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Hydration of Oligosaccharides

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The spin-lattice relaxation times, T_1, of $H_2{}^{17}O$ have been measured for aqueous solutions of 2 di-, 2 trisaccharides, α-, and γ-cyclodextrins as a function of the concentration at 25 °C. The dynamic hydration numbers, n_{DHN}, for 17 sugars including monosaccharides were expressed by the linear relation of the mean number of the equatorial OH groups. The second virial coefficients showed a good correlation with n_{DHN}. Though the rotational correlation times, $\tau_c{}^h$, of water molecules in the cosphere of sugar molecules increased with increasing the number of equatorial OH groups for monosaccharides, those for trisaccharides and cyclodextrins showed almost constant values. The relation between the values of the limiting diffusion coefficients and n_{DHN} for sugars was found to be expressed by two lines with a large negative slope for mono- and di- saccharides, and a small negative slope for trisaccharides and cyclodextrins.

The dynamic hydration number, n_{DHN}, is an essential quantity which expresses the hydration properties of the solutes. In previous reports,[1,2] we showed that the hydration properties of sugars and amino acids can be systematically explained by n_{DHN}. Consequently, if the n_{DHN} of a solute molecule is known, its physico-chemical properties can be estimated.

We recently showed that the hydration of several sugars can be determined by their conformation in aqueous solutions.[1,3] That is to say, it has been found that n_{DHN} can be expressed by a good linear relation of the mean number of the equatorial OH groups, n(e-OH). The physico-chemical properties of oligosaccharides found in nature have hardly been investigated. It is, therefore, important to obtain n_{DHN} of biochemically interesting oligosaccharides.

In previous papers,[1,3] we evaluated the values of n(e-OH) for di- and trisaccharides from those for the constituent monosaccharides, which were determined by Angyal and Picles.[4] We must confirm the validity of the n(e-OH) values for the oligosaccharides.

Cyclodextrins(CDs) take only one conformation with a definite n(e-OH) value in an aqueous solution. The calculated values of n(e-OH) for CDs, based on the same assumption which we used for estimating the values of n(e-OH) for the other oligosaccharides, are obviously the same as the real value of n(e-OH) for CDs. Therefore, the relation between the values of n(e-OH) and the experimental values of n_{DHN} for CDs can be used for checking data concerning the validity of the assumption in estimating n(e-OH) values of the oligosaccharides.

In this paper we report the spin-lattice relaxation time, T_1, of natural-abundance ^{17}O nuclei of water in aqueous solutions of 2 di- and 2 tri-saccharides, α-, and γ-cyclodextrins. We examine the relation between n_{DHN} and n(e-OH) for sugars, including monosaccharides. The relation between their second virial and limiting diffusion coefficients, and n_{DHN} are discussed.

Experimental

Melibiose, trehalose, and melezitose were purchased from Fluka AG, and maltotriose, α-, and γ-cyclodextrins were purchased from Tokyo Kasei. All of the oligosaccharides were of G. R. grade and used without further purification. Distilled and deionized water was used.

All natural abundance oxygen-17 NMR experiments were performed using a JEOL GX-500 spectrometer operating at 67.8 MHz. Details of the experiments are described elsewhere.[1]

The temperature was maintained at 25±0.3 °C by means of a gas thermostat.

Results and Discussion

Dynamic State of Aqueous Solutions of Oligosaccharides. In Fig. 1, the values of T_1^0/T_1 for $H_2{}^{17}O$ in

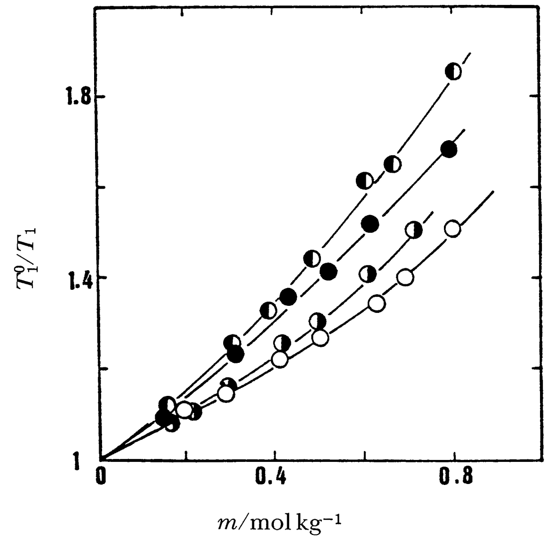

Fig. 1. T_1^0/T_1 of $H_2{}^{17}O$ in aqueous solutions of di- and trisaccharides as a function of the molality. —◐— melezitose; —●— maltotriose; —◑— melibiose; —○— trehalose.

aqueous solutions of di- and trisaccharides are plotted against their concentrations, where T_1^0 and T_1 are the spin-lattice relaxation times of ^{17}O in pure water and the solutions, respectively.

