

Ionization and solvation of D-glucose

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IONISATION AND SOLVATION OF D-GLUCOSE

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ABSTRACT

For a quantitative description of chemical reactions of carbohydrates in concentrated solutions, a detailed knowledge of the ionisation equilibria is a prerequisite. In a series of experiments involving a wide range of concentrations of D-glucose, the ideal or non-ideal solution models did not accord with the observations unless hydration was taken into account. A hydration number of 3.5 was found for molecular D-glucose, but no hydration for dissociated D-glucose. This result is discussed in terms of intramolecular hydrogen-bonding within the D-glucose ion.

INTRODUCTION

This study is part of a project on the heterogeneous alkaline isomerisation of carbohydrates using ion-exchange resins¹. In considering these reactions, the ionisation and solvation of the carbohydrates is of great importance. The ionisation of carbohydrates in alkaline aqueous solutions causes mutarotation, and, *via* carbanions (enolate ion), isomerisation and degradation.

Reducing mono- and oligo-saccharides are weak acids and the ionisation of the anomeric hydroxyl group is an essential step in the isomerisation and epimerisation reactions. As ionisation is much faster than mutarotation^{2,3}, the ionisation constants of α and β forms can be distinguished. Los and Simpson⁴ found a value of 0.29 for $\Delta pK_{\text{Glc}} (= pK_{\alpha\text{-Glc}} - pK_{\beta\text{-Glc}})$ for the pyranose forms, whereas De Wit *et al.*⁵ found a value of 0.19. When only one pK_a value is reported, it must be considered to be an overall ionisation constant and these have been determined for many carbohydrates at various temperatures^{6–25}, using a variety of methods. Table I lists the pK_a values at 298 K for D-glucose, D-fructose, and D-mannose. All concentrations are expressed in $\text{mol}\cdot\text{m}^{-3}$. The concentrations used for pH and pK_s are expressed in $\text{kmol}\cdot\text{m}^{-3}$, so that pK and pH values can be compared with literature data. From the data in Table I, it can be concluded that, at 298 K, $pK_{\text{Glc}} = 12.4 \pm 0.25$, $pK_{\text{Fru}} = 12.1 \pm 0.3$, and $pK_{\text{Man}} = 12.1 \pm 0.1$.

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TABLE I

IONISATION CONSTANTS (pK_S) FOR AQUEOUS SOLUTIONS AT 298 K

D-Glucose	D-Fructose	D-Mannose	Ref.
12.23	11.99		11
12.107	11.693		12
12.09	11.68		13
12.96			14
12.34			15
12.49 ^a			16
12.20 ^b			
12.87	12.67		17
12.35	12.21	12.13	18
12.38			19
12.46	12.27	12.08	20
12.51	12.31		21
12.72 ^c	12.553 ^c		22
12.35			22
12.78 ^{a,d}			5
12.60 ^{b,d}			5
13.9 ^{d,e}	14.2 ^{d,e}	14.0 ^{d,e}	5

^a α -Anomer. ^b β -Anomer. ^cAt 283 K. ^dAt 276–278 K. ^eAt 1100 mol.m⁻³

TABLE II

LITERATURE pK_{Glc} VALUES AS A FUNCTION OF THE CONCENTRATION OF D-GLUCOSE, AND DETERMINED POTENTIOMETRICALLY

Concentration of D-glucose (kmol.m ⁻³)	Michaelis and Rona ²⁵	Thamsen ²⁴	
	290–292 K	291 K	273 K
0.05		12.46	12.97
0.10	12.38	12.44	12.93
0.20	12.28	12.40	12.88
0.50	12.26		
1.0	12.05		

When the results of De Wit *et al.*⁵ are omitted, D-fructose seems to be more acidic than D-glucose ($\Delta pK_a = 0.27 \pm 0.10$). Izatt *et al.*²⁰ ascribed the lack of agreement between the results of the various studies to the differences of the ionic strength of the solutions used. At 273 K, Thamsen²⁴ found a slight increase of pK_a with increase in ionic strength. Degani²³, however, was unable to find any influence. Only three authors have described a dependence of the pK_a on the concentration of hexose. Michaelis and Rona²⁵ and Thamsen²⁴, using a potentiometric method, found that pK_S decreased with increase in the concentration of D-glucose (Table II). The data of De Wit and co-workers^{5,26}, obtained using n.m.r. and u.v. techniques, reflected an increase of pK_{Glc} with increase in concentration of hexose.

