Technical note

The relationship between the rate constant of acid-catalyzed hydrolysis of sucrose and the concentration of hydrochloric acid

Zevkirlioglu T[1], Eroltu K[2]

Submitted: July 11, 2023, Revised: version 1, August 2, 2023, version 2, August 17, 2023
Accepted: August 26, 2023

Abstract

The rate constant of the acid-catalyzed hydrolysis of sucrose was determined using different concentrations of the catalyst, hydrochloric acid. An optical approach was followed using a polarimeter to measure the angle of rotation when the light was projected through sucrose solutions. This angle was measured in 3-minute intervals for 21 minutes. To obtain the angle of rotation after complete hydrolysis, sucrose solutions were heated in a water bath followed by measurement of the angle of rotation. Results showed that there was a linear correlation between the rate constant of the hydrolysis reaction and the concentration of hydrochloric acid. Moreover, the calculated values for the rate constants decreased as the reaction progressed. The influence of the concentration of the hydrochloric acid as a catalyst decreased as the reaction proceeded.

Keywords

Sucrose inversion, Polarimetry, Catalysis, Reaction rates, Glucose, Fructose, Hydrolysis, Hydrochloric acid, Rate constant, Mutarotation

---

[1] Tuna Zevkirlioğlu, Uskudar American Academy, Selamiali, Vakıf Sk. No:1, 34664 Uskudar, Istanbul, Turkey. tzevkirlioglu24@my.uaa.k12.tr
[2] Kaan Eroltu, United World College of the Adriatic, Frazione Duino, 29, 34011 Duino, Trieste, Italy. ad22kero@uwcad.it

I. Introduction

Any chemical reaction in which a water molecule breaks one or more chemical bonds is known as hydrolysis (1). When water is the nucleophile, the term is used generically to refer to substitution, elimination, and solvation processes. Salt hydrolysis, base hydrolysis, and acid hydrolysis are the three different types of hydrolysis (2). This study focuses on acid hydrolysis, and more particularly, sucrose hydrolysis, or sugar inversion.

Typically, a chemical reaction is accompanied by observable physical consequences, such as light emission, an optical spectrum shift, or a change in chirality. Every known life form has distinctive chiral characteristics in its chemical structures as well as in its macroscale morphology, growth, and behavior (3). Therefore, there is a great deal of interest in the real-time monitoring of chemical reactions. In general, measuring the reaction rate using chemical means may have extraneous and unwanted effect(s) on the reactants, which makes such a type of measurement more challenging and difficult. To preserve the original chemical structures, it is beneficial to investigate a solution's properties using an optical approach, whenever applicable. Depending on the chirality of the molecules, the plane of polarization rotates either clockwise or anticlockwise as polarized light passes through the molecule. One of the most effective methods for examining the characteristics of chiral compounds is optical rotation. Using a polarimeter, a common scientific tool, the rotation angle caused by projecting polarized light through chiral compounds can be measured (4).

A substance's ability to rotate the plane of polarization of plane-polarized light is known as optical activity. The substance with this kind of activity is said to as chiral and is classified as being optically active (5). The nature and concentration of the chiral substance in the sample affects the angle at which it rotates the plane of polarization of plane-polarized light.

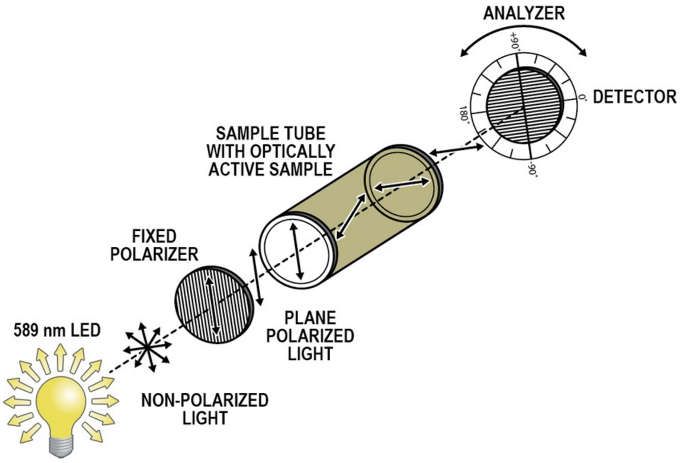

Figure 1: Sections of a Polarimeter (6)

Enantiomers are optical isomers that differ in their three-dimensional shape despite having the same arrangement of atoms and links. Dextrorotatory (+) refers to an enantiomer rotating plane-polarized light in the positive or clockwise direction, and laevorotatory (-) refers to an enantiomer rotating plane-polarized light in the negative or counterclockwise direction (7). In this experiment, fructose rotates the plane of polarization in the opposite direction from that of glucose. Due to fructose's higher optical activity, the hydrolysis of sucrose causes the overall rotation to be laevorotatory, or simply in the opposite direction. A polarimeter is used to quantify optical activity, which depends on the sample's concentration, temperature, sample tube length, and wavelength of light entering the tube. If the last three variables are kept constant, the optical rotation is proportional to the concentration.

