

CONSTRUCTION OF A LOW-COST POLARIMETER FOR EDUCATIONAL PURPOSES

Claudio A. G. da Camara^{a,*}, ^aDepartamento de Química, Programa de Pós-graduação em Química, Universidade Federal Rural de Pernambuco, 52171-900 Recife – PE, Brasil

Recebido em 06/07/2020; aceito em 28/09/2020; publicado na web em 28/10/2020

This paper describes the construction of a polarimeter for the identification of chemical substances. The device was built with low-cost materials, measures the phenomenon of optical activity and has educational applicability. The measurement of optical activity is achieved through the measurement of the resulting polarized radiation in a photodiode connected to a voltmeter after passing through polarizing and analyzing filters.

Keywords: chemical substance; optical activity; polarimeter.

INTRODUCTION

In chemistry, the existence of a large number of substances is due to the innumerable possibilities of how atoms can interact to form molecules. Molecular structure is characterized by the type, quantity and proportionality of the elements, the order in which they are linked and the type of geometric arrangement. Thus, isomerism is, without a doubt, one of the most fascinating and important aspects of the behavior of a chemical substance.

Isomers are different compounds that have the same molecular formula. Prior to the theory of molecular structure, which was developed in the 1860s, the elucidation of the molecular formulas of substances with the same elemental chemical composition but different physical properties posed a challenge to chemists. Compounds with the same chemical and physical properties but that differed when submitted to polarized light were even more complex.¹ Today, we know that these compounds are stereoisomers, meaning that they have the same order of connectivity of their atoms but differ in their spatial arrangement.

There is a variety of type of stereoisomers and chirality is the basis of the stereoisomerism of many molecules. Chiral is the term used for objects, including molecules, that cannot be superimposed onto their mirror images. These molecules are denominated enantiomers, which have the same chemical and physical properties but differ in the presence of polarized light on the specific rotation plane $[\alpha]$.² $[\alpha]$ is the intrinsic property of an optically active molecule and optical activity is the phenomenon that certain molecules have to deviate the plane of polarized light. The use of light in organic analysis began with polarimetry. This technique uses the phenomenon of the polarization of light to differentiate substances that have optical activity and a polarimeter is an instrument used to determine the displacement of the angle of polarized light caused by a chemical substance.

Undergraduate or high school students face a number of difficulties in the learning process regarding concepts related to stereochemistry, such as configuration, enantiomers, chirality, polarized light and optical activity. Understanding such concepts goes beyond observation associated with experimentation.³ A historical-conceptual approach combined with teaching tools can be a significant help to show the path traveled in the understanding of concepts and the role of each researcher who contributed to knowledge building over time.

Among the many aspects that have characterized studies in science teaching, two merit special attention: studies on historical-conceptual

developments and those related to experimentation for teaching purposes.⁴ One of the ways to make the learning process a more pleasant experience is the use of teaching resources.⁵ As the motivation of students is an important aspect of the learning process, experimentation is an excellent tactic for mitigating the difficulties students face regarding abstract concepts that are difficult to understand, such as those in the field of stereochemistry.⁶

Fully exploring experimentation means creating conceptual links from a historical contextualization of facts and experiments that serve as the foundation for the concepts to be learned, thereby demystifying scientific knowledge. The use of practical activities involving experiments can facilitate the acquisition or reformulation of concepts that students normally find difficult to grasp.

Thus, the use of a teaching resource, such as a polarimeter built from low-cost materials for use in practical organic chemistry classes, is an excellent alternative to traditional methods. Moreover, it can stimulate the curiosity of students regarding the historical-conceptual process and how terms like optical activity, chirality and light polarization emerged. The result of such an approach is a dynamic, motivating teaching-learning process that favors the engagement of the students, bringing them closer to scientific knowledge by linking it to their day-to-day experiences.

Considering the polarimeter to be an important scientific instrument for the determination of the optical activity of chemical substances and an educational tool that enables a historical-conceptual, multidisciplinary, interdisciplinary approach to the learning of physical, chemical and biological processes in the field of stereochemistry, this paper describes the construction of a low-cost polarimeter to be used for educational purposes at high schools, colleges and universities.

