

A Thermodynamic Study of Glucose and Related Oligomers in Aqueous Solution: Vapor Pressures and Enthalpies of Mixing

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Vapor pressures above aqueous solutions of glucose and maltose at both 298.06 K and 317.99 K and vapor pressures above aqueous solutions of cellobiose, maltotriose, maltotetraose, and maltopentaose at 317.99 K have been measured. The excess enthalpies have been recorded for all of the above-mentioned systems at 318.15 K. A theoretical model is examined in which existing interaction parameters, calculated for the water + 1,2-ethanediol system by using a molecular mechanical approach, are incorporated into the UNIQUAC equation to describe the vapor pressures of the aforementioned series of saccharides in aqueous solution. This so-called transference principle is found to be of interest in furthering the discussion concerning the applicability of lattice-based models for solution theory.

Introduction

Cellulose and starch are biopolymers with significance in the biochemistry of fauna and flora. The polymers are related by a common building block, namely, the glucose molecule. When glucose units are consecutively joined by a β -(1–4) glycosidic linkage, cellulose is formed; in amylose the linkage is of the α -(1–4) type. The difference between the type of linkage is the key factor in the structural differences of the polymers.¹ In studying the aqueous chemistry of these two large macromolecules, it is useful, initially, to consider smaller, related systems such as cellobiose, maltose, and related oligosaccharides. Given the importance of these simple sugars, the apparent sparsity of thermodynamic information is surprising. Standard works concerning the vapor pressures of glucose, maltose, and other mono- and disaccharides in aqueous solution include studies by Taylor and Rowllison,² Aberdafi and Bounahmidi,³ Ruegg and Blanc,⁴ Apelblat et al.,⁵ and others. Taylor has recorded solubilities and enthalpies of solution for a series of cellulosic oligosaccharides including cellobiose.⁶ Beyond maltose, in the α -(1–4) glucose-linked oligomeric series, available thermodynamic data are even more sparse. Ring and co-workers⁷ have studied the crystallization and melting properties of maltopentaose hydrate. Data for solution properties have not been found.

The available literature clearly indicates that the glycosidic linkage plays an important role in some of the bulk properties of saccharides. As discussed above, cellobiose and maltose are isomeric, differing only in that the former possesses a β -(1–4) glycosidic linkage and the latter has an α -(1–4) linkage. The solution properties of these two molecules are very different. To illustrate this, it may be observed that maltose saturates in aqueous solution at a mole fraction of 0.0424 (45.7 mass %) at 298.15 K;⁴ on the other hand, cellobiose saturates at a mole fraction of 0.0080

(13.3 mass %) at the same temperature.⁶ An exact understanding of the behavior of these simple saccharides in solution has been elusive and almost certainly is related to the solid-state properties of the sugar, the conformation of the sugar in solution, the structure of the surrounding water, and, of course, the intermolecular interactions.

Experimental and theoretical techniques can give insight into the solution chemistry of glucose, cellobiose, maltose, and related oligomers; several relevant studies are mentioned here. NMR studies have been performed on the series maltose to maltoheptaose.⁸ In that study it is postulated that the energy lowering side-by-side interactions of adjacent glucose residues within an oligomer in solution are weakened because of the ability of the water molecules to orient between the glucose residues and hence produce a “looser” structure than is observed for these saccharides in other solvents such as DMSO (Me₂SO). This postulate is in good agreement with the conclusions that may be drawn from the observed negative deviation from ideal behavior for the vapor pressures of glucose solutions. Such a deviation is explained by the fact that the attractive forces occurring between water and glucose are greater than those between water and water or glucose and glucose, respectively. NMR data are also available for cellobiose in aqueous solution.⁹ Other conformational information is available from molecular dynamics simulations; interestingly, a study by Naidoo and Brady¹⁰ on dixylose, the pentose analogue of maltose, has indicated a new potential energy minimum occurs for the saccharide in solution compared to the saccharide in a vacuum. An interesting, experimental insight into water structures associated with glucose, maltose, and maltotriose has been provided by microwave dielectric techniques. Mashimo et al.¹¹ and Mashimo and Miura¹² have advanced compelling evidence for a local and high order structure for water at 298 K within which the glucose molecule “fits” very well; maltotriose is postulated to protrude from the water structure with maltose showing some critical behavior. The work indicates that an almost unique position is held by glucose with respect to its involvement and interaction with water. Molecular mechanical methods¹³ have been em-

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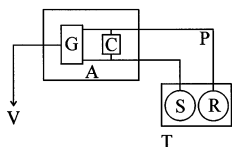


Figure 1. Scheme of the experimental apparatus for the measurements of vapor pressures.

ployed to study the potential energy surfaces of cellobiose and maltose in aqueous solution and optical rotations have been well-reproduced. In addition, a combined thermodynamic and molecular mechanical approach has been used to compare the hydration properties of maltose and amylose.¹⁴ For maltose, the hydration is found to depend on the configuration and hydration numbers of 10 or 11 are reported.

Although of direct use to a number of industries, thermodynamic data do not, of course, provide a molecular picture of the system. However, such data are of considerable use in the testing of statistical thermodynamic models that are put forward to describe the chemistry of saccharides in solution. One such model, a combined molecular mechanical–chemical engineering model has been proposed by Jónsdóttir et al.,¹⁵ Jónsdóttir and Klein,¹⁶ and Jónsdóttir and Rasmussen.¹⁷ Here, “generic” interaction energies are accessed by molecular mechanical methods and then used in the UNIQUAC equation.^{18,19} The term “generic” alludes to the possibility of transferring interaction energies between related systems. The UNIQUAC equation involves a quasi-chemical, local composition approach to solution theory. Another statistical thermodynamic model discussed briefly in this work is the extended Flory–Huggins solution theory.²⁰ This lattice-based model is primarily intended to describe polymer solutions and is based on the assumption of total random mixing where end-of-chain effects are negligible. However, the simplicity of the method has the advantage of enabling an insight into the interconnection between the coordination number and the interaction energies for the solute and solvent in lattice solution theory.

