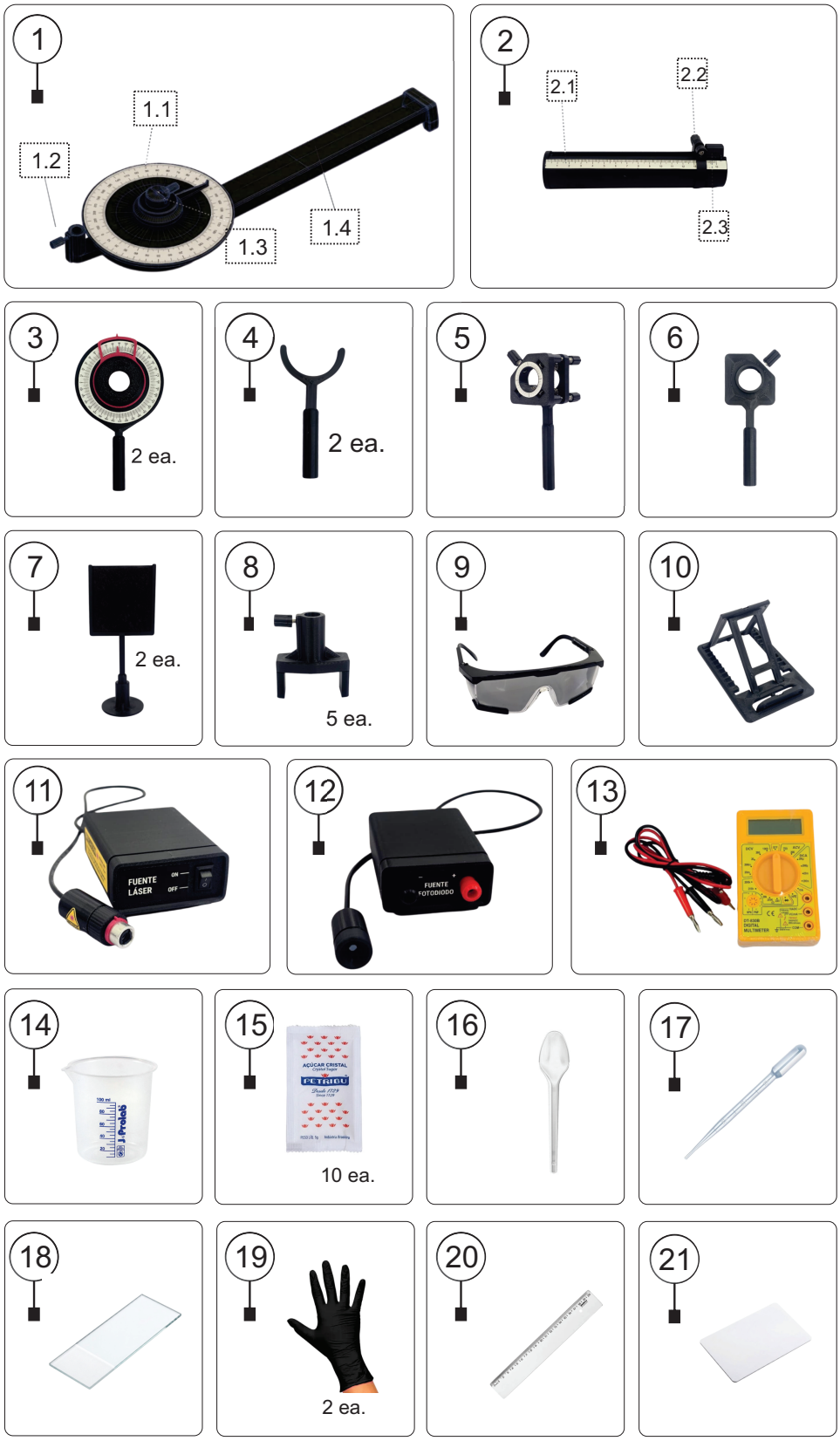
Checking and Identifying the Kit

The photograph below gives an overview of the kit materials. The diagram on the next page identifies each component. Check the items before starting assembly, and report any missing or damaged item to the staff. List numbers refer exclusively to the numbers in the diagram.



Overview of the components supplied in the experimental kit.

Kit Identification Diagram



Item	Description	Quantity
1	Optical rail and goniometer assembly with sample holder	1
1.1	Goniometer angular scale	—
1.2	Photodiode mount	—
1.3	Sample holder	—
1.4	Metal rail	—
2	Variable-length cell	1
2.1	External millimetre scale	—
2.2	Sealing ring	—
2.3	Cylindrical piston	—
3	Polarizers with angular scale	2
4	Cell mounts	2
5	Laser mount with adjustment screws	1
6	Photodiode mount	1
7	Screens to block laser reflections	2
8	Bases for support rods	5
9	Protective goggles	1
10	Multimeter mount	1
11	Power supply and laser emitter	1 set
12	Photodiode power supply and sensor	1 set
13	Multimeter with test leads	1 set
14	Graduated beaker	1
15	Sugar sachets	10
16	Plastic spoon	1
17	Graduated transfer pipette	1
18	Glass plate	1
19	Surgical gloves	2
20	Millimetre ruler	1
21	White card for viewing the laser beam	1

The quantities reproduce the illustrated materials and the labels in the diagram. A dash in the quantity column denotes a component of assembly 1 or 2, not an additional piece.

