Ionization and solvation of D-glucose

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IONISATION AND SOLVATION OF D-GLUCOSE

 JOHN A. W. M. BEENACKERS*, BEN F. M. KUSTER, AND HESSEL S. VAN DER BAAN
Laboratory of Chemical Technology, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven (The Netherlands)
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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 anumeric hydroxyl group is an essential step in the isomerisation and epimerisation reactions. As ionisation is much faster than mutarotation2-3, 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 temperatures6-25, 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 mol.m\(^{-3}\). The concentrations used for pH and \( pK_s \) are expressed in kmol.m\(^{-3}\), so that pH and \( pK \) values can be compared with literature data. From the data in Table I, it can be concluded that, at 298 K, \( pK_{\text{Glc}} = 12.4 \pm 0.25 \), \( pK_{\text{Fr}} = 12.1 \pm 0.3 \), and \( pK_{\text{Man}} = 12.1 \pm 0.1 \).

*Present address: DSM Research and Patents, P.O. Box 18, 6160 MD Geleen, The Netherlands.
TABLE I

IONISATION CONSTANTS (pKₐ) FOR AQUEOUS SOLUTIONS AT 298 K

<table>
<thead>
<tr>
<th>D-Glucose</th>
<th>D-Fructose</th>
<th>D-Mannose</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.23</td>
<td>11.99</td>
<td></td>
<td>11</td>
</tr>
<tr>
<td>12.107</td>
<td>11.693</td>
<td></td>
<td>12</td>
</tr>
<tr>
<td>12.09</td>
<td>11.68</td>
<td></td>
<td>13</td>
</tr>
<tr>
<td>12.96</td>
<td>11.867</td>
<td></td>
<td>14</td>
</tr>
<tr>
<td>12.34</td>
<td>11.34</td>
<td></td>
<td>15</td>
</tr>
<tr>
<td>12.49</td>
<td>11.49</td>
<td></td>
<td>16</td>
</tr>
<tr>
<td>12.20₉</td>
<td>11.67</td>
<td></td>
<td>17</td>
</tr>
<tr>
<td>12.35</td>
<td>12.21</td>
<td>12.13</td>
<td>18</td>
</tr>
<tr>
<td>12.38</td>
<td>12.27</td>
<td>12.08</td>
<td>20</td>
</tr>
<tr>
<td>12.46</td>
<td>12.31</td>
<td></td>
<td>21</td>
</tr>
<tr>
<td>12.72₉</td>
<td>12.55₅</td>
<td></td>
<td>22</td>
</tr>
<tr>
<td>12.35</td>
<td>12.2₇</td>
<td></td>
<td>22</td>
</tr>
<tr>
<td>12.7₈₉,₉</td>
<td>12.6₇₉</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>12.60₉,₉</td>
<td>12.2₆₉</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>13.9₉,₉</td>
<td>14.2₉,₉</td>
<td>14.0₉,₉</td>
<td>5</td>
</tr>
</tbody>
</table>

₉α-Anomer. ₉β-Anomer. ₉At 283 K. ₉At 276–278 K. ₉At 1100 mol.m⁻³

TABLE II

LITERATURE pKₐ GLC VALUES AS A FUNCTION OF THE CONCENTRATION OF D-GLUCOSE, AND DETERMINED POTENTIOMETRICALLY

<table>
<thead>
<tr>
<th>Concentration of D-glucose (kmol.m⁻³)</th>
<th>Michaelis and Rona²⁵</th>
<th>Thamsen²⁴</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>290–292 K</td>
<td>291 K</td>
</tr>
<tr>
<td>0.05</td>
<td>12.46</td>
<td>12.97</td>
</tr>
<tr>
<td>0.10</td>
<td>12.38</td>
<td>12.44</td>
</tr>
<tr>
<td>0.20</td>
<td>12.28</td>
<td>12.40</td>
</tr>
<tr>
<td>0.50</td>
<td>12.26</td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td>12.05</td>
<td></td>
</tr>
</tbody>
</table>