In this paper, we report measurements of the vapor pressures of a series of α -(1–4)-linked glucose oligomers from maltose to maltopentaose and the prototype β -(1–4)-linked oligomer, cellobiose, each in aqueous solution. Excess enthalpies have also been measured for these systems and are also reported. In addition to this, we discuss the applicability of a lattice-based solution theory such as UNIQUAC in describing the systems studied here.

Experimental Section

Chemicals. D-(+)-Glucose monohydrate, D-(+)-maltose monohydrate, maltotriose, maltotetraose, maltopentaose, and cellobiose were purchased from Fluka, and despite catalog lists indicating purities as low as 95 mass % for some compounds, consultation of the lot certificate of analysis indicated purities, by mass, of >99.5%, >99%, >99%, >99.4%, >99.4%, and >99%, respectively.

Experimental Methods. Vapor pressures were measured using an electronic barometer system (Barocel 570 capacitance pressure sensor, Edwards high vacuum, Crawley, U.K.) connected to an electronic benchtop manometer (Edwards high vacuum, Crawley, U.K.). A schematic of the system is shown in Figure 1. This figure depicts the sample cell (S) and reference cell (R) immersed in a thermostatically controlled water bath (T). The cells are connected by glass pipes (P) to the barometer (C). The gas-handling apparatus (G) enables removal of controlled amounts of

water from the sample cell. Both (C) and (G) are housed in a thermostatically controlled air bath (A) at $\approx 20^\circ\text{C}$ higher in temperature than the water bath (T). The apparatus is connected to a vacuum line (V), enabling evacuation of the system to pressures below 10^{-3} Pa (10^{-5} mbar). The system is a slight modification of that described by Koga and co-workers.^{21,22} The technique involves the measurement of a differential pressure between pure water in a reference cell and the solution of interest in the sample cell. Both cells are housed in a thermostatically controlled water bath that has a stability of $\pm 0.005^\circ\text{C}$. To determine the absolute vapor pressure of the solution, the absolute vapor pressure of the pure water in the reference cell is also recorded. The Barocel is housed within an air bath kept at $\approx 20^\circ\text{C}$ higher in temperature than the water bath, thus preventing condensation from occurring at undesirable locations in the apparatus.

First, a dilute solution of the sugar was prepared at room temperature. The sample was introduced to the apparatus via a “glass-blown” hole, which was then closed, ensuring a good seal; an outgassing, freeze–thaw procedure was then undertaken. It was here assumed that a negligible amount of water was removed. An equilibration period of ≈ 1 h under constant stirring was allowed prior to measurement of the vapor pressure over the solution; this period was extended, in a few cases, up to as long as 2 days for the viscous, concentrated sugar solutions. The pressure in the sample cell was monitored during the equilibration time. After each measurement a controlled amount of water was removed from the sample in situ and the next measurement was then taken. In this way a satisfactory composition range was investigated. Water removal was achieved by allowing the water vapor from the sample cell to expand into an evacuated glass bulb of known volume. The sample cell was then isolated from the vacuum line and the pressure in the glass bulb recorded. A knowledge of the volume of the glass bulb and the pressure of the water vapor it contains allowed the new mole fraction of sugar in the sample cell to be calculated accurately. The accuracy of all pressure measurements was estimated to be within 0.5 Pa.

The cyclic nature of the procedure introduces a small cumulative error with respect to the mole fraction for the sugar in the sample. To ensure repeatability and to allow greater precision at higher sugar mole fractions, each series recorded involved the introduction of at least a second sample with a higher starting mole fraction. The uncertainty in the sugar mole fraction was evaluated from the uncertainties in the measured vapor pressures of the water removed, in the temperature measured, and in the amount of sugar in the original sample, using standard uncertainty estimation techniques.

An isothermal titration calorimeter (MicroCal Inc., North Adams, MA) was used to measure excess enthalpies for the solutions of interest. A concentrated solution of the saccharide was prepared at room temperature and placed into the sample cell of the calorimeter; it was then allowed to equilibrate to 318.15 K. Heat changes were recorded following the systematic injection of controlled amounts of water into the solution. The process was repeated for a series of sugar concentrations. In this way, the partial molar excess enthalpy of water in the sugar solution was obtained and then, via the Gibbs–Duhem relation, the excess partial molar enthalpy of the sugar in aqueous solution could be calculated. In this calculation the hypothetical state of a sugar melt at 318 K is chosen as a reference state. From the partial molar excess enthalpies,

the excess enthalpy of the solution was calculated with the following equation,

$$H^E = x_1 H_1^{E(\text{partial})} + x_2 H_2^{E(\text{partial})} \quad (1)$$

where H^E is the excess enthalpy of the mixture and x_i and $H_i^{E(\text{partial})}$ are the mole fraction and the partial molar excess enthalpy of component i , respectively.

Heat changes corresponding to a required energy of <2 μcal could be recorded directly with the calorimeter used. Small uncertainties arise from sample preparation and the titration process, and the overall accuracy of the measurement is estimated to be within 2% for the calculated molar enthalpies of mixing.

In-house FORTRAN programs were written to fit empirical equations to all data. As indicated above, the vapor pressure experiments result in uncertainties occurring in both the mole fraction and the measured vapor pressure. While the uncertainties are small, they are accounted for in the program using a so-called rigorous least-squares analysis. FORTRAN programs were also written to utilize the UNIQUAC equation and the extended Flory–Huggins solution theory.

Theoretical Model

Jónsdóttir et al.^{15,16} have developed a method for calculating UNIQUAC interaction parameters with molecular mechanics methods by adhering to the following process. First, a potential energy minimization process determines equilibrium structures for all conformers for both molecules. Second, interaction energies are determined for molecular complexes formed between two molecules of (a) type 1 and type 1, (b) type 2 and type 2, and c) between molecules of type 1 and type 2. Inherent in this second step is the requirement for an acceptable, computationally economic method for the sampling of conformational space to select the starting geometries prior to the minimization process. This is provided via the Boltzmann Jump Procedure. A random change to the configuration of the complex is allowed; the change is assigned a probability from the Boltzmann factor, with temperature of ≈ 5000 K, and acceptance of the change is based on the classic Metropolis criteria. Hence, “jumps” over potential energy barriers can occur. From these energies, UNIQUAC interaction parameters are then calculated. The development and details of this method can be found elsewhere.^{15–17}

In this work the so-called “transference principle” is utilized. The benefits of taking interaction energies calculated, as above, for smaller systems with less degrees of freedom and “transferring” it to more complicated systems are evident. The validity of this approximation has already been demonstrated.^{16,17} Vapor–liquid equilibria data for aqueous solutions of 1,2-propanediol, glycerol, glucose, and sucrose and solid–liquid equilibria data of aqueous solutions of glucose and sucrose have been accurately predicted using interaction parameters, calculated for the water + 1,2-ethanediol system. The theoretical model also shows good predictive ability for several other aqueous polyol and saccharide systems.²³ It may be postulated that the portion of the larger sugar or polyol with which the water interacts resembles the 1,2-ethanediol molecule. This is a similar approach to considering 1,2-ethanediol to be a repeat unit in a polymer.