Hydrolysis of Sucrose:

The chemical equation for the hydrolysis of sucrose can be expressed as:

Sucrose + Water ⇌ Glucose + Fructose

$C_{12}H_{22}O_{11} + H_2O \rightleftharpoons C_6H_{12}O_6 + C_6H_{12}O_6$

Similarly when hydrochloric acid is used as a catalyzer:

$C_{12}H_{22}O_{11} + H_2O + H_3O^+ \rightleftharpoons C_6H_{12}O_6 + C_6H_{12}O_6 + H_3O^+$

Sucrose hydrolysis is a pseudo-first-order reaction, which means that although it is actually a second-order reaction; because of the higher concentration of one reactant than the other, it appears to be; and can be mathematically treated as a first-order reaction (8). The concentration of water is significantly higher than the concentration of sucrose in the particular reaction of sugar inversion. Since its concentration does not significantly change during the process, it is therefore approximately regarded as constant. Hence, the rate equation for the reaction becomes

$$\text{Rate} = k\ [Sucrose] \quad (1)$$

$$\text{Rate} = k_1\ [C_{12}H_{22}O_{11}] \quad (2)$$

and,

$$k_1 = k_2\ [Water] \quad (3)$$

$$k_1 = k_2\ [H_2O] \quad (4)$$

If the bond between fructose and oxygen is broken, various anomeric and isotopic variants of glucose are produced, which can be seen in Figure 2. In this hydrolysis reaction, the acid's role as a catalyst is to protonate, or simply add a hydrogen ion to the oxygen holding the two halves of the molecule together, breaking their link. Glucose and fructose are formed when the remaining portion of the water molecule, the hydroxide (OH^-) ion is added to the right side of the molecule.

Water is a key component of the reaction that breaks down sucrose during hydrolysis or inversion. The reaction results in the synthesis of glucose and fructose molecules by rupturing the glycosidic link between the two sugars in sucrose. This hydrolysis process cannot take place without the presence of water molecules. The glycosidic bond in sucrose, which connects glucose and fructose, undergoes a reaction with a water molecule. The glucose and fructose molecules are produced after the glycosidic bond is broken.

