5. Polarisation

5.1 Introduction

Interference and diffraction phenomena, as analysed in the interference and spectrometer experiment, show the wave nature of light. Measurements of polarisation demonstrate that light waves are transversal waves. As illustrated in Figure 5.1 and 5.2 by the example of a mechanical wave on a cord, the transmission of transversal waves can depend on the direction of oscillation.

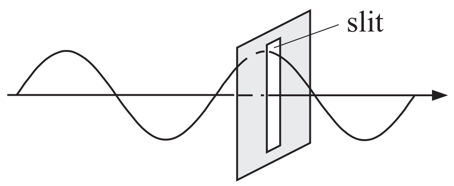

Figure 5.1: If the direction of oscillation of the incoming cord wave is parallel to the slit, the wave can move through the slit unhindered.

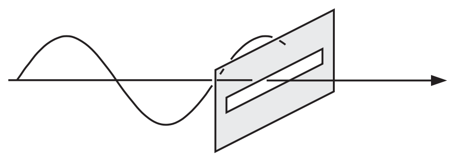

Figure 5.2: If the direction of oscillation of the incoming cord wave is perpendicular to the slit, the wave cannot move through and is reflected.

The direction of oscillation of the wave is called the direction of polarisation. The transmission of the cord wave through the slit depends on the direction of polarisation and the facing of the slit. The model also shows that the polarisation of a wave can only be detected in an anisotropic medium. In the model, an anisotropic medium would correspond to a circular hole instead of the slit. The transmission through the hole would be independent of the direction of polarisation.

In this experiment, different measurements of the polarisation of visible light are made. The observations are to be described and explained. Keywords to this experiments are:

- (Electromagnetic) waves, their description and properties
- Polarisation

5.2 Theory

Visible light consists of electromagnetic waves with wavelengths in the range between ca. 400-700 nm. The spatially and temporally variable electric and magnetic fields are perpendicular to the direction of propagation (Figure 5.3 and 5.4).

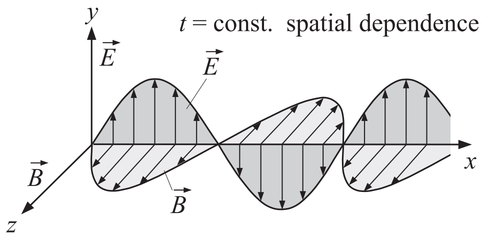

Figure 5.3: Electromagnetic wave in the space frame.

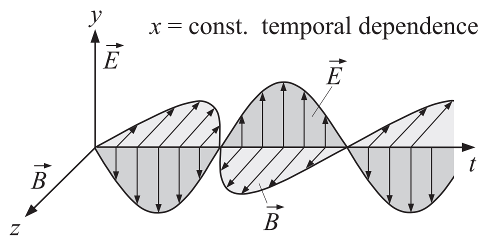

Figure 5.4: Electromagnetic wave in the time frame.

The direction of the $\vec{E}$-vector is called the direction of polarisation of an electromagnetic wave (older books occasionally call the direction of the $\vec{B}$-field the direction of polarisation)

If the $\vec{E}$-vector of an electromagnetic wave oscillates in always the same direction, the light is said to be linearly polarised. Natural light is unpolarised. The atoms of a light source independently emit wave trains, whose $\vec{E}$-vectors oscillate statistically distributed in all directions perpendicular to the direction of propagation. Linearly polarised light can be created out of natural light by the use of polarisators.

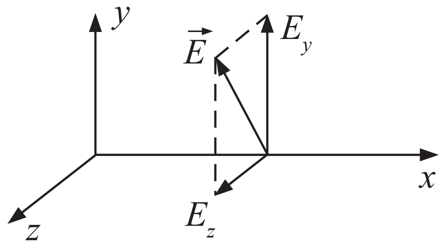

Figure 5.5: Decomposition of the electric field $\vec{E}$.

When choosing a y- and a z-direction in a plane perpendicular to the direction of propagation of the wave, every $\vec{E}$-vector can be decomposed into two components E_y and E_z (Figure 5.5). During the "polarisation" of light, one component (e.g. E_y) is suppressed and the other allowed through. After the polarisation, a wave linearly polarised in z-direction is produced. There are different methods for the polarisation of light, two of which are discussed shortly in the following.

