this determination, when corrected for the small amount of maltose originally present in the dextrin, gives a value of 170 for the specific rotation of achroödextrin, which is the value twice obtained by direct determination by the alcoholic method of separation already described.

Conclusions.

1. The digestion of erythrodextrin by ptyalin is a monomolecular reaction.

2. The optimum temperature for this digestion is 51°. The temperature coefficient is relatively small at the ordinary temperature, being about the same as that of chemical reactions in general. The enzyme is destroyed at 65°.

3. The digestion becomes disproportionately slow when the ratio of substrate to enzyme becomes very large. This ratio is constant for different concentrations, and probably represents a compound formed by the union of the enzyme and the substrate preliminary to hydrolysis.

4. The retarding influence of maltose is shown to be relatively small and to vary directly as its concentration.

5. The relatively slow digestion of achroödextrin is again pointed out, and a preliminary redetermination of its specific rotation made.

HAHNEMANN MEDICAL COLLEGE
AND HOSPITAL OF CHICAGO.

[CONTRIBUTION FROM THE PHYSICAL LABORATORY, PRINCETON UNIVERSITY, AND THE CARBOHYDRATE LABORATORY, BUREAU OF CHEMISTRY, UNITED STATES DEPARTMENT OF AGRICULTURE.]

STUDIES ON THE FORMS OF *d*-GLUCOSE AND THEIR MUTAROTATION.

BY C. S. HUDSON AND J. K. DALE.

Received December 1, 1916.

1. Introduction.

It is generally recognized that the mutarotation of glucose is due to a balanced reaction which may be expressed in the form

$$\alpha\text{-Glucose} \rightleftarrows \beta\text{-Glucose.}^{1}$$

α-Glucose is the usual form in which the sugar crystallizes and its initial specific rotation, when the sugar is dissolved in cold water, is near +110°. This value falls gradually to +52° during the course of the mutarotation reaction. β-Glucose is the form which was first isolated in the crystalline

---

[1] For a summary of the literature on this subject, see THIS JOURNAL, 32, 889 (1910).

condition by C. Tanret[1] in 1895. Its initial specific rotation is near +19°, which also changes gradually at room temperature to +52°, the same value that the α-form finally attains. It was found by Urech[2] that the mutarotation of α-glucose, that is, the change in rotation from +110° to +52°, follows the formula for a unimolecular reaction. Lowry[3] has shown that this formula also applies to the mutarotation of β-glucose, that is, the change in its rotation from +19° to +52°. J. Meyer[4] has further shown that the velocity coefficients of the unimolecular mutarotation reactions of α- and β-glucose are numerically equal, a conclusion that Hudson[5] had previously reached from experimental as well as theoretical grounds in a study of the similar mutarotation of the closely related sugar lactose. This numerical equality of the velocity coefficients of the mutarotation of the α and β forms of a sugar is a striking fact, and gives conclusive proof that the mutarotation is caused by a balanced reaction between the α and β forms of the sugar, because it follows from theoretical considerations that the coefficients should be numerically equal in such a case.[6] Thus, if a solution contains at the start a mols. of α- and b mols. of β-glucose, the rate of formation of beta may be expressed:

$$dx/dt = k_1(a - x) - k_2(b + x),^{7}$$

where x denotes the amount of β which has been formed up to the time t, and k_1 and k_2 are coefficients. This equation is the same as the fundamental equation for the mutarotation of lactose, and in similar manner it gives on integration and the substitution of rotations in place of a, b, and x, the equation of a unimolecular reaction,

$$1/t \log \frac{r_0 - r_\infty}{r - r_\infty} = k_1 + k_2,$$

where r_0 is the initial rotation of the solution, r_∞ its final constant rotation, and r the rotation at the time t. The equation applies alike to the mutarotation of α-glucose from +110° to +52°, the mutarotation of the β form from +19° to +52°, and to any portions of these changes.