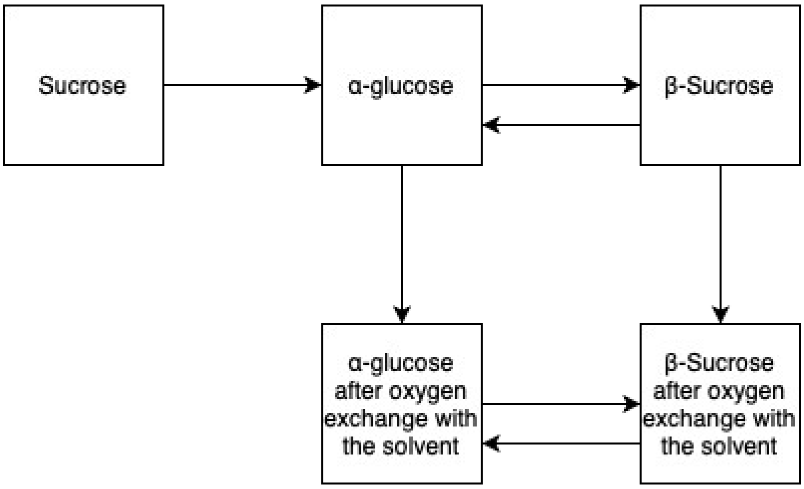

Figure 2: Formation of glucose and sucrose

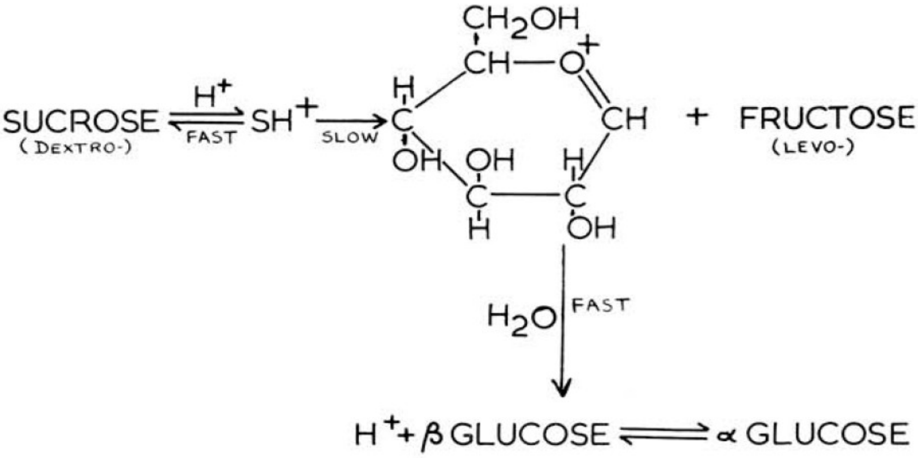

Figure 3: Mechanism of the hydrolysis of sucrose (9)

Furthermore, though it is a pseudo-first-order reaction, the Hammett-Zucker theory is in agreement with the bimolecular reaction mechanism that applies when the enzyme sucrase is used to catalyze this reaction. The Hammett-Zucker hypothesis is a theory that links the electronic and steric effects of substituents on the reactants to the rate of a chemical reaction. It is frequently used to explain how reactions involving acids and bases work. The Hammett-Zucker hypothesis supports a bimolecular reaction mechanism in the context of sucrose inversion primarily by the reaction rate dependence on the acid concentration (9). The rate of a bimolecular reaction depends on how much of each reactant is present. In the case of sucrose inversion, the concentration of sucrose and the acid catalyst (H^+ ions from the acidic medium or the sucrase enzyme) both have an effect on the reaction rate. This is consistent with a bimolecular reaction in which the rate-determining step involves both the acid catalyst and sucrose. The inversion of sucrose is catalyzed by enzymes such as sucrase. By bringing reactants together in the proper orientation—a property of a catalyst—enzymes are known to speed up reactions. The acid can donate a proton to one of the oxygen atoms in the glycosidic bond, making the oxygen more electrophilic and facilitating the nucleophilic attack by water. Hence, the idea of a bimolecular reaction mechanism for sucrose inversion is further supported by the catalytic activity of enzymes such as sucrase.

The hydrolysis of sucrose is exothermic. This indicates that heat is released during the process. Depending on the circumstances, ΔH's precise value can change, though it is usually negative. Entropy typically increases when the single sucrose molecule splits into two molecules (glucose and fructose). This is due to the fact that a system with two molecules as opposed to one has more microstates that can exist. Thus, for this reaction, ΔS is frequently positive. The spontaneity of the reaction is determined by the Gibbs free energy Change or ΔG. Under normal circumstances, the reaction should be spontaneous ($\Delta G < 0$), as it is exothermic ($\Delta H < 0$) and causes an increase in entropy ($\Delta S > 0$). The fact that sucrose solutions will gradually hydrolyze over time into glucose and fructose, especially in the presence of acid catalysts, is a further indication of the reaction's spontaneity.

Although thermodynamics gives information about the favorability and equilibrium position of this reaction, it does not provide any information regarding the rate of the reaction. Hence, a reaction may be kinetically slow without a catalyst even though it may be thermodynamically favorable. In sucrose hydrolysis, the reaction without HCl, an acid catalyst, is very slow.

The Rate constant of the hydrolysis of sucrose:

When it is considered that the rate of change at any time is proportional to the concentration of sucrose, the equation for the rate constant can be expressed as (10):

$$\mathrm{k} = \frac{2.303}{t} \cdot \log\left(\frac{a_0 - a_\infty}{a_t - a_\infty}\right) \qquad (5)$$

where a_0 represents the initial rotation of pure sucrose, a_∞ represents the rotation at the time the reaction is complete, and a_t represents the rotation at a given time t.

