ORIGINAL PAPER

Dipole moment and self-association of cyclohexylsulfamic acid in 1,4-dioxane solution at 298.15 K

Cveto Klofutar · Mateja Ajnihar ·
Nataša Poklar Ulrih · Darja Rudan-Tasic

Abstract The density, refractive index, and electrical permittivity of cyclohexylsulfamic acid in 1,4-dioxane solutions were measured at 298.15 K. The limiting apparent specific volume, refraction, and polarization were calculated from the experimental data. The electrical dipole moment of cyclohexylsulfamic acid was estimated using the Debye, Onsager, and Kirkwood equations. The dipole association of cyclohexylsulfamic acid was treated with the assumption that the dipole moment of dimeric species is zero. The dimerization constant and dipole moment of monomeric species were evaluated.

Introduction

Cyclohexylsulfamic acid and its sodium or calcium salts are intense sweeteners widely used in foods, beverages, and pharmaceuticals [1]. In an aqueous solution of an artificial sweetener some degree of solute–solvent interaction occurs. The taste of a sweet substance in such a medium can be interpreted by understanding the structure and properties of such molecules or ions in aqueous solution [2, 3]. In our previous studies the conductometric [4], volumetric [5], and viscous properties of aqueous solutions of cyclohexylsulfamic acid [6] were studied to elucidate the effect of the individual ionic and molecular species on the solution properties. It has been found that cyclohexylsulfamic acid is a relatively strong acid, and that in aqueous solutions it exists in zwitterionic form [4] (Fig. 1). All of the substances studied so far that appear in zwitterionic form are completely insoluble in nonpolar solvents [7], with the exception of cyclohexylsulfamic acid.

The electric dipole moment of cyclohexylsulfamic acid has been determined previously in the solvents *N,N*-dimethylacetamide and 1-methyl-2-pyrrolidinone [8]. We investigated the volumetric and electric permittivity properties of solutions of cyclohexylsulfamic acid in 1,4-dioxane solution (i.e., in a medium of low relative permittivity). Owing to strong polarization effects which arise from the very large dipole moment of cyclohexylsulfamic acid, besides the Debye equation we also used the Onsager and Kirkwood equations to obtain more reliable values for the electric dipole moment of the acid [9]. The experimental data were treated by using the corresponding apparent specific values to obtain the limiting partial molar values of the solute.

C. Klofutar · M. Ajnihar · N. Poklar Ulrih · D. Rudan-Tasic (✉)
Biotechnical Faculty, University of Ljubljana,
Jamnikarjeva 101, 1000 Ljubljana, Slovenia
e-mail: darja.rudan.tasic@bf.uni-lj.si

N. Poklar Ulrih
e-mail: natasa.poklar@bf.uni-lj.si

D. Rudan-Tasic
Krog-MIT, Tržaška cesta 43, 1000 Ljubljana, Slovenia
e-mail: info@krog-mit.com

Results and discussion

Apparent specific quantity of solute and partial specific quantity of solute and solvent

The density ρ, refractive index n_D, and relative permittivity ε of the investigated solutions are given in Tables 1, 2 and 3 as a function of (solute/solvent) mass ratio ς_2. The partial

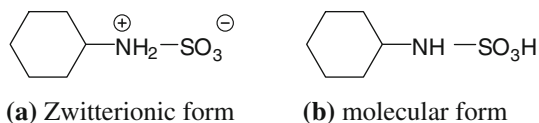**(a)** Zwitterionic form   **(b)** molecular form

Fig. 1 Structural formulae of cyclohexylsulfamic acid. **a** Zwitterionic form, **b** molecular form

Table 1 Density (ρ) of a 1,4-dioxane solution of cyclohexylsulfamic acid and the apparent specific volume (v_Φ) of cyclohexylsulfamic acid as a function of the (solute/solvent) mass ratio (ς_2) at 298.15 K

ς_2	ρ (g cm^{-3})	v_Φ (cm^3 g^{-1})
0.01098	1.03083	0.71997
0.01825	1.03274	0.71951
0.02673	1.03493	0.71973
0.03854	1.03793	0.72001
0.04742	1.04015	0.72018
0.05522	1.04206	0.72058
0.06652	1.04481	0.72069
0.07286	1.04631	0.72106
0.08131	1.04830	0.72132
0.09014	1.05035	0.72159
0.09938	1.05244	0.72210
0.11015	1.05485	0.72253
0.11868	1.05672	0.72292