Also, in an alkaline ion-exchange resin, proton abstraction will take place

TABLE III

EXPERIMENTAL RESULTS AND CALCULATIONS OF $K_{G(a)}$; C_{GH} IS NOT IN THE TABLE BECAUSE $C_{GH} \sim C_G$

<i>Expt.</i> <i>no.</i>	$C_G \times 10^{-3}$ (<i>mol.m</i> ⁻³)	$C_G \times 10^{-3}$ (<i>mol.m</i> ⁻³)	<i>pH</i>	$C_{K^+(a)}$ (<i>mol.m</i> ⁻³)	$C_{HO^-(a)}$ (<i>mol.m</i> ⁻³)	$C_{G^-(a)}$ (<i>mol.m</i> ⁻³)	$K_{G(a)} \times 10^6$ (<i>mol.m</i> ⁻³)	$pK_{G(a)}$	$\overline{pK}_{G(a)}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
1	0.0635	0.0602	10.05	0.559	0.112	0.447	0.632	12.200	12.226
	0.0611		11.00	4.301	1.000	3.301	0.571	12.243	
	0.0563		11.50	11.936	3.162	8.774	0.584	12.234	
2	0.0635	0.0602	10.97	0.571	0.117	0.454	0.612	12.213	12.218
	0.0610		11.00	4.462	1.000	3.462	0.602	12.221	
	0.0561		11.50	12.142	3.162	8.980	0.603	12.220	
3	0.171	0.158	10.04	1.234	0.110	1.124	0.604	12.219	12.220
	0.156		11.00	9.986	1.000	8.986	0.611	12.214	
	0.148		11.20	14.331	1.58	12.746	0.595	12.226	
4	0.171	0.158	10.03	1.221	0.107	1.114	0.612	12.213	12.222
	0.156		11.00	9.782	1.000	8.782	0.597	12.224	
	0.148		11.20	14.231	1.585	12.646	0.590	12.210	
5	0.371	0.351	10.00	2.828	0.100	2.728	0.741	12.130	12.159
	0.352		10.50	7.757	0.316	7.441	0.683	12.166	
	0.329		10.80	13.772	0.631	13.141	0.659	12.181	
6	0.371	0.351	10.01	2.737	0.102	2.635	0.699	12.156	12.171
	0.353		10.50	7.584	0.316	7.268	0.665	12.177	
	0.329		10.80	13.830	0.631	13.199	0.662	12.179	
7	0.690	0.657	9.81	3.945	0.065	3.880	0.876	12.057	12.061
	0.673		10.11	7.573	0.129	7.444	0.868	12.061	
	0.609		10.50	16.442	0.316	16.126	0.860	12.065	
8	0.711	0.679	9.90	5.037	0.079	4.958	0.884	12.054	12.064
	0.701		10.01	6.314	0.102	6.212	0.874	12.059	
	0.626		10.50	16.361	0.306	16.045	0.932	12.080	
9	1.194	1.102	9.53	4.479	0.034	4.445	1.103	11.958	11.985
	1.106		10.00	11.448	0.100	11.348	1.037	11.984	
	1.007		10.30	19.366	0.199	19.167	0.972	12.012	
10	1.144	1.100	9.53	4.403	0.034	4.369	1.131	11.946	11.982
	1.108		10.00	11.281	0.100	11.181	1.019	11.992	
	1.047		10.20	16.175	0.168	16.017	0.980	12.009	
11	1.526	1.469	9.30	4.040	0.020	4.020	1.324	11.878	11.901
	1.496		9.50	5.966	0.032	5.934	1.259	11.900	
	1.384		9.90	12.986	0.079	12.907	1.185	11.926	
12	1.524	1.467	9.33	4.207	0.021	4.186	1.288	11.890	11.900
	1.493		9.50	6.162	0.032	6.130	1.304	11.885	
	1.384		9.90	12.998	0.079	12.919	1.186	11.926	

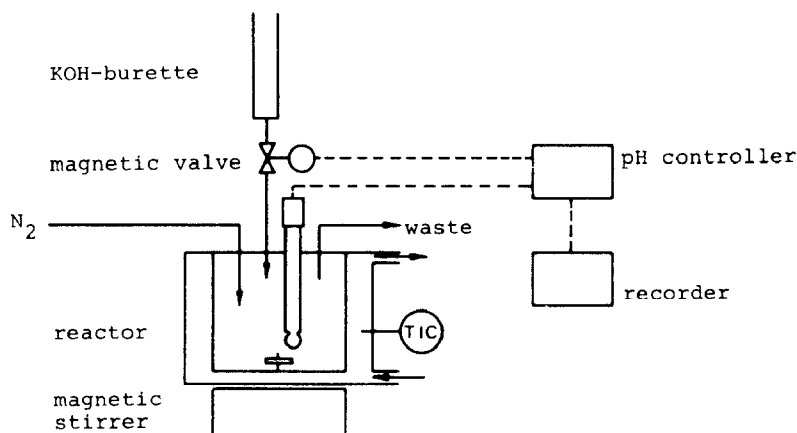


Fig 1. Reactor for potentiometric titrations.

before isomerisation. Inside such a catalyst, the concentration of the components is relatively high. In view of the discrepancies associated with the literature data, the degree of ionisation at high concentrations of hexose has been determined.