In executing this procedure, it is clear that the successes or failures of the molecular mechanical methods employed are dependent upon the ability of the statistical thermodynamic model to accurately represent the solution. The

Table 1. Structural Parameters Used in the UNIQUAC Equation

molecule	r_i	q_i	molecule	r_i	q_i
water	0.9200	1.400	maltotriose	15.7762	12.664
glucose	5.8028	4.840	maltotetraose	20.7629	16.576
maltose	10.7985	8.752	maltopentaose	25.7496	20.488

derivation and validity of the UNIQUAC equation^{18,19} has been subject to much discussion, and several articles have been published on that matter. Most of these publications focus on the validity of the local composition approach and the physical meaning of the interaction parameters, but still there are many unanswered questions. A more detailed discussion of these matters is given elsewhere.²³ An immediate failure of this type of model is its inability to distinguish sugar isomers such as cellobiose and maltose; these issues will be discussed further below. The structural parameters for the van der Waals volume, r_i , and van der Waals surface area, q_i , used in this work for the saccharides are calculated using Bondi's method.²⁴ The parameter values are given in Table 1. For all systems the interaction parameters $A_{12} = 396$ K and $A_{21} = -334$ K are used in the UNIQUAC equation.¹⁶

Results and Discussion

Experimental Results. Vapor pressure measurements are given in Table 2. The raw data could be satisfactorily fitted to quadratic polynomials and the coefficients to the polynomials are given in Table 3. The exact temperature of the thermostatically controlled bath was determined from the vapor pressure recorded for the pure water held in the reference cell; see Figure 1. At the lower temperature, here referred to as 298 K, the vapor pressure of pure water was recorded as 3.1520 ± 0.0016 kPa; at the higher temperature, here referred to as 318 K, the vapor pressure of pure water was recorded as 9.5140 ± 0.0047 kPa. These readings, when read from steam tables, correspond to temperatures of 298.06 ± 0.01 K and 317.99 ± 0.01 K, respectively.

For validating the experimental procedure, the measurements obtained for the water + glucose mixture at 298.06 K were compared to existing literature data by Rüegg and Blanc.⁴ Furthermore, after the measurements were completed, the solution was allowed to stay in the sample cell for 2 days such that the solution crystallized. Then the vapor pressure over the solution was measured; the mole fraction at the saturation point was determined from the measured vapor pressure curve and was compared to solubility data from the literature. The saturation point was determined to be at a sugar mole fraction of 0.0929, which is identical to the value given by Rüegg and Blanc.⁴ An interpolated value from the solubility data given by Stephen and Stephen²⁵ is 0.0936. In all cases the agreement with the literature values is good and well within the experimental uncertainty. The equipment has previously been tested for a variety of systems, including NaCl in aqueous solution.

When solubility data are known, it was observed that measurements of vapor pressures could take place well into the region of supersaturation. It is suspected that for all of the systems studied here measurements occurred within the supersaturated region. This phenomenon will be discussed further below. Measurements were taken at the slightly elevated temperature of 318 K to permit a greater range of study for the less soluble sugars. For glucose and maltose, measurements were also taken at 298 K. Figure 2 shows the natural logarithm of the activity coefficients

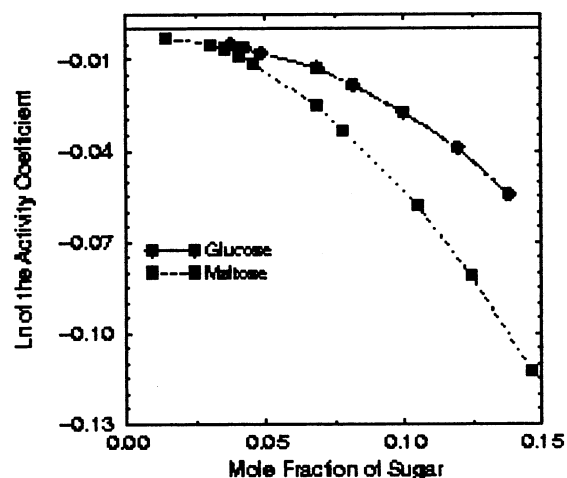
Table 2. Vapor Pressures of Water Measured above the Aqueous Solutions of the Glucose Oligomers at 298.06 K and 317.99 K; Measurements Taken at Supersaturated Conditions Are Marked with *