Table 2 Refractive index (n_D) of a 1,4-dioxane solution of cyclohexylsulfamic acid and the apparent specific refraction (r_Φ) of cyclohexylsulfamic acid as a function of the (solute/solvent) mass ratio (ς_2) at 298.15 K

ς_2	n_D	r_Φ (cm^3 g^{-1})
0.01098	1.42093	0.22549
0.01825	1.42155	0.22604
0.02673	1.42220	0.22507
0.03854	1.42310	0.22453
0.04742	1.42384	0.22515
0.05522	1.42435	0.22431
0.06652	1.42520	0.22436
0.07286	1.42562	0.22409
0.08131	1.42630	0.22458
0.09014	1.42688	0.22430
0.09938	1.42753	0.22437
0.11015	1.42824	0.22425
0.11868	1.42882	0.22433

molar quantities of solute and solvent were analyzed via corresponding apparent specific quantities. The apparent specific quantity y_Φ [10] was calculated by Eq. 1, where y is the specific quantity of the solution and y_1^0 is the corresponding quantity of an appropriate amount of pure solvent, as

Table 3 Relative permittivity (ε) of a 1,4-dioxane solution of cyclohexylsulfamic acid and the apparent specific polarization (p_Φ, p_Φ^*) according to the Debye and Onsager models, respectively, as a function of the (solute/solvent) mass ratio (ς_2) at 298.15 K

ς_2	ε	p_Φ (cm^3 g^{-1})	p_Φ^* (cm^3 g^{-1})
0.01004	2.482	4.327	6.530
0.01374	2.567	4.117	6.305
0.01837	2.674	3.947	6.157
0.02294	2.767	3.751	5.943
0.02737	2.862	3.633	5.849
0.03339	2.983	3.475	5.707
0.03743	3.059	3.372	5.607
0.04223	3.153	3.280	5.356
0.04537	3.216	3.230	5.508
0.05169	3.338	3.130	5.439
0.05508	3.400	3.075	5.395

$$y_\Phi = \frac{(y - y_1^0)}{\varsigma_2} \quad (y = v, r, p) \tag{1}$$

where v denotes the specific volume, r the specific refraction, and p the specific polarization of the solution.

The apparent specific quantity of solute is not seriously influenced by the uncertainty in the mass ratio, but it is very sensitive to experimental uncertainties in the specific quantity of the solution at high dilutions. The error in y_Φ due to the uncertainty in the mass ratio is given by Eq. 2, and that due to the uncertainties in y and y_1^0 (i.e., δy and δy_1^0) is given by Eq. 3:

$$(\delta y_\Phi)_{\varsigma_2}^2 = \left(-\frac{y_\Phi}{\varsigma_2}\right)^2 (\delta \varsigma_2)^2 \tag{2}$$

$$(\delta y_\Phi)_y^2 = \frac{1}{\varsigma_2^2}[(\delta y)^2 + (\delta y_1^0)^2] \tag{3}$$

The total uncertainty is thus $(\delta y_\Phi)_{tot}^2 = (\delta y_\Phi)_{\varsigma_2}^2 + (\delta y_\Phi)_y^2$.

The dependence of the apparent specific quantity of solute on ς_2 at a definite temperature and for a non-electrolyte solution is conventionally given by Eq. 4:

$$y_\Phi = y_\Phi^\infty + a_y \varsigma_2 + a_{yy} \varsigma_2^2 + \cdots \tag{4}$$

where y_Φ^∞ represents the specific apparent quantity of solute at infinite dilution, equal to the limiting partial specific quantity of solute, and y_2^0, a_y, a_{yy}, … are regression constants that depend on the solute, solvent, and temperature. The partial specific quantity of solute y_2 may be obtained from the relation [10]

$$y_2 = \varsigma_2 \left(\frac{\partial y_\Phi}{\partial \varsigma_2}\right)_T + y_\Phi \tag{5}$$