HISTORY

Isomerism, stereochemistry and optical activity

Before the step-by-step description of the construction of the teaching tool, it is important to present the historical-conceptual process that gave rise to the conception and construction of the low-cost polarimeter from the discovery of the phenomenon of the polarization of light to its use for distinguishing optically active stereoisomers the led to the concept of molecular dissymmetry (currently denominated molecular chirality) coined by Louis Pasteur (1822-1895) in 1848.⁷

*e-mail: claudio_agc@hotmail.com

The properties of the interaction between light and matter are fundamental to optical analytical methods. Polarization is one of the primary physical aspects associated with the electromagnetic field. White light is an electromagnetic wave that exhibits an oscillation of an electrical field and a magnetic field that are perpendicular to each other and propagate on all planes. However, it is not the direct interaction between this light and particular objects and chemical substances that enables distinguishing whether a given substance had optical activity, but rather white light submitted to physical phenomena, such as refraction or reflection, that results in a light beam that is characterized by oscillating on a single plane, denominated plane polarized light.

The first reports of phenomena involving the polarization of light date back to the 17th Century and are related to experiments involving the interaction of sunlight with ultrapure crystals. The first to record this phenomenon was Danish mathematician Rasmus Bartholin (1625-1698) in 1669, who observed the double refraction (today known as birefringence) of light through Iceland spar (calcite crystal),⁸ known to the Vikings as sunstone. Bartholin observed two rays of sunlight (one following a slightly different path from that of the main beam) and was the first to use the terms 'ordinary ray' and 'extraordinary ray'.⁹ A short time later and unaware of the phenomenon of polarization, the Dutch physicist and astronomer Christiaan Huygens (1629-1695) developed the theory of double refraction using the same principle that described refraction.¹⁰ One hundred thirty years after the first observation of birefringence, French engineer, physicist and mathematician Étienne-Louis Malus (1775-1812) used the term polarized light for the first time for the phenomena observed by Huygens and Bartholin.¹¹ He also discovered that polarized light was not restricted to certain crystals, but could be produced by light reflected in the air on the surfaces of water, glass and other transparent solids.¹² In 1811, French physicist and astronomer Dominique François Jean Arago (1786-1853) observed optical rotation and rotary optical dispersion and also discovered that moonlight is polarized.¹³

In 1812, Scottish physicist David Brewster (1781-1868) established a mathematical expression investigating reflection and refraction stemming from the polarization of light and determined the angle of incidence at which the complete polarization of a reflected light beam occurred, which received his name (Brewster's angle).¹⁴ In the same year, French physicist, astronomer and mathematician Jean-Baptiste Biot (1774-1862) turned his attention toward the investigation of phenomena in the field of optics, particularly the polarization of light. To perform his experiments, he constructed an instrument to measure the optic rotation of substances, called the polarimeter.¹⁵ This instrument consisted of a system of black mirrors to produce polarized light and had low quality.¹⁶ A significant improvement was achieved by German physicist Ventzke,¹⁷ who used Nicol prisms as polarizing and analyzing filters. This prism was made in 1829 by English geologist William Nicol (1768-1851), who used two pieces of Iceland spar bonded with Canada balsam.¹⁸

Biot's work revealed that not only crystals but also some liquid substances had the capacity to deviate the plane of light to the right or left, such as turpentine or alcoholic solutions of camphor, sugar and tartaric acid. Biot called the phenomenon of the displacement of the plane of polarized light by substances "optical activity".¹⁵ Subsequent investigations showed that the angle of rotation was a direct measure of the concentration of the substance, which provided a simple mechanism for analyzing saccharine solutions.¹⁵ Biot deduced that the phenomenon of optical activity was inherent to the molecular structure, but did not explain what phenomenon caused the optical activity of the compounds studied. This task was left up to French chemist and bacteriologist Louis Pasteur (1822-1895), who explained the phenomenon using paratartaric acid.⁷

Natural tartaric acid is a product in the form of salt obtained from the fermentation of grapes. It was first isolated in its free form by Carl Wilhelm Scheele (1742-1786) in 1770. In 1818, through the superheating of tartar, which is a byproduct of winemaking, a novel form of tartaric acid was obtained and denominated paratartaric acid or racemic acid, in reference to the vineyard fruit (from the Latin *remus*, meaning bunch). This novel byproduct of the fermentation of grapes caused a divergence among researchers at the time with regards to its chemical structure. According to Jöns Jacob Berzelius (1779-1848), who was one of the most widely respected chemists of the time, tartaric acid and paratartaric acid were isomers. Around 1831, at the Berzelius' request, German crystallographer Eilhard Mitscherlich (1794-1863) began to investigate the two salts (natural tartaric and paratartaric acid) in light of the theory of isomorphism (similarity in the crystalline structure of different compounds) in the search for possible differences between the two.¹⁹ In 1836, using his polarimeter, Biot discovered that natural tartaric acid was dextrorotatory (rotating the plane of polarized light clockwise), whereas paratartaric acid was found to be optically inactive. In 1844, Mitscherlich reached the conclusion that these salts are isomorphous and identical in density, solubility and all physical properties, except optical activity,²⁰ as Biot had demonstrated eight years earlier.