x_2	vapor pressure		vapor pressure	
	kPa	x_2	kPa	
Glucose 298.06 K				
0.00000(0)	3.1520(16)	0.04439(10)	2.9947(15)	
0.022108(13)	3.0754(15)	0.04840(9)	2.9754(15)	
0.023007(13)	3.0700(15)	0.05007(11)	2.9713(15)	
0.023995(20)	3.0668(15)	0.05337(12)	2.9540(15)	
0.026569(28)	3.0587(15)	0.05574(16)	2.9485(15)	
0.026742(24)	3.0535(15)	0.05958(15)	2.9271(15)	
0.028142(15)	3.0613(15)	0.06605(20)	2.9061(15)	
0.02978(4)	3.0475(15)	0.06854(26)	2.8980(14)	
0.030608(25)	3.0479(15)	0.0815(4)	2.8413(14)	
0.03201(4)	3.0380(15)	0.0948(4)	2.7796(14)*	
0.03361(4)	3.0375(15)	0.0998(6)	2.7595(14)*	
0.03572(6)	3.0268(15)	0.1195(8)	2.6672(13)*	
0.03761(5)	3.0181(15)	0.1286(8)	2.6150(13)*	
0.03937(7)	3.0100(15)	0.1382(11)	2.5705(13)*	
0.04240(7)	3.0002(15)			
Maltose 298.06 K				
0.00000(0)	3.1520(16)	0.0406(3)	2.9977(15)	
0.006412(6)	3.1292(16)	0.0457(4)	2.9731(15)*	
0.007030(8)	3.1313(16)	0.05062(10)	2.9549(15)*	
0.009873(18)	3.1133(16)	0.0562(6)	2.9198(15)*	
0.01451(4)	3.0973(15)	0.0664(9)	2.8635(14)*	
0.01983(8)	3.0806(15)	0.06857(20)	2.8623(14)*	
0.02543(13)	3.0574(15)	0.07803(27)	2.8101(14)*	
0.03049(18)	3.0401(15)	0.0814(13)	2.7756(14)*	
0.032581(19)	3.0327(15)	0.1047(5)	2.6606(13)*	
0.03550(25)	3.0206(15)	0.1241(7)	2.5441(13)*	
0.04020(5)	3.0104(15)	0.1462(10)	2.4028(12)*	
Glucose 317.99 K				
0.00000(0)	9.514(5)	0.10023(10)	8.242(4)	
0.025011(17)	9.235(5)	0.12058(17)	7.916(4)	
0.029211(28)	9.191(5)	0.14100(26)	7.578(4)	
0.03917(6)	9.061(5)	0.1614(4)	7.229(4)*	
0.04791(9)	8.938(5)	0.1819(5)	6.869(3)*	
0.05699(13)	8.819(4)	0.2024(6)	6.500(3)*	
0.06607(18)	8.695(4)	0.2285(8)	6.054(3)*	
0.08855(6)	8.416(4)			
Maltose 317.99 K				
0.00000(0)	9.514(5)	0.06058(13)	8.757(4)	
0.007164(6)	9.447(5)	0.0915(3)	8.256(4)*	
0.010046(15)	9.398(5)	0.1222(6)	7.708(4)*	
0.01997(6)	9.265(5)	0.1431(9)	7.317(4)*	
0.03085(15)	9.137(5)	0.1650(12)	6.932(4)*	
0.04103(27)	9.009(5)	0.1872(16)	6.547(3)*	
0.0514(4)	8.864(4)	0.2129(21)	6.029(3)*	
Maltotriose 317.99 K				
0.00000(0)	9.514(5)	0.01018(28)	9.392(5)	
0.000796(4)	9.499(5)	0.01565(20)	9.332(5)	
0.002053(27)	9.487(5)	0.0208(4)	9.271(5)	
0.00313(6)	9.486(5)	0.02559(27)	9.194(5)	
0.00528(8)	9.461(5)	0.0261(6)	9.191(5)	
0.00769(16)	9.422(5)	0.0309(4)	9.135(5)	
0.00815(6)	9.423(5)	0.0420(7)	8.967(5)	
0.01015(9)	9.399(5)	0.0639(17)	8.579(4)	
Maltotetraose 317.99 K				
0.00000(0)	9.514(5)	0.0264(4)	9.154(5)	
0.002678(4)	9.465(5)	0.0369(8)	8.971(5)	
0.003210(7)	9.471(5)	0.0423(16)	8.863(4)	
0.00778(5)	9.426(5)	0.0554(17)	8.561(4)	
0.01232(8)	9.380(5)	0.0949(52)	7.541(4)	
0.01857(19)	9.279(5)			
Maltopentaose 317.99 K				
0.00000(0)	9.514(5)	0.0327(9)	8.907(5)	
0.003471(8)	9.492(5)	0.0462(21)	8.452(4)	
0.01545(19)	9.330(5)	0.0470(19)	8.389(4)	
0.0216(4)	9.195(5)	0.0696(45)	7.392(4)	
Cellobiose 317.99 K				
0.00000(0)	9.514(5)	0.01142(7)	9.369(5)	
0.001046(4)	9.493(5)	0.01319(9)	9.360(5)*	
0.001169(5)	9.491(5)	0.01538(11)	9.328(5)*	
0.002056(10)	9.481(5)	0.02059(20)	9.269(5)*	
0.004031(12)	9.464(5)	0.0315(5)	9.111(5)*	
0.01014(5)	9.385(5)			

Table 3. Coefficients for Empirically Fitted Lines for Vapor Pressures of the Measured Aqueous Systems^a

	A	B	C (fixed)	RMS
	kPa	kPa	kPa	deviation
glucose at 298.06 K	-6.581(22)	-3.297(41)	3.152	0.0027
maltose at 298.06 K	-11.93(16)	-3.421(73)	3.152	0.0063
glucose at 317.99 K	-18.609(3)	-11.033(72)	9.514	0.0163
maltose at 317.99 K	-21.47(66)	-11.928(69)	9.514	0.0250
maltotriose at 317.99 K	-63(2)	-10.56(38)	9.514	0.0064
maltotetraose at 317.99 K	-102(21)	-11.09(16)	9.514	0.0112
maltopentaose at 317.99 K	-324(74)	-8(1)	9.514	0.0135
cellobiose at 317.99 K	-28(10)	-11.80(63)	9.514	0.0068

^a $P = Ax_2^2 + Bx_2 + C$. x_2 represents the mole fraction of the sugar. The equations are valid over the composition range studied; see Table 2.