Q1 — Rotation of the polarization direction in a sugar solution (10 points)

Keep the laser on the right and the first polarizer fixed throughout all series. Before recording data, align the beam with the centres of the cell, analyser and photodiode, and determine the angular resolution. These adjustments are operating procedures, not scored questions.

PART A — Reference curve with the empty cell (4,0 pts)

Install the empty cell, keep the scale zeros fixed, and rotate only the analyser.

A.1 **2,0 pts**

Guided background. The empty-cell curve includes the optical windows and provides the reference for all measurements with solution.

Task. Measure the reference current i_{ref} as a function of the angular position θ_A. Present a table of θ_A and i_{ref}, including units and the applicable instrumental uncertainties. Plot i_{ref} against θ_A, identifying the axes and showing uncertainties where appropriate.

A.2 **2,0 pts**

Guided background. The angular position of the reference curve can be described by the phase parameter ϕ_{ref} (polarization direction) in a shifted Malus law.

Task. Fit the data from A.1 to the model

$$i_{\text{ref}}(\theta_A) = a_{\text{ref}} + b_{\text{ref}} \cos^2(\theta_A - \phi_{\text{ref}})$$

and determine ϕ_{ref} with its uncertainty. State the fitting method used and report the fitted parameters with their units.

PART B — Rotation of light polarization on passing through a sugar solution (6,0 pts)

Rotation of the polarization direction shifts the intensity curve horizontally. Choose a reference point on the curve and check how it shifts with the path length L travelled by light in the sample.

B.1 **2,0 pts**

Guided background. Comparisons require the geometry and angular references to remain unchanged between series.

Task. Prepare a solution containing 0,40 g of sugar per millilitre of water, measured before dissolution. Choose at least three different lengths $L_1, \ldots, L_n$ within the cell's length limit. Choose a reference point on the intensity curve and construct a table of L as a function of the curve shift $\Delta\phi$.

B.2 **2,0 pts**

Guided background. Optical rotation is determined from the horizontal shift needed to align each curve measured with solution with the reference curve.

Task. Plot $\Delta\phi(L_k)$ against L_k, with the corresponding error bars.

B.3 **2,0 pts**

Guided background. The dependence to be tested is

$$\Delta\phi(L) = \alpha(\lambda, T)\, L^n C,$$

where $\alpha(\lambda, T)$ characterizes the medium and depends on the wavelength λ and temperature T; n is the length exponent, and C is the solution concentration. During the experiment, λ, T and C must be treated as constant.

Task. From the behaviour observed in the graph in B2, propose a suitable fit and determine n and α.

Q2 — Polarization by reflection from a glass plate (10 points)

Unscored operating adjustments

Assemble the system with the laser on the right. Without the plate, align the rail, goniometer centre and photodiode for direct beam incidence. Install the plate with its normal at $\theta_i = 0°$ and determine the angular resolution. Retain this reference throughout Q2.

PART A — Intensity of reflected light (6,0 pts)

Before the angular scan, identify the operating orientations for s and p polarization and balance the reflected intensities. After balancing, keep the laser orientation fixed and retain the established angular references.

A.1 **2,0 pts**

Guided background. With the plate at $\theta_i \approx 70°$, the maximum reflected intensity as the polarizer rotates defines α_s, the operating reference for s polarization. The observed minimum defines α_p, the operating reference for p polarization, provided its separation from α_s agrees with 90° within the uncertainties.

Task. Rotate the polarizer through 180° and determine α_s and α_p, their uncertainties and the corresponding reflected intensities. Check that $|\alpha_p - \alpha_s|$ agrees with 90°. If not, switch off the laser, rotate its body slightly about its longitudinal axis, recheck alignment, and repeat. Tabulate the tested laser orientations, α_s, and α_p, currents and angular separation.

A.2 **2,0 pts**

Guided background. Balancing establishes a fixed source orientation for comparing the two polarizations. With the plate at $\theta_i = 70°$, compare the currents $i_{s,70}$ and $i_{p,70}$ measured at the fixed positions α_s and α_p.

Task. Alternate the polarizer between α_s and α_p and record $i_{s,70}$ and $i_{p,70}$. If necessary, switch off the laser, rotate its body slightly, and repeat the readings without redefining α_s or α_p. Calculate

$$\varepsilon_{\text{bal}} = \frac{|i_{s,70} - i_{p,70}|}{(i_{s,70} + i_{p,70})/2}$$

and adjust the source until $\varepsilon_{\text{bal}} \leq 0{,}10$. Report the readings for every attempt, the final laser orientation and the percentage difference $100\varepsilon_{\text{bal}}$ %.

Choose incidence angles spanning both sides of the current minimum for p polarization. Use smaller steps near the minimum. At each angle, place the photodiode in the specular direction and measure i_s and i_p without changing the laser orientation.

