Molecular Dynamics of Carbohydrate Aqueous Solutions. Dielectric Relaxation as a Function of Glucose and Fructose Concentration

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At some solute concentrations c between 1 and 5.4 mol/L, the complex (electric) permittivity of aqueous solutions of D-glucose and D-fructose has been determined as a function of frequency ν between 300 kHz and 40 GHz. The permittivity spectrum of the 5.4 mol/L D-fructose solution has been measured at six temperatures between 10 and 35 °C, and the other spectra have been taken at 25 °C. All dielectric spectra revealed one dispersion/dielectric loss region, which indicated a rather homogeneous relaxation of the solute and solvent dipole moments. Analytically, the measured spectra were represented by the Cole−Cole relaxation spectral function, which corresponds with a continuous, symmetrically bell shaped relaxation time distribution. The parameters of the spectral function are discussed to show that the monosaccharides exhibit unusual hydration properties. Particularly, when treated in terms of a wait-and-switch model of dipole reorientation, the principal dielectric relaxation time is indicative of the extraordinary hydration behavior of the saccharides. It is suggested that this behavior reflects the compatibility of the ring molecule's −OH group topology with the water structure.

1. Introduction

The solution properties of carbohydrates are of considerable interest for various aspects of basic research and in many applications as well. Saccharides and their derivatives are important chemicals in life processes. They constitute an energy resource for biological cells, they are significant constituents of nucleic acids, and they are linked to various proteins and lipids. Many functional features of saccharides in biology are now becoming obvious but are far from being fully understood. Therefore, the increasing interest in biophysical and biochemical research is presently being directed toward the novel subdiscipline termed "glycobiology".[1] Many of the technological applications of carbohydrates utilize the exotic rheological properties of their aqueous solutions;[2] these include the control of gelling processes[3] and the osmoregulation of tissues and organs in cryoprotective provisions.[4,5]

Recently, attention has been paid, in particular, to the rich conformational variety of carbohydrates.[6,7] As part of glycoproteins, glycolipids, and other biomolecules, carbohydrates, due to their conformational flexibility, offer an additional "alphabet" in many biological processes, such as signaling, cell−cell recognition, and molecular and cellular communication.[8] Carbohydrates stabilize labile biomolecules. Most probably the ability of carbohydrates to substitute water in the hydrogen network is essential for their role in biomolecule stabilization and protection.[9] The hydration properties of carbohydrates are thus a key feature in determining their structural and functional properties.[10,11]

To elucidate the behavior of some saccharides in solution, dielectric relaxation studies were performed.[12−14] The reported results, however, are conflicting in some points. Suggett et al.[12,13,15] evaluated their dielectric spectra from time-domain measurements in terms of a multiple-Debye-term[16] model. Mashimo et al.[14] also used time-domain spectrometry but preferred the Havriliak−Negami relaxation spectral function,[17] which is based on a continuous distribution of relaxation times. Despite these details in the evaluation of spectra, the existing dielectric relaxation data for carbohydrate aqueous solutions seem to show unusual characteristics, as compared to many other organic molecule/water mixtures. It has been shown recently that the molecular dynamics of many aqueous systems can be treated in terms of rather uniform aspects of relaxation mechanisms in associating liquids.[18,19] The bond strength of the hydrogen network fluctuates rapidly, with correlation times as small as 0.1−1 ps.[20−22] Reorientation of a molecule through a significant angle occurs only if two preconditions are simultaneously fulfilled. First, the angular distribution of potential barriers of reorientation has to be flattened in order to facilitate rotation of a molecule through a significant angle. In addition, a suitable site for a new hydrogen bond has to be offered in order to reduce the probability for the re-formation of the original bond. Both of the requirements are met by the existence of an additional hydrogen bonding neighbor molecule.[23,24] For the predominantly tetrahedrally coordinated water, a "fifth neighbor"[23] has to be present. At room temperature it takes about 10 ps until these favorable conditions for the reorientation of a given molecule in water exist.[18,20,25] The reorientation itself resembles a switching, as it occurs within about 0.1 ps.[20,21]

Within the framework of this wait-and-switch model, the dielectric relaxation time is predominantly given by the period for which a molecule has to wait until favorable conditions for the reorientation exist.[21] For this reason, it is obvious that the dielectric relaxation time of aqueous systems and, more generally, of associating liquids is significantly controlled by the concentration c_μ of hydrogen bonding sites.[18,26] A rather uniform dependence of the relaxation time upon c_μ has been found for aqueous solutions, particularly for monohydric alcohol/water mixtures, and for alcohols.[18,26]

The relaxation times for aqueous solutions of monosaccharides seem not to follow the uniform behavior. Carbohydrates, therefore, offer the opportunity to further study features that

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TABLE 1: Solute (c, m) and Solvent (c_w) Concentration, Concentration c_μ of H−Bonding Groups and Water Molecules, and Density ρ and Shear Viscosity η_s of the Aqueous Solutions of Monosaccharides at 25 °C

c, mol/L ± 0.2%	m, mol/kg ± 0.1%	c_w, mol/L ± 0.2%	c_μ, mol/L ± 0.2%	ρ, g cm^{-3} ± 0.1%	η_s, 10^{-3} Pa·s ± 0.2%
		D-Glucose			
1	1.127	49.10	55.10	1.065	1.47
2	2.587	42.79	55.13	1.132	2.89
3	4.561	36.41	54.41	1.197	6.54
4	7.371	30.03	54.03	1.212	20.61
4.73	10.27	25.49	53.87	1.312	70.48
		D-Fructose			
1	1.120	49.16	55.16	1.066	1.47
2	2.578	42.93	54.93	1.134	2.69
3	4.530	36.65	54.65	1.201	5.82
4	7.329	30.20	54.20	1.265	16.80
4.73	10.27	25.51	53.89	1.312	50.21
5.4	13.94	21.42	53.82	1.359	212.7

might be important in determining the solution properties of molecules in water. These features may include the conformation of the solute, the steric arrangement of its polar groups relative to the water structure, and the flexibility of the solute molecule. We therefore found it interesting to first investigate aqueous solutions of glucose and fructose, with different ring structures and conformations, as a function of solute concentration and to compare their dielectric spectra to those of other aqueous solutions of organic solutes.