**Figure 2. Natural logarithm of the activity coefficients for water in solutions of glucose and maltose at 298.06 K.**

for water both in glucose and in maltose solutions at 298 K; Figure 3 shows the corresponding plot for solutions of glucose, maltose, maltotriose, maltotetraose, and maltopentaose at 318 K. The activity coefficients of the water (γ_1) are calculated with a modified Raoult's law ($\gamma_1 = P/(x_1 P_1^{\text{sat}})$), where P is the measured vapor pressure over the solution, x_1 is the mole fraction of water, and P_1^{sat} is the vapor pressure of the pure water. The figures indicate that negative deviations from ideal behavior occur for all of the systems at both temperatures. Both figures illustrate the trend of increased deviation from ideal behavior with increased solute molecular size. Figure 4 gives the comparison of vapor pressures at five different concentrations for the aqueous solutions of the α -(1-4)-linked glucose series from glucose (one glucose unit) to maltopentaose (five glucose units). An interesting trend is observed in which differences in vapor pressures over the solutions of different oligomers become more distinct at higher concentrations. At a sugar mole fraction of 0.01 the choice of dissolved sugar from the series gives little difference in the vapor pressure observed. At the increased mole fraction of 0.05 the choice of dissolved sugar greatly affects the vapor pressure of the solution. The small fluctuations occurring in the lower concentration ranges are likely to be due to

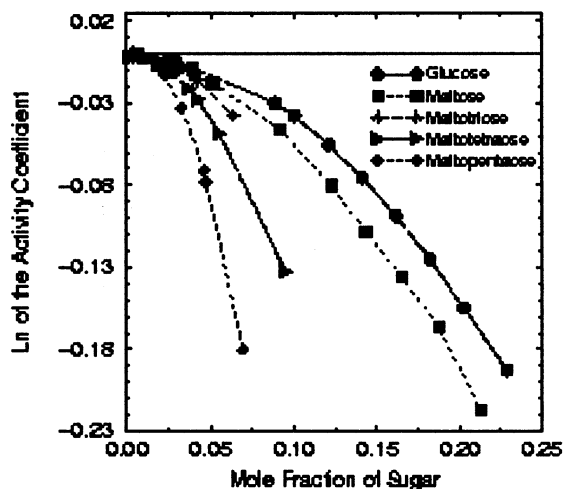


Figure 3. Natural logarithm of the activity coefficients for water in aqueous solutions of the α -(1-4)-linked glucose series, glucose through to maltopentaose at 317.99 K.

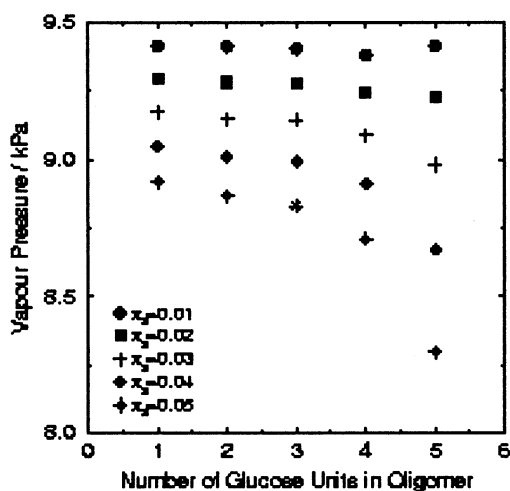


Figure 4. Vapor pressures of aqueous solutions of glucose, maltose, maltotriose, maltotetraose, and maltopentaose at 317.99 K compared at five different concentrations. The vapor pressures are calculated by using the polynomials fitted through the measured data points.

experimental uncertainties and small uncertainties introduced in the fitting procedure of the polynomial.

Deviation from ideal behavior observed for cellulose, and the α -(1-4)-linked series, glucose through to maltopentaose in aqueous solution. This is indicative of the strong hydrogen bond networks that exist between these sugars and the surrounding water molecules. A classical interpretation indicates that the interactions between solute and solvent are favorable compared to solute-solute or solvent-solvent interactions. The deviations from ideality increase with increasing solute molecular size. It should be noted that while the solubilities of maltose and cellobiose in water are very different, the observed water vapor pressures for these sugar solutions, over the dilute concentration range, are very similar, the nature of the glycosidic linkage appearing to not significantly affect this solution property.

The measurements of vapor pressures above supersaturated solutions of sugars are interesting. Glucose in water was found to form a meta-stable phase and several measurements could be recorded before the solution crystallized. The glucose oligomers did not crystallize, but formed very viscous glassy liquids. Again, a meta-stable

Table 4. Calorimetric Data for All Systems. All Measurements Taken at 318.15 K

sugar mole fraction	excess partial molar enthalpy of water in sugar solution	molar heat of mixing
	J·mol ⁻¹	J·mol ⁻¹
	Water + Glucose	
0.00515	-0.47(1)	-77(3)
0.00874	-1.48(3)	-130(5)
0.01683	-5.46(5)	-248(6)
0.03211	-17.83(15)	-464(10)
	Water + Maltose	
0.00422	-0.47(2)	-110(5)
0.00915	-2.48(3)	-238(7)
0.01398	-5.41(15)	-361(16)
0.02377	-14.35(15)	-607(18)
0.03226	-28.51(15)	-818(20)
	Water + Maltotriose	
0.00128	0.02(2)	-25(2)
0.00195	0.01(2)	-39(3)
0.00303	-0.18(2)	-61(5)
0.00345	-0.54(1)	-69(6)
0.00482	-0.64(2)	-96(6)
0.00541	-1.77(3)	-109(8)
0.01259	-5.07(3)	-249(15)
	Water + Maltotetraose	
0.00123	-0.01(1)	not calculated
0.00171	-0.10(1)	not calculated
0.00250	-0.22(1)	not calculated
	Water + Maltopentaose	
0.00084	0.05(1)	not calculated
0.00113	-0.02(1)	not calculated
0.00159	-0.10(1)	not calculated
0.00229	-0.14(1)	not calculated
	Water + Cellobiose	
0.00150	-0.04(1)	-88 (3)
0.00229	-0.05(1)	-135 (4)
0.00351	-0.29(1)	-207 (4)
0.00543	-1.02(1)	-320 (6)
0.00750	-2.02(3)	-440 (10)

Table 5. Coefficients for Empirically Fitted Lines for the Molar Enthalpies of Mixing of the Measured Systems at 318.15 K

	A	RMS deviation
	kJ·mol ⁻¹	
water/glucose	-14.30(20)	2.9
water/maltose	-25.20(20)	3.1
water/maltotriose	-20.00(50)	0.9
water/cellobiose	-58.70(50)	0.3

^a $H_E = Ax_2$. x_2 represents the mole fraction of the sugar. The equations are valid over the composition range studied; see Table 4.

phase was reached, and measurements were taken until the solution became too viscous to be stirred. The ability of certain sugars to form glasses has been well-studied (see for example refs 26 and 27). The phenomenon is utilized by plants for the purposes of protection against severe dehydration.