5.2.1 Polarisation Filter

For some crystals (e.g. Herapathit and Turmalin), the absorption capacity depends on the direction of polarisation of the incoming light. In polarisation filters, spicular crystals lie aligned in an amorph carrier substance (Figure 5.6). In the longitudinal direction of the crystals, the electrons of the moleculs are slightly mobile. Under the influence of the, to this direction, parallel component of the $\vec{E}$-vector, currents flow in the crystals and field energy is absorbed. The component of the $\vec{E}$-vector parallel to the longitudinal axis of the crystals is thereby strongly absorbed, the component perpendicular to the longitudinal axis however is mostly allowed through. After passing through the filter, the light is to a large extent linearly polarised.

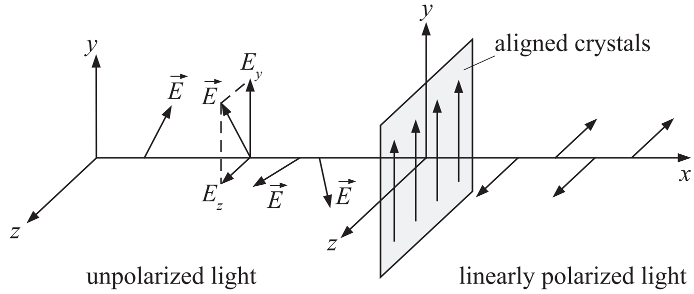

Figure 5.6: Linear polarisation in a crystal.

5.2.2 Birefringence

The velocity of propagation of light in a medium is $v = c/n$. Where c is the speed of light and n the refraction index of the material. In optically anistropic crystals, meaning in all crystals with non-cubic symmetry, the refraction index depends on the direction of arrival of the light, respectively on its direction of polarisation.

If a beam of light hits such a crystal, the beam splits into two perpendicularly polarised beams: the so-called ordinary and extraordinary beams (Figure 5.7). The ordinary beam obeys the refraction law of optics, the extraordinary beam does not. These types of crystals are called birefringent. In every crystal, there exists at least one direction in which there is no birefringence, so every crystal has at least one or more optical axes.

The most commonly used birefringent crystal is the calcspar ($CaCO_3$).

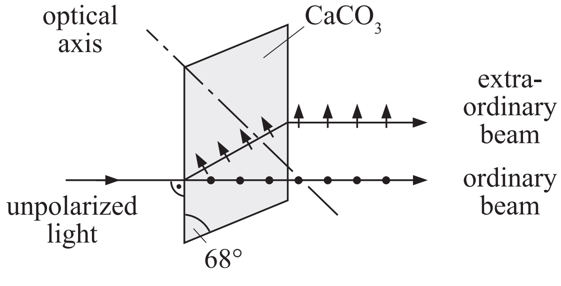

Figure 5.7: Birefringence in an anisotropic crystal, e.g. calcspar ($CaCO_3$).

To produce linearly polarised light, one of the two beams has to be blinded out (Figure 5.8). A calcspar is cut in two along the smaller diagonal and puttied together again using Canada balsam. The refracted, i.e. the ordinary beam experiences total reflection at the seperation layer and is blinded out. The practically unrefracted extraordinary beam is linearly polarised.

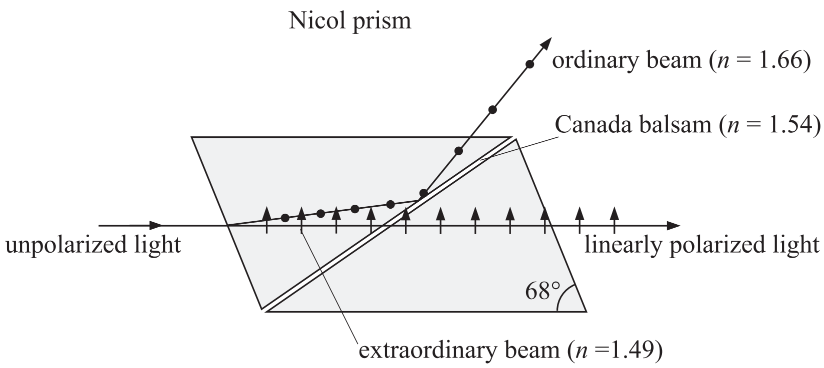

Figure 5.8: Polarisation with a Nicol prism.

5.2.3 Polarisation through Scattering

If unpolarised light passes through a turbid liquid, then it is partly scattered on the particles (the scattering is stronger, the shorter the wavelength). The light scattered perpendicular to the direction of arrival is completely polarised. In all other directions ($\alpha \neq 90°$), the polarisation is partial (Figure 5.9).

The sunlight is scattered when passing through the atompshere, where the blue component is preferentially scattered to all sides. That is why a clear blue sky appears to be blue. The sky blue is thereby partially polarised; the strongest under an angle of 90° to the sun. On a clear day, one can experience this easily using a polarisation filter.