2. Experimental Section

Aqueous Solutions. D-(+)-glucose (>99.5%) and D-(−)-fructose (>99%) were purchased from Sigma Chemical Co. (Deisenhofen, Germany) and were used without further purification. Water was deionized by bed ion exchange, additionally distilled, and sterilized by UV irradiation. The solutions were prepared by depositing preweighed amounts of the saccharides into suitable flasks, which were filled up with water to the fiducial mark. After preparation, the samples were kept for 20 h to reach their tautomer equilibrium. Afterward, all measurements were performed within 2 days in order to avoid any effects from disintegration of the monosaccharides by microorganisms.

The density ρ of the liquids was determined pycnometrically. The shear viscosity η_s of the solutions was measured using a falling-ball viscometer (model B/BH, Haake, Karlsruhe, Germany). The ρ and η_s values, the molar (c) and molal (m) concentrations of the solute, the concentration of the solvent water (c_w), and the concentration $c_\mu = 6c + c_w$ of hydrogen bonding groups and water molecules are given in Table 1. In the calculation of c_μ each H-bonding group or water molecule is counted once, regardless of its number of hydrogen bonding sites. Hence c_μ is the sum of the water concentration, the concentration of the ring oxygens, and the concentration of the exocyclic hydroxy groups. It is interesting to note that c_μ is almost independent of the solute concentration here.

In aqueous solutions, D-(+)-glucose and D-(−)-fructose exist in different forms. The common conformations of these monosaccharides in water are shown in Figure 1.

Dielectric Spectrometry. Between 300 kHz and 40 GHz the complex (electric) permittivity

$$\epsilon(\upsilon) = \epsilon'(\upsilon) - i\epsilon''(\upsilon) \qquad (1)$$

of the liquid samples has been measured as a function of frequency υ using different frequency domain methods ($i^2 = -1$). At frequencies below 3 GHz the wavelength of an

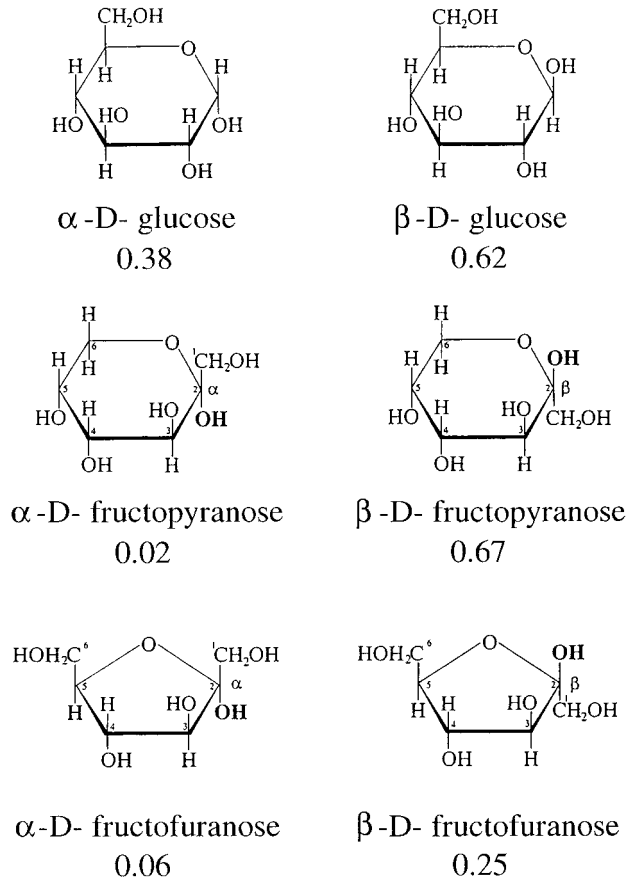

Figure 1. D-Glucose and D-fructose tautomers in water.

electromagnetic wave within the sample is sufficiently large so as to allow for a quasistatic approach. For this purpose, the liquid was contained in a coaxial line/circular waveguide transition. The waveguide, filled with the liquid, was excited below the cutoff frequency of its fundamental TM_{01} field mode.[27] In order to match the cell capacity to a measuring range, a device with geometrical length $l = 10$ mm of the coaxial line part, filled with the liquid, was used at 300 kHz $\leq \upsilon \leq$ 100 MHz. At frequencies between 10 MHz and 3 GHz, $l = 0$ was appropriate. Taking into consideration the effect of evanescent electromagnetic field modes in the waveguide section, the effective cell length and the length of the feeding piece of coaxial line were determined from calibration measurements using water[18] and air as reference dielectrics. For all measurements completed with cells of the "cutoff" variety, the input impedance of the cells was determined as a function of frequency utilizing a computer controlled network analyzer (HP8753A), combined with an appertaining reflection test set (HP85044A).