The present investigation was undertaken for the purpose of measuring as accurately as possible the mutarotation coefficient, $k_1 + k_2$, over the temperature range in which observations are possible. This extends approximately from the freezing point of water to a warmer temperature,

---

[1] *Compt. rend.*, 120, 1060 (1895).

[2] *Ber.*, 15, 2130 (1882); 16, 2270 (1883); 17, 1547 (1884); 18, 3047 (1885).

[3] *J. Chem. Soc.*, 75, 213 (1899); 83, 1314 (1903).

[4] *Z. physik. Chem.*, 62, 71 (1908).

[5] *Ibid.*, 44, 487 (1903).

[6] The deduction of this conclusion from the general formulas of chemical kinetics appears to have been made first by Kistiakowsky (see Nernst, "Theoretical Chemistry," 1911 edition, p. 575), who also showed by experiments that the rates of formation and of decomposition of esters are equal.

[7] *J. Am. Chem. Soc.*, 26, 1065 (1904).

about 40°, above which the mutarotation of glucose proceeds too fast for measurement. Before the observations could be undertaken, it was necessary to prepare pure glucose in the α and β crystalline forms. For this purpose the following methods have been devised, which give a high yield of the pure isomers and are suitable for preparing them in considerable quantity. It may be emphasized that while methods have long been known for preparing pure α-glucose fairly free from the β form, the method which we have used for preparing β-glucose is a procedure which renders easily accessible this form of glucose.

2. The Purification of Glucose.[1]

The usual method for purifying glucose consists in recrystallizing it from aqueous alcohol. We have learned from Dr. I. K. Phelps,[2] however, that glacial acetic acid is far preferable to alcohol in the crystallization of many of the sugars, and we have used this solvent with excellent results in the purification of glucose, and also, as will be described later, in the preparation of crystalline β-glucose by a simple procedure.

The most convenient and cheapest source from which the preparation of pure glucose may start is the corn sugar of commerce, a form of starch sugar which is manufactured in the United States on a large scale by the acid hydrolysis of cornstarch. Several grades of this corn sugar are on the market and of those available that one should be chosen which gives the lightest colored solution after dissolving in water. The corn sugar used in this work had the trade name "Cerelose" and was manufactured by the Corn Products Refining Company of New York. Five hundred grams of the dry corn sugar are dissolved in 2.5 l. of cold water, about 20–30 g. of decolorizing carbon, such as "eponite" or "norit," are added and the mixture is stirred for a few minutes. It is then heated to about 97° and made just acid to litmus with a few drops of H_3PO_4 and filtered through an asbestos mat. The colorless filtrate is evaporated in glass under reduced pressure to a content of 70 to 75% solids. Glacial acetic acid is now added in the ratio of one part of acid to one part of sirup. This solution is placed in a jar, seeded with pure glucose crystals, and stirred occasionally. Crystallization will commence almost immediately, while the solution is still warm. It is well to stir in one more part of acid as crystallization proceeds to prevent the formation of a solid mass of crys-

---

[1] The authors desire to express their thanks to Mr. T. S. Harding who has aided in the development of these directions.

[2] Personal communication. The use of glacial acetic acid in crystallizing sucrose, and in washing the crystals of that sugar, was described in full by Wernicke and Pfitzinger (U. S. Patent No. 260,340, dated June 27, 1882, German Patent No. 20,595, of April 15, 1882, reviewed in *Ber.*, 15, 3105 (1882)), but their excellent method does not appear to have received the attention from chemists that it deserves. Griffin and Nelson (THIS JOURNAL, **37**, 1555 (1915)) have recently called attention to the usefulness of glacial acetic acid in washing crystals of the cyclic sugar inosite.