When the results of De Wit et al.⁵ are omitted, D-fructose seems to be more acidic than D-glucose (ΔpKₐ = 0.27 ± 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 pKₐ with increase in ionic strength. Degani²³, however, was unable to find any influence. Only three authors have described a dependence of the pKₐ on the concentration of hexose. Michaelis and Rona²⁵ and Thamsen²⁴, using a potentiometric method, found that pKₐ decreased with increase in the concentration of D-glucose (Table II). The data of De Wit and co-workers⁵,²⁶, obtained using n.m.r. and u.v. techniques, reflected an increase of pKₐ 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 $C_{GH} \sim C_G$

<table>
<thead>
<tr>
<th>Expt. no.</th>
<th>$C_G \times 10^{-3}$ (mol.m$^{-3}$)</th>
<th>$C_K \times 10^{-3}$ (mol.m$^{-3}$)</th>
<th>$pH$</th>
<th>$C_{K(a)}$ (mol.m$^{-3}$)</th>
<th>$C_{K(b)}$ (mol.m$^{-3}$)</th>
<th>$K_G \times 10^8$ (mol.m$^{-3}$)</th>
<th>$pK_G$</th>
<th>$\overline{pK}_G(a)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0635</td>
<td>10.05</td>
<td>0.559</td>
<td>0.112</td>
<td>0.447</td>
<td>0.632</td>
<td>12.200</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.0610</td>
<td>11.00</td>
<td>4.301</td>
<td>1.000</td>
<td>3.301</td>
<td>0.571</td>
<td>12.243</td>
<td>12.226</td>
</tr>
<tr>
<td>3</td>
<td>0.0563</td>
<td>11.50</td>
<td>11.936</td>
<td>3.162</td>
<td>8.774</td>
<td>0.584</td>
<td>12.234</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.171</td>
<td>10.04</td>
<td>1.234</td>
<td>0.110</td>
<td>1.124</td>
<td>0.604</td>
<td>12.213</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.156</td>
<td>11.00</td>
<td>9.986</td>
<td>1.000</td>
<td>8.986</td>
<td>0.611</td>
<td>12.214</td>
<td>12.220</td>
</tr>
<tr>
<td>6</td>
<td>0.148</td>
<td>11.20</td>
<td>14.331</td>
<td>1.58</td>
<td>12.746</td>
<td>0.595</td>
<td>12.220</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.371</td>
<td>10.00</td>
<td>2.828</td>
<td>0.100</td>
<td>2.728</td>
<td>0.741</td>
<td>12.130</td>
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<tr>
<td>8</td>
<td>0.352</td>
<td>10.50</td>
<td>7.757</td>
<td>0.316</td>
<td>7.441</td>
<td>0.683</td>
<td>12.166</td>
<td>12.159</td>
</tr>
<tr>
<td>9</td>
<td>0.329</td>
<td>10.80</td>
<td>13.772</td>
<td>0.631</td>
<td>13.141</td>
<td>0.659</td>
<td>12.181</td>
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</tr>
<tr>
<td>10</td>
<td>0.371</td>
<td>10.01</td>
<td>2.737</td>
<td>0.102</td>
<td>2.635</td>
<td>0.699</td>
<td>12.156</td>
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</tr>
<tr>
<td>11</td>
<td>0.353</td>
<td>10.50</td>
<td>7.584</td>
<td>0.316</td>
<td>7.268</td>
<td>0.665</td>
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<td>12.171</td>
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<tr>
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<td>9.81</td>
<td>3.945</td>
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<td>3.880</td>
<td>0.876</td>
<td>12.057</td>
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<td>0.673</td>
<td>10.11</td>
<td>7.573</td>
<td>0.129</td>
<td>7.444</td>
<td>0.868</td>
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<td>12.061</td>
</tr>
<tr>
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<td>0.619</td>
<td>10.50</td>
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<td>0.316</td>
<td>16.126</td>
<td>0.860</td>
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<td></td>
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<tr>
<td>15</td>
<td>0.711</td>
<td>9.90</td>
<td>5.037</td>
<td>0.079</td>
<td>4.958</td>
<td>0.884</td>
<td>12.054</td>
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</tr>
<tr>
<td>16</td>
<td>0.701</td>
<td>10.01</td>
<td>6.314</td>
<td>0.102</td>
<td>6.212</td>
<td>0.874</td>
<td>12.059</td>
<td>12.064</td>
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<td>17</td>
<td>0.626</td>
<td>10.50</td>
<td>16.361</td>
<td>0.306</td>
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<td>0.932</td>
<td>12.080</td>
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</tr>
<tr>
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<td>1.194</td>
<td>9.53</td>
<td>4.479</td>
<td>0.034</td>
<td>4.445</td>
<td>1.103</td>
<td>11.958</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>1.106</td>
<td>10.00</td>
<td>11.448</td>
<td>0.100</td>
<td>11.348</td>
<td>1.037</td>
<td>11.984</td>
<td>11.985</td>
</tr>
<tr>
<td>20</td>
<td>1.007</td>
<td>10.30</td>
<td>19.366</td>
<td>0.199</td>
<td>19.167</td>
<td>0.972</td>
<td>12.012</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>1.144</td>
<td>9.53</td>
<td>4.403</td>
<td>0.034</td>
<td>4.369</td>
<td>1.131</td>
<td>11.946</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>1.108</td>
<td>10.00</td>
<td>11.281</td>
<td>0.100</td>
<td>11.181</td>
<td>1.019</td>
<td>11.992</td>
<td>11.982</td>
</tr>
<tr>
<td>23</td>
<td>1.047</td>
<td>10.20</td>
<td>16.175</td>
<td>0.168</td>
<td>16.017</td>
<td>0.980</td>
<td>12.009</td>
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</tr>
<tr>
<td>24</td>
<td>1.526</td>
<td>9.30</td>
<td>4.040</td>
<td>0.020</td>
<td>4.020</td>
<td>1.324</td>
<td>11.878</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>1.496</td>
<td>9.50</td>
<td>5.966</td>
<td>0.032</td>
<td>5.934</td>
<td>1.259</td>
<td>11.900</td>
<td>11.901</td>
</tr>
<tr>
<td>26</td>
<td>1.384</td>
<td>9.90</td>
<td>12.986</td>
<td>0.079</td>
<td>12.907</td>
<td>1.185</td>
<td>11.926</td>
<td></td>
</tr>
</tbody>
</table>
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, CO$_2$-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 TIT lc), 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 CO$_2$-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 component$^{27}$ is