EXPERIMENTAL

The ionisation measurements were carried out by potentiometric titration using analytical grade chemicals, doubly distilled, CO₂-free water, and a thermostated reactor (150 mL) provided with a magnetic stirrer (Fig. 1). The pH was measured with a glass electrode (Radiometer, type GK 2401 B) in combination with a pH controller (Radiometer, type TTT 1c), and corrections were applied for the temperature and the concentration of the alkali. The electrode was calibrated with buffer solutions (Merck Titrisol). The titration was controlled by titrating pure water with CO₂-free M KOH. When >5 mL of KOH solution was added, the measured and the calculated concentration of HO⁻ differed by <5%. The isomerisation of the carbohydrate under study was neglected.

A solution (50 mL) of D-glucose of known concentration under nitrogen was titrated to three different pH values at 298 K.

Columns (1)–(5) of Table III show the final composition of the D-glucose solutions after adding the appropriate amount of alkali.

RESULTS AND DISCUSSION

In solution, the chemical potential of each component²⁷ is

$$\mu_1 = \mu_1^* + RT \ln (y_1 \cdot C_1), \quad (1)$$

and for the solvent,

$$\mu_{\text{H}_2\text{O}} = \mu_{\text{H}_2\text{O}}^* + RT \ln (y_{\text{H}_2\text{O}} \cdot C'_{\text{H}_2\text{O}}), \quad (2)$$

where $\mu_{\text{H}_2\text{O}}^*$ is the chemical potential of pure water, and consequently the concentration of water is expressed as a fraction:

$$C'_{\text{H}_2\text{O}} = C_{\text{H}_2\text{O}}/C_{\text{H}_2\text{O,pure}}. \quad (3)$$

As the experiments were carried out at constant pressure, μ_i^* is a function only of the temperature. For non-ideal solutions, $y_i \neq 1$.

When a solution is in equilibrium, the chemical potential (G) will be a minimum and ΔG will be zero. Hence,

$$\sum \nu_i \cdot \mu_{i \text{ eq}} = \sum \{ \nu_i \cdot \mu_i^* \} + RT \sum \{ \nu_i \cdot \ln (y_i \cdot C_i) \}_{\text{eq}} = 0, \quad (4)$$

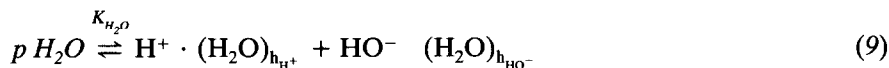
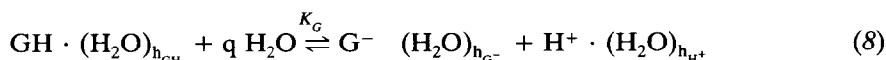
$$\Delta G^* = \sum \{ \nu_i \cdot \mu_i^* \} = - RT \sum \{ \nu_i \cdot \ln (y_i \cdot C_i) \}_{\text{eq}}, \text{ and} \quad (5)$$

$$\Delta G^E = - RT \sum \{ \nu_i \cdot \ln y_i \}. \quad (6)$$

As μ_i^* is a function only of the temperature, ΔG^* will be also a function only of the temperature. The equilibrium constant is defined as

$$\ln K_1 = \sum \{ \nu_i \cdot \ln (y_i \cdot C_i) \} = - \Delta G^*/RT. \quad (7)$$

Because the pressure remains constant, the equilibrium constant should be only a function of the temperature. Applied to a solution of D-glucose (G) and including hydration of all species:



where h = hydration number,

$$q = \text{h}_{\text{G}^-} + \text{h}_{\text{H}^+} - \text{h}_{\text{GH}}, \text{ and} \quad (10)$$

$$p = \text{h}_{\text{H}^+} + \text{h}_{\text{HO}^-} + 1. \quad (11)$$

$$K_G = y_{\text{G}^-} \cdot C_{\text{G}^-} \cdot y_{\text{H}^+} \cdot C_{\text{H}^+} / (y_{\text{GH}} \cdot C_{\text{GH}} \cdot y_{\text{H}_2\text{O}}^q \cdot C_{\text{H}_2\text{O}}^q) \quad (12)$$

$$K_{\text{H}_2\text{O}} = y_{\text{H}^+} \cdot C_{\text{H}^+} \cdot y_{\text{HO}^-} \cdot C_{\text{HO}^-} / (y_{\text{H}_2\text{O}}^p \cdot C_{\text{H}_2\text{O}}^p) \quad (13)$$

In the following sections, the equilibrium constant will be calculated on the basis of three assumptions: (a) ideal solution, no hydration, (b) non-ideal solution, no hydration, (c) non-ideal solution, hydration.

