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ISOMERIZATION OF D-GLUCOSE BY DISODIUM PENTASILICATE ($Na_2Si_5O_{11}.xCH_3OH.yH_2O$) IN METHANOL–WATER SOLUTIONS

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ABSTRACT

Disodium pentasilicate ($Na_2Si_5O_{11}.xCH_3OH.yH_2O$, DPS), prepared from sodium metasilicate, was found effective for the isomerization of D-glucose in methanol–water. The isomerization was accelerated markedly as a function of methanol concentration; in 80% (v/v) methanol, the production of D-fructose was 1.7 times that in water alone. A 67.7% conversion of D-glucose into D-fructose was achieved by a batch reaction operated for 18 h at 40°. The disappearance of D-glucose in the isomerization reaction follows second-order kinetics, and the activation energy of the forward reaction is 129 $kJ.mol^{-1}$.

INTRODUCTION

The isomerization of D-glucose, D-mannose, and D-fructose by the action of aqueous alkali has been thoroughly investigated by many researchers[1–6]. The conversion of D-glucose into D-fructose by the action of isomerases has been shown to range from 80–90%, depending on the temperature[7], and the use of sodium aluminate for the isomerization of D-glucose to D-fructose has been reported in the patent[8] claiming formation of 70–80% of D-fructose. A possible explanation for the high yields of D-fructose from D-glucose in the presence of sodium aluminate is that, in order for the isomerization of D-glucose in alkali solution to occur, the D-fructose produced must be able to form a stable complex with aluminate[9–12].

The isomerization of D-glucose in water solution under various conditions has been extensively investigated. In contrast, relatively few studies of the reaction in aqueous solvent mixtures have been published[13]. The isomerization reaction in the present experiment was carried out successfully in 80% of methanol–water*.

The DPS, comprised of polysilicate($Si_5O_{11}^{2-}$), was obtained by a new procedure and was employed for the isomerization of D-glucose in methanol–water. Several polysilicate ions, such as thortveitite ($Si_2O_7^{6-}$), albite ($Si_3O_8^{4-}$), benitoite

*All solvent concentrations are expressed as v/v.

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($Si_3O_9^{6-}$), neptunite ($Si_4O_{12}^{8-}$), and beryl ($Si_6O_{18}^{12-}$) are known as the components of various silicate minerals.

It has been reported that the isomerization of D-glucose under alkaline conditions follows first-order kinetics[2,4–6,13], and the enol-intermediate theory is widely accepted[4,6,14]. In the present investigation, the isomerization of D-glucose to D-fructose and D-psicose was found to be a second-order reaction. If the mechanism for the interconversion between the sugars were the same as for the simple, base-induced reaction, then the product distribution of the sugars would be altered and high yields of D-fructose from D-glucose could not be expected.

RESULTS AND DISCUSSION

A solution having pH 13.65 was obtained when 20 g of sodium metasilicate ($Na_2SiO_3.9H_2O$) was dissolved in 40 mL of water. Cation-exchange resin (Dowex 50W × 4, 400 mesh H^+) was added slowly in small portions to the solution with stirring and the pH of the solution was measured. The relationship between the weight of resin added and the pH of the solution is shown in Fig. 1. The pH curve shows an inflection near pH 11.50. Next, 20 g of sodium metasilicate was dissolved in 40 mL of water and adjusted to pH 11.50 by the addition of Dowex 50W × 4 resin. The resin was then removed by filtration and abs. methanol was

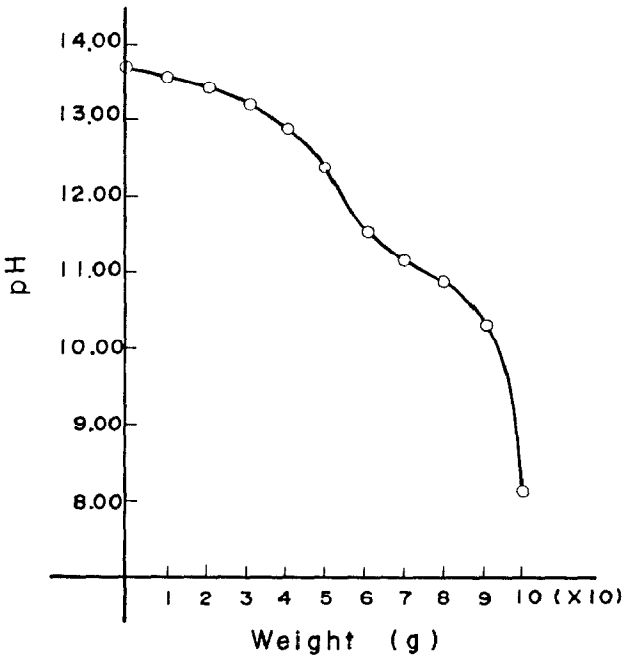


Fig. 1 pH curve for decationization of a solution of sodium metasilicate by cation-exchange resin. The numbers on the abscissa indicate the weight of the resin.