At frequencies above 5.3 GHz the transfer function of suitable double-beam interferometers, constructed from waveguide devices, was recorded at variable cell length l. The cells, which essentially formed one branch of the respective interferometer, consisted of a circular cylindrical waveguide filled with the sample liquid. Another circular waveguide was immersed in the liquid. At each frequency of measurement, this waveguide was precisely shifted along the direction of wave propagation. The electromagnetic field within the cells was thereby probed at varying sample length, allowing us to derive the propagation constant

$$\gamma = (\beta_c^2 - \epsilon(\upsilon)\beta_o^2)^{1/2} \qquad (2)$$

of the sample cells, and thus, the permittivity $\epsilon(\upsilon)$ of the liquid. In eq 2, β_o ($=2\pi/\lambda_o = 2\pi\upsilon/c$) and β_c denote the wavenumber in free space and the cutoff constant of the fundamental TM_{01} mode of the waveguide used as the specimen cell, respectively. Here, λ_o is the wavelength of the electromagnetic field of frequency υ in free space and $c = \upsilon\lambda_o$ denotes the speed of light in a vacuum. Two interferometers, operated in the frequency bands 5.3−8 GHz and 12.4−18 GHz, respectively, were run at continuously varying cell length, applying a computer-controlled mode of operation.[28] Two other interferometers (18−26 GHz and 26−40 GHz) were used at frequencies at which the attenuation coefficient $\alpha = 0.5\epsilon''\beta_o^2/\beta$ of the liquids was sufficiently high so as to enable propagating waves, that were undisturbed by multiple reflections, to be set up in the cell.[29] Here, β is the wavenumber within the sample. Measurements of the complex propagation constant γ were therefore possible by manual adjustment of the zero-output signal of the interferometer.

Experimental Errors. The use of various cell lengths l for the cutoff cells and also of different reference liquids resulted in the relative errors $\Delta\epsilon'/\epsilon'$ and $\Delta\epsilon''/\epsilon''$ of 3% at $\upsilon < 5$ MHz, of 1% at 5 MHz $\leq \upsilon \leq 1$ GHz, and of 7% at $\upsilon > 1$ GHz. The errors in the permittivity data, measured with the interferometer methods, were 2% in both the real part ϵ' and the imaginary part ϵ'' of the permittivity. In the complete frequency range of measurement, the relative error in υ was smaller than 0.1%. The temperature of the samples was controlled to within 0.05 K and was measured with an error of less than 0.02 K.

3. Results and Treatment of Data

In Figure 2 complex dielectric spectra are displayed for both a glucose and a fructose solution at high solute concentration. Also shown for comparison is the solvent spectrum at the same temperature. It is well known that the microwave dielectric spectrum of water ($\upsilon < 100$ GHz) can be well represented by a Debye-type relaxation spectral function[18,19] given by the relation[16]

$$R_D(\upsilon) = R'_D(\upsilon) - iR''_D(\upsilon) = \epsilon_w(\infty) + \frac{\epsilon_w(0) - \epsilon_w(\infty)}{1 + i\omega\tau_w} \quad (3)$$

In this function, $\epsilon_w(\infty)$ denotes the high-frequency permittivity limiting the microwave dispersion in $R'_D(\upsilon)$: $\epsilon_w(\infty) = \lim_{\upsilon\to\infty} R'_D(\upsilon)$, $\upsilon < 100$ GHz. Parameter $\epsilon_w(0)$ denotes the low-frequency $\upsilon \to 0$ ("static") permittivity and τ_w is the discrete dielectric relaxation time of water. At 25 °C, $\epsilon_w(\infty) = 5.2 \pm 0.4$, $\epsilon_w(0) = 78.36 \pm 0.05$, and $\tau_w = 8.27 \pm 0.02$ ps.[18,19]

The spectra for the monosaccharide solutions differ from the spectrum for water by the substantially smaller static permittivity, the distinctly smaller relaxation frequency υ_r, and also by the fact that the dispersion ($d\epsilon'(\upsilon)/d\upsilon < 0$)/ dielectric loss ($\epsilon''(\upsilon) > 0$) region extends over a much broader frequency range. Here, the relaxation frequency υ_r is just the frequency at which the $\epsilon''(\upsilon)$ values adopt their maximum. There are no indications in the monosaccharide solution spectra for the presence of two well-separated relaxation regions, as might be intuitively expected for polarization mechanisms in which the solute and solvent dipoles reorient almost independently of each other. Rather, there seems to exist a broad continuous distribution of relaxation times. This point is substantiated by the complex plane representation of spectra in Figure 3. The microwave permittivity data for water follow a semicircle as predicted by the Debye relaxation spectral function (eq 3). The data for the 6 M solution of the nondipolar 1,4-dioxane ($O(CH_2$-$CH_2)_2O$) in water define a circular arc with its center below the ϵ' axis. The same is true for the solution of D-(+)-glucose in water. However, the shift in the center of the circular arc is much stronger for the monosaccharide solution than for the dioxane/water spectrum.