tals. Crystallization is complete in a few hours or overnight. The thick mass of crystals is then filtered from the mother liquor on a Büchner funnel fitted with a strong filter paper, and washed with glacial acetic acid. After draining as dry as possible on the Büchner funnel, the crystals are washed with 95% alcohol, then with absolute alcohol, and dried in a vacuum oven at 50°, this temperature being raised to 70° in the course of one or two hours. The dry, crystalline sugar weighs about 300–350 g. The sugar thus obtained is entirely colorless and its ash content is less than 0.1%. It is a better product than any crystalline glucose that has been upon the market for C. P. chemicals, as its 30% solution in water is entirely colorless and without any cloudiness. In all cases this purified sugar is the anhydride, $C_6H_{12}O_6$, since its loss in weight on drying at 100° is found to be less than 0.1%. The initial rotation of the product shows that the sugar is a mixture of α- and β-glucose. The proportions of the components seem to depend upon the temperature at which the crystallization takes place and the rate of crystallization. When the sirup is seeded and stirred immediately after filtering, while still hot, the crystals obtained have an initial specific rotation in the neighborhood of +26°, indicating that they consist almost entirely of the β form. If the sirup is allowed to come to a temperature near zero before seeding and stirring, the initial specific rotation of the product obtained is in all cases between +40 and +50°, which is nearly that of an equilibrium mixture. This behavior of pure glucose on crystallizing from glacial acetic acid has been used to prepare pure β-glucose with a yield of about 90%, as will now be described.

3. The Preparation of Pure β-Glucose.

Five hundred grams of very pure glucose (which may be prepared by the method which is described in Section 2), are heated in a large beaker with 50 cc. of distilled water on a water bath and the mass finally brought to complete solution over a flame. After solution is complete, the beaker with its contents is set on a water bath and 600 cc. of glacial acetic acid, which has previously been warmed nearly to 100°, are added. The acid and sirup are thoroughly mixed, the solution is stirred and, if possible, seeded with crystals of pure β-glucose. Crystallization commences almost immediately after the beaker is removed from the water bath, proceeding rapidly as the sirup cools. The thick mass of crystals and mother liquor can be poured on a Büchner funnel where in a short time, with a good suction, the crystals will become dry. The product obtained by this process is a beautifully granular, crystalline substance consisting largely of β-glucose. The initial specific rotations of three quantities prepared in this manner were +24.5°, +25° and +24.6°, indicating that the product consists of about 7% α- and 93% β-glucose. The small amounts of the α-isomer may be removed by recrystallizing the sugar from a concentrated, ice-cold, aqueous solution with the addition of absolute alcohol. The dissolving and crystallizing must be carried out at this low temperature in order that the β- may be prevented from changing into the α-modification during the process.

One hundred grams of the sugar are poured into 100 cc. of water at 0°. The β form of glucose is very soluble, and with vigorous stirring all dissolves in a few seconds. This solution is quickly filtered and 500 cc. of absolute alcohol are mixed with the filtrate. Seeding and stirring causes an immediate and rapid crystallization of β-glucose. By this method β-glucose has been recrystallized several times in succession and the specific rotation determined after each crystallization, the rotation being observed within one minute of the time when the sugar was dissolved in water at 0°.

	First experiment.	Second experiment.
Original β-glucose	+24.5°	+27°
After first recrystallization	+21°	+21°
After second recrystallization	+19.8°	+19.8°
After third recrystallization	+19.5°	+19.9°
After fourth recrystallization	+19.7°	+19.2°

It appears that after the second recrystallization the β-glucose is free from the α-isomer. In each of these experiments the initial specific rotation of the β-glucose which resulted from the fourth recrystallization has been carefully determined by observing the progress of the mutarotation in water at 0.7°, where the rate is slow, and extrapolating the values to the time of dissolving the sugar. By this method the initial specific rotation of β-glucose has been found to be, in the first experiment +19.2° and in the second one +18.8°, giving an average of +19.0°. This value agrees completely with that which C. Tanret[1] records in his latest measurement Roux[2] found it to be +19.8°.