Previous studies and literature review

Though the exact environmental conditions and concentrations of chemicals used in this study were not used eleswhere, the rate constant of the hydrolysis of sucrose when catalyzed with acid has been determined before. A study using 4.0 M and 6.0 M hydrochloric acid found that the rate constant values at 50 minutes were 7.47 X 10^{-4} s^{-1} and 1.43 X 10^{-3} s^{-1} respectively (11). Another study determined the rate constant to be 2.05 X 10^{-4} s^{-1}, on average, when hydrochloric acid with a concentration of 2.0 M was used (12). Both studies found that as the reaction approached completion, the rate constant decreased.

By offering a different pathway with lower activation energy, a catalyst accelerates the reaction both forward and backward (13). More reactant molecules can surmount the energy barrier if the activation energy is decreased. As a result, the rate of reaction, and possibly, the rate constant increases when a catalyst such as hydrochloric acid is added to a reaction. Additionally, without changing the temperature, there is a positive correlation between the catalyst hydrochloric acid concentration and the reaction rate constant k, indicating that the amount of catalyst hydrochloric acid present has a significant effect on how fast sucrose is hydrolyzed (14).

II. Materials and methods

Preparation of solutions

A 750 mL sucrose solution (200 g/L) was prepared by dissolving 150 grams of sucrose in water. Sucrose was added to a 750 mL volumetric flask followed by distilled water until the meniscus of the solution reached the 750 mL mark. In order to ensure that sucrose was fully dissolved, the contents were stirred using a magnetic stirrer for 5 minutes at 800 rpm. Hydrochloric acid solutions were prepared by dilution to concentrations of 0.5 M, 1.0 M, and 1.5 M, preparing 250 mL of each different concentration.

Measurement of the angle of rotation

20 mL of the sucrose solution was added to 20 mL of hydrochloric acid solution in a beaker. After thoroughly mixing, the solution was added to the polarimeter tube. The readings were recorded every 3 minutes until an elapsed time of 21 minutes. In order to obtain the angle of rotation when the reaction was complete, the solution was heated in a test tube immersed in a water bath at 70°C for 15 minutes. After the solution cooled down and reached room temperature, the angle was once again measured with the polarimeter (± 0.05°). The room temperature was kept constant at 24.7 °C. This process was repeated for each different concentration of hydrochloric acid. The data was then used to calculate the rate constant of the reaction using the equation presented in the introduction section.

III. Results

Unprocessed data

Table 1: Angle of rotation(°), α_t, at time t when hydrolysis was catalyzed by 0.5 M hydrochloric acid

Time (min)	0.00	3.00	6.00	9.00	12.00	15.00	18.00	21.00	∞
Trial 1	13.50	13.35	13.20	13.15	13.15	13.10	13.05	12.90	-3.40
Trial 2	13.45	13.30	13.15	13.05	12.95	12.90	12.80	12.80	-3.50
Trial 3	13.60	13.40	13.25	13.15	13.05	13.00	12.95	12.95	-3.30
Trial 4	13.50	13.30	13.20	13.20	13.10	13.10	13.05	13.00	-3.35
Trial 5	13.45	13.25	13.10	13.05	13.00	12.90	12.80	12.80	-3.50
Trial 6	13.45	13.25	13.20	13.05	13.00	12.90	12.85	12.75	-3.50
Trial 7	13.35	13.20	13.10	13.05	12.95	12.90	12.85	12.85	-3.45
Trial 8	13.45	13.25	13.10	13.05	13.00	12.95	12.90	12.90	-3.30

Table 2: Angle of rotation(°), α_t, at time t when hydrolysis was catalyzed by 1.0 M hydrochloric acid

Time (min)	0.00	3.00	6.00	9.00	12.00	15.00	18.00	21.00	∞
Trial 1	13.40	13.15	12.95	12.85	12.80	12.70	12.60	12.50	-3.35
Trial 2	13.35	13.10	12.90	12.80	12.70	12.65	12.50	12.50	-3.40
Trial 3	13.40	13.10	12.90	12.75	12.70	12.60	12.60	12.55	-3.35
Trial 4	13.55	13.20	13.00	12.90	12.90	12.85	12.75	12.70	-3.30
Trial 5	13.60	13.35	13.10	12.90	12.90	12.85	12.80	12.80	-3.35
Trial 6	13.40	13.15	12.95	12.75	12.70	12.65	12.50	12.50	-3.45
Trial 7	13.45	13.20	13.00	12.85	12.80	12.75	12.65	12.55	-3.50
Trial 8	13.55	13.25	13.10	12.95	12.85	12.85	12.75	12.75	3.30

Table 3: Angle of rotation(°), α_t, at time t when hydrolysis was catalyzed by 1.5 M hydrochloric acid