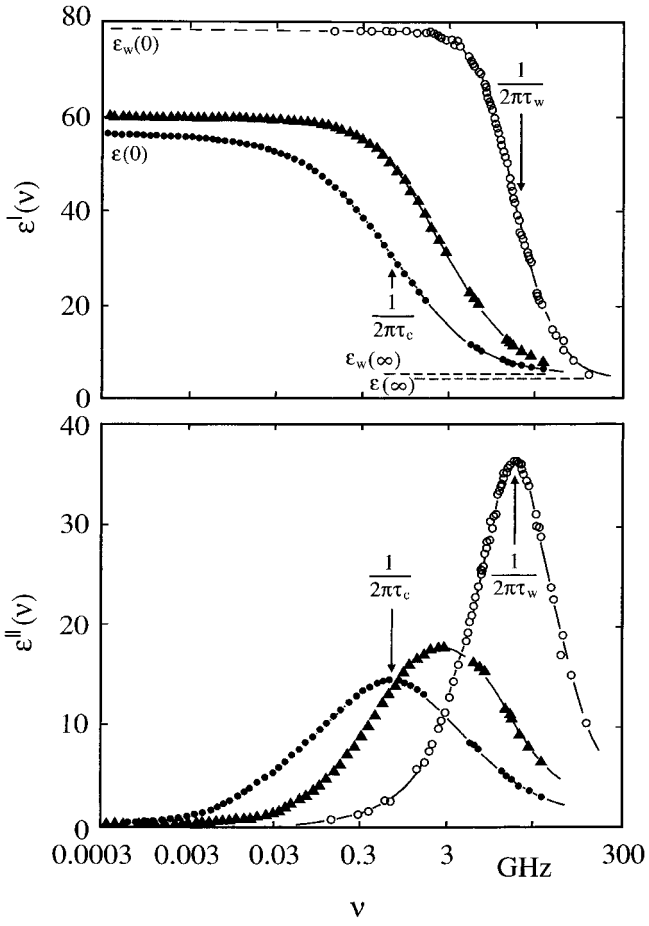

Figure 2. Real part $\epsilon'(\upsilon)$ and negative-imaginary part $\epsilon''(\upsilon)$ of the microwave dielectric spectra for water (○), and for aqueous solutions of D-glucose (▲, 4 mol/L) and D-fructose (●, 5.4 mol/L) at 25 °C. Water permittivity values from this laboratory[25] and from recent compilations of literature data[30,31] are shown. The curves are graphs of the Debye (○) and Cole−Cole (▲,●) relaxation spectral functions, eqs 3 and 5, respectively.

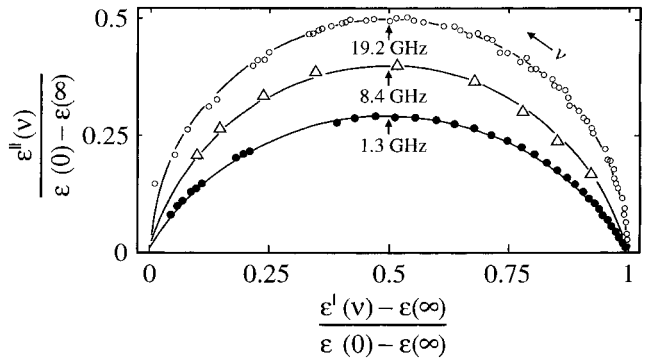

Figure 3. Complex plane representation of the reduced complex permittivity spectra for water (○, refs 25, 30, 31), for a 6 M aqueous solution of 1,4-dioxane (△, ref 32), and for an aqueous solution of D-glucose (●, 4.73 mol/L) at 25 °C. The drawn circular arcs represent the Debye spectral function $R_D(\upsilon)$ (water, eq 3) and the Cole−Cole spectral function (aqueous solutions, eq 5), respectively. Parameters for the 1,4-dioxane/water mixture are $\epsilon(\infty) = 3.7 \pm 0.3$, $\epsilon(0) = 38.1 \pm 0.7$, $\tau_C = 19.0 \pm 0.3$ ps, and $h = 0.09 \pm 0.01$.

The graphical representation of the monosaccharide/water spectra points at an underlying Cole−Cole relaxation time distribution $G_C(\tau)$ defined by[33]

$$\tau G_C(\tau) = \frac{1}{2\pi} \frac{\sin(\pi h)}{\cosh((1-h)\ln(\tau/\tau_C)) - \cos(\pi h)} \quad (4)$$

Here, τ_C denotes the most frequent relaxation time of $\tau G(\tau)$, which, when plotted as a function of $\ln(\tau/\tau_C)$, is symmetrically bell shaped. The parameter h controls the width of the relaxation time distribution. Due to the obvious characteristics in the spectra of saccharide solutions, we fitted the measured frequency-dependent permittivity data to the Cole−Cole spectral function, $R_C(\upsilon)$, which corresponds with $G_C(\tau)$. This spectral function is given by the relation

$$R_C(\upsilon) = \epsilon(\infty) + (\epsilon(0) - \epsilon(\infty))\int_0^\infty \frac{G_C(\tau)\, d\tau}{1 + i\omega\tau}$$

$$= \epsilon(\infty) + \frac{\epsilon(0) - \epsilon(\infty)}{1 + (i\omega\tau_C)^{(1-h)}} \quad (5)$$

It is briefly mentioned that the Cole−Cole spectral function (eq 5) is a special version of the Havriliak−Negami function which, as previously mentioned, was used by Mashimo, Miura, and Umehara[14] to represent their spectra of aqueous carbohydrate solutions. Besides parameter h, the Havriliak−Negami spectral function uses a second distribution parameter to account for an unsymmetry in the shape of the relaxation time distribution.

We are aware of the fact that the $R_C(\upsilon)$ function does not meet the requirements of a correct relaxation spectral function for the extrapolation toward low and very high frequencies.[34] Nevertheless, the empirical Cole−Cole function is used here because it enables, within the frequency range of measurements, the analytical representation of the measured permittivity data with a minimum of unknown parameters. To determine the parameter values of $R_C(\nu)$ a Marquardt algorithm,[35] minimizing the reduced variance,

$$\chi^2 = \frac{1}{N - P - 1}\sum_{n=1}^{N}\left[\left(\frac{R'_C(\nu) - \epsilon'(\nu_n)}{\Delta\epsilon'(\nu_n)}\right)^2 + \left(\frac{R''_C(\nu_n) - \epsilon''(\nu_n)}{\Delta\epsilon''(\nu_n)}\right)^2\right] \quad (6)$$

has been applied. Here, ν_n, $n = 1,...N$ denotes the frequencies of measurement, P (= 4) is the number of adjustable parameters of R_C, and the inverse experimental errors, $1/\Delta\epsilon'(\nu_n)$ and $1/\Delta\epsilon''(\nu_n)$, are used as weighing factors. The parameter values that were obtained from the nonlinear least-squares regression analysis are collected in Tables 2 and 3.