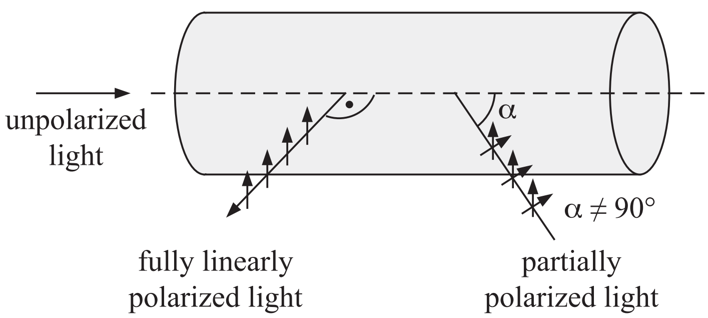

Figure 5.9: Polarisation through scattering.

5.2.4 Detection of Linearly Polarised Radiation

If unpolarised light is sent through two polarisation filters one after the other, then the final intensity depends on the relative position of the two polarisation filters. With the parallel alignment, the intensity is maximal. With cross alignment, the intensity is minimal (Figures 5.10 and 5.11). The second polarisation filter thus becomes the analyser. Polarisation filter and analyser in cross alignment is called a dark field array.

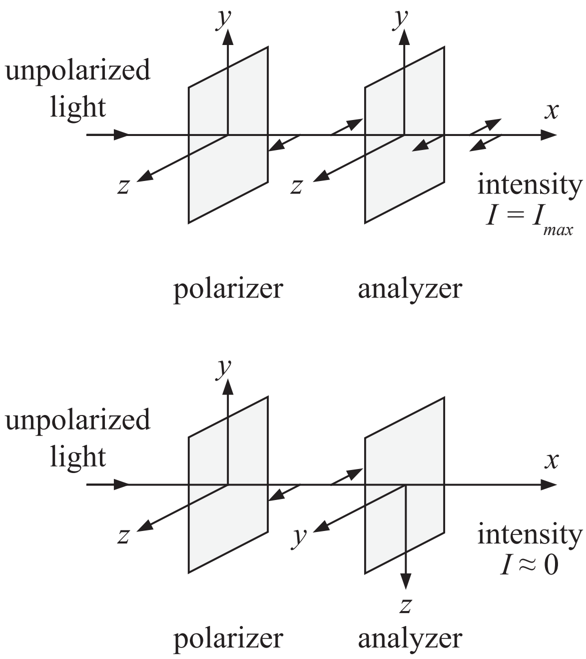

Figure 5.10: Parallel (above) und cross (below) alignment of two polarisation filters.

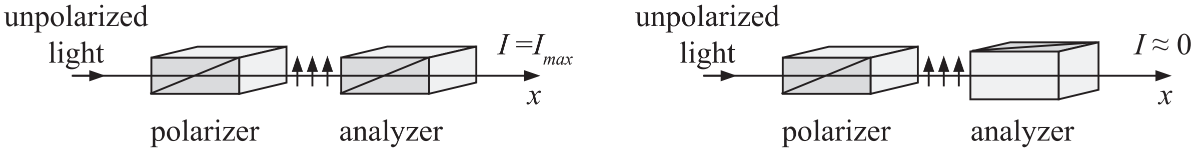

Figure 5.11: Parallel (left) und cross (right) alignment of two Nicol prisms.

5.3 Experimental Part

5.3.1 Qualitative Preliminary Tests

Conduct the first two of these tests yourself, let the assistant demonstrate the third and the fourth!

Describe in the test report the observations and explain as much as possible.

- Position two polarisation filters in succession (Figure 5.12) and observe the variation of intensity on the screen due to the different positioning of the analyser.
- Radiate a cuvette filled with a turbid liquid, whose particles are evenly distributed, with unpolarised light (Figure 5.13). Look at the laterally scattered light under different angles through a polarisation filter (analyser). Describe your observations.

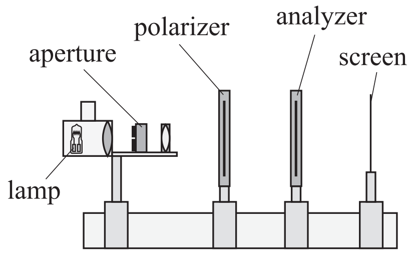

Figure 5.12: Experimental setup with two polarisation filters.