Time (min)	0.00	3.00	6.00	9.00	12.00	15.00	18.00	21.00	∞
Trial 1	13.35	13.05	12.75	12.50	12.35	12.20	12.00	11.85	-3.55
Trial 2	13.20	12.95	12.70	12.55	12.30	12.15	11.95	11.75	-3.55
Trial 3	13.15	12.95	12.55	12.40	12.10	12.00	11.90	11.70	-3.60
Trial 4	13.15	12.85	12.55	12.25	12.15	12.05	11.85	11.80	-3.60
Trial 5	13.35	13.00	12.70	12.50	12.40	12.25	12.00	11.90	-3.45
Trial 6	13.25	12.95	12.65	12.50	12.20	12.05	11.95	11.85	-3.50
Trial 7	13.10	12.80	12.45	12.20	12.10	12.00	11.90	11.80	-3.50
Trial 8	13.20	12.95	12.75	12.40	12.30	12.00	11.85	11.75	-3.55

Processed data

Table 4: The mean value of the rate constant (s^{-1}) for the hydrolysis of sucrose at different concentrations of hydrochloric acid

Concentration (M)	0.5	1.0	1.5
6.00 min	5.09 X 10^{-5}	8.57 X 10^{-5}	9.81 X 10^{-5}
12.00 min	3.70 X 10^{-5}	6.12 X 10^{-5}	8.38 X 10^{-5}
18.00 min	3.14 X 10^{-5}	4.99 X 10^{-5}	7.44 X 10^{-5}

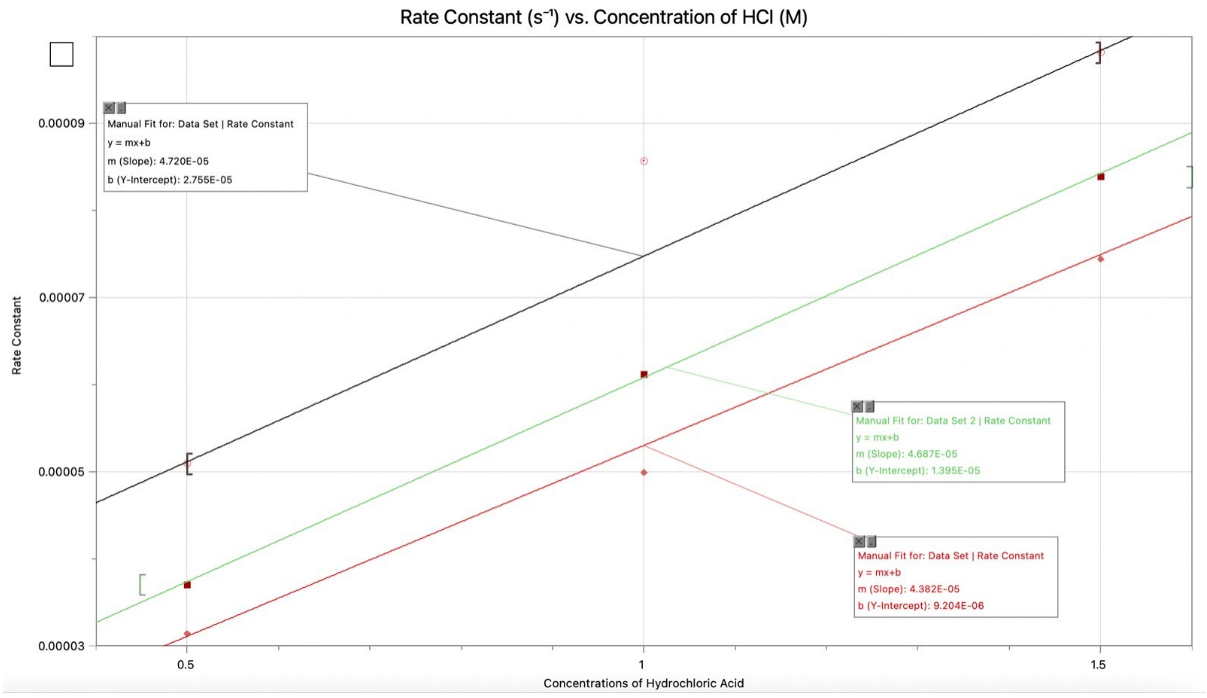

Figure 4. Rate constant vs. concentration of HCl, Blue: 6 minutes, Green: 12 minutes, Red: 18 minutes, RMSE as percent of slope were 23.2%, 0.44% and 7.2% for the regression lines at 6, 12 and 18 minutes respectively.