TABLE 2: Parameters of the Cole−Cole Relaxation Spectral Function (Eq 5) for Aqueous Solutions of Monosaccharides at 25 °C

c, mol/L	$\epsilon(\infty)$ ±0.4	$\epsilon(0)$ ±0.4	τ_c, ps ±1%	h, ±0.005
		D-Glucose		
1	3.0	74.3	10.7	0.097
2	2.7	69.9	15.6	0.160
3	3.4	65.3	26.6	0.212
4	4.3	60.2	55.3	0.256
4.73	4.7	55.8	123	0.304
		D-Fructose		
1	3.5	74.4	10.6	0.081
2	3.3	71.2	15.3	0.141
3	4.5	66.2	25.3	0.181
4	4.2	62.4	48.7	0.240
4.73	4.1	59.2	100	0.303
5.4	4.4	56.4	226	0.348

TABLE 3: Density ρ, Shear Viscosity η_s, and Parameters of the Cole−Cole Relaxation Spectral Function (Eq 5) for the 5.4 mol/L D-Fructose Solution at Various Temperatures

T, K	ρ, g cm^{-3} ± 0.1%	η_s, 10^{-3}Pa s ± 0.2%	$\epsilon(\infty)$ ± 0.4	ϵ (0) ± 0.5	τ_c, ps ± 5%	h ± 0.01
283.15	1.368	839.9	3.9	60.5	453	0.383
288.15	1.364	505.6	4.0	60.0	413	0.383
293.15	1.361	313.4	3.9	58.1	283	0.371
298.15	1.359	212.7	4.4	56.4	226	0.348
303.15	1.355	138.7	4.2	55.4	187	0.348
308.15	1.350	99.87	3.8	54.4	171	0.370

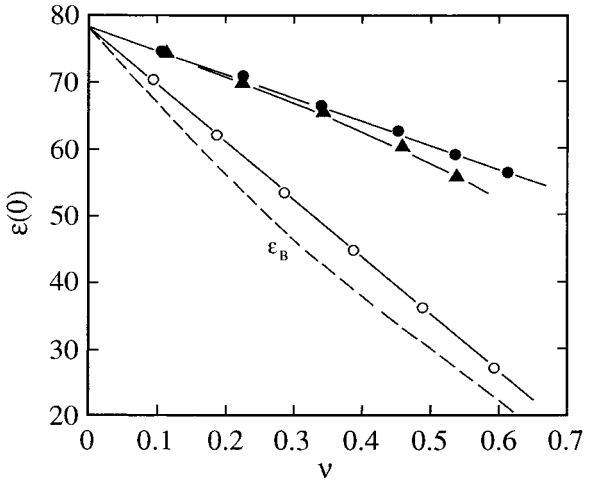

Figure 4. Extrapolated static permittivity $\epsilon(0)$ as a function of volume fraction ν of solute for aqueous solutions of D-glucose (▲), D-fructose (●), and 1,4-dioxane[32,36] (○) at 25 °C. Also shown is the graph of the Bruggemann mixture relation,[37] defined by eq 7.

3. Discussion

Static Permittivity, Dipole Moments. In Figure 4, the extrapolated static permittivities $\epsilon(0)$ of the monosaccharide solutions are displayed as a function of the volume fraction ν of solute. For comparison, $\epsilon(0)$ values for aqueous solutions of nondipolar 1,4-dioxane[32,36] are also shown, as are the static permittivites ϵ_B that resulted from the theoretical mixture relation.[3] Written to apply for aqueous systems at 25 °C, this relation predicts the resulting permittivity ϵ_B of a mixture of spherically shaped nondipolar particles ($\epsilon_e = 2$) as[37]

$$\frac{\epsilon_B - \epsilon_e}{\epsilon_w(0) - \epsilon_e}\left(\frac{\epsilon_w(0)}{\epsilon_B}\right)^{1/3} = 1 - \nu \quad (7)$$

with $\epsilon_w(0) = 78.36$. The static permittivity data for the dioxane/water mixtures exceed the predictions by the Bruggemann mixture formula (eq 7), which indicates a slight enhancement of the orientation polarizability of water with respect to the pure solvent. This tendency has been found in the experimental data of various aqueous solutions of organic solutes[26,37] and has been assumed to be due to hydrophobic hydration effects. These hydration effects are also likely to exist in the monosaccharide solutions. For this reason, and since the deviations of the experimental permittivities from those predicted by the mixture relation (eq 7) depends only weakly upon special characteristics of the solute molecules,[26,38] we compare the $\epsilon(0)$ data of the saccharide solutions to those of the dioxane/water system rather than to those from the Bruggemann formula. Extending the

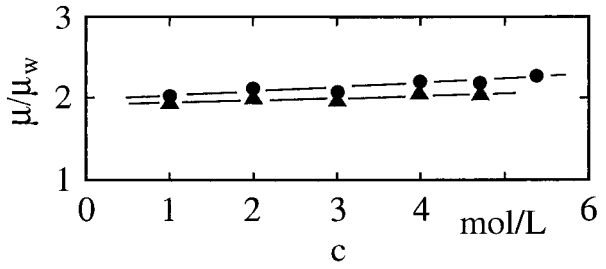

Figure 5. Monosaccharide-to-water dipole-moment ratio μ/μ_w versus solute concentration c for D-glucose (▲) and D-fructose (●) as following from eq 11.

Fröhlich theory for the static permittivity of a one-compound dipolar liquid,[39] the relation

$$\epsilon(0) - \epsilon(\infty) = \frac{N_A}{3\epsilon_0 k_B T}\frac{3\epsilon(0)}{2\epsilon(0)+\epsilon_\infty}\left(\frac{\epsilon_\infty+2}{3}\right)^2 g_{eff}(c\mu_{ww}^2 + c\mu^2) \quad (8)$$

may be used to relate the $\epsilon(0)$ data to the dipole moments of the solute (μ) and solvent (μ_w) in the gaseous state. In eq 8, N_A is Avogadro's number, k_B is the Boltzmann constant, and g_{eff} is an effective orientation correlation factor. For a one-compound liquid, this factor corresponds with the Kirkwood dipole-orientation factor g.[40] Here, strictly water−water, water−carbohydrate, and carbohydrate−carbohydrate dipole-orientation correlations have to be taken into account. Since the evaluation of three parameters from only one static permittivity value would be an unavailing attempt, we shall restrict ourselves to a simplified treatment of the $\epsilon(0)$ data using the effective orientation correlation factor.