In an ideal solution, the dissociation constants for D-glucose and water (Eqs. 12 and 13) are simplified to:

$$K_{g(a)} = C_{G^-} \cdot C_{H^+} / C_{GH}, \text{ and} \quad (14)$$

$$K_{H_2O(a)} = C_{H^+} \cdot C_{HO^-}, \quad (15)$$

where the index (a) refers to the assumption (a). During titration, the total concentration of D-glucose decreases and the following relations hold:

$$C_{H^+(a)} = 10^{3-pH} \quad \text{mol.m}^{-3} \quad (16)$$

$$C_{HO^-(a)} = K_{H_2O(a)} / C_{H^+(a)} \quad (pK_{H_2O,298} = 13.9965) \quad (17)$$

$$C_{G^-(a)} = C_{K^+(a)} + C_{H^+(a)} - C_{HO^-(a)} \quad (\text{electro-neutrality}) \quad (18)$$

$$C_{GH(a)} = C_{G(a)} - C_{G^-(a)} \quad (\text{D-glucose balance}) \quad (19)$$

In Table III, columns (6) and (7) show the results of the calculations of C_{HO^-} and C_{G^-} . Furthermore, the values of $K_{G(a)}$ and $pK_{G(a)}$ according to Eq. 13 are

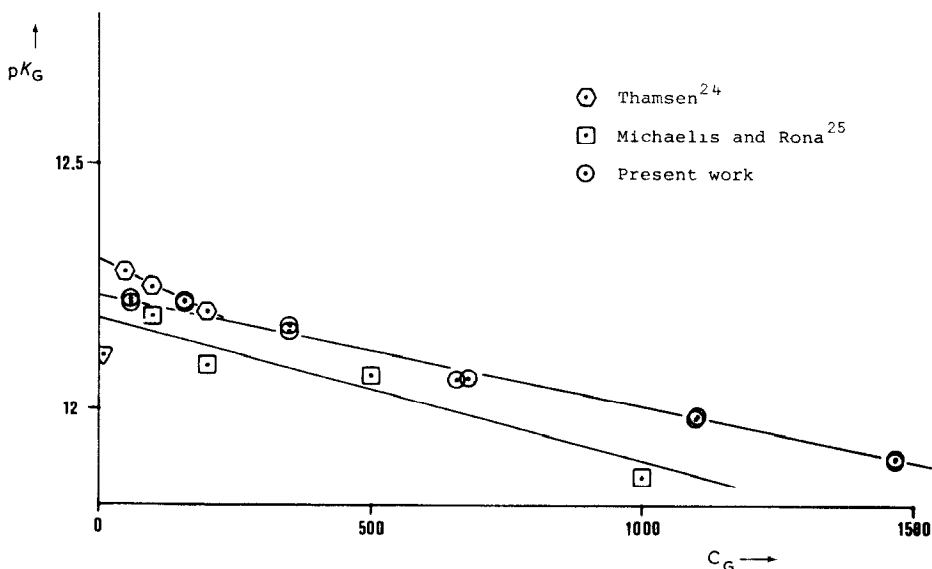


Fig. 2. pK_G as a function of the concentration of D-glucose at 298 K. The temperature dependence of the data of Thamsen²⁴ were used to recalculate them to the reference temperature of 298 K.

presented in columns (8)–(10). Our results, in combination with the potentiometric data of Thamsen²⁴ and of Michaelis and Rona²⁵, are given in Fig. 2. Our data give roughly the same concentration– pK_G relation as found by the other authors. However, it is clear that this approach does not lead to an equilibrium constant that is independent of the concentration. For a non-ideal solution without hydration, Eqs. 12 and 13 are simplified to:

$$K_{G(b)} = y_{G^-} \cdot C_{G^-} \cdot y_{H^+} \cdot C_{H^+} / (y_{GH} \cdot C_{GH}), \text{ and} \quad (20)$$

$$K_{H_2O(b)} = y_{H^+} \cdot C_{H^+} \cdot y_{HO^-} \cdot C_{HO^-} / (y_{H_2O} \cdot C_{H_2O}), \quad (21)$$

$$\text{with } a_{H_2O} = y_{H_2O} \cdot C_{H_2O}. \quad (22)$$

It is difficult to calculate the thermodynamic activity of water in a multi-component system²⁹. For our experimental conditions (Table III), the concentration of D-glucose C_{GH} is much higher than the ionic concentrations. For this reason, the activity of water was provisionally assumed to be equal to a_{H_2O} in a pure solution of D-glucose. The latter can be calculated from the measurements of Bonner and Breazeale³⁰, who gave the activity coefficient of D-glucose (γ_{GH}) and the osmotic coefficient (ϕ_{GH}) as a function of the molality (m_{GH}) of D-glucose in a neutral solution:

$$\gamma_{GH} = 1 + 0.022m_{GH}^{1.25} \quad (0 < m_{GH} < 2) \quad (23)$$

$$\phi_{GH} = 1 + 0.012m_{GH}^{1.25} \quad (0 < m_{GH} < 2) \quad (24)$$

The activity of water can be calculated from ref. 31 as

$$\ln a_{H_2O} = -m_{GH} \cdot M_{H_2O} \cdot \phi_{GH} \cdot 10^{-3} \quad (0 \leq m_{GH} \leq 2). \quad (25)$$