4. Preparation of Pure α-Glucose.

α-Glucose is the predominating form of the sugar when the crystallization takes place slowly at room temperature from somewhat diluted acetic acid. Five hundred grams of pure glucose are dissolved in 250 cc. of water. When every trace of the crystalline sugar has disappeared, the sirup is removed from the source of heat and 1000 cc. of cold glacial acetic acid added. During the crystallization, which proceeds slowly, due to the considerable amount of water present, it is well to stir the sirup occasionally to prevent caking. When filtered on a Büchner funnel by means of suction and washed with 95% alcohol and absolute alcohol, the product consists of fine granular crystals of anhydrous α-glucose, having an initial specific rotation of about +110°. The yield is from 75 to 80%.

---

[1] *Bull. soc. chim.*, **26**, 1065 (1904).

[2] *Ann. chim. phys.*, 7e, **30**, 429 (1903).

5. The Variation of the Rate of Mutarotation with the Concentration of Sugar.

The velocity coefficient $(k_1 + k_2)$ of the mutarotation of β-glucose in water at 25° has been measured for solutions containing from 3 to 64 g. of the sugar in 100 cc. of the solution and the results are recorded in Table I. The coefficients are expressed in terms of minutes and decimal logarithms. β-Glucose was used in preference to the α form for two reasons: first, its higher solubility allowed the extension of the measurements to concentrated solutions, and, second, it was desired to compare the coefficient for β-glucose very accurately with that for α-glucose, which is known with considerable precision at 25° from other measurements (see Tables II and III).

TABLE I.

Grams of glucose in 100 cc.	$t = 25°$ $(k_1 + k_2)$.	Grams of glucose in 100 cc.	$t = 25°$ $(k_1 + k_2)$.
3	0.01050	16	0.01104
3	0.01057	25	0.01135
3	0.01068	32	0.01068
6	0.01048	37	0.01060
9.6	0.01059	52	0.01008
		64	0.00931

From these constants it appears that there is a slight increase in the rate of mutarotation with the concentration until a maximum rate is reached, which lies in the neighborhood of 25 g. of the sugar in 100 cc. of the solution, although these changes are not much in excess of the experimental error; further increase in the concentration causes a decided decrease in the rate. In dilute solutions (under 10 g. in 100 cc.), the rate is independent of the concentration, or the variation in rate is so small that it is beyond the present limit of observation.

6. The Influence of Temperature upon the Rate of Mutarotation.

The velocity coefficient $(k_1 + k_2)$, for both α- and β-glucose has been measured at temperatures from 0° to 40°. The values of this coefficient, which are recorded in Table II, refer to solutions that contained less than 10 g. of glucose in 100 cc., which represents a range of concentration in which the coefficient is independent of the concentration, as has been shown.

TABLE II.

Temperature.	α-Glucose $(k_1 + k_2)$.	β-Glucose $(k_1 + k_2)$.	Calculated $(k_1 + k_2)$.
0.7°	0.00074	0.00074	(0.00074)
5°	0.00129	0.00150	0.00122
10°	0.00225	0.00223	0.00216
15°	0.00399	0.00379	0.00374
20°	0.00635	0.00654	0.00633
25°	0.01050	0.01057	(0.01057)
30°	0.0175	0.0168	0.0173
40°	0.0437	0.0395	0.0442

From Table II it is seen that the velocity coefficient for α- and β-glucose is the same at each temperature, within the limits of experimental error. At 40° the rate becomes difficult to measure on account of its rapidity.