The values of T_1^0/T_1 for sugar solutions are adequately represented by an empirical equation of the form

$$T_1^0/T_1 = 1 + Bm + Cm^2, \qquad (1)$$

where m is the molality of the sugar. The solid lines in Fig. 1 were calculated by a least-squares method. The correlation coefficients were in the range 0.9—0.82.

Owing to the low solubility of α- and γ-CDs, the maximum concentrations of the measurements of T_1^0/T_1 of $H_2{}^{17}O$ for these sugars were 0.1 m; within this concentration range, the values of T_1^0/T_1 are well represented by a linear function of m.

The dynamic hydration number, n_{DHN}, is defined by the following relation:[1]

$$n_{\mathrm{DHN}} = 55.5B = n_{\mathrm{h}}(\tau_{\mathrm{c}}^{\mathrm{h}}/\tau_{\mathrm{c}}^{0} - 1), \qquad (2)$$

where superscripts h and zero refer to water of the hydration sphere(cosphere) and bulk water, respectively; n_{h} is the coordination number and τ_{c} the rotational correlation time. The values of n_{DHN} can be obtained from Eqs. 1 and 2.

We show in the table the values of n_{DHN}, n(e-OH), n_{h}, and $\tau_{\mathrm{c}}^{\mathrm{h}}/\tau_{\mathrm{c}}^{0}$ for each sugar. We estimated the n(e-OH) values for di- or tri-saccharides by substracting 2 or 4 from the sum of n(e-OH) values for the monosaccharides which constitute the oligosaccharides.[1,3] α- and γ-CDs have the definite conformations, and their n(e-OH) values are 16 and 24, respectively.[5]

In Fig. 2, we show the relation between n(e-OH) and n_{DHN} for 17 sugars. The straight line shown in Fig. 2 is expressed in the following relation by a least-squares method:

$$n_{\mathrm{DHN}} = 6.17 + 2.94\, n(\text{e-OH}). \qquad (3)$$

As can be seen in Fig. 2, the n(e-OH) values for di- and

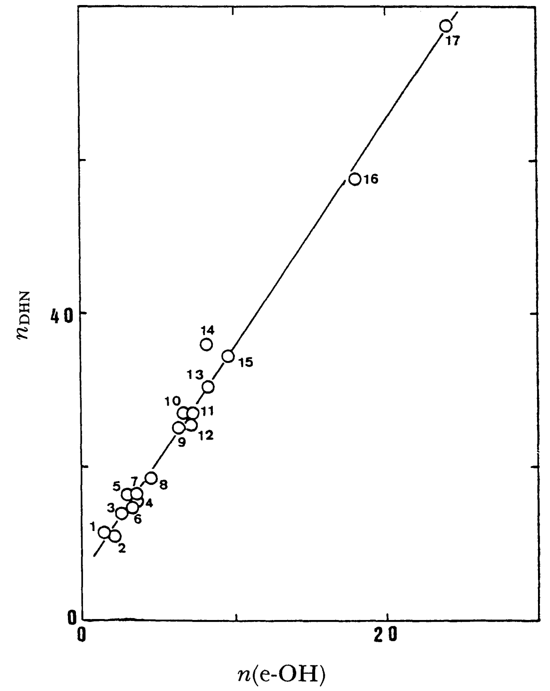

Fig. 2. The relation between n_{DHN} and n(e-OH).
1. deoxyribose; 2. ribose; 3. arabinose; 4. xylose; 5. fructose; 6. mannose; 7. galactose; 8. glucose; 9. sucrose; 10. melibiose; 11. maltose; 12. trehalose; 13. raffinose; 14. melezitose; 15. maltotriose; 16. α-cyclodextrin; 17. γ-cyclodextrin.

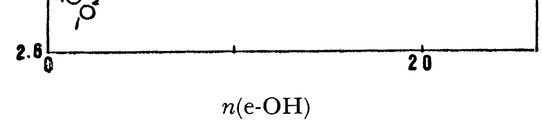

Fig. 3. The relation between $\tau_{\mathrm{c}}^{\mathrm{h}}/\tau_{\mathrm{c}}^{0}$ and n(e-OH). The numbers in figure denote the same sugar as in Fig. 2.