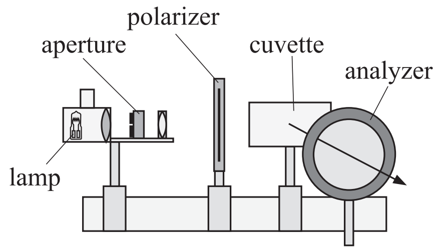

Figure 5.13: Experimental setup with polarisation filter and cuvette.

- Hold a calcspar over a printed or written word. Take a note of your observations and let the assistant explain it to you.
- Two polarisation filters are to be positioned in cross alignment. Then hold a quartz plate between the two filters. Write down your observations and reflect on the phenomenon you see. (As the rotatory dispersion of quartz depends heavily on the wave length of the light, monochromatic light has to be used for this experiment.)

5.3.2 Analysis of Optical Activity of a Sugar Solution

Principle of the Measurement

Radiating a vessel, that contains a sugar solution, with linearly polarised light rotates the direction of polarisation by an angle α (Figure 5.14). The rotation angle α is proportional to the concentration c of the solution and to the length d of the path of light in the solution:

$$\alpha = [\alpha] \cdot c \cdot d \tag{5.1}$$

The material constant $[\alpha]$ is called the specific rotation. In tables, $[\alpha]$ is usually given in $\frac{\text{Grad}\cdot\text{cm}^3}{\text{g}\cdot\text{dm}}$, i.e. the rotation angle α is measured in degrees, the length d in dm, and the concentration c in g/cm^3.

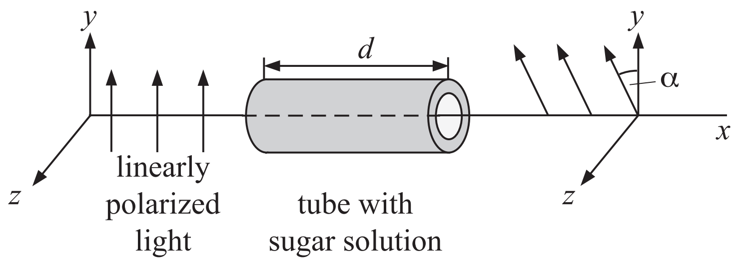

Figure 5.14: Setup for the measuring of the optical activity of a sugar solution.

Substances, which cause a rotation of the direction of polarisation, are called optically active. Not only the sugars, but e.g. also the proteins count to this group. The direction of rotation is determined by the molecular structure. The optical activity is often used for the detection and determination of concentration of sugar and protein (polarimetric measurement).

In the process, the vessel with the solution is positioned between two cross aligned polarisators. The direction of polarisation of the light is being rotated in the solution and the image on the observation screen brightens up. The analyser has to be rotated by the angle α to minimise the intensity again (Figure 5.15).

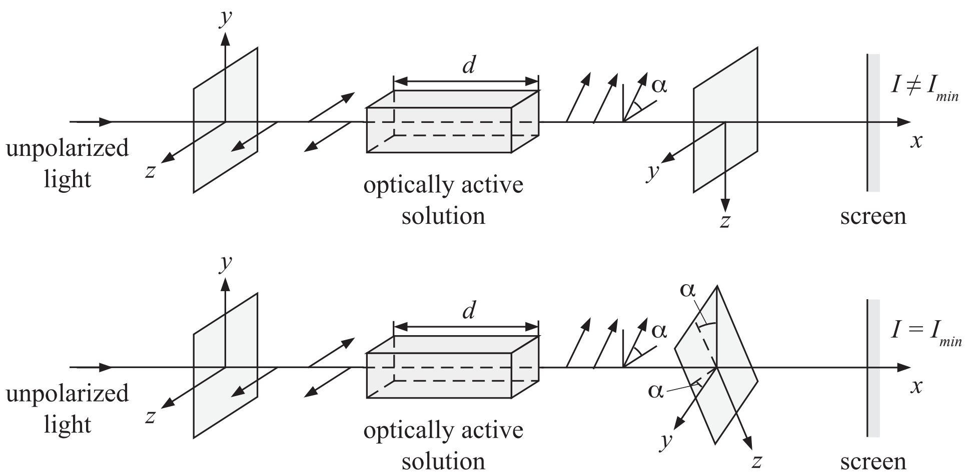

Figure 5.15: Experimental setup with an optically active solution.

Model Experiment

- Build the polarimeter following Figure 5.16. The tubes with the sugar solution can be put in the holder between the two filters.
- Measure the relation of the rotatory angle α to the length d: Put 1, 2, and then 3 measuring tubes in succession with solutions of the same concentration in the holder and observe the increasing rotation of the direction of polarisation. The length of the tube is 10 cm.
- Determine the specific rotation $[\alpha]$ of saccharose: Put in three measuring tubes of different concentration seperately in the holder and measure for each concentration the angle α.