A.3 **1,0 pts**

Guided background. Use the same angular scale for both polarization curves so that they can be compared directly.

Task. Present a table of θ_i, i_s, i_p, units and uncertainties. Plot $i_s(\theta_i)$ and $i_p(\theta_i)$ together on the same sheet of graph paper, using different symbols or line styles and a legend to distinguish them.

A.4 **1,0 pt**

Guided background. The ratio $q = i_s/i_p$ is defined only when i_p is positive and distinguishable from zero within its uncertainty.

Task. Calculate q for each valid angle, add the values to a table, and plot $q(\theta_i)$. Do not calculate or plot q at points whose denominator is not positive and distinguishable from zero within its uncertainty.

PART B — Brewster angle and refractive index (4,0 pts)

B.1 **2,0 pts**

Guided background. The Brewster angle corresponds to the minimum of i_p and the region of the largest reliable ratio q.

Task. Determine θ_B by comparing the minimum of i_p with the region of the largest reliable ratio. Calculate $\theta_B^{\text{exp}} \pm u_\theta$ and show how the position and uncertainty follow from the angular resolution and local sampling.

B.2 **1,0 pts**

Guided background. For incidence from air into glass, $n_{\text{vidrio}} = n_{\text{aire}} \tan\theta_B$.

Task. Use $n_{\text{aire}} = 1{,}000$ and calculate n_{vidrio} with its uncertainty.

B.3 **1,0 pts**

Guided background. The nominal value $n = 1{,}50$ is used only as a reference for comparison.

Task. Calculate the percentage deviation between θ_B^{exp} and θ_B^{teo}. Present a final table containing the angular resolution, θ_B^{exp}, u_θ, θ_B^{teo}, n_{vidrio}, its uncertainty limits and the percentage deviation.

Glossary

Analyser
A polarizer placed after the sample or interface, used to investigate the direction or state of polarization of the emerging light.

Brewster angle, θ_B
The incidence angle at which the reflectance of the p component is minimal and, ideally, zero at an interface between transparent media.

Optical activity
A medium's ability to rotate the polarization direction of linearly polarized light as it propagates.

Sample length, L
The geometric distance travelled by the beam inside the solution, with all other experimental conditions fixed. In Q1, the lengths freely chosen by the student are denoted $L_1, \ldots, L_n$, where n is the number of lengths chosen within the cell's dimensional limit. In a homogeneous medium of refractive index n_{medio}, the corresponding optical path is $n_{\text{medio}}L$.

Background current, i_{fondo}
Current recorded by the detection system without the useful light signal, under the same conditions and in the same range as the measurements. It may include detector dark current, electronic contributions and residual ambient light.

Standard deviation of the mean
Estimate of the mean's statistical spread for N repeated readings, $s_{\bar{x}} = s/\sqrt{N}$, where s is the sample standard deviation.

Transmission axis
The direction of a polarizer along which the electric-field component is preferentially transmitted.

Enantiomers
Molecular structures that are non-superimposable mirror images of one another.

Laser
A source producing an intense, directional, approximately monochromatic beam with high coherence.

Malus's law
The relation describing the intensity transmitted by an analyser in terms of the squared cosine of the angle between its transmission axis and the incident polarization.

Instrumental limit
The error limit calculated from the instrument's accuracy specification. It is not, by itself, a standard deviation or the statistical uncertainty of the mean.

Linearly polarized light
Light whose electric field oscillates along a well-defined transverse direction.

Unpolarized light
Light whose electric-field oscillations have no preferred transverse direction over time.

Cell adjustment knob
A manually operated part that tightens the sealing-ring screw and prevents leaks. It is not the cursor used to read the length L.

Chiral molecule
A molecule whose structure cannot be superimposed on its mirror image by rotations or translations.

Normalization
Division of the values in a series by a reference. In Q1, use $i^{\text{corr}}_{\text{máx},k}$, the largest corrected current among the regular-grid points selected for series k; this need not coincide with the maximum of the complete curve. In Q2, calculate the ratio of the two reflected-polarization currents, subtracting background current when necessary, without normalizing each curve by its own maximum. This ratio is not a direct measure of reflectance.

Plane of incidence
The plane defined by the incident ray and the surface normal at the point of incidence.

p polarization
Polarization whose electric field oscillates parallel to the plane of incidence.

s polarization
Polarization whose electric field oscillates perpendicular to the plane of incidence.

Circular polarization
A state in which the tip of the electric-field vector rotates around the propagation direction while its magnitude remains approximately constant.

Reflectance
The ratio of reflected light power to incident light power for a specified polarization and geometry.

Optical rotation
Rotation of the polarization direction during propagation in an optically active medium; in this examination, a sugar solution.

Mechanical zero of the goniometer
The fixed mechanical reference of the assembly, with the rail axis, goniometer rotation centre and photodiode centre aligned for direct incidence without the plate. With the plate installed and its normal aligned with the beam, this reference corresponds to $\theta_i = 0^\circ$ and must not be redefined from current readings.