Another crucial parameter in eq 8 is the high-frequency permittivity ϵ_∞ for which only the range of admissible values ($n^2 \le \epsilon_\infty \le \epsilon(\infty)$) is known, but not the exact value.[19,41] To avoid difficulties with the unknown parameter in the extended Fröhlich model (eq 8) we evaluate the static permittivities of the carbohydrate solutions assuming

$$\epsilon_\infty = \epsilon(\infty) = \epsilon_d(\infty) \quad (9)$$

and

$$g_{eff} = g_{eff,d} \quad (10)$$

Subscript "d" refers to the dioxane/water mixtures. If, on these assumptions, eq 8 is analogously applied to the dioxane solutions

$$\frac{\mu^2}{\mu_w^2} = \frac{c_w}{c}\left[\frac{(\epsilon(0)-\epsilon(\infty))(2\epsilon(0)+\epsilon(\infty))\epsilon_d(0)}{(\epsilon_d(0)-\epsilon(\infty))(2\epsilon_d(0)+\epsilon(\infty))\epsilon(0)} - 1\right] \quad (11)$$

follows. In Figure 5, the μ/μ_w values resulting from eq 11 are displayed as a function of solute concentration. It was found that the dipole moments derived for both monosaccharides do not noticeably depend on c. Hence, obviously, dipole-orientation correlations in the carbohydrate solutions do not seem to substantially vary with the solute content. The dipole moment for D-fructose appears to be slightly larger than that for D-glucose. This finding reflects the conformer equilibrium of the former monosaccharide in water (Figure 1), involving 31% furanose with a larger estimated dipole moment, particularly due to the additional exocyclic $-CH_2OH$ group which is almost free to rotate its dipole moment.

Using $\mu_w = 1.84$ D from the literature,[42] 3.5 D $\le \mu \le$ 3.9 D follows for the dipole moment of the D-glucose molecule in the gaseous state. When compared to estimates for the monosaccharide dipole moments that are based on group moments[43] and bond angles, the evaluation of permittivity data yields a suggestive mean for both D-glucose conformers in water.

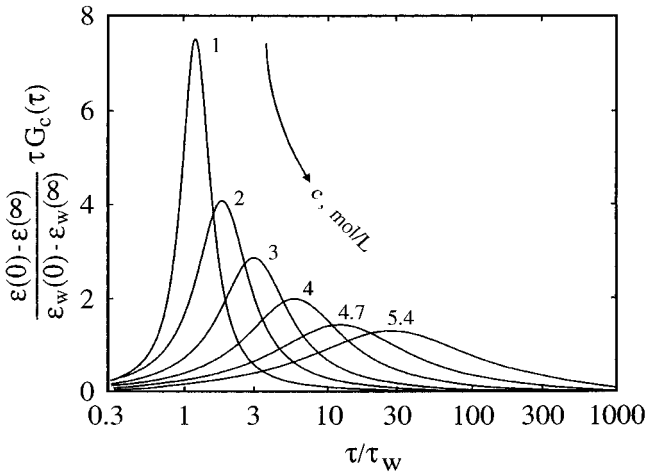

Figure 6. Normalized relaxation-time distribution function corresponding with the dielectric spectra of solutions of D-fructose in water at 25 °C.

Cole−Cole Parameters, Relaxation Time Distribution. The parameter h in the relaxation spectral function (eq 5), measuring the width of the underlying relaxation time distribution, increases with monosaccharide content and adopts values up to 0.35 (Table 2). To illustrate the effect of these Cole−Cole parameter values, the relaxation-time distribution function (eq 4) for the aqueous solutions of D-fructose is shown as a function of the relaxation time ratio τ/τ_w in Figure 6. In that diagram, reduced $\tau G_C(\tau)$ values are given in order to account for the variation of the relaxation strength $\epsilon(0) - \epsilon(\infty)$ with solute concentration. The range of τ/τ_w values selected in this plot roughly corresponds with the frequency range of measurements, thus indicating that, at all solute concentrations under consideration, the distribution function is determined over a significant range of relaxation times by the measurements.

Hence the use of the "static" shear viscosity in the Debye model of relaxation, which predicts a dielectric relaxation time proportional to the molecular volume, leads to the conclusion that contributions from the rotational motions of the complete monosaccharide molecules seem to play a minor role in the relaxation-time distribution. The small contribution of this mode of dipole reorientation to the dielectric relaxation may be considered to reflect the existence of additional parallel pathways that are promoted by the saccharide flexibility.

Principal Relaxation Time, Trends in the Underlying Molecular Mechanisms. In Figure 7, a common plot of the principal dielectric relaxation time τ_C, as a function of molal concentration m of solute, is shown for the D-glucose/water and the D-fructose/water systems, and also for aqueous solutions of some nondipolar cyclic solutes. The data for solutions of the aromatic quinoxaline refer to a description of the dielectric spectra, by the Havriliak−Negami spectral function, corresponding with an unsymmetrical relaxation-time distribution. However, this unsymmetry of $\tau G(\tau)$ is of minor importance here. To account for the large ranges of molality and relaxation time values, a bilogarithmic plot is given in Figure 7. As far as data are available, the τ_C versus m relations for the monosaccharide solutions develop between those of the 1,4-dioxane and the 1,4-diazabicyclo[2,2,2]octane (triethylenediamine, TED) solutions. The data for quinoxaline fit into the general trend indicated by the relaxation times for the other systems, though, due to the