Taking into account Eq. 4, y_2 is given by

$$y_2 = y_\Phi^\infty + 2a_y\varsigma_2 + 3a_{yy}\varsigma_2^2 + \cdots \qquad (6)$$

An analogous relation can be obtained for the partial specific quantity of solvent:

$$y_1 = y_1^0 - a_y\varsigma_2^2 - 2a_{yy}\varsigma_2^3 - \cdots \qquad (7)$$

where y_1^0 is the partial specific quantity of solvent equal to the specific quantity of pure solvent. The corresponding partial molar quantities (i.e., the partial molar quantity of solute Y_2 and that of the solvent Y_1) are obtained by multiplying y_2 or y_1 by the molecular weight of the solute and solvent.

Partial molar volume of cyclohexylsulfamic acid in 1,4-dioxane

From the density of solution, given in Table 1, the apparent specific volume of solute v_Φ was calculated from Eq. 1, where $y = v = (1 + \varsigma_2)/\rho$ and $y_1^0 = v_1^0 = 1/\rho_1^0$; ρ and ρ_1^0 are the density of solution and that of the pure solvent, respectively. For 1,4-dioxane we used a value of $\rho_1^0 = 1.02792$ g cm^{-3}, which is close to the literature value ($\rho = 1.02797$ g cm^{-3}) [11]. The v_Φ values are collected in Table 1. The uncertainty in v_Φ is 6×10^{-5} cm^3 g^{-1} at the highest value of ς_2 and 7×10^{-4} cm^3 g^{-1} at the lowest ς_2 value.

The apparent specific volume of cyclohexylsulfamic acid can be represented by the quadratic form of Eq. 4, where $y_\Phi^\infty \equiv v_\Phi^\infty$ is the limiting apparent specific volume of solute, equal to the limiting partial specific volume of solute v_2^0, and a_v and a_{vv} are the regression constants of Eq. 4. The parameters of Eq. 4 were calculated by a least squares procedure and amount to $v_\Phi^\infty = (0.7196 \pm 0.0001)$ cm^3 g^{-1}, $a_v = (0.003 \pm 0.005)$ cm^3 g^{-1}, and $a_{vv} = (0.21 \pm 0.04)$ cm^3 g^{-1}, with a standard error in the estimate of 1.4×10^{-4} cm^3 g^{-1}. The partial molar volume of cyclohexylsulfamic acid at infinite dilution was calculated from the limiting apparent specific volume and found to be $V_2^0 = (128.9 \pm 0.1)$ cm^3 mol^{-1}. This value is close to the van der Waals volume of cyclohexylsulfamic acid determined earlier, $V_{vdW} = 128.0$ cm^3 mol^{-1} [12], and to the crystal molar volume, $V_2^* = 127.93$ cm^3 mol^{-1} [13]. A comparison of the limiting partial molar volume of cyclohexylsulfamic acid V_2^0 and the corresponding crystal volume V_2^*, calculated from the density of pure solute [13], shows that V_2^0 is greater than V_2^*. The ratio of V_2^0 to V_2^* is 1.01 ± 0.02. Thus, the value of the partial molar excess volume of solute V_2^E, as given by Eq. 8:

$$V_2^E = V_2^0 - V_2^* \qquad (8)$$

is positive. Hence, the value of the partial molar excess volume, which characterizes the volume changes associated with the transfer of one mole of solute from its pure state to solution at infinite dilution, is positive and relatively small; $V_2^E = (1.0 \pm 0.1)$ cm^3 mol^{-1}.

Assuming that the molar volume of solute V_2^* consists of the volume of $N_A v_{vdW}$ (that is, the van der Waals molecular volume of the solute v_{vdW} multiplied by Avogadro's constant) plus a varying amount of empty space between the solute molecules, then the ratio of the molar volume of pure solute to the van der Waals volume depends only on the properties of the substance. Thus, the empty space in the structure of the pure solute depends on the shape of the molecules, any hydrogen bonding, and other intermolecular interactions. For relatively nonpolar substances, this ratio V_2^*/V_{vdW} is ≈ 1.5 [14], while for cyclohexylsulfamic acid it is 1.0. On the other hand, from the ratio of V_2^0 to V_{vdW}, which is 1.01, it follows that the empty space between the solute molecules in 1,4-dioxane solution is practically the same as that in the pure solute.