added to the filtrate with stirring until it reached 80%. The resulting white mass was homogenized with a Teflon homogenizer and then filtered off. The solid mass obtained was washed with abs. methanol and heated at 300° under vacuum to constant weight, affording 5.48 g of final product named silicate-11.5. A portion of silicate-11.5 (15 mg) was heated for 7 h at 500° *in vacuo* and then subjected to pressure (400 kg/cm^2) under vacuum for 30 min. The weight loss of 5.1% after heating at 500° is attributable to the water and methanol present. The presence of methanol was revealed by the observation of charcoal in the specimen at the outset of heating at high temperature. It is convenient to imagine that the water and methanol molecules act partly as ligands and partly as constituents bonded covalently in the solid matrix, otherwise, these molecules would be lost completely by heating at 300°. The quantities of SiO_2 and Na_2O in the pressed pellet were determined with a computer-controlled Electron Probe X-ray Microanalyzer. The molar ratio of SiO_2/Na_2O in the pellet was 5.00. Consequently, the composition of silicate-11.5 is represented by $Na_2Si_5O_{11}.xCH_3OH.yH_2O$, where x and y denote the number of moles of methanol and water, respectively. The sum of x and y corresponds to the weight loss of 5.1%. Similarly, other products named silicate-13.0, -12.5, -12.0, -11.0, -10.5, and -10.0, were prepared from solutions of sodium metasilicate. Quantitative data for these silicates are shown in Table I.

X-Ray diffraction measurements were conducted on the silicates that had been quantitatively analyzed and the spectra for silicate-12.5, -11.5, and 10.5 are shown in Fig. 2. Literature concerning superionic conductors has reported that anions fixed on lattice points contribute to the oscillatory diffuse background, and this is characteristic of liquid or amorphous substances[16]. Moreover, the asymmetric anharmonic thermal vibration for cation atoms has been shown to exert a considerable effect on the intensities of Bragg reflection[16–18]. The spectra of the silicate-12.5 (Fig. 2A) and -10.5 (Fig. 2C) show an almost simple, diffuse background. In contrast, the spectrum of the silicate-11.5 (Fig. 2B) is characterized by several distinct Debye lines on the diffuse background. This difference may be related to the labile moving cations present in the lattice of polysilicate anions of the silicate-11.5. The

TABLE I

COMPOSITION OF THE SILICATES BY QUANTITATIVE ANALYSIS

Silicates	*Mol of SiO_2*	*Mol of Na_2O*	*Molar ratio (SiO_2/Na_2O)*
Silicate-13.0	1.149	0.404	2.84
Silicate-12.5	1.176	0.369	3.19
Silicate-12.0	1.203	0.338	3.56
Silicate-11.5	1.311	0.262	5.00
Silicate-11.0	1.353	0.216	6.26
Silicate-10.5	1.366	0.165	8.28
Silicate-10.0	1.479	0.0729	20.29