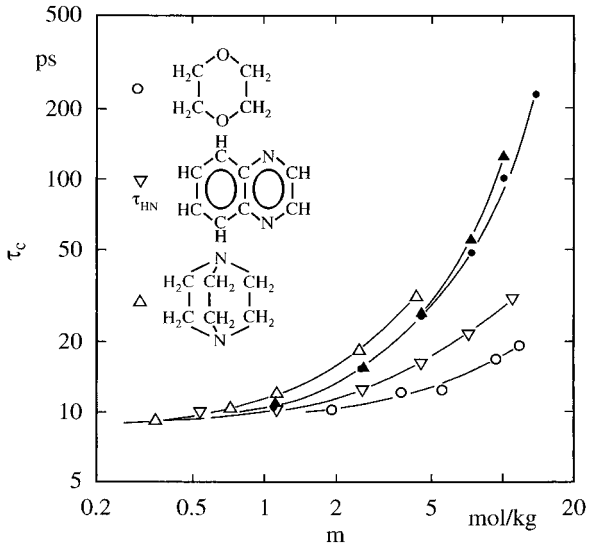

Figure 7. Principal dielectric relaxation time versus molal concentration of solute for aqueous solutions of D-glucose (●), D-fructose (▲), 1,4-dioxane (○, refs 32, 44), quinoxaline (▽, ref 45), and 1,4-diazabicyclo-[2,2,2]octane (△, TED, ref 38). The characteristic Havriliak−Negami[17] relaxation time τ_{HN} is shown for the quinoxaline/water system, the Cole−Cole[33] relaxation time τ_C for the others.

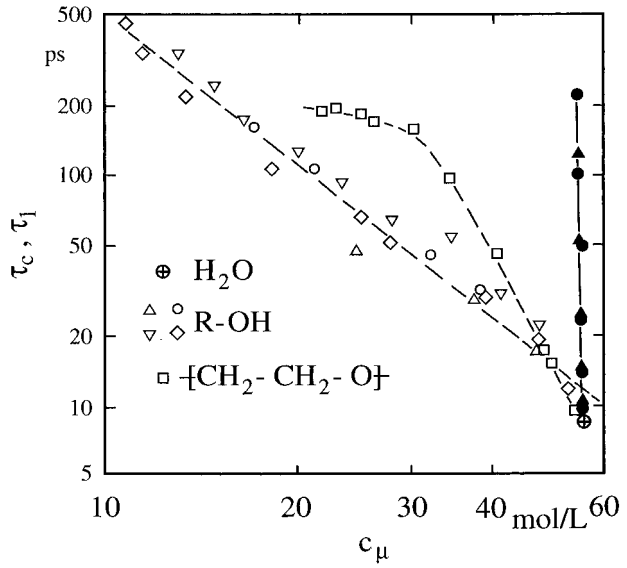

Figure 8. Relaxation time τ_1 of the dominating relaxation process in the dielectric spectra of mixtures of water with monohydric alcohols (△, methanol, ref 47; ○, ethanol, ref 19; ▽, 2-propanol, ref 47; ◇, *tert*-butyl alcohol, ref 48) and principal relaxation time τ_C of the Cole−Cole distribution for mixtures of water with poly(ethylene oxide), (□, ref 49) D-glucose (●), and D-fructose (▲) at 25 °C. Results are displayed as a function of the concentration c_μ of hydrogen bonding groups and water molecules. Also shown is the dielectric relaxation time τ_w of water at 25 °C(⊗).

delocalized ring electrons, quinoxaline may be considered a special solute.

With many organic solute/water systems a linear τ_C versus m relaxation is found at small solute concentrations. Therefore, the limiting relative molal shift in the principal relaxation time, defined by

$$B_d = \frac{1}{\tau_w} \lim_{m \to o} \frac{d\tau_C}{dm} \tag{12}$$

may be simply calculated from the difference quotient

$$B_d = \frac{1}{m}\left(\frac{\tau_C}{\tau_w} - 1\right) \tag{13}$$

at small m. $B_d = 0.25 \pm 0.02$ (mol/kg)$^{-1}$ is found for D-glucose and $B_d = 0.26 \pm 0.02$ (mol/kg)$^{-1}$ for D-fructose, whereas $B_d = 0.13 \pm 0.03$ (mol/kg)$^{-1}$ for 1,4-dioxane and $B_d = 0.36 \pm 0.02$ (mol/kg)$^{-1}$ for TED. Within the homologous series of solutes a tendency normally exists for the B_d values to increase with the hydrophobic part of the solute molecule, for instance $B_d = 0.13$, 0.19, 0.25, and 0.32 (mol/kg)$^{-1}$ for aqueous solutions of pyrazine, methylpyrazine, 2,6-dimethypyrazine, and 2,3,5-trimethylpyrazine, respectively.[18] This behavior suggests that the B_d values monotonously depend on the hydrophilic/hydrophobic balance, $N_n = n_{phil}/n_{phob}$, of the solute. Here n_{phil} denotes the number of hydrophilic groups per molecule and n_{phob} denotes the number of hydrophobic groups per molecule. The series of B_d values for solutions of 1,4-dioxane, D-glucose, D-fructose, and TED does not follow the hydrophilic/hydrophobic balance, which is $N_h = 0.5$, 1, and 0.33, respectively, for the solutes. In calculating these N_h values only the number of hydrophilic groups has been considered. The number of hydrogen bonding sites per dipolar group has not been taken into account.