General trend

The aim of this experiment was to establish a correlation between the acid catalyst concentration and the rate constant. In order to determine this relationship, the graphs of calculated rate constant vs. concentration of hydrochloric acid were plotted. As seen from the graph, it was determined that the two variables were a linearly related and directly proportional. Additionally, their constant of proportionality varied and was dependent on the extent of the progress of the reaction.

In order to obtain an accurate overview, Figure 4 utilized the reaction times to be 6.00, 12.00, and 18.00 minutes. This ensured that the data from the beginning to the end of the reaction was considered when determining the relationship between the variables. From the data presented in the tables, it is seen that in each trial, the angle of rotation decreased as the reaction proceeded for longer times. Accordingly, when the rate constant was calculated using the equation presented in the Introduction section, it was seen that the value decreased as the reaction proceeded toward completion. Table 4 presents the value of the rate constant for different reaction times for different HCl concentrations.

From Figure 4, three linear equations represented the relationship between the variables:

$$k_{6.00\ \mathrm{min}} = 4.720 \ \mathrm{X}\ 10^{-5} \left[HCl\right] + 2.755 \ \mathrm{X}\ 10^{-5} \quad (6)$$

$$k_{12.00\ \mathrm{min}} = 4.687 \ \mathrm{X}\ 10^{-5} \left[HCl\right] + 1.395 \ \mathrm{X}\ 10^{-5} \quad (7)$$

$$k_{18.00\ \mathrm{min}} = 4.382 \ \mathrm{X}\ 10^{-5} \left[HCl\right] + 9.204 \ \mathrm{X}\ 10^{-6} \quad (8)$$

The three equations indicate how the rate constant and, consequently, the rate of reaction change over time, which is useful information. This can be demonstrated by plotting the identical acid concentration value into the three equations, which will show a difference in the rates of reaction.

IV. Discussion

The trend in the graphs

All the lines in Figure 4 presented with a y-intercept that is larger than zero. This may be taken as evidence that hydrolysis can proceed even in the absence of a catalyzing acid ((HCl) = 0 M), albeit at a slower rate, as evidenced by the modest value of the rate constant. The three lines linearity also served to demonstrate that the acid-catalyzed hydrolysis of sucrose was, in reality, a pseudo-first-order reaction, which was in agreement with the Hammet-Zucker theory.

Another important trend could also be seen in the slope values of the lines. At 6.00, 12.00, and 18.00 minutes the slopes were found to be 4.720 X 10^{-5}, 4.687 X 10^{-5}, and 4.382 X 10^{-5} s^{-1} respectively. As the reaction proceeded for longer times, the slope of the rate constant vs. concentration of hydrochloric acid decreased. The influence of the concentration of hydrochloric acid as a catalyst on the rate constant decreased as the reaction progressed closer to completion. This behavior may be influenced by a number of factors. Changes in the reaction medium's characteristics, such as increased viscosity due to the synthesis of glucose and fructose, could be a reason. Additionally, even with an excess of HCl, the reactants' or the products' protonation states could change due to pH changes, which could slow down the reaction (15). In addition, the behavior might also be caused by possible temperature changes, structural alterations in the solution, or the production of intermediates that either catalyzed or impeded the process (16, 17).

A change in the angle of rotation of the solution indicated that the concentration of the reactants (sucrose) and products (glucose and fructose) in a solution of sucrose changed over time at a constant temperature. The specific rotation of the solution, which is the measured angle of rotation, is directly influenced by this change in concentration. As polarized light travels through the sample, the polarimeter measures its optical rotation. The balance of the optically active components in the solution changes in the case of sucrose inversion when the sucrose is digested into glucose and fructose. The quantity of chiral (optically active) molecules in a solution affects a substance's optical activity. When the reaction first began, there was a larger concentration of sucrose, which rotated the plane of plane polarized light in a unique way. The concentrations of the products glucose and fructose increased as the reaction progressed, while the concentration of sucrose decreased due to hydrolysis. The overall value in optical rotation was a change in the observed angle of rotation since glucose and fructose have different specific rotations that the specific rotation of sucrose.