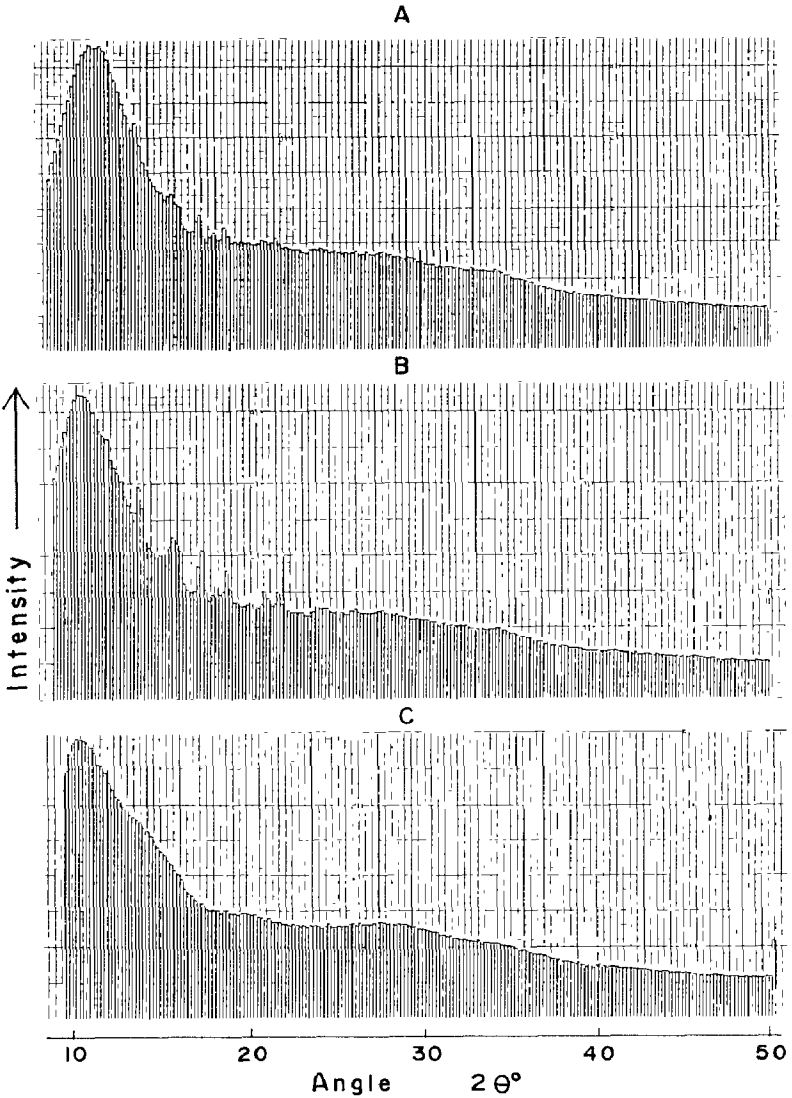


Fig. 2. X-Ray diffraction pattern: *A* for silicate-12.5, *B* for silicate-11.5, and *C* for silicate-10.5. The diffraction angle was kept at 0.2° step width for the measurements. The intensities of 205 reflections having $9° < \Theta < 50°$ were measured by using MoK_α ($\lambda = 0.70296$Å) radiation, which was rendered monochromatic by a LiF crystal monochromater. No corrections were made for absorption or extinction.

silicate-11.5 (DPS), having a unique structure, was chosen for reagent of the isomerization of D-glucose to D-fructose.

Various solvents, such as 40 and 80% of methanol, ethanol, and 1,4-dioxane in water, were evaluated for their suitability for the isomerization of D-glucose with DPS. To 2 mL of solvent containing 180 mg (0.5 mmol/mL) of D-glucose was added

TABLE II

ISOMERIZATION OF D-GLUCOSE TO D-FRUCTOSE IN THE PRESENCE OF DPS IN VARIOUS SOLVENTS

Solvents and concentrations (%)		*Fructose (mg)*	*Glucose (mg)*	*Fructose × 100 (%) / 180*
Methanol	80	103.8	63.6	57 7
	40	89.2	73.2	49.6
Ethanol	80	59.0	114.4	32.8
	40	79.8	82.0	22.2
1,4-Dioxane	80	37.2	127.6	20.7
	40	69.8	93.4	38.8
Water		60.4	103.2	33.6

TABLE III

EFFECTS OF VARIOUS AMOUNTS OF DPS FOR THE ISOMERIZATION WITH A DEFINITE AMOUNT OF D-GLUCOSE IN 80% METHANOL

DPS (mg)	*Fructose (mg)*	*Glucose (mg)*	*Fructose × 100 (%) / 180*
20	49.4	124.6	27.4
60	76.6	91.4	42.6
100	88.0	72.2	48.9
140	94.0	64.4	52.2
180	98.2	49.4	54.6
300	94.4	57.6	52.4

180 mg of DPS. Each reaction was conducted with constant shaking for 5 h at 45° under N_2 in the dark. The reaction vessels were then cooled in an ice bath, and 2 mL of water was added to each. The samples were centrifuged to remove undissolved material. The residues were washed three times with 2-mL portions of 40% methanol. The combined washings and supernatant solutions were assayed colorimetrically for sugars. The results are shown in Table II. All attempts with propanol, acetone, acetonitrile, and tetrahydrofuran gave unsatisfactory results.