Table 4 shows the excess partial molar enthalpies of water, in the sugar solution under study, along with the molar enthalpies of mixing for the respective solution. The molar enthalpies of mixing are calculated from the excess partial molar enthalpies, using pure water and pure sugar melt as reference systems, respectively. Table 5 gives the values of the constants for the fitted equations for the molar enthalpies of mixing data. Each data set was fitted with a linear equation; the residuals indicate that the fits are reasonable. Fitting the data with a quadratic equation has the effect of reducing the residuals with the consequence

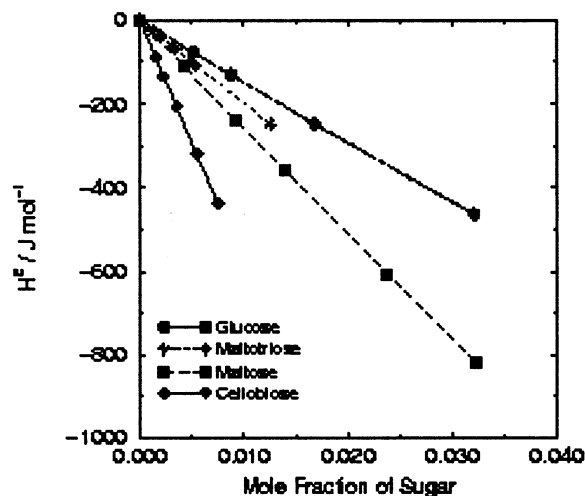


Figure 5. Molar enthalpies of mixing for aqueous solutions of glucose, cellobiose, maltose, and maltotriose at 318.15 K.

that the fitted constants themselves have very large uncertainties because of the small size of the data sets and limited data range. The excess partial molar enthalpies for water in solutions of maltotetraose and maltopentaose were small, with a magnitude less than ± 0.3 J/mol of water; given the uncertainties on the measurements, it was not considered profitable to calculate molar enthalpies of mixing for these systems. The calorimetric data for maltotetraose and maltopentaose are given here purely to indicate the relative magnitudes of the quantities measured. The excess partial molar enthalpies of water in all of the sugar solutions investigated show the process to be exothermic.

Figure 5 depicts graphically the molar enthalpies of mixing data. All the systems studied show exothermic behavior, with magnitude greater than -1 kJ \cdot mol $^{-1}$ within the composition ranges studied. Interestingly, it can be observed with respect to the molar enthalpies of mixing that the aqueous maltotriose system has an intermediate gradient between the aqueous maltose and aqueous glucose systems.

The molar heat of mixing data shows exothermic behavior, which is in good accordance with the vapor pressure data. In the mixing process, interactions between like species are disrupted and interactions between the unlike species are promoted. If unlike species have *stronger* attractions on average than those between like species, an exothermic process is anticipated; an endothermic process is expected if the reverse is true. The related water + 1,2-ethanediol system shows similar behavior.²⁸ The molar enthalpies of mixing for the solutes in aqueous solution investigated here decrease according to the series glucose > maltotriose > maltose > cellobiose. When the measured molar enthalpies of mixing data for maltose and cellobiose are compared to the measured values for sucrose,²⁹ it can be seen that the lower the solubility of these compounds,²³ the more negative will be the molar enthalpies of mixing. In the absence of any further thermodynamic information for maltotriose, an explanation concerning the trend indicated above for the molar enthalpies of mixing of the sugars in water is withheld.

Model Calculations. The UNIQUAC equation contains compound-specific parameters, describing the size and shape of the molecules and their interactions with one another. Furthermore, UNIQUAC includes a parameter for the number of nearest neighbors, the coordination number (z). The value for the coordination number usually em-

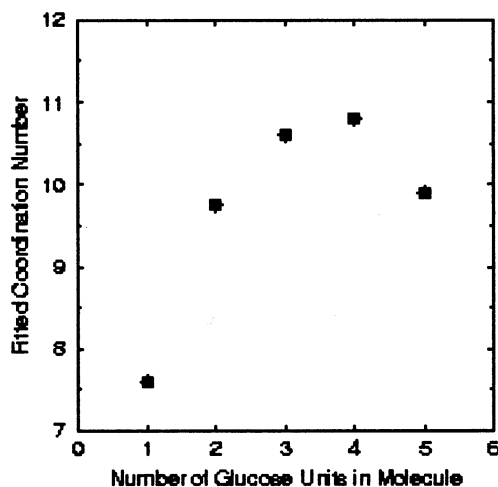


Figure 6. Values for the coordination number of the UNIQUAC equation fitted to the vapor pressure data for the aqueous solutions of the α -(1-4)-linked glucose series, glucose through to maltopentaose at 317.99 K, with interaction parameters fixed for values obtained theoretically for the water + ethanediol system.

ployed is 10; values between 6 and 12 are permissible.¹⁸

Figure 6 shows the results from fitting the coordination number, z , used in the UNIQUAC equation to the experimental vapor pressure data at 318 K for the α -(1-4)-linked glucose series, glucose through to maltopentaose in aqueous solution, listed in Table 2. This fit was performed keeping the appropriate structural parameters, shown in Table 1, constant along with fixing the interaction parameters at $A_{12} = 396$ K and $A_{21} = -334$ K for all cases. These interaction parameters have been determined for a smaller model system; see the Theoretical Model section for details. The coordination number can be seen to go through a maximum of approximately 11 for maltotriose and maltotetraose with glucose requiring the coordination number to be less than 8, maltopentaose and maltose both requiring a value of 10. Application of the combined theoretical-UNIQUAC model, used directly to predict the vapor pressures of the aqueous solutions of cellobiose and the glucose oligomers investigated in this work, has been performed for the vapor pressure data sets and is discussed elsewhere.³⁰ This model approach, in its current form, is not sufficiently accurate for the prediction of molar enthalpies of mixing.

Figure 7 shows a related plot in which the vapor pressure data at 318 K for the α -(1-4)-linked glucose series, glucose through to maltopentaose, are fitted to the extended Flory-Huggins solution theory, keeping all quantities constant with the exception of the mixing parameter, χ . The plot shows a very similar trend to that observed in Figure 6.