This time dependency, however, is unlikely to be caused by errors such as the mutarotation lag. The hydrolysis of sucrose produces glucose and fructose, which both undergo mutarotation at a speed approximately 100 times faster than the hydrolysis process itself. As a result, the optical rotation observed at any given time will have a slight, variable difference compared to what it would be if mutarotation occurred instantly. This phenomenon is often referred to as the "mutarotation lag. While this phenomenon does depend on time, it is a different process from the inversion of sucrose that is catalyzed by acid. Mutarotation would increase the time dependence of the optical rotation of a solution of sucrose (or its inversion product, which consists of glucose and fructose), but it would have negligible impact on the rate of the acid-catalyzed inversion. For this reason, the overall correlation between the rate constant and the time can be said to be unaffected by the mutatotation lag.

Limitations

There was a short time lag from the time the sucrose and the HCl solutions were mixed, to the time the measurement at time zero was made. However, since this time was similar for all the experiments, the relative values were not affected. It can be seen from the tables that for some times during certain trials, the angle of rotation did not change. This may be attributed to the low sensitivity of the polarimeter (± 0.05°).

Additionally, data was collected with hydrochloric acid solutions with concentrations between 0.5 M and 1.5 M. This was a small range which eliminated the possibility of other kinds of interactions (non-linear) between the two variables had a wider range of hydrochloric acid concentrations been studied. Also, graphs were only drawn for the data collected at time 6.00 min, 12.00 min, and 18.00 min. While this allowed to demonstrate a consistent correlation for all the reactions with different concentrations of hydrochloric acid, it negatively impacted the precision, because only three points were used.

The optical rotation of the solution is a widely used metric for assessing the degree of the reaction in the study of hydrolysis or inversion of sucrose. A combination of glucose and fructose, both of which have optical activity, is produced by the hydrolysis of sucrose. However, both glucose and fructose experience mutarotation, a condition in which many isomeric forms interact in solution and alter optical rotation. In the measured optical rotation of the reaction mixture, mutarotation can cause a sizable lag. It is standard procedure to quickly chill the reaction mixture to 0°C, a temperature at which mutarotation is significantly slowed, and then carry out all optical rotation measurements, in order to circumvent this limitation. This procedure was not followed in this study due to experimental limitations. As mentioned before, the mutarotation lag affect exact but not relative values of rotation.

Since the experiment was not replicated, the results could not be compared to previous results in order to determine their accuracy. Still, the obtained trends were consistent with previously published data (18-20) and the linear relationship between acid molarity and rate constant corresponded with literature values.

V. Conclusion and further research

The concentration of the acid that acts to catalyze the hydrolysis of sucrose, and the reaction rate constant possessed a linear relationship, which implied that as the concentration of the acid increased, the reaction rate constant also increased, within the range of acid concentrations studied. As can be seen from Figure 4 and their corresponding equations of the three lines, the slope, or coefficient of proportionality between the two variables, changed with time. These equations are presented below.

$$k_{6.00\ \mathrm{min}} = 4.720 \text{ X } 10^{-5}\ [HCl] + 2.755 \text{ X } 10^{-5} \quad (9)$$
$$k_{12.00\ \mathrm{min}} = 4.687 \text{ X } 10^{-5}\ [HCl] + 1.395 \text{ X } 10^{-5} \quad (10)$$
$$k_{18.00\ \mathrm{min}} = 4.382 \text{ X } 10^{-5}\ [HCl] + 9.204 \text{ X } 10^{-6} \quad (11)$$

The slope of the rate constant vs. concentration of hydrochloric acid decreased as the reaction progressed for longer periods of time. It can therefore be concluded that as the reaction approached completion, the influence of hydrochloric acid concentration on the rate constant decreased.

Further research ideas considering this topic include repeating the same procedure with weaker acids. While hydrochloric acid is a strong acid and is able to catalyze the hydrolysis of sucrose, some other weak acids could also have the ability to release the appropriate amount of hydrogen ions by dissociating enough. Hence, it is possible to study their impact on the rate constant of the reaction, as a catalyst. For instance, methanol, an amphoteric substance, can be used accordingly (21). Another possible research idea is investigating the influence of temperature on the rate constant. To conduct this experiment, the concentration of hydrochloric acid can be kept as a constant variable. By changing the temperature of the solutions and collecting data, the relationship between the temperature and the rate constant can be determined.