In the methanol–water solvent system, the solid material was brought into colloidal dispersion, and the yield of D-fructose from D-glucose accelerated markedly as a function of the methanol concentration; in 80% methanol, it was 1.7 times the corresponding value in the water solution. The presence of the solvent may, at least partly, contribute to the changes in isomerization equilibria. An amount of 180 mg of D-glucose was not dissolved completely in 2 mL of methanol–water containing >80% methanol.

To study the influence of concentrations of DPS on the isomerization of D-glucose, various amounts of DPS were added to 2 mL of 80% methanol containing 180 mg of D-glucose and the reactions were performed as already described (Table III). The most satisfactory result was obtained by using 180 mg of DPS. As the DPS

TABLE IV

TIME–CONCENTRATION DATA FOR THE ISOMERIZATION OF D-GLUCOSE WITH DPS IN 80% METHANOL

At 35°			
Reaction time (h)	*Glucose (mg)*	*Fructose (mg)*	*Psicose (mg)*
3	138.6	39.6	1.4
9	91.4	83.8	4.0
18	60.8	104.2	12.8
27	45.0	111.2	18.6
At 45°			
2	90.0	87.6	2.1
9	32.4	108.0	17.2
18	17 4	113 2	23 8
27	11.9	114.4	26.9

is expressed by the formula $Na_2Si_5O_{11}.xCH_3OH.yH_2O$, a concentration of 90 mg/mL of DPS corresponds to 0.24 mmol/mL of DPS, and is almost 0.5 mol per mol of D-glucose employed in the reaction.

For kinetic analysis of the isomerization of D-glucose with DPS in 80% methanol, time–concentration relationships at 35 and 45° were studied. All experiments were performed batchwise, with mixtures comprised of 2 mL of 80% methanol containing 180 mg of D-glucose and 180 mg of DPS.

The sugars contained in isomerized mixtures were quantified by measurement of peak heights after separation by l.c. Peaks were identified by addition of standards, and concentrations of unknowns were determined by using calibration constants based on peak areas for the standards. D-psicose was prepared from D-fructose according to the method of Doner[19]. The amount of D-glucose in the mixtures was also checked colorimetrically by using glucose oxidase. Only three major sugar species were observed in the isomerization reactions, namely D-glucose, D-fructose, and D-psicose. If mannose were present, it would have given a peak between D-glucose and D-fructose. Separate t.l.c. analysis showed no spot corresponding to mannose. Other degradation products were formed when the sugars were exposed to high-temperature conditions, but these were not identified. The results are given in Table IV. The highest yields of D-fructose from 180 mg of D-glucose in the presence of DPS ranged between 111.2 and 114.4 mg, according to the reaction periods and the temperatures.

The rates calculated from the disappearance of D-glucose during the reaction followed the second-order kinetic equation:

$$k = C_0 - C_t/t\, C_0\, C_t,$$

Where C_0 denotes the initial concentration of D-glucose (0.5 mmol/mL) and C_t denotes the concentration of D-glucose after time t. From the results in Table IV, the plots of $C_0 - C_t/C_0\, C_t$ against t gave straight lines, as shown in Fig. 3. The

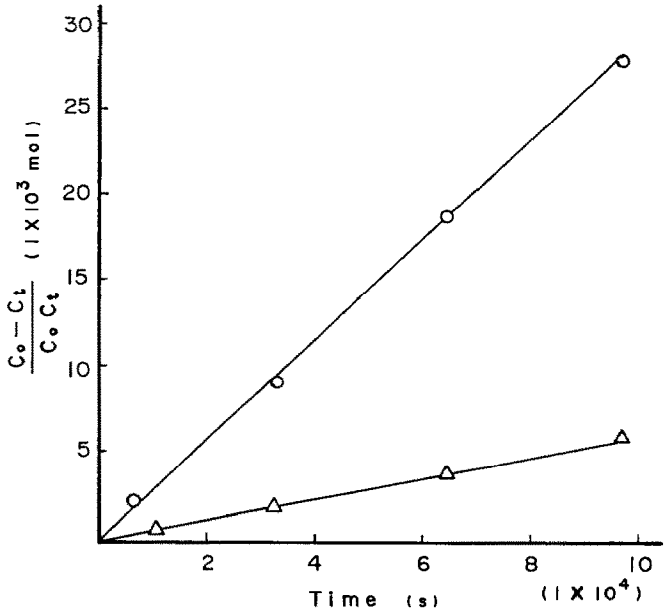
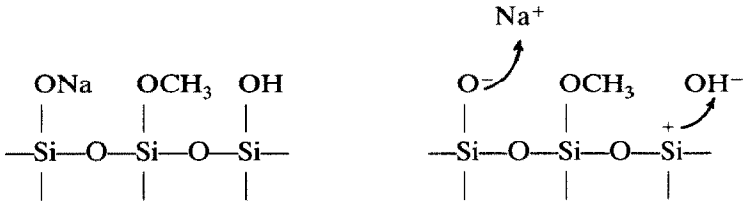