The activity coefficients γ_{G^-} and γ_{HO^-} have been calculated with the Debye–Hückel expression, as corrected by Robinson and Stokes³¹ for solvation and the activity of the solvent:

$$\log \gamma = -A_T \cdot I^{1/2} / (1 + B_T \cdot d_i \cdot I^{1/2}) - \log(1 - 0.018 h_i \cdot m_i) - h_i \cdot \log a_{H_2O}. \quad (26)$$

with $A_{298 K} = 0.5115 \text{ kg}^{1/2} \cdot \text{mol}^{-1/2}$ (Debye–Hückel constant),

$B_{298 K} = 3.291 \cdot 10^9 \text{ kg}^{1/2} \cdot \text{mol}^{-1/2} \cdot \text{m}^{-1}$ (Debye–Hückel constant),

d_{G^-} = diameter $G^- \sim 8 \times 10^{-10} \text{ m}$,

d_{HO^-} = diameter $HO^- \sim 2 \times 10^{-10} \text{ m}$,

h_i = solvation number: mol H_2O per mol i ,

$I = m_{K^+} + m_{H^+} = m_{G^-} + m_{HO^-}$ = ionic strength ($\text{mol} \cdot \text{kg}^{-1}$).

The activity of water is calculated from y_{GH} , y_{G^-} , and y_{HO^-} with the Gibbs–Duhem equation 26. It appeared that a_{H_2O} calculated with Eq. 25 is a good approximation. The thermodynamic quantities are between the following limits.

$$1.000 < \gamma_{GH} < 1.045 \quad (27)$$

$$0.882 < \gamma_{G^-} < 1.000 \quad (28)$$

$$0.853 < \gamma_{HO^-} < 1.000 \quad (29)$$

$$0.967 < a_{H_2O} < 1.000 \quad (30)$$

To calculate the ionisation constant, a molality–molarity conversion has to be applied, namely

$$m_1 = C_1 / (\rho - M_{GH} \cdot C_{GH} - M_{G^-} \cdot C_{G^-} - M_{HO^-} \cdot C_{HO^-}), \quad (31)$$

and for the density of the solution,

$$\rho = 1000 + 0.067C_G. \quad (32)$$

In Fig. 3, the equilibrium constant $pK_{G(b)}$ is given as a function of the concentration of D-glucose. It is seen that the concentration dependence of $pK_{G(b)}$ is almost unchanged with respect to that of $pK_{G(a)}$. Apparently, it is impossible to

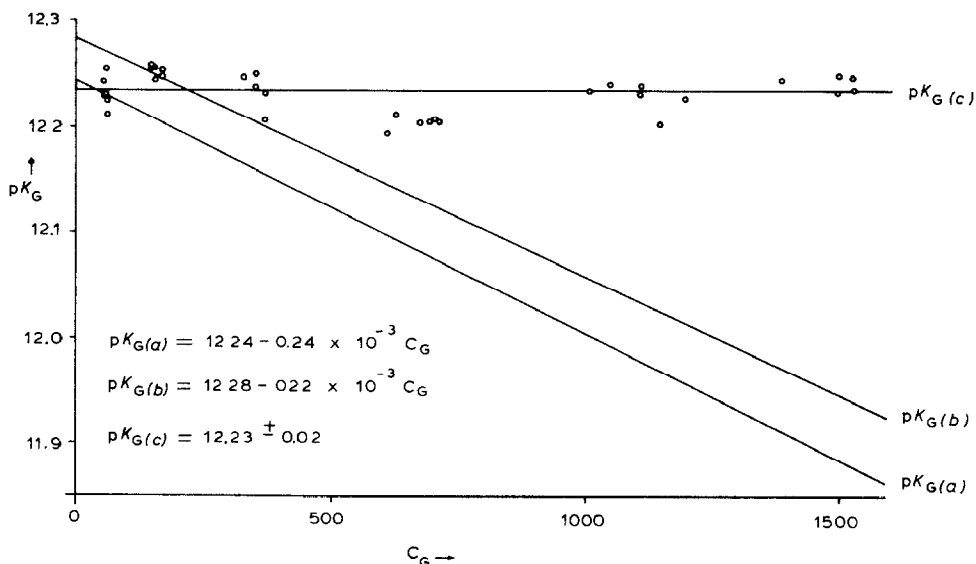


Fig. 3. pK_G as a function of the concentration of D-glucose. The points belong to $pK_{G(c)}$.

TABLE IV

HYDRATION OF D-GLUCOSE (LITERATURE DATA)

h_{GH}			<i>Experimental method</i>
267 K	278 K	298 K	
		3.5	Ultrasonic ⁴⁶
		3.5	Ultrasonic ⁵²
	2.3	1.8	Dielectric relaxation ⁵³
	2.2		¹⁷ O-N.m.r. relaxation ⁵³
	6		Dielectric relaxation ⁵¹
	5		¹⁷ O-N.m.r. relaxation ⁵¹
		3.5	Compressibility ⁵¹
>10			¹⁷ O-N.m.r. relaxation ⁴⁷
		3.7	Dielectric relaxation ⁵⁴
	2.7		Freezing process ⁵⁴
		2.0	Activity method ⁵⁵

eliminate this concentration dependency in this way, even when using the best thermodynamic data from the literature.