In the search for possible interrelations between hemihedrism (crystallization of a substance in a hemihedral shape) and analyses of the optical rotation of the crystals of natural tartaric and paratartaric acid performed by Mitscherlich and Biot, Pasteur conducted a new crystallographic evaluation of these salts, which confirmed previous studies by Mitscherlich that the crystals of these salts are hemihedral. To his surprise, however, analyzing the crystals of paratartaric acid more closely, Pasteur found that the substance was actually a mixture or conglomerate of two types of crystals – one with hemihedral faces slightly to the right and the other with hemihedral faces slightly to the left.^{19,21} After the meticulous separation of these crystals and the polarimetric analysis of the individual solutions, he found that they resulted in opposite optical rotations.¹⁹ Thus, the two forms of crystals that he was able to separate manually are non-superimposable specular images, which, in the current terminology are enantiomorphs or a pair of enantiomers. The fact that Biot had found that paratartaric acid did not have optical activity was because this compound is a conglomerate of equimolecular quantities of hemihedral crystals to the right and to the left.

As a consequence of Pasteur's work, beside achieving the first resolution of a racemic mixture (mixture with equimolecular quantities of a pair of enantiomers) that crystallize as conglomerates, the manual classification of the hemihedral crystals of paratartaric acid demonstrated the link between molecular dissymmetry (chirality) and optical activity.⁷

Optical activity is a fundamental property found in many chemical substances of interest to the chemical, food and pharmaceutical industries. Moreover, among quality control methods, polarimetry has proven to be important to all branches of science. Until the mid-19th Century, the main limitations of polarimetry were the use of the sun as the primary light source and the eye as the detector.¹² Current technology for measuring the phenomenon of optical activity consists of a highly precise and quite sophisticated system, which increases the cost.

EXPERIMENTAL

Construction of polarimeter

A viable alternative to expensive, sophisticated instruments for use in science classes in high school or even in colleges and

universities is the construction of a teaching instrument capable of determining the optical property of chemical substances, which can arouse the curiosity of students and motivate them with regards to learning abstract concepts, such as stereochemistry.

The materials used for the construction of a polarimeter are easily found in shops specialized in photographic equipment, hardware, electrical supplies and woodworking. The wooden base that served as the framework of the polarimeter was constructed at the woodworking shop of the *Universidade Federal Rural de Pernambuco* (UFRPE). The glass tube for holding the sample solution to be analyzed was made by a glasswork shop. Table 1 lists all materials used in the construction of the polarimeter and the cost of each component.

Table 1. List of materials used for construction of polarimeter and respective costs

Components	Price (R\$ - Brazilian currency)
Polarizing disc 50 mm (polarizer)	29.0
Polarizing disc 50 mm (analyzer)	29.0
Digital voltmeter	21.0
360-degree protractor	1.5
Photodiode detector	13.0
Support box for photodiode detector	5.0
Light source – laser pointer	23.0
Light source support and polarimeter base	15.0
PVC pipe 50 mm	2.0
Glass tube 10 mL	25.0
Total*	

* The total price does not include the labor cost for mounting the polarimeter.

The polarimeter consists of a PVC pipe measuring 30 cm in length with a diameter of 50 mm suspended between two wooden supports (20 cm x 5.4 cm) attached to a wooden base measuring 50 x 25 cm. The pipe has a centered opening measuring 15 cm for the placement of the glass tube with an optical path of 100 or 200 mm used to contain the substance to be analyzed. At each end of the tube, a circular filter (50 mm in diameter) is attached (filters used in cameras). The polarizing filter receives the electromagnetic radiation directly from the light source attached to a third support. The light source consists of a laser pointer (a polarized light source) at a wavelength of 650 nm (red) with a low divergence collimated beam and is positioned such that the light rays pass concentrically through the polarizing filter. A 360° protractor is positioned behind this filter. The filter is rotatable and can be turned to the right or left. The angle formed is measured by the protractor. The light that passes concentrically through the polarizing filter passes through the glass tube containing the sample to be analyzed and reaches the second filter, denominated the analyzer, followed by the photodiode, which is connected to a voltmeter (Figure 1).