Fig. 3. Plot of $C_0 - C_t/C_0C_t$ against t for the disappearance of D-glucose as a function of temperature: (△) for 35° and (○) for 45°.

values of k_{35} for 35° and k_{45} for 45° calculated (method of least squares) from the slope of the lines were 6.18×10^{-5} and 3.02×10^{-4} $cm^3.mol^{-1}.s^{-1}$, respectively. From the rate constants, the activation energy (ΔE) of the forward reaction is given by:

$$\frac{k_{45}}{k_{35}} = \frac{e^{-\Delta E/318\,R}}{e^{-\Delta E/308\,R}}, \text{ which gives } \Delta E = 129\ \text{KJ.mol}^{-1}.$$

In the methanol–water system, the concentration of OH^- ion seems to play an important role in the isomerization of D-glucose. The DPS may be a convenient donor of OH^- ions and some of the catalytic effect of the DPS appears to occur at the negative and positive sites in the silicate.



Rendleman and Hodge[9] have reported that complex formation between hydrous aluminate and carbohydrate occurs readily in aqueous solution and many

TABLE V

WEIGHT LOSS OF SAMPLES OF SILICATE-11.5 AFTER HEATING

Heating temperature (°)	110	200	300	400	500	600
Weight loss (%)	18.5	20.2	23.1	27.4	28.1	28.4

TABLE VI

ISOMERIZATION OF D-GLUCOSE WITH SAMPLES OF SILICATE-11.5 HEATED IN THE RANGE OF 110–600° IN 89% METHANOL SOLUTION

Heating temp. (°)	*Amount (mg)*	*Glucose (mg)*	*Fructose (mg)*	*$\frac{\text{Fructose} \times 100\ (\%)}{180}$*
110	188	49.2	103 4	57.4
110	185	37.0	113.2	62.9
300	180	33.1	121.8	67 7
400	172	28.7	120.7	67 1
500	171	35.7	112.9	62 7
600	170	99.2	71.0	39.4

aluminate complexes of alditols and reducing sugars are precipitated in high yield by addition of ethanol to an equimolar aqueous mixture of sodium aluminate and carbohydrate. They also demonstrated that the extent to which eluminate is complexed with each carbohydrate depends upon the relative reactivities of the carbohydrates, and that D-fructose is four times more reactive than D-glucose.

As molecules of water and methanol are bound by polar ionic forces or partial covalent bonds to the silicon atoms of the polysilicate to complete the coordination, but are replaceable by other ligands, it seems probable that diffuse ion–dipole complexes of hydroxide–carbohydrate (ionic intermediates)[10] on the polar silicate may form.

The samples of DPS obtained by heating for 1 h below 200° were soluble in hot water, but those heated for 1 h above 300° were comparatively insoluble. A three-dimensional structure seems to be developed by heat treatment. The i.r. spectrum of DPS heated to 300° indicates the presence of -Si-OCH_3 groups at 1080 cm^{-1}, and methyl groups at 1450 and 2700–3000 cm^{-1}. However, the i.r. spectrum of the sample heated at 600° showed no bands at 1450 and 2700–3000 cm^{-1}, and the band shape in the range 1200–250 cm^{-1} changed markedly.

To test the isomerizing ability with samples of DPS obtained by heating from 110 to 600°, the following experiments were performed. The silicate-11.5, obtained as already described, was dried in a stream of hot air at 50–80°. The preparation was divided into 6 groups and the individual samples were heated at 110, 200, 300, 400, 500, and 600° under vacuum for 1 h. The weight losses of the samples after heating are shown in Table V. The isomerization of D-glucose with these samples was performed with stirring for 18 h at 40° under N_2 in the dark. However, the amount of sample employed in each run was adjusted by the results of Table V on

the basis of the quantity of the sample heated at 300°. The results are shown in Table VI. A 67.7% conversion of D-glucose into D-fructose was achieved by the sample heated at 300°.