The partial specific volumes of solute v_2 and solvent v_1 were calculated via Eqs. 6 and 7. The values of v_2 slightly increase with mass ratio while those of v_1 slightly decrease and are close to the v_1^0 value of 1,4-dioxane.

The associative solute–solute interactions can be obtained from the volumetric properties of the non-electrolyte solution. Equation 4 can also be represented in the following form for volumetric data:

$$v = v_1^0 + v_2^0\varsigma_2 + a_v\varsigma_2^2 + a_{vv}\varsigma_2^3 \qquad (9)$$

where $v^E = v - v_1^0 - v_2^0\varsigma_2$ is the excess specific volume of the solution. Taking into account that $\varsigma_2 = bM_2$, where b is the molality (mol kg^{-1}), the Eq. 9 may be given as

$$V_{1,2} = V_1^0 + V_2^0 b + V_v b^2 + V_{vv} b^3 \qquad (10)$$

where $V_{1,2}$ is the volume of solution containing 1.0 kg of solvent and b moles of solute, V_1^0 is the volume of 1.0 kg of solvent (cm^3 kg^{-1}), and according to the McMillan–Mayer theory of solution [15], V_v and V_{vv} are the virial coefficients that represent the contributions to the volumetric excess property from pair, triplet, and higher-order solute aggregates. The values of V_v and V_{vv} were calculated from the relations

$$V_v = a_v M_2^2 \qquad (11)$$

and:

$$V_{vv} = a_{vv} M_2^3 \qquad (12)$$

and amount to $V_v = (0.09 \pm 0.16)$ cm^3 kg mol^{-2} and $V_{vv} = (1.21 \pm 0.23)$ cm^3 kg^2 mol^{-3}. These parameters of Eq. 10 are positive and could yield information on solute–solute as well as solvent–solvent interactions. From the positive values of V_v and V_{vv} it may be concluded that association of cyclohexylsulfamic acid molecules occurs in 1,4-dioxane [15, 16].

Partial molar refraction of cyclohexylsulfamic acid

The specific refraction of the solution, i.e., $y \equiv r = (n_D^2 - 1)v/(n_D^2 + 2)$, was calculated from the refractive index given in Table 2 and the specific volume, and the apparent specific refraction of cyclohexylsulfamic acid was obtained via Eq. 1. The uncertainty in the value of r_Φ calculated by Eqs. 2 and 3 at the lowest mass ratio is 6×10^{-4} cm^3 g^{-1}, and at the highest value 6×10^{-5} cm^3 g^{-1}. When calculating the r_Φ values, a value of $n_D^0 = 1.42001$ was used for the refractive index, which is somewhat lower than the literature value, $n_D = 1.42025$ [11]. The apparent specific refraction of cyclohexylsulfamic acid is given in Table 2. As can be seen from this table, the apparent specific refraction of the solute does not show any dependence on mass ratio, so we calculated a weighted average value using the reciprocal value of the squared error of r_Φ, i.e., $1/(\delta r_\Phi)^2$, as the weight. The value of the limiting apparent specific refraction amounts to $r_\Phi^0 = (0.2244 \pm 0.0002)$ cm^3 g^{-1}, and the limiting partial molar refraction of cyclohexylsulfamic acid is $R_2^0 = (40.22 \pm 0.04)$ cm^3 mol^{-1}. The molar refraction of cyclohexylsulfamic acid, calculated from the respective atomic or atomic group refractions, as given by Vogel [17–19], amounts to 43.1 cm^3 mol^{-1}.