We are aware that a direct comparison of the B_d values may be questioned since, in contrast to the nondipolar 1,4-dioxane and TED, the dipolar D-glucose and D-fructose molecules also contribute to the dielectric spectrum. Hence, the relaxation-time distribution does not only reflect the water properties. The effect from the solute dipoles, however, is small at low monosaccharide concentrations.[11] Thus, the conclusion may be drawn that the hydration properties of D-glucose and D-fructose are not controlled by one simple parameter alone, like the hydrophilic/hydrophobic balance. Other factors, among them the overall size and shape with respect to the water structure, the steric arrangement of the hydrogen-bond donating and accepting abilities, and the flexibility of the solute molecule, are obviously also important in determining the hydration behavior.

The complex hydration characteristics of the monosaccharides are also illustrated by a comparison of the principal relaxation times of the D-glucose and D-fructose solutions with the relaxation times for mixtures of water with monohydric alcohols and with poly(ethylene oxide), PEO. In Figure 8, the relaxation-time values are plotted versus the concentration c_μ of H-bonding groups and water molecules (Table 1). This concentration appears to be a key factor in a recent model, based on computer simulation studies, as briefly described in the Introduction. In conformity with this model, the principal relaxation time τ_C for the aqueous solutions of PEO also decreases with c_μ, even though the τ_c versus c_μ relation is somewhat different from the corresponding plot for the alcohol/water mixtures. The τ_C values for the monosaccharide solutions, however, show an unusually strong dependence upon small changes in c_μ. Empirically, the relation

$$\frac{\tau_C}{\tau_w} = \left(\frac{c_\mu}{c_w}\right)^{-n} \tag{14}$$

holds when $n = 110 \pm 30$ for the monosaccharide solutions, whereas $n = 2.5$ for the series of monohydric alcohol/water mixtures and $n = 6$ for the aqueous solutions of TED (Figure 7). This strikingly high exponent for D-glucose and D-fructose is another indication for the singular properties of these carbohydrates in aqueous solutions.

In view of this outstanding solution behavior, Franks and Grigera have suggested to count the hydroxy groups of the carbohydrate molecules with the water and to consider the

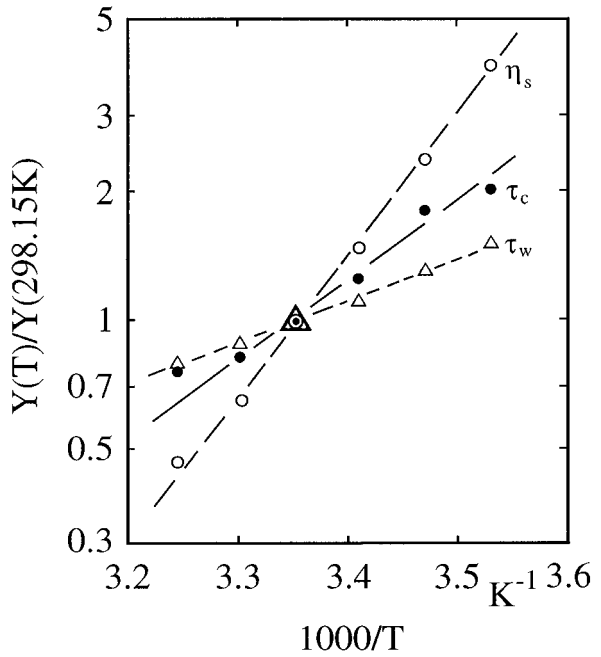

Figure 9. Eyring plot for the shear viscosity η_s and principal relaxation time τ_C of the 5.4 mol/L D-fructose solution and the dielectric relaxation time τ_w of water.

remaining saccharide skeleton a strongly hydrophobic solute.[2] The essence of this view seems, to us, to be almost the perfect spatial correspondence of the equatorial −OH group topology of pyranose rings to the water structure.[2,14,50] If this is accepted as a reason for the extraordinarily strong dependence of the dielectric relaxation time upon c_μ, a similar compatibility may be inferred from our relaxation time data for the furanose tautomers of D-fructose because of the nearly identical τ_c versus c_μ relation of both monosaccharides investigated.

Assuming an activated-jump mechanism of reorientation,[51] an Eyring plot for the temperature dependence of the principal relaxation time τ_C and of the shear viscosity η_s of the most concentrated D-fructose solution is given in Figure 9. Also presented for comparison is the dielectric relaxation time τ_w of water. With the exception of the τ_C value at 35 °C ($T^{-1} = 3.245 \times 10^{-3}$ K^{-1}), the data follow Eyring-type behavior

$$Y(T) = \frac{h}{k_B T} C_Y \exp(\Delta G_Y^{\ddagger}/RT) \qquad (15)$$

In this equation $Y = \tau_C$, η_s, or τ_w, respectively, C_Y denotes a configurational factor, and $\Delta G_Y^{\ddagger} = \Delta H_Y^{\ddagger} - T\Delta S_Y^{\ddagger}$ is the Gibbs free energy of activation that corresponds with the parameter Y. From the straight lines drawn in Figure 9, $\Delta H_{\tau_C}^{\ddagger} = 26$ J/mol, $\Delta H_{\eta_s}^{\ddagger} = 60$ J/mol, and $\Delta H_{\tau_w}^{\ddagger} = 16.8$ J/mol values result. For water, the activation enthalpy for the shear viscosity ($\Delta H_{\eta_{sw}}^{\ddagger} = 14.9$ J/mol from the literature data[52]) nearly agrees with the $\Delta H_{\tau_w}^{\ddagger}$ value obtained for the dielectric relaxation time. With the concentrated D-fructose solution, however, $\Delta H_{\eta_s}^{\ddagger}$ is substantially larger than $\Delta H_{\tau_C}^{\ddagger}$. Obviously, the static viscosity contains contributions which are absent at high frequencies; therefore, the (micro)viscosity to be used in the Debye model of dielectric relaxation is different from η_s. These contributions may be related to conformational changes, like ring inversion, of D-fructose which cannot follow the fast variations in the frequency range around $(2\pi\tau_C)^{-1}$.

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