For a non-ideal solution with hydration, the literature data on the hydration of molecular D-glucose are given in Table IV. At 298 K, it is seen that most authors have reported a hydration number of 3.5. For the hydration number of G^- , no literature data are available. From the entropy change during ionisation, conclusions have been drawn^{28,32,33} about the hydration of GH and G^- . The entropy change during ionisation in water is a result of (a) the change of the number of particles (from the point of view of statistical thermodynamics, an increase of the number of particles causes an increase in the entropy of the system; when the hydration of the species formed differs from that of the non-dissociated compound, hydration will have an influence on the total entropy change), (b) the increased ionic strength (ions give an increase of the electrostatic field in the solution; the solvent water is strongly polar, so that the water molecules will be hindered in their rotation^{34,35}, and this effect causes a decrease in entropy upon ionisation), (c) the intramolecular hydrogen-bonding (an increase will lead to a decrease of the entropy of the D-glucose molecule^{32,36}).

For D-glucose in solution, an entropy change upon ionisation of $-110 \text{ J.mol}^{-1}.\text{K}^{-1}$ is calculated^{14,20,22,49}. Allen and Wright³³ ascribed this negative entropy effect to a decrease in the number of particles by an increase in the hydration of D-glucose during ionisation.

However, in our opinion, the entropy change upon ionisation cannot be explained only by assuming an increase of the hydration of D-glucose. The electrostatic field, combined with intramolecular hydrogen-bonding, must have a dominating effect.

The stoichiometric coefficient p , as defined in Eqs. 9 and 11, is generally given as 2 in the literature^{10-13,37,38}. For the hydration of H^+ and HO^- , mostly 1

and 0 are assumed^{37,38}. Inside the ion-exchange resin, the concentration of SH, S⁻, and HO⁻ can be very high. According to Schwabe²⁹, it is impossible to determine activity coefficients at high concentrations of electrolyte. In seeking to describe the ionisation inside the resin, the literature information on the activity coefficients of the various components in our system was replaced for the simple assumption that the excess free energy ΔG^E (Eq. 5) is zero and that further effects must be ascribed to hydration. For the water, the relative concentration ($C'_{H_2O,free}$) of hydration water is not taken into account. This approach was also used by others³⁹⁻⁴⁴. Eqs. 12 and 13 then are transformed into:

$$K_{G(c)} = C_{G^-}{}_{aq} \cdot C_{H_2O^+}/C_{GH}{}_{aq} \cdot C_{H_2O,free}{}^q \text{ and} \quad (33)$$

$$K_{H_2O(c)} = C_{H_2O^+} \cdot C_{HO^-}/C'_{H_2O,free}{}^2, \quad (34)$$

$$\text{with } C'_{H_2O,free} = 1 - (6.28 C_G + h_{GH} \cdot C_{GH} + h_{G^-} \cdot C_{G^-})/55508. \quad (35)$$

In Eq. 35, the total relative water concentration was used:

$$C_{H_2O,total} = 1 - 6.28 C_G/55508 \quad (0 \leq C_G \leq 2000) \quad (36)$$

as calculated directly from literature data⁴⁵.

To obtain a concentration-independent $K_{G(c)}$, an optimisation criterion δ was defined (Eq. 37):

$$\delta = \sum_1^{36} \{ (K_{G(c)} - \overline{K_{G(c)}})/\overline{K_{G(c)}} \}^2, \quad (37)$$

to be calculated from all 36 experiments of Table III. Minimising this criterion, with the requirement that $h_1 > 0$, yields as optimal data:

$$h_{GH} \approx 3.5 \text{ and } h_{G^-} \approx 0 \text{ for } q = 1 - h_{GH} = -2.5.$$

The hydration number of 3.5 for molecular D-glucose agrees well with most of the literature data for this temperature (see Table IV). With these best estimates of the hydration numbers, the $pK_{G(c)}$ value can be plotted as a function of the concentration of D-glucose. In Fig. 3, it is seen that, in this way, a concentration-independent ionisation constant is obtained.