Table 1. Hydration Characteristics and Physicochemical Properties of Sugars in Aqueous Solutions at 25 °C

Sugar	n(e-OH)	n_{DHN}	n_{h}	$\tau_{\mathrm{c}}^{\mathrm{h}}/\tau_{\mathrm{c}}^{0}$	B_2^* cm^3 mol^{-1}	$D_0 \times 10^{10}$ m^2 s^{-1}
Melibiose	6.6	27.1	10	3.71		4.89
Trehalose	7.2	25.4	10	3.54		5.08
Melezitose	8.2	36.0	14	3.57		4.19
Maltotriose	9.8	34.6	14	3.47		4.25
α-CD	18	57.5	24	3.40	1173	3.52[13]
β-CD	21	67.5	28	3.41		3.33,[11] 3.21[13]
γ-CD	24	77.3	32	3.41	1373	3.15

tri-saccharides are reasonable.

The values of τ_c^h/τ_c^0 are plotted against n(e-OH) in Fig. 3. It is shown in Fig. 3 that the τ_c^h/τ_c^0 values for monosaccharides are in a good linear correlation with n(e-OH). As stated in a previous report,[1)] in the case of monosaccharides, the dynamic state of water molecules in the cosphere strongly depends on the conformation of sugar; thus, τ_c^h/τ_c^0 is proportional to n(e-OH). This effect brings about an increase in the τ_c^h/τ_c^0 values.

While the τ_c^h/τ_c^0 values for oligosaccharides scatter over the range of τ_c^h/τ_c^0 monosaccharides with smaller n(e-OH) values, the values approach a constant value with increasing n(e-OH). The results for oligosaccharides suggest the existence of another effect, which decreases the τ_c^h/τ_c^0 of oligosaccharides with large n(e-OH). Hertz and Zeidler[6)] observed that the τ_c^h/τ_c^0 values of tetraalkyl ammonium ion increased with increasing alkyl chain length of the cations; that of the Bu_4N^+ ion, however, was less than the Pr_4N^+ ion, indicating a maximum structure-making effect for the Pr_4N^+ ion in this series. They concluded that the mobility of water molecules around ions which are too large is less restricted than that around ions with a certain size; thus, the molecular size effect decreases τ_c^h/τ_c^0 value.

Kjellander and Marcelia[7)] also proposed that close to a large surface, the number of hydrogen bonds between the water molecules decreases, simply for geometrical reasons. In the case of oligosaccharides, the increase in n(e-OH) is accompanied by an increase in the molecular size; this size effect seems to lead to a constant value of τ_c^h/τ_c^0.

The τ_c^h/τ_c^0 value for β-CD in the table was obtained by interpolation (Fig. 3) using the known value of n(e-OH).

Relation between Physico-Chemical Properties and DHN. We recently reported that the values of the partial molar heat capacities at infinite dilution,[8)] and the relative increments in the ultrasound velocity[9)] of sugars in aqueous solutions, are well expressed by a linear relation of n(e-OH). In this report we consider the relation between the second virial and the limiting diffusion coefficients, and n_{DHN}.

According to the McMillan-Mayer theory of solutions,[10)] the second virial coefficient B_2^* can be calculated by the relation[11,12)]

$$B_2^* = (V_2^0 - V_1^0) + V_1^0\,(1/2 - B), \tag{4}$$

where V_1^0 and V_2^0 are the partial molar volumes of solvent and solute at infinite dilution. B is the coefficient of the first in the power-series expansion of the water activity coefficient.

In Fig. 4, the B_2^* values for sugars, calculated by Eq. 4, are plotted against n_{DHN}. We calculated the values of B_2^* for α- and γ-CDs using the data of Miyajima et al.[13)] and quoted them from Ref. 12 for other sugars. The thermodynamic properties, such as partial molar heat capacity and second virial coefficient, are affected by interactions between the solute and water molecules in the cosphere.[2)] Therefore, B_2^* can be expressed by a linear relation of n_{DHN}, as shown in Fig. 4.

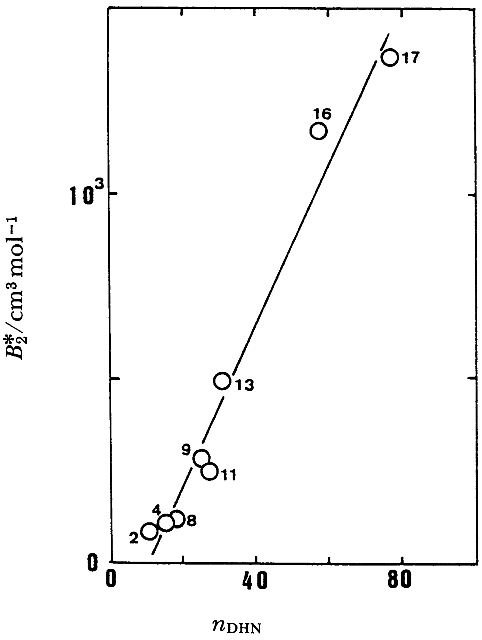

Fig. 4. The relation between B_2^* and n_{DHN}. The numbers in figure denote the same sugar as in Fig. 2.