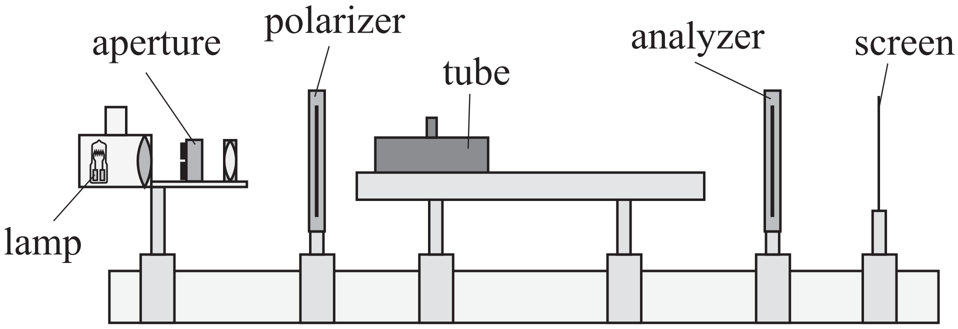

Figure 5.16: Experimental setup for the determination of the rotatory dispersion of saccharose.

Estimate the error of the angle measurement and put the numerical results together in a table.

- Draw the angle α as a function of the concentration. The resulting straight line has the slope $\Delta\alpha/\Delta c = [\alpha] \cdot d$ (compare with Eq. 5.1). Calculate the specific rotation from the slope of this straight line.
- Measure the rotatory angle α for tube No. 6 and determine from the depiction the concentration c of the solution 6.

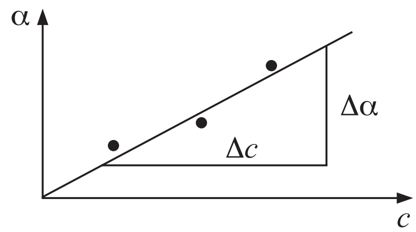

Figure 5.17: Angle α as a function of the concentration.

Polarimetric Concentration Measurement

The simplest polarimeters correspond in the setup to our model polarimeter. Instead of a polarisation filter, one uses usually 2 Nicol prisms. Instead of the screen, an observation telescope. Because of the limited sensitivity of the eye for absolute brightness, the intensity maximum is hard to determine and the measurement of the angle α shows large errors. In practice, better methods have been developed. The so-called half-shade method is wide-spread nowadays: The field of vision of the telescope is split in half. Without an optically active substance, the analyser is adjusted as for the two halves to be equally bright. When adding the substance in the beam of light, the brightness will distribute. Now the analyser is to be rotated until the difference in brightness disappears. Because the eye is very sensitive for differences in brightness of two adjacent areas, the angle can be accurately determined (ca. 1/5 - 1/10 degree accuracy).

For the measurement in the half-shade polarimeter, there are measurement tubes with glucose solutions at your disposal. The concentration can be read directly on the percentage scale of the polarimeter. The handling of the polarimeter will be demonstrated by the assistant.

5.3.3 Lab Report

- Answer the following questions:
  - Waves can be longitudinal or transversal. Cite examples for both of these types.
  - What is the so-called direction of polarisation of an electromagnetic wave?
  - Why is natural light unpolarised?
  - Can natural light be made into linearly polarised light? Describe and sketch 2 methods.
  - How can one determine experimentally that light is linearly polarised?
  - Sugar is optically active. What does that mean?
  - How can the rotation of the direction of polarisation be experimentally observed?
  - Describe and explain the observations that you have made in the qualitative preliminary tests.

- Estimate the measurement error on the measured specific rotation $[\alpha]$ of saccharose: Plot for each measurement point the estimated measurement error in the graphical diagram. Draw not only the best, but also the smallest and the largest possible slow through the measurement error bars (Figure 5.18). Determine from the slopes of these additional straight lines an estimation of the measurement error on $[\alpha]$.

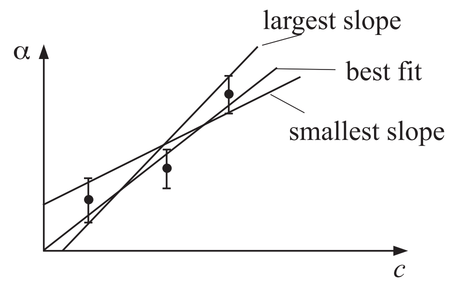

Figure 5.18: Angle α as a function of the concentration.