It was noted above that hydration decreases with increase in temperature. Shii⁴⁶ described the "adsorption" of water per hydroxyl group with a Langmuir adsorption equation:

$$\ln [h_{GH}/n_{GH}/(1 - h_{GH}/n_{GH})] = \Delta H/(RT) + c_1, \quad (38)$$

TABLE V

HYDRATION OF D-GLUCOSE AS A FUNCTION OF THE TEMPERATURE^a

Temperature (K)	Experimental data of Shiio ⁴⁶	Calculated data			
		Langmuir adsorption		Linear/Freundlich	
	$h_{GH,exp}$	h_{GH}	δ_{hyd}	h_{GH}	δ_{hyd}
293	4.2	4.05	1.28	4.12	0.40
298	3.5	3.72	3.93	3.60	0.80
308	2.8	2.92	1.74	2.79	0.02
318	2.2	2.07	3.47	2.19	0.01
			10.42		1.23
ΔH (kJ.mol ⁻¹)			- 55		- 20

^aIncluding the data of Shiio⁴⁶.

where n_{GH} = number of hydroxyl groups (for D-glucose, $n_{GH} = 5$) and c_1 = a constant. For D-glucose, a heat of hydration of -55 kJ.mol⁻¹ was found. According to this model, the hydration of D-glucose cannot exceed the number of hydroxyl groups. At low temperature, however, Harvey *et al.*⁴⁷ found a hydration number of at least 10. For this reason, the experimental data of Shiio⁴⁶ were recalculated with a linear and with a Freundlich adsorption model. The temperature dependence of those two models can be described with Eq. 39.

$$\ln h_{GH} = - \Delta H/(RT) + c_2 \quad (\text{Linear/Freundlich}) \quad (39)$$

The results are given in Table V. In columns (3) and (5), the hydration numbers calculated using Eqs. 38 and 39, respectively, using best estimates for ΔH and c_1 are given: δ_{hyd} is defined as

$$\delta_{hyd} = (h_{GH} - h_{GH,exp})^2/h_{GH,exp} \times 1000. \quad (40)$$

It is clear that the linear/Freundlich adsorption models give a better fit for the description of the hydration of D-glucose. The corresponding heat of “adsorption” is then calculated to be -20 kJ.mol⁻¹. When this temperature dependence was applied to our experimental results, the hydration numbers given in Table VI were

TABLE VI

HYDRATION OF GH AS A FUNCTION OF THE TEMPERATURE

T (K)	267	278	298	303	313	323	333
h_{GH}	9.2	6.4	3.6	3.2	2.4	1.9	1.5

found. The low-temperature hydration number $h_{\text{GH},267\text{ K}}$ is about the same as that found by Harvey *et al.*⁴⁷.

The temperature dependency of the ionisation constant is given by De Wilt²¹ as:

$$E_{\text{ion,G}} = -16.8 \text{ kJ}\cdot\text{mol}^{-1}. \quad (41)$$

The best formulae for the ionisation of D-glucose can thus be presented as a function of the hydration number:

$$K_{\text{G(c)}} = C_{\text{G}^-} \cdot C_{\text{H}_3\text{O}^+} / [C_{\text{GH}} \cdot C'_{\text{H}_2\text{O,free}} (1-h_{\text{GH}})] \quad (42)$$

$$K_{\text{G(c)}}/K_{\text{H}_2\text{O(c)}} = C_{\text{G}^-} \cdot C'_{\text{H}_2\text{O,free}} (1+h_{\text{GH}}) / C_{\text{GH}} \cdot C_{\text{HO}^-} \quad (43)$$

$$\text{with } h_{\text{GH}} = 3.6 \exp [20000/R \cdot (1/T - 1/298)], \text{ and} \quad (44)$$

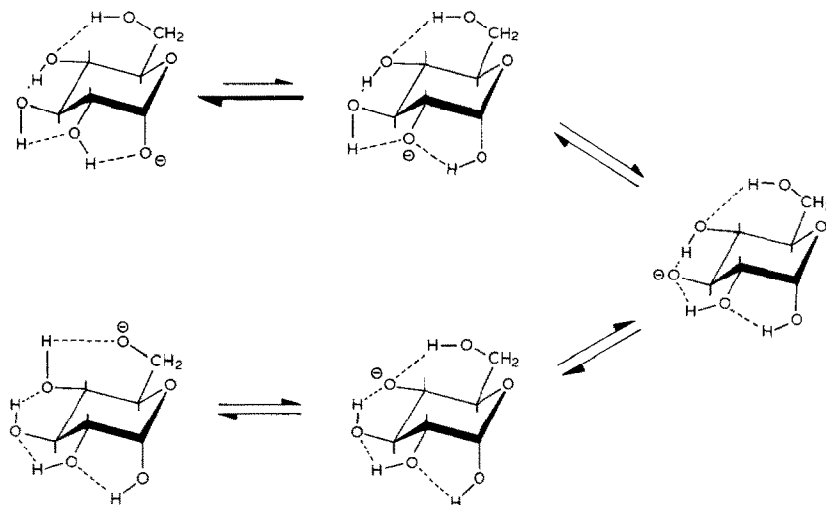
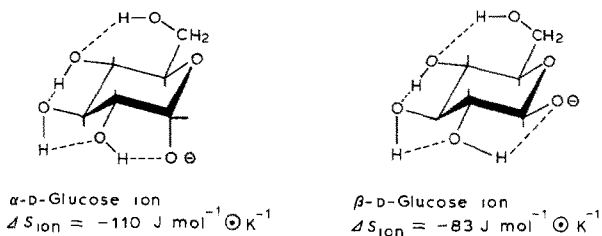
$$K_{\text{G(c)}} = 0.583 \exp [16800/R \cdot (1/T - 1/298)]. \quad (45)$$

DISCUSSION

It has been found that, during the ionisation of D-glucose, the hydration disappears. This can be understood from the difference in conformation between the ionic and the molecular forms of D-glucose.