A laser pointer was chosen as the light source because it is directed and the loss of incidence in the filters is minimized, unlike what would occur with the use of a non-collimated light source. The purpose of the protractor is to measure the angle of displacement of the polarized light caused by the interaction of the polarized light with the molecules in the test solution contained in the glass tube. The polarizing and analyzing filters are initially positioned parallel, enabling the maximum detection of light intensity. If the chemical substance investigated is optically active, as evidenced by the displacement of the polarized light, the light intensity measured by

the voltmeter is reduced. The polarizing filter is then turned to the right or left until achieving maximum light intensity.

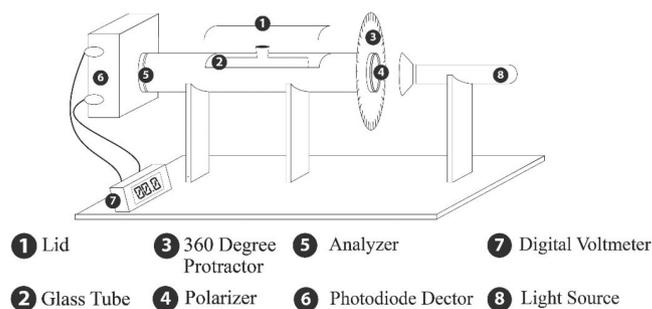


Figure 1. Schematic of educational polarimeter constructed with low-cost materials

Analysis of sucrose with educational polarimeter

To validate the polarimeter as an instrument capable of determining whether a chemical substance exhibits the phenomenon of optical activity, an experiment was conducted with different concentrations of a sucrose solution. The experiment was performed at room temperature (24 ± 2 °C), using distilled water as the solvent. The procedure for the determination of the optical rotation of sucrose with the educational polarimeter followed the protocol described below:

- The collimated light source was activated. The polarizing and analyzing filters were aligned in parallel, enabling the complete passage of the polarized collimated light. This procedure was repeated three times. Under this condition, the light intensity detected by the photodiode and recorded by the voltmeter was 6.9 ± 0.1 v.
- The light source was switched off and the 10-cm glass tube containing 10 mL of distilled water was positioned between the two filters (polarizer and analyzer).
- The light source was switched on and the light intensity was read by voltmeter. This procedure was performed in triplicate and the mean light intensity measured was 7.0 ± 0.1 v, which did not differ significantly from the reading performed without the glass tube, confirming that distilled water has no optical activity.
- After the calibration of the instrument, the analyses were performed for the determination of the optical activity of sucrose at different concentrations in an aqueous solution. Procedures “b” and “c” were repeated with the glass tube containing 10.0 mL of aqueous solutions and sucrose concentrations of 1, 10, 15 and 20%.

When the light source was activated during procedure “c”, the light intensity reduced drastically only with the solution containing the highest concentration of sucrose (20 %), for which the voltmeter reading was 2.1 ± 0.1 v. This reading differed significantly from the reading with the glass tube containing water alone. The reduction in light intensity indicates the displacement of the polarized light, suggesting that sucrose exhibits the phenomenon of optical activity. To determine the angle of this displacement, the analyzer was turned (toward the side of lesser rotation) until the light intensity was closer to that recorded during the blank test (glass tube with water alone). The rotation angle for sucrose under these conditions was $105 \pm 0.2^\circ$, with displacement to the right (+), indicating a dextrorotatory substance.

The specific rotation of the sucrose solutions was calculated using the following formula: $[\alpha]_t^\lambda = \alpha \cdot 100 / l \cdot c$, in which α is the observed rotation, l is the length of the tube in cm, c is the concentration of the substance (g/cm^3), t is the temperature at which the experiment was conducted and λ is the wavelength of the light source.

RESULTS AND DISCUSSION

The educational polarimeter constructed with low-cost materials is showed in Figure 2.



Figure 2. Educational polarimeter constructed with low-cost materials

Table 2 displays the measurements of light intensity and rotation angle of the solutions with different concentrations of sucrose as well as the calculated specific rotations.