If we use the empirical formula of van't Hoff, $\frac{d \log (k_1 + k_2)}{dT} = \frac{A}{T^2}$,[1] where T is the absolute temperature and A is a constant, an equation can be derived from which the velocity coefficient for any temperature can be calculated. The integrated form is $\log (k_1 + k_2) = C - A/T$, where A and C are constants which can be calculated from the values of $k_1 + k_2$ at two temperatures. From the measured values of $k_1 + k_2$ at 0.7° and 25°, the values of these constants are found to be $A = 3873$ and $C = 11.0198$, and the equation becomes $\log_{10} (k_1 + k_2) = 11.0198 - 3873/T$. The values of $k_1 + k_2$ calculated by means of this equation (see the last column of Table II) agree within the limits of experimental error with those actually measured. For an increase of 10° in temperature, the rate increases 2.8 fold. Approximately the same increase has been noticed for other sugars, lactose[2] 2.8 fold, and mannose[3] 2.6.

A number of investigators during recent years have measured the rate of mutarotation of glucose, their work covering a range of temperature from 0° to 40°. These measurements are recorded in Table III for comparison with the values which may be calculated from our temperature formula, $\log (k_1 + k_2) = 11.0198 - 3873/T$.

There is in most cases good agreement between the values calculated by our formula and those obtained by independent observers. The mutarotation coefficient of glucose is a characteristic physical constant for the sugar and is now known with a fair degree of accuracy at ordinary temperatures. In particular, this coefficient at 25° is probably known with an accuracy of 1%.

7. The Influence of Temperature on the Catalysis of the Mutarotation by Acids.

In general, the catalysis by acids is more pronounced the higher the temperature. While at constant temperature the rate is not proportional to the concentration of the hydrogen ions in the solutions[4] the relation between the two is a linear one,[5] showing that the increase in the rate is proportional to the increase in the hydrogen-ion concentration. The velocity coefficient $(k_1 + k_2)$ may therefore be expressed for acid solutions, $(k_1 + k_2) = A + B(H^\cdot)$, where A and B are constants at constant

---

[1] van't Hoff, "Vorlesungen über Chemie," 229 (1901).

[2] THIS JOURNAL, 26, 1073 (1904).

[3] Hudson and Sawyer, forthcoming publication.

[4] Osaka, *Z. physik. Chem.*, 35, 701 (1900).

[5] Hudson, THIS JOURNAL, 29, 1571 (1907).

TABLE III.

Temperature.	Observed. I.	Calculated. II.	Observer.
0°	0.00070	0.00069	Hudson*
3°	0.00100	0.00097	Trey[1]
11°	0.0030	0.0024	Lowry[2]
12°	0.0035	0.0027	Müller[3]
13°	0.0045	0.0030	Urech[4]
14°	0.0040	0.0034	Müller[3]
14°	0.0034	0.0034	Urech[4]
14°	0.0061	0.0034	Lowry[2]
17.5°	0.0065	0.0049	Lowry[2]
18°	0.0049	0.0052	J. Meyer[5]
18°	0.0044	0.0052	Roux[6]
20°	0.0065	0.0063	Trey[1]
20°	0.0059	0.0063	Parcus and Tollens[7]
20°	0.0061	0.0063	Levy[8]
20°	0.0092	0.0063	Schadee van den Does[9]
21.7°	0.0067	0.0074	Pratolongo[10]
25°	0.0104	0.0105	Osaka[11]
25°	0.0074	0.0105	Trey[12]
25°	0.0100	0.0105	J. Meyer[5]
25°	0.0106	0.0105	Hudson[13]
25°	0.0103	0.0105	Boeseken[14]
30°	0.0167	0.0172	Hudson*
40.2°	0.052	0.044	Hudson*

temperature. In what manner does B change with the temperature? One of us found B to have the value 0.26 at 25°, 0.45[15] at 30°, from Levy's[16] measurements at 20° the value 0.17 may be calculated, and Trey's[16] measurements give the value 0.024 for 3°, while for 25° they give 0.21. The ratio of the coefficients for 3° and 30° is $0.45/0.024 = 19$, while the ratio for the rates of mutarotation in water at these two temperatures, from Table III, is $0.172/0.00097 = 18$. This is sufficient agreement to show that the acceleration of the hydrogen-ion catalysis of the mutarotation with rising temperature is the same as the acceleration by increased temperature of the rate of mutarotation in pure water. Accordingly, in Table IV the coefficient of the acid catalysis (B) is calculated from the integrated form of the equation $d(\log B)/dT = A/T^2$, using for

---

* Unpublished observations.