The Flory-Huggins mixing parameter (χ) is given by

$$\chi = -cw/kT \quad (2)$$

where c is the coordination number, w is the interchange energy = $w_{11} + w_{22} - 2w_{12}$, k is the Boltzmann constant, w_{ij} is the interaction energy between molecules i and j , and T is the temperature in Kelvin; see ref 20. In fitting to obtain this mixing parameter, it can be seen that the resulting values are the direct product of the coordination number and the interchange energy. The trend shown in Figure 7, i.e., the low value for glucose, increasing to a maximum for maltotriose and maltotetraose and then decreasing again for maltopentaose, all in aqueous solution, is similar to that observed in Figure 6 for the UNIQUAC

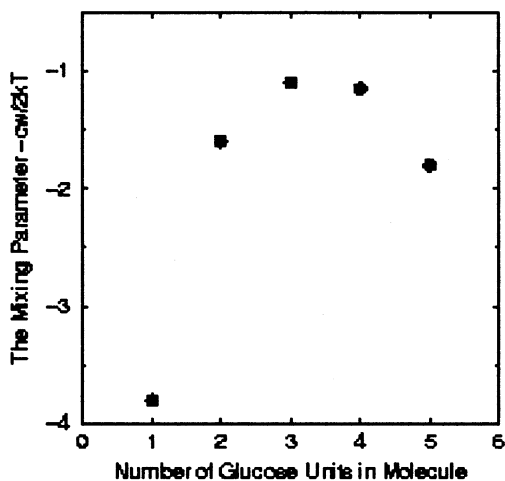


Figure 7. Values for the mixing parameter for the extended Flory–Huggins model obtained by fitting the parameter to the vapor pressure data for the aqueous solutions of the α -(1–4)-linked glucose series, glucose to maltopentaose at 317.99 K.

equation. It is evident that the interchange energy is critically dependent upon the number of nearest neighbors.

In the UNIQUAC model the relationship between interaction energy and coordination number is not as clear as in the simpler Flory–Huggins model. Hence, the procedure of fitting the coordination number for the UNIQUAC equation to the vapor pressure data, keeping interaction parameters constant, may well have the effect of causing the coordination number to “take up” or compensate for the adjustments that are required in the interaction energies. The apparent inseparability of the coordination number from the interaction parameters in the UNIQUAC model has the consequence that any attempt at fitting the interaction energies and coordination numbers independently yields unrealistic values. Interestingly, a UNIFAC-type model using interaction energies derived from a variety of experimental phase equilibrium data for mono- and disaccharides in aqueous solution predicts almost identical vapor pressures of water over the oligosaccharides in this study as the theoretical approach does.³⁰ The UNIFAC model uses a fixed coordination number of 10. The similar predictive abilities of the UNIFAC-type model and the theoretical model suggests that for the oligosaccharide systems studied here the coordination number is more likely to require variation in the lattice-based model than the interaction parameters. It is possible that the values obtained for the coordination number, given in Figure 6, reflect the folding of the oligosaccharide molecules around the glycosidic bonds and, in the case of maltopentaose, the beginning of coiling. A solution to this problem may be to obtain coordination numbers from large-scale molecular dynamics simulations.

Conclusion

The experimental thermodynamic data obtained in this work adds to the data available from other experimental studies to further the discussion concerning the properties of mono-, di-, and oligosaccharides in aqueous solution. A series of vapor pressure and calorimetric measurements have successfully been made on aqueous solutions of glucose, cellobiose, maltose, maltotriose, maltotetraose, and maltopentaose. All vapor pressures measured show a negative deviation from ideality. Molar enthalpies of mixing are found to be exothermic, decreasing in value according to the series of solutes glucose > maltotriose > maltose

> cellobiose. While excess partial molar enthalpies for water in aqueous solutions of maltotetraose and maltopentaose were recorded, the values were small in magnitude ($<0.3 \text{ J}\cdot\text{mol}^{-1}$) over the composition range studied; calculation of molar enthalpies of mixing for these two systems was not carried out.

The systematic nature of this study result in a data set being generated which contributes to the development of a statistical thermodynamic model for these types of systems. Two simple lattice-related solution theories have been applied to the vapor pressure data obtained in this work. While these models are useful, the interdependence of the coordination number and the interaction energies indicate that calculating the interaction energies theoretically and then utilizing them within a lattice-based model is not straightforward and inevitably leads to the introduction of an undesirable, empirical aspect within the procedure. The structural properties and folding of these molecules in an aqueous environment might be reflected through the variation in the coordination number that is required by these models. Large-scale molecular simulations would, however, have to be carried out for truly gaining a better understanding of the structuring of these substances in aqueous solution.