EXPERIMENTAL

Preparation of homogeneous cation-exchange resin for titration. — The grain size of the cation-exchange resin (Dowex 50W × 4, 400 mesh) suspended in water was adjusted by repeated centrifugation at 3000 and at 500 r.p.m. The resin (100 g) was stirred for 30 min in 600 mL of 4M HCl. After filtration through a fritted-disc funnel, the resin was suspended in 1000 mL of 2M NaCl, filtered, again treated with 600 mL of 4M HCl, and finally washed with distilled water until the washings were no longer acidic. The moist resin obtained was used as the titrant for a solution of sodium metasilicate.

Analysis of the silicates. — Quantitative analysis of SiO_2 and Na_2O was performed with a Jeol Model JXA-5A EPMA instrument, using albite as a standard. Measurements were conducted with an electron current of 2×10^{-8} A and acceleration voltage of 15 kV. Background corrections were made by using a computer control system. Analyses were repeated three times.

For X-ray diffraction measurements, a conventional scintillation counter and pulse-height analyzer were used to measure the intensity of diffracted beam. The X-ray tube was operated with an electron current of 20 mA and voltage of 45 kV.

Analyses for carbohydrates. — L.c. was performed on a column of 2 mm internal diameter and 50 cm length, packed with Lichrosorb-NH_2 (Merck), with an Atto model instrument equipped with a differential-refraction detector. The eluent was 82:18 (v/v) acetonitrile–water at a flow-rate of 1.8 mL/min, and the elution pressure was generally 2000 lb.in.$^{-2}$. Normally, a total of 1 mg solute/10 μL was injected onto the column by using a loop injector. The ketoses are appreciably more responsive to refractive-index detection than are aldoses. Typical chromatograms are shown in Fig. 4.

A enzymic method using glucose oxidase was adopted for quantitative determination of D-glucose. A blood-sugar determination kit (Glucose B test Wako, supplied by Wako Pure Chemical Co.) was used according to the instructions. The calibration curve was linear in the concentration range 0–5 mg/mL and was not affected by the presence of other sugars. For determination of D-fructose, the Seliwanoff method was used. Although the results were not affected by the presence of D-glucose, the presence of D-psicose interfered. The reagent was prepared just before using by mixing together 5 mL of 0.5% resorcinol solution, 15 mL of concentrated hydrochloric acid, and 50 mL of water. Absorption measurements were made at 485 nm. The calibration curve was linear in the range from 0–35 mg/mL. The reagent (5 mL) was added to 0.02 mL of the sample, which had been diluted to the optimal concentration. The mixture was heated for 10 min at 100°, and then cooled in water for 10 min at 15° and measured. As the results were

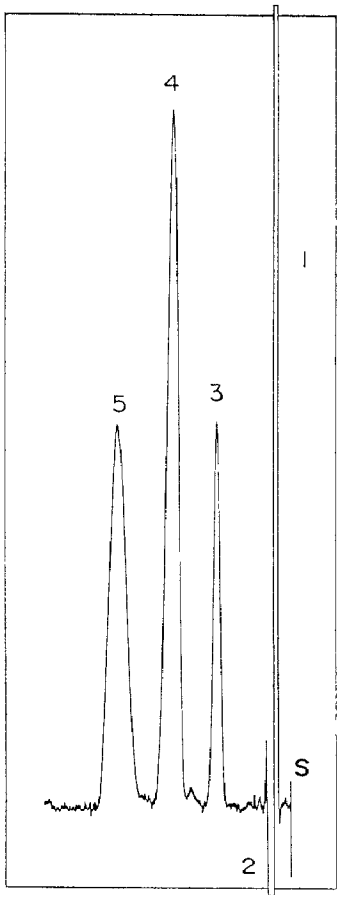


Fig. 4. Liquid chromatogram from experiments on isomerization of D-glucose with DPS in 80% methanol performed for 18 h at 35°: starting point (s), water (1), methanol (2), D-psicose (3), D-fructose (4), and D-glucose (5). The strip-chart recorder was set at 2 mm/min. The running time for each sample was 12 min.

markedly affected by the temperature and time of heating, a standard reference sample was used in each determination.

T.l.c. analysis for the mixtures was performed on cellulose plates (Merck). The sheets were developed with 6:4:3 1-butanol–pyridine–water. The sugars were made visible by spraying the plates with a solution consisting of 0.91 mL of aniline, 1.66 g of *o*-phthalic acid, and 100 mL of 1-butanol saturated with water, followed by heating for 5 min at 110°. For ketoses, the color reagent was prepared by mixing equal amounts of 0.25M HCl and a 0.2% ethanolic solution of resorcinol. After spraying with reagent, the plates were heated for 5 min at 100°.

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