[1] *Z. physik. Chem.*, 18, 205 (1895). [2] *J. Chem. Soc.*, 83, 1321 (1903). [3] *Compt. rend.*, 118, 428 (1894). [4] *Ber.*, 18, 3060 (1885). [5] *Z. physik. Chem.*, 62, 59 (1908). [6] *Ann. chim. phys.*, 7e, 30, 428 (1903). [7] *Ann. Chem.*, 257, 160 (1890). [8] *Z. physik. Chem.*, 17, 307 (1895). [9] *Chem. Ztg.* (Repertorium), 65 (1901). [10] *Ren. del R. Inst. Lomb. di Sc. e litt.*, 45, 972 (1912). [11] *Z. physik. Chem.*, 35, 702 (1900). [12] *Z. physik. Chem.*, 22, 427 (1897). [13] THIS JOURNAL, 29, 1573 (1907). [14] *Ber.*, 2626 (1913).

[15] Hudson, THIS JOURNAL, 30, 1577 (1908). This value is calculated from the increase in $(k_1 + k_2)$ between the hydrochloric acid concentrations of 0.05 and 0.20 normal.

[16] *Loc. cit.*

A the value 3873 previously found (see p. 326) from the measurements of the mutarotation of glucose in pure water at different temperatures, and for the constant of integration the value obtained from the quoted measurement of the catalysis at 30°, 0.45, the final equation being $\log_{10} B = 12.435 - 3873/T$. The values for B thus calculated on the assumption that the temperature has exactly the same accelerative action on the acid catalysis as on the mutarotation in pure water, agree well with the values that have been observed at different temperatures by independent observers, as is shown in Table IV.

TABLE IV.

Influence of Temperature on the Coefficient of the Acid Catalysis of the Mutarotation of Glucose.

	Coefficient (B).		
Temperature.	Observed.	Calculated.	Observer.
3°	0.024	0.025	Trey[1]
14°	0.13	0.089	Lowry[2]
18°	0.13	0.13	J. Meyer[3]
20°	0.17	0.16	Levy[1]
25°	0.21	0.27	Trey[1]
25°	0.37	0.27	J. Meyer[3]
25°	0.26	0.27	Hudson[1]
30°	0.45	(0.45)	Hudson[1]

WASHINGTON, D. C.

NEW BOOKS.

Practical Physical Chemistry. By J. B. FIRTH, Assistant Lecturer and Demonstrator in Chemistry, Armstrong College, Newcastle-on-Tyne. New York: D. Van Nostrand Co., 1916. Pp. ix + 178. Price, $1.00.

This volume adds one more to the list of books on laboratory work in physical chemistry and resembles its predecessors rather closely. The following topics are treated: weighing, thermostats, density of gases liquids and vapors, surface tension, solubility, molecular weights, transition points, osmotic pressure, refractivity, polarimetry, spectrum analysis, partition coefficient, calorimetry, transport numbers, conductivity, electromotive force, velocity of reaction, quantitative electrolytic determinations, electrolytic preparations, preparation of colloids. The last three topics present the only innovations. The introduction of simple experiments on colloids is especially to be commended. The electrolytic work would be of more value if an attempt were made to bring out the fundamental principles of electrolytic processes, as is done admirably, for example, in Allmand's "Applied Electrochemistry."

The other topics are treated in conventional fashion by the apparatus

---

[1] *Loc. cit.*

[2] *J. Chem. Soc.*, **83**, 1321–1323 (1903).

[3] *Z. physik. Chem.*, **62**, 59–88 (1908).