Partial molar polarization of cyclohexylsulfamic acid

The polarization of the solution and consequently the apparent specific polarization of solute depends on the theoretical model used [9]. The Debye model, as applied to homogeneous fluid mixtures, gives the following expression for the specific polarization of solution p:

$$p = \frac{(\varepsilon - 1)}{(\varepsilon + 2)}v \qquad (13)$$

An analogous relation is valid for the specific polarization of pure solvent. This theory is quite successful for dilute solutions in nonpolar solvents. The Onsager model, which can be used for solutions in polar solvents, and which takes into account the reaction field, yields the following for the specific polarization of solution p^*:

$$p^* = \frac{(\varepsilon - 1)(2\varepsilon + 1)}{9\varepsilon}v \qquad (14)$$

and an analogous relation for the specific polarization of pure solvent. The Onsager theory becomes inaccurate for solutions in which there is molecular complexing between solute and solvent. For such systems, Kirkwood derived a general theory that allows for the coupling of dipoles due to molecular complexing. His expression for the polarization of solution $p^\dagger$ is formally identical to Onsager's equation; i.e., $p^* \equiv p^\dagger$ [9].

The apparent specific polarization of solute was calculated from the relative permittivity data collected in Table 3 and the specific volume via Eq. 1, using Eq. 13 (Debye model) and Eq. 14 (Onsager's model) for the polarization of solution. When calculating the apparent specific polarization of solute, we used a value of $\varepsilon_0 = 2.216$ for the relative permittivity of 1,4-dioxane, which is about 0.3 per cent higher than that given in the literature ($\varepsilon_0 = 2.209$) [11, 20]. The uncertainty in the p_Φ value given by Eqs. 2 and 3 for the Debye model at the lowest mass ratio is 0.05 cm^3 g^{-1} and 0.004 cm^3 g^{-1} at the highest value, and for Onsager's model it is 0.03 cm^3 g^{-1} at the lowest mass ratio and 0.006 cm^3 g^{-1} at the highest mass ratio.

The apparent specific polarization of the solute as a function of mass ratio for both models (Eqs. 13, 14) can be expressed by Eq. 4 in quadratic form. The values of the parameters calculated by a least squares procedure are: Debye model: $p_\Phi^\infty = (4.79 \pm 0.03)$ cm^3 g^{-1}, $a_p = -(54 \pm 2)$ cm^3 g^{-1}, and $a_{pp} = (412 \pm 33)$ cm^3 g^{-1}, with a standard error in the estimate of 0.02 cm^3 g^{-1}; and for the Onsager model: $p_\Phi^{\infty *} = (7.00 \pm 0.04)$ cm^3 g^{-1}, $a_{p*} = -(55 \pm 3)$ cm^3 g^{-1}, and $a_{p*p*} = (484 \pm 43)$ cm^3 g^{-1}, with a standard error in the estimate of 0.03 cm^3 g^{-1}. As an example, Fig. 2 shows the dependence of the partial specific polarizations of solute p_2^* and solvent p_1^* (Onsager and Kirkwood models) on the mass ratio at 298.15 K. The partial specific values were calculated according to Eqs. 6 and 7. Figure 2 shows that p_2^* strongly depends on the mass ratio of the solute, while p_1^* values are almost constant and amount to an average value of (0.339 ± 0.008) cm^3 g^{-1} relative to the value for pure solvent, $p_1^{0*} = 0.322$ cm^3 g^{-1}. Furthermore, p_2^* reaches a minimum value at $\varsigma_2 = 0.03815$. The decrease in the p_2^* values may be ascribed to the disappearance of strongly polar monomeric species and to the
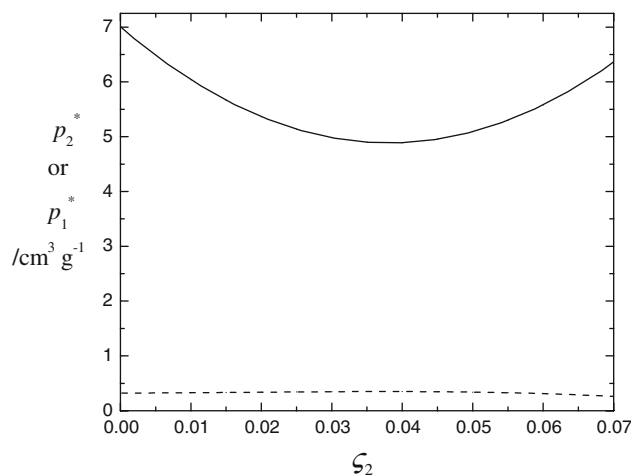