\[ \mu_i = \mu_i^* + RT \ln (y_i \cdot C_i), \]

and for the solvent,
IONISATION AND SOLVATION OF D-GLUCOSE

\[ \mu_{H_2O} = \mu_{H_2O}^* + RT \ln (y_{H_2O} \cdot C_{H_2O}'), \]  
where \( \mu_{H_2O}^* \) is the chemical potential of pure water, and consequently the concentration of water is expressed as a fraction:

\[ C_{H_2O}' = C_{H_2O}/C_{H_2O,pure}. \]

As the experiments were carried out at constant pressure, \( \mu_i^* \) 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 \( \Delta G \) will be zero. Hence,

\[ \Sigma v_i \cdot \mu_i \text{eq} = \Sigma \{ v_i \cdot \mu_i^* \} + RT \Sigma \{ v_i \cdot \ln (y_i \cdot C_i)\} \text{eq} = 0, \]  
\[ \Delta G^* = \Sigma \{ v_i \cdot \mu_i^* \} = - RT \Sigma \{ v_i \cdot \ln (y_i \cdot C_i)\} \text{eq}, \]  
\[ \Delta G^E = - RT \Sigma \{ v_i \cdot \ln y_i \} . \]

As \( \mu_i^* \) is a function only of the temperature, \( \Delta G^* \) will be also a function only of the temperature. The equilibrium constant is defined as

\[ \ln K_i = \Sigma \{ v_i \cdot \ln (y_i \cdot C_i)\} = - \Delta G^*/RT. \]