In the D-glucose molecule, there are few if any intramolecular hydrogen-bonds⁴⁸. Proton abstraction from the anomeric hydroxyl group gives a negative charge on O-1. Delocalisation of this negative charge to C-2/6 by intramolecular hydrogen-bonding was suggested by Rendleman⁴⁸. The conformation of D-glucose can then be considered as shown in Fig. 4 for the α form. All ions shown in Fig. 4 would exist in equilibrium with each other, with the C-1-anion preponderating. Due to intramolecular hydrogen-bonding, the free rotation of the hydroxyl groups decreases and they will be oriented preferentially in certain directions for optimal hydrogen-bonding. This effect contributes to the decrease in entropy of the D-glucose molecule on ionisation. The difference in entropy decrease between α - and β -D-glucopyranose during ionisation, measured by Los and Simpson⁴⁹, can be ascribed to a difference of the strength of *ax,eq* and *eq,eq* hydrogen bonds (see Fig. 5). In an *ax,eq* sequence of hydroxyl groups, *e.g.*, HO-1,2 in α -D-glucose, the system can easily adopt the geometry for efficient hydrogen bonding. The reverse is true for an *eq,eq* sequence of hydroxyl groups⁵⁰.

The hydration of sugars can be considered as hydration of the hydroxyl groups^{46,51}, involving hydrogen bonding as well as further hydration of hydrate water molecules. After ionisation of D-glucose, the hydroxyl groups are oriented and stabilised by intramolecular hydrogen-bonding. Consequently, no hydroxyl groups of D-glucose are then available for bonding to solvent water molecules.


 Fig. 4. Intramolecular hydrogen-bonding in the α -D-glucopyranose ion.

 Fig. 5. Intramolecular hydrogen-bonding in the ions of α - and β -D-glucopyranose.

LIST OF SYMBOLS

A_T	Debye-Hückel constant	$\text{kg}^{0.5} \cdot \text{mol}^{-0.5}$
a_i	activity of component i	
B_T	Debye-Hückel constant	$\text{kg}^{0.5} \cdot \text{mol}^{-0.5} \cdot \text{m}^{-1}$
C_i	concentration of component i	$\text{mol} \cdot \text{m}^{-3}$
$C'_{\text{H}_2\text{O}}$	relative water concentration	$\text{mol} \cdot \text{mol}^{-1}$
c_i	constant	
d_i	diameter of component i	m
E	activation energy	$\text{kJ} \cdot \text{mol}^{-1}$
F, FH, Fru	D-fructose	
G, GH, Glc	D-glucose	
ΔG	change of chemical potential	$\text{kJ} \cdot \text{mol}^{-1}$
ΔG^*	difference of free energy of pure components	$\text{kJ} \cdot \text{mol}^{-1}$
ΔG^E	excess free energy	$\text{kJ} \cdot \text{mol}^{-1}$

ΔH	change of enthalpy	$\text{kJ}\cdot\text{mol}^{-1}$
h_1	hydration number of sugar i	
I	ionic strength	$\text{mol}\cdot\text{kg}^{-1}$
K_1	equilibrium constant	
M, MH, Man	D-mannose	
M_i	mol weight of component i	$\text{kg}\cdot\text{mol}^{-1}$
m_i	molality of component i	$\text{mol}\cdot\text{kg}^{-1}$
n_{GH}	number of hydroxyl groups of GH	
p	stoichiometric coefficient	
pH	acidity: $\text{pH} = 3 - \log C_{\text{H}^+}$	
$\text{p}K_s$	$\text{p}K_a$: $\text{p}K_s = 3 - \log K_s$	
q	stoichiometric coefficient	
R	gas constant	$\text{J}\cdot\text{mol}^{-1}\cdot\text{K}^{-1}$
S	sugar ($\text{S} = \text{SH} + \text{S}^-$): G, F, M	
S^-	ionised sugar	
SH	molecular sugar	
T	temperature	
y_i	activity coefficient of component i on molarity scale	
γ_i	activity coefficient of component i on molality scale	
δ	optimisation criterion	
μ_i	chemical potential of component i in the solution	$\text{J}\cdot\text{mol}^{-1}$
μ_i^*	chemical potential of the pure component	$\text{J}\cdot\text{mol}^{-1}$
$\mu_{\text{H}_2\text{O}}$	chemical potential of pure water	$\text{J}\cdot\text{mol}^{-1}$
ν_i	stoichiometric coefficient	
ρ	liquid density	$\text{kg}\cdot\text{m}^{-3}$
ϕ_i	osmotic coefficient of component i	

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