We previously calculated the limiting diffusion coefficients, D_0, of oligomers and found that the calculated values were in good agreement with the experimental data.[14)] The values of D_0 for melibiose, trehalose, and maltotriose can be calculated by the equations reported.[14)] Melezitose, with the structure α-D-Glc$p$-(1→3)-β-D-Fru$f$-(2↔1)-α-D-Glc$p$, has an L shape. Its frictional coefficient, f_3, is given by the following equation using the shell model:[15)]

$$f_3/f_1 = \frac{(2+k^2)(1+k)}{(2+k^3)(1+k)+2k^2+1/\sqrt{2}}, \tag{5}$$

where f_1 is the frictional coefficient of monomer and $k = D_0(\mathrm{glc})/D_0(\mathrm{fru})$. The D_0 value of melezitose can be calculated using Eq. 5 from the values of D_0(glc) and D_0(fru).[14)]

We give the values of D_0 for the oligomers in the 7th column in the table. We also estimated the D_0 value of γ-CD by the ring model[14)] using the experimental values for α-[16)] and β-[14)] CDs. As can be seen from Fig. 5, in which the D_0 values are plotted against n_{DHN}, the relation of D_0 versus n_{DHN} consists of two straight lines. The equation for mono- and disaccharides was given in a previous report.[1)] The equation for 3 trisaccharides and 3 CDs was found by a least-squares method,

$$D_0 \times 10^{10} = 5.138 - 0.0262\, n_{\mathrm{DHN}}\ (\mathrm{m^2\,s^{-1}}), \tag{6}$$

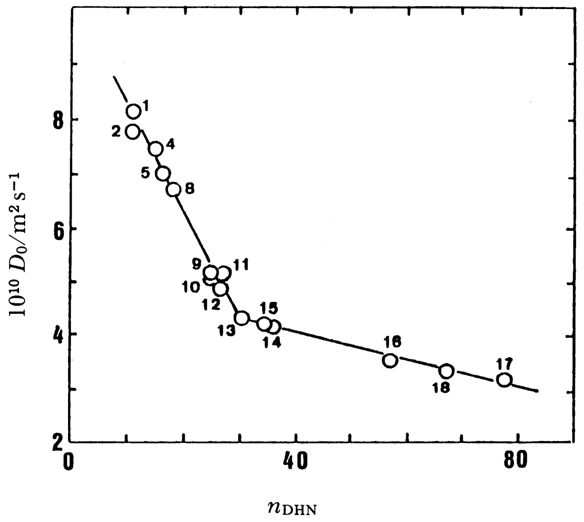

Fig. 5. The relation between D_0 and n_{DHN}. The numbers in figure denote the same sugar as in Fig. 2. 18. β-CD.

where the correlation coefficient is 0.994.

D_0 is in inverse proportion to the radius of the molecule and the microviscosity and, thus, to $n_{\mathrm{h}}^{1/2}$ and $\tau_{\mathrm{c}}^{\mathrm{h}}$.1,3) Therefore, the effect of $\tau_{\mathrm{c}}^{\mathrm{h}}$ on D_0 is much larger than that of n_{h}. Since the $\tau_{\mathrm{c}}^{\mathrm{h}}/\tau_{\mathrm{c}}^{0}$ values for trisaccharides and CDs are almost constant (Fig. 3), the D_0 values for oligomers slightly decrease with increasing n_{DHN}.

Conclusions

In summary we obtained the following results:

1) The n_{DHN} values can be expressed by a linear equation of n(e-OH). This means that the hydration of sugars is determined by their conformation.

2) The thermodynamic properties of sugars can be expressed by a linear equation of n_{DHN}.

3) The $\tau_{\mathrm{c}}^{\mathrm{h}}/\tau_{\mathrm{c}}^{0}$ values increase linearly with increasing n(e-OH) for monosaccharides. The $\tau_{\mathrm{c}}^{\mathrm{h}}/\tau_{\mathrm{c}}^{0}$ values for oligomers gradually become less on passing from disaccharides to trigsaccharides, and become constant for CDs.

4) The relation between D_0 and n_{DHN} consists of two straight lines, and the line for trisaccharides and CDs has a very small slope. These results correspond to the change of $\tau_{\mathrm{c}}^{\mathrm{h}}/\tau_{\mathrm{c}}^{0}$.

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