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:

\[ GH \cdot (H_2O)_{h_G} + q H_2O \; K_G \; \equiv \; G^- \cdot (H_2O)_{h_G^-} + H^+ \cdot (H_2O)_{h_H}, \]  
\[ p H_2O \; K_{H_2O} \; \equiv \; H^+ \cdot (H_2O)_{h_H^+} + HO^- \cdot (H_2O)_{h_HO^-}, \]

where \( h = \) hydration number,

\[ q = h_{G^-} + h_{H^+} - h_{GH}, \]  
\[ p = h_{H^+} + h_{HO^-} + 1. \]

\[ K_G = y_{G^-} \cdot C_{G^-} \cdot y_{H^+} \cdot C_{H^+} / (y_{GH} \cdot C_{GH} \cdot y_{H_2O} \cdot C_{H_2O}^q) \]  
\[ K_{H_2O} = y_{H^+} \cdot C_{H^+} \cdot y_{HO^-} \cdot C_{HO^-} / (y_{H_2O} \cdot C_{H_2O}^p) \]
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:

\[
K_{G(a)} = \frac{C_G^- \cdot C_{H^+}}{C_{GH^+}}, \quad \text{and} \\
K_{H_2O(a)} = C_{H^+} \cdot C_{HO^-},
\]

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

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

\[
C_{HO^-}^{(a)} = \frac{K_{H_2O(a)} \cdot C_{H^+}^{(a)}}{C_{H^+}^{(a)}} \quad (pK_{H_2O,298} = 13.9965) \quad (17)
\]

\[
C_{G^-}^{(a)} = C_{K_+(a)} + C_{H^+}^{(a)} - C_{HO^-}^{(a)} \quad \text{(electro-neutrality)} \quad (18)
\]

\[
C_{GH(a)} = C_{G(a)} - C_{G^-}^{(a)} \quad \text{(d-glucose balance)} \quad (19)
\]

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

![Graph](Fig. 2. \(pK_G\) as a function of the concentration of d-glucose at 298 K. The temperature dependence of the data of Thamsen\(^24\) 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:

\[
K_{G(b)} = \frac{y_{G^-} \cdot C_{G^-} \cdot y_{H^+} \cdot C_{H^+}}{y_{G} \cdot C_{G}}, \quad (20)
\]

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

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 (\(\gamma_{GH}\)) and the osmotic coefficient (\(\phi_{GH}\)) 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 \(\gamma_{G^-}\) and \(\gamma_{HO^-}\) 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 \(A_{298K} = 0.5115 \text{ kg}^{1/2} \cdot \text{mol}^{-1/2} \) (Debye–Hückel constant), \(B_{298K} = 3.291 \times 10^9 \text{ kg}^{1/2} \cdot \text{mol}^{-1/2} \cdot \text{m}^{-1} \) (Debye–Hückel constant), \(d_{G^-} = \text{diameter } G^- \sim 8 \times 10^{-10} \text{ m} \), \(d_{HO^-} = \text{diameter } HO^- \sim 2 \times 10^{-10} \text{ m} \), \(h_i = \text{solvation number: mol } H_2O \text{ per mol } i\), \(I = m_{K^+} + m_{H^+} = m_{G^-} + m_{HO^-} = \text{ionic strength (mol.kg}^{-1}\).
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.

$$1.000 < y_{GH} < 1.045$$ (27)

$$0.882 < y_{G^-} < 1.000$$ (28)

$$0.853 < y_{HO^-} < 1.000$$ (29)

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

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

$$m_i = C_i/(\rho - M_{GH} \cdot C_{GH} - M_{G^-} \cdot C_{G^-} - M_{HO^-} \cdot C_{HO^-}),$$ (31)

and for the density of the solution,

$$\rho = 1000 + 0.067C_G.$$ (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 $pK_{G(a)}$.](image)
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 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, 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).