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Literature Cited

- Rees, D. A. *Polysaccharide Shapes*; Chapman and Hall: Cambridge, 1977.
- Taylor, J. B.; Rowilson, J. S. The Thermodynamic Properties of Aqueous Solutions of Glucose. *Trans. Faraday Soc.* **1955**, *51*, 1183–1192.
- Aberdafi, S.; Bounahmidi, T. Measurement and Modeling of Atmospheric Pressure Vapour-Liquid Equilibrium Data for Binary, Ternary and Quaternary Mixtures of Sucrose, Glucose, Fructose and Water Components. *Fluid Phase Equilib.* **1994**, *93*, 337–351.
- Ruegg, M.; Blanc, B. The Water Activity of Honey and Related Sugar Solutions. *Lebensm.-Wiss. Technol.* **1981**, *14*, 1–6.
- Apelblat, A.; Korin, E. The Vapour Pressure of Saturated Aqueous Solutions of D(+)-Glucose, D(+)-Galactose and β -Lactose at Temperatures From $T = 278 \text{ K}$ to $T = 318 \text{ K}$. *J. Chem. Thermodyn.* **1998**, *30*, 1263–1269.
- Taylor, J. B. The Water Solubilities and Heats of Solution of Short Chain Cellulosic Oligosaccharides. *Trans. Faraday Soc.* **1957**, *53*, 1198–1203.
- Moates, G. K.; Noel, T. R.; Parker, R.; Ring, S. G.; Cairns, P.; Morris, V. J. Observations on the Crystallization and Melting of Maltopentaose Hydrate. *Carbohydr. Res.* **1997**, *299*, 91–94.
- Sugiyama, H.; Nitta, T.; Horii, M.; Motohashi, K.; Sakai, J.; Usui, T.; Hisamichi, K.; Ishiyama, J. The Conformation of α -(1–4)-Linked Glucose Oligomers From Maltose to Maltoheptaose and Short Chain Amylose in Solution. *Carbohydr. Res.* **2000**, *325*, 177–182.
- Mulloy, B.; Frenkiel, T. A.; Davies, D. B. Long-Range Carbon-Proton Coupling Constants: Application to Conformational Studies of Oligosaccharides. *Carbohydr. Res.* **1988**, *184*, 39–46.
- Naidoo, K. J.; Brady, J. W. Calculation of the Ramachandran Potential of Mean Force for a Disaccharide in Aqueous Solution. *J. Am. Chem. Soc.* **1999**, *121*, 2244–2252.
- Mashimo, S.; Miura, N.; Umehara T. The Structure of Water Determined by Microwave Dielectric Study on Water Mixtures With Glucose, Polysaccharides, and L-Ascorbic Acid. *J. Chem. Phys.* **1992**, *97* (9), 6759–6765.
- Mashimo, S.; Miura, N. High Order and Local Structure of Water Determined by Microwave Dielectric Study. *J. Chem. Phys.* **1993**, *99* (12), 9874–9881.
- Stevens, E. S.; Sathyanarayana, B. K. Potential Energy Surfaces of Cellobiose and Maltose in Aqueous Solution: A New Treatment of Disaccharide Optical Rotation. *J. Am. Chem. Soc.* **1988**, *111*, 4149–4154.
- Fringant, C.; Tvaroska, I.; Mazeau, K.; Rinaudo, M.; Desbrieres, J. Hydration of α -Maltose and Amylose: Molecular Modeling and Thermodynamics Study. *Carbohydr. Res.* **1995**, *278*, 27–41.

- (15) Jónsdóttir, S. Ó.; Rasmussen, K.J.; Fredenslund Aa. UNIQUAC Parameters Determined by Molecular Mechanics. *Fluid Phase Equilib.* **1994**, *100*, 121–138.
- (16) Jónsdóttir, S. Ó.; Klein, R.A. UNIQUAC Interaction Parameters for Molecules With –OH Groups on Adjacent Carbon Atoms in Aqueous Solutions Determined by Molecular Mechanics—Glycols, Glycerol and Glucose. *Fluid Phase Equilib.* **1997**, *132*, 117–137.
- (17) Jónsdóttir, S. Ó.; Rasmussen, P. Phase Equilibria of Carbohydrates in Polar Solvents. *Fluid Phase Equilib.* **1999**, *158–160*, 411–418.
- (18) Abrams, D. S.; Prausnitz, J. M. Statistical Thermodynamics of Liquid Mixtures: A New Expression for the Excess Gibbs Energy of Partly or Completely Miscible Systems. *AIChE J.* **1975**, *21* (1), 116–128.
- (19) Maurer, G.; Prausnitz, J. M. On the Derivation and Extension of the UNIQUAC Equation. *Fluid Phase Equilib.* **1978**, *2*, 91–99.
- (20) Flory, P. J. *Principles of Polymer Chemistry*; Cornell University Press: Ithaca, NY, 1953.
- (21) Koga, Y.; Wong, T. Y. H.; Sui, W. W. Y. Vapour Pressures of Aqueous *tert*-Butanol in the Water Rich Region: Transition in the Mixing Scheme. *Thermochim. Acta* **1990**, *169*, 27–38.
- (22) Andersen, K. B.; Koga, Y.; Westh, P. A Differential Vapor-Pressure Equipment for Investigations of Biopolymer Interactions. *J. Biochem. Biophys. Methods* **2002**, *50*, 269–288.
- (23) Jónsdóttir, S. Ó.; Cooke, S.A.; Macedo, E. A. Modeling and Measurements of Solid–Liquid and Vapor–Liquid Equilibria of Polyols and Carbohydrates in Aqueous Solution. Submitted for publication to *Carbohydr. Res.*
- (24) Bondi, A. *Physical Properties of Crystal, Liquids and Glasses*; Wiley: New York, 1968.
- (25) Stephen, H.; Stephen, T. *Solubility of Inorganic and Organic Compounds*; Pergamon Press: London, 1963; Vol. 1, Part 1.
- (26) Wolkers, W. F.; Oldenhof, H.; Alberda, M.; Hoekstra, F.A. A Fourier Transform Infrared Microspectroscopy Study of Sugar Glasses: Application to Anhydrobiotic Higher Plant Cells. *Biochim. Biophys. Acta* **1998**, *1379*, 83–96.
- (27) Noel, T. R.; Parker, R.; Ring, S. G. A Comparative Study of the Dielectric Relaxation Behavior of Glucose, Maltose, and Their Mixtures With Water in the Liquid and Glassy States. *Carbohydr. Res.* **1996**, *282*, 193–206.
- (28) Matsumoto, Y.; Touhara, H.; Nakanishi, K.; Watanabe, N. Molar Excess Enthalpies for Water + Ethandiol, + 1,2-Propanediol, and + 1,3-Propanediol at 298.15 K. *J. Chem. Thermodyn.* **1977**, *9*, 801–805.
- (29) Cooke, S. A.; Jónsdóttir, S. Ó.; Westh, P. The Vapor Pressure of Water as a Function of Solute Concentration Above Aqueous Solutions of Fructose, Sucrose, Raffinose, Erythritol, Xylitol and Sorbitol. *J. Chem. Thermodyn.*, in press.
- (30) Cooke, S. A.; Jónsdóttir, S. Ó.; Westh, P. Phase Equilibria of Carbohydrates: The Study of a Series of Glucose Oligomers from Glucose to Maltopentaose in Aqueous Solution Experimental Versus Predicted Data Using Various UNIQUAC/UNIFAC Models. *Fluid Phase Equilib.* **2002**, *194–197*, 947–956.

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