References

1 *hydrolysis definition*. (n.d.). Northwestern.edu. Retrieved August 17, 2023, from http://groups.molbiosci.northwestern.edu/holmgren/Glossary/Definitions/Def-H/hydrolysis.html

2 Phillips, Theresa. “What You Need to Know about Hydrolysis.” *ThoughtCo*, 2 Dec. 2019, www.thoughtco.com/what-is-hydrolysis-375589#:~:text=2%EF%BB%BF%20There%20are%20three,to%20form%20one%20larger%20molecule

3 Jiang, W., Yi, X., & McKee, M. D. (2019). Chiral biomineralized structures and their biomimetic synthesis. *Materials Horizons*, *6*(10), 1974–1990. https://doi.org/10.1039/c9mh00431a

4 *Chemistry online @ UTSC*. (n.d.). Utoronto.Ca. Retrieved August 17, 2023, from https://www.utsc.utoronto.ca/webapps/chemistryonline/production/polarimetry.php

5 Hunt, I. R., & Mozol, V. (n.d.). *Ch 7: Optical Activity*. Ucalgary.Ca. Retrieved August 17, 2023, from https://www.chem.ucalgary.ca/courses/350/Carey5th/Ch07/ch7-4.html

6 *Understanding polarimetry*. (2019, December 8). Vernier. http://www.vernier.com/experiment/chem-o-6_understanding-polarimetry/

7 Chirality and Optical Activity. (n.d.). Purdue.edu. Retrieved August 17, 2023, from http://chemed.chem.purdue.edu/genchem/topicreview/bp/1organic/chirality.html

8 (N.d.). Edu.Iq. Retrieved August 17, 2023, from http://uomustansiriyah.edu.iq/media/lectures/6/6_2021_01_01!09_20_02_PM.pdf

9 Dawber, J. G., Brown, D. R., & Reed, R. A. (1966). Acid-catalyzed hydrolysis of sucrose: A student study of a reaction mechanism. *Journal of Chemical Education*, *43*(1), 34. https://doi.org/10.1021/ed043p34

10 Awan, S. (2017). *Physical chemistry: lab report 1*. http://www.academia.edu/32347354/Physical_chemistry_lab_report_1

11 Awan, Shaherbano. “Physical Chemistry: Lab Report 1.” *Academia.Edu*, 9 Apr. 2017, www.academia.edu/32347354/Physical_chemistry_lab_report_1

12 Brazuelo, Laura. *Researchgate.net. Retrieved August 17, 2023, from https://www.researchgate.net/publication/343970485_KINETICS_OF_SUCROSE_INVERSION*

13 “12.7: Catalysis.”. Libretexts.org. Retrieved August 17, 2023, from http://chem.libretexts.org/Bookshelves/General_Chemistry/Chemistry_1e_(OpenSTAX)/12%3A_Kinetics/12.7%3A_Catalysis

14 Brazuelo, Laura. *KINETICS OF SUCROSE INVERSION*, www.researchgate.net/profile/Laura-Brazuelo/publication/343970485_KINETICS_OF_SUCROSE_INVERSION/links/6115993f1ca20f6f861b574b/KINETICS-OF-SUCROSE-INVERSION . Accessed 25 June 2023.

15 Nelson, D.L., & Cox, M.M (2017). Protonation State of the Medium (pH changes) Lehninger Principles of Biochemistry (7th ed.). W.H. Freeman and Company.

16 Atkins, P., & de Paula, J. (2014). Physical Chemistry (10th ed.). Oxford University Press.

17 Jones, M., & Fleming, S.A. (2014). Organic Chemistry (5th ed.). W.W. Norton & Company.

18 H. Reeves, J., & Halpern, A. M. (2012). Hall effect of light. Appl. Phys. Lett., 101, 251602. https://doi.org/10.1063/1.4767641

19 Kenneth W. Busch, Carlos Calleja-Amador, Denis H. Rabbe, Marianna Busch (2009). Spectroscopic determination of sucrose. Patents Encyclopedia. https://patents.google.com/patent/US8026483B2/en

20 Daniels, F., Williams, J. W., Bender, P., Alberty, R. A., Cornwell, C. D., & Harriman, J. E. (1970). Experimental Physical Chemistry (7th ed.). McGraw-Hill.

21 Lilić, A., Wei, T., Bennici, S., Devaux, J.-F., Dubois, J.-L., & Auroux, A. (2017). A comparative study of basic, amphoteric, and acidic catalysts in the oxidative coupling of methanol and ethanol for acrolein production. *ChemSusChem*, *10*(17), 3459–3472. https://doi.org/10.1002/cssc.201701040