For D-glucose in solution, an entropy change upon ionisation of $-110 \text{J.mol}^{-1}.\text{K}^{-1}$ is calculated. Allen and Wright 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. For the hydration of H+ and HO-,

<table>
<thead>
<tr>
<th>$h_{GH}$</th>
<th>Experimental method</th>
</tr>
</thead>
<tbody>
<tr>
<td>267 K</td>
<td>3.5</td>
</tr>
<tr>
<td>278 K</td>
<td>3.5</td>
</tr>
<tr>
<td>298 K</td>
<td>1.8</td>
</tr>
<tr>
<td>&gt;10</td>
<td>3.7</td>
</tr>
<tr>
<td>2.7</td>
<td>2.0</td>
</tr>
</tbody>
</table>
and 0 are assumed. Inside the ion-exchange resin, the concentration of SH, S⁻, and HO⁻ can be very high. According to Schwabe, 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 by the simple assumption that the excess free energy ∆Gₑ (Eq. 5) is zero and that further effects must be ascribed to hydration. For the water, the relative concentration (C_H₂O_free) of hydration water is not taken into account. This approach was also used by others. Eqs. 12 and 13 then are transformed into:

\[ K_{G(c)} = C_{G⁻}_{aq} \cdot \frac{C_{H₂O}}{C_{GH}_{aq} \cdot C_{H₂O}_{free}} \]  
\[ K_{H₂O(c)} = C_{H₂O} \cdot \frac{C_{HO}^-}{C_{H₂O}_{free}^2} \]

with \( C_{H₂O_{free}} = 1 - (6.28 C_G + h_{GH} \cdot C_{GH} + h_{G⁻} \cdot C_{G⁻})/55508 \).  

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

\[ C_{H₂O_{total}} = 1 - 6.28 C_G/55508 \quad (0 \leq C_G \leq 2000) \]

as calculated directly from literature data.

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

\[ \delta = \sum \frac{((K_{G(c)} - \bar{K}_{G(c)})/\bar{K}_{G(c)})^2}{1} \]

To be calculated from all 36 experiments of Table III. Minimising this criterion, with the requirement that \( h > 0 \), yields as optimal data:

\[ h_{GH} = 3.5 \text{ and } h_{G⁻} \approx 0 \text{ for } q = 1 - h_{GH} = -2.5. \]

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. Shioi described the “adsorption” of water per hydroxyl group with a Langmuir adsorption equation:

\[ \ln \left[ h_{GH}/n_{GH}(1 - h_{GH}/n_{GH}) \right] = \Delta H/(RT) + c_1, \]
TABLE V

HYDRATION OF D-GLUCOSE AS A FUNCTION OF THE TEMPERATURE

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>Experimental data of Shiio</th>
<th>Calculated data</th>
<th>Langmuir adsorption</th>
<th>Linear/Freundlich</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>h$_{GH}$,exp</td>
<td>h$_{GH}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>δ$_{hyd}$</td>
<td>h$_{GH}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>δ$_{hyd}$</td>
</tr>
<tr>
<td>293</td>
<td>4.2</td>
<td>4.05</td>
<td>1.28</td>
<td>4.12</td>
</tr>
<tr>
<td>298</td>
<td>3.5</td>
<td>3.72</td>
<td>3.93</td>
<td>3.60</td>
</tr>
<tr>
<td>308</td>
<td>2.8</td>
<td>2.92</td>
<td>1.74</td>
<td>2.79</td>
</tr>
<tr>
<td>318</td>
<td>2.2</td>
<td>2.07</td>
<td>3.47</td>
<td>2.19</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10.42</td>
<td>1.23</td>
</tr>
</tbody>
</table>

$\Delta H$ (kJ.mol$^{-1}$) $-55$ $-20$

*Including the data of Shiio.$^{66}$

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 Shiio$^{66}$ were recalculated with a linear and with a Freundlich adsorption model. The temperature dependence of those two models can be described with Eq. 39.