Table 2. Means of light intensity (LI), observed rotation angle (ORA) and specific rotation (SR) of aqueous solution with different concentrations of sucrose determined by educational polarimeter

Concentration (%)	LI (volts)	ORA ^a (degree)	SR ^b (degree cm ² g ⁻¹)
1	3.4 ± 0.1	98.0 ± 1.0	9800
10	3.0 ± 0.2	99.0 ± 2.0	990
15	2.6 ± 0.1	103.0 ± 1.0	680
20	2.1 ± 0.1	105.0 ± 2.0	525

^aObserved displacement of polarized light was to the right in all cases.
^bExperiments conducted at temperature of 24°C and with light source at wavelength of 650 nm.

The reduction in light intensity with the increase in the concentration of the sucrose solution confirmed the property of optical activity for this sugar. As the concentration of a chiral substance increases, polarized light interacts with a larger quantity of molecules, which intensifies the displacement of the polarized light and reduces the detected light intensity. The optical property of sucrose was initially confirmed by the rotation angles found among the different concentrations tested (1, 10, 15 and 20 %), as this angle is directly proportional to concentration. The optical activity of sucrose was also confirmed by the specific rotation ($[\alpha]_D^{25}$) obtained for each test solution, which is inversely proportional to concentration (Table 2).

Although the results obtained by the educational polarimeter are coherent with regards to the determination of the rotatory power of sucrose in an aqueous solution, revealing that it is dextrorotatory, the calculated specific rotation differs from that reported in the literature (+ 66.5°). This difference may be explained by the quality and precision of the instrument, as the use of Nicol prisms, digital reading and other compensatory systems leads to greater precision. Another aspect to consider is the condition under which the experiment was conducted, as specific rotation varies with the temperature, wavelength of the light source, etc. The specific rotation of sucrose reported in the literature was determined at a temperature of 20 °C and using an light source at a wavelength of 489 nm,²² whereas the

present experiment was conducted at a temperature of 24 °C and using a light source at a wavelength of 650 nm.

Considering the configuration of this educational instrument and its aim of meeting the demand for teaching resources that can facilitate the learning of abstract concepts that are difficult to grasp, such as stereochemistry, the limitation of this polarimeter regards its precision in obtaining the specific rotation when used for the scientific publication of a result regarding the optical property of a known or unknown substance.

There are other educational polarimeters described in the literature with basically the same setup [PVC pipe, polarizing filter (photographic filters), protractor, light (white and other colors), or the use of LED as the light source] and limitations.^{23,24} However, the main difference between is that the polarimeters constructed by Sulzbach & Ludke²³ and Sousa²⁴ used the naked eye for the detection of optical rotation, whereas the polarimeter described herein employs a photodiode connected to a voltmeter to determine optical rotation. To protect the intellectual property of this device, a patent request was submitted to the Brazilian National Industrial Property Institute in December 2016 and was published in July 2018.²⁵

CONCLUSIONS

The polarimeter constructed with low-cost materials for educational purposes enables clearly distinguishing whether a chemical substance has optical activity or not. It was also capable of measuring the rotation angle of sucrose solutions, characterizing these solutions with larger and smaller rotation angles and specific rotation as a function of concentration. Unlike educational polarimeters reported in the literature, which use the naked eye to detect the rotation of light, the device described herein replaces the vision of the observer with a photodiode connected to a voltmeter for the detection of the displacement of polarized light. An important aspect of this educational instrument for use in the classroom is that the components (polarizing and analyzing filters, light source, etc.) are exposed, which can arouse the curiosity of the students, facilitating the teaching-learning process through active knowledge building and the understanding of each component of the teaching model, its function and the role it plays in the determination of the optical activity of chemical substances.

ACKNOWLEDGMENTS

This work received funding from the Brazilian fostering agencies *Conselho Nacional de Desenvolvimento Científico e Tecnológico* (CNPq [National Council of Scientific and Technological Development]; PQ-2 - 302735/2019-4) and *Fundação de Amparo à Ciência e Tecnologia do Estado de Pernambuco* (FACEPE [State of Pernambuco Science and Technology Assistance Foundation]; APQ-0476-1.06/14; APQ-0398-1.06/19). The author is grateful to Prof. Marcilio Martins de Moraes of the UFRPE Chemistry Department for revising the manuscript.

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