$$\ln h_{GH} = -\frac{\Delta H}{(RT)} + c_2 \quad \text{(Linear/Freundlich)}$$  \hspace{1cm} (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 $\Delta H$ and $c_1$ are given: $\delta_{hyd}$ is defined as

$$\delta_{hyd} = \frac{(h_{GH} - h_{GH,exp})^2}{h_{GH,exp}} \times 1000.$$  \hspace{1cm} (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

<table>
<thead>
<tr>
<th>T (K)</th>
<th>267</th>
<th>278</th>
<th>298</th>
<th>303</th>
<th>313</th>
<th>323</th>
<th>333</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h_{GH}$</td>
<td>9.2</td>
<td>6.4</td>
<td>3.6</td>
<td>3.2</td>
<td>2.4</td>
<td>1.9</td>
<td>1.5</td>
</tr>
</tbody>
</table>
found. The low-temperature hydration number $h_{GH,267 K}$ is about the same as that found by Harvey et al.$^{47}$.

The temperature dependency of the ionisation constant is given by De Wilt$^{21}$ as:

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

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

$$K_{G(c)} = C_{G^-} \cdot C_{H_2O^{+}}/[C_{GH} \cdot C_{H_2O,free}^{(1-h_{GH})}] \quad (42)$$

$$K_{G(c)}/K_{H_2O(c)} = C_{G^-} \cdot C_{H_2O,free}^{(1+h_{GH})}/C_{GH} \cdot C_{HO^-} \quad (43)$$

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

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

**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-bonds$^{48}$. 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 Rendleman$^{48}$. The conformation of D-glucose can then be considered as shown in Fig. 4 for the $\alpha$ 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 $\alpha$- and $\beta$-D-glucopyranose during ionisation, measured by Los and Simpson$^{49}$, 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 $\alpha$-D-glucose, the system can easily adopt the geometry for efficient hydrogen bonding. The reverse is true for an $eq,eq$ sequence of hydroxyl groups$^{50}$.

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

\[ \begin{align*}
\Delta G & \quad \text{change of chemical potential} & \quad \text{kJ.mol}^{-1} \\
\Delta G^* & \quad \text{difference of free energy of pure components} & \quad \text{kJ.mol}^{-1} \\
\Delta G^E & \quad \text{excess free energy} & \quad \text{kJ.mol}^{-1}
\end{align*} \]
\( \Delta H \)  
change of enthalpy  
kJ.mol\(^{-1}\)

\( h_i \)  
hydration number of sugar i  

\( I \)  
ionic strength  
mol.kg\(^{-1}\)

\( K_i \)  
equilibrium constant

\begin{align*}
M, MH, \text{Man} & \quad \text{D-mannose} \\
M_i & \quad \text{mol weight of component } i \\
m_i & \quad \text{molality of component } i \\
n_{GH} & \quad \text{number of hydroxyl groups of GH} \\
p & \quad \text{stoichiometric coefficient} \\
pH & \quad \text{acidity: } pH = 3 - \log C_{H^+} \\
pK_S & \quad pK_a : pK_S = 3 - \log K_S \\
q & \quad \text{stoichiometric coefficient} \\
R & \quad \text{gas constant} \\
S & \quad \text{sugar } (S = SH + S^-): G, F, M \\
S^- & \quad \text{ionised sugar} \\
SH & \quad \text{molecular sugar} \\
T & \quad \text{temperature} \\
y_i & \quad \text{activity coefficient of component } i \text{ on molarity scale} \\
\gamma_i & \quad \text{activity coefficient of component } i \text{ on molality scale} \\
\delta & \quad \text{optimisation criterion} \\
\mu_i & \quad \text{chemical potential of component } i \text{ in the solution} \\
\mu_i^* & \quad \text{chemical potential of the pure component} \\
\mu_{H_2O} & \quad \text{chemical potential of pure water} \\
\nu_i & \quad \text{stoichiometric coefficient} \\
\rho & \quad \text{liquid density} \\
\phi_i & \quad \text{osmotic coefficient of component } i
\end{align*}

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IONISATION AND SOLVATION OF D-GLUCOSE

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