Fig. 2 Dependence of the partial specific polarizations of solute p_2^* (*solid line*) and solvent p_1^* (*dashed line*) on the (solute/solvent) mass ratio (ς_2) at 298.15 K

appearance of nonpolar or slightly polar species. A similar plot to that shown in Fig. 2 can be also obtained for p_2 or p_1 values (Debye model). The corresponding limiting apparent molar values amount to $P_\Phi^\infty = (859 \pm 6)$ cm^3 mol^{-1} and $P_\Phi^{\infty *} = (1{,}255 \pm 7)$ cm^3 mol^{-1} for the Debye and Onsager models, respectively. The limiting apparent specific or molar polarization of solute for the Onsager model is substantially higher than that for the Debye model.

Electrical dipole moment of cyclohexylsulfamic acid

According to the Debye model, the partial molar polarization of solute at infinite dilution is given by [9]

$$P_2^0 = \frac{4\pi N_A}{3}\left(\alpha_e + \frac{\mu_2^2}{3kT}\right) \tag{15}$$

where μ_2 is the permanent molecular electric dipole moment, k is Boltzmann's constant, α_e is the electronic polarizability of solute, and T is the absolute temperature. When calculating μ_2 via Eq. 15, the electronic polarizability was multiplied by a factor of 1.05 to allow for atomic polarization [21]. The electronic polarization was calculated from the limiting partial molar refraction of solute R_2^0 as $\alpha_e = 3R_2^0 \times 1.05/4\pi N_A = 1.7 \times 10^{-23}$ cm^3. The value of the permanent molecular dipole moment amounts to $\mu_2 = (2.109 \pm 0.008) \times 10^{-29}$ C m.

Onsager's model leads to the partial molar polarization of solute at infinite dilution as [9]

$$P_2^{0*} = \frac{4\pi N_A}{3}\left(\alpha_e^* + \frac{(\mu_2^*)^2}{3kT}\right) \tag{16}$$

where α_e^* is the effective polarizability of solute and μ_2^* is Onsager's dipole moment. Onsager's relationship between α_e^* and α_e is given by Eq. 17 [9], where μ_2^0 is the dipole moment of solute in the gas phase:

$$\frac{\mu_2^0}{\mu_2^*} = \frac{\alpha_e}{\alpha_e^*} = 1 - \frac{4\pi N_A \alpha_e (2\varepsilon_0 - 2)}{3\,V_2^0(2\varepsilon_0 + 1)} \tag{17}$$

The effective polarizability of solute amounts to $\alpha_e^* = 2 \times 10^{-23}$. This value is substantially higher than α_e, as is Onsager's electric dipole moment, which amounts to $\mu_2^* = (2.563 \pm 0.007) \times 10^{-29}$ C m. Holt and Sears [8] determined the dipole moment of cyclohexylsulfamic acid in the solvents N,N-dimethylacetamide and 1-methyl-2-pyrrolidinone via Onsager's procedure and obtained values of 2.68×10^{-29} C m in N,N-dimethylacetamide and 2.52×10^{-29} C m in 1-methyl-2-pyrrolidinone. The agreement between our value and that determined in 1-methyl-2-pyrrolidinone is quite good, while the value determined in N,N-dimethylacetamide is somewhat higher.

The partial molar polarization of solute at infinite dilution on the basis of Kirkwood's theory is expressed as [9]

$$P_2^{0\dagger} = \frac{4\pi N_A}{3}\left(\alpha_e + \frac{g_2(\mu_2^\dagger)^2}{3kT}\right) \tag{18}$$

in which $\mu_2^\dagger$ is Kirkwood's molecular dipole moment in solution, including any enhancement due to the reaction field, and g_2 is a correlation factor whose deviation from unity allows for coupling between the orientation of the given dipole and the surrounding dipoles. Generally g_2 will deviate substantially from unity if this coupling is quite strong [22]; ordinary dipole–dipole coupling alone is not enough. Beyond that, g_2 is also a function of composition. However, in dilute solution it is sufficient to assume that g_2 is constant for the solute [23]. From Eq. 18 it follows that the value of g_2 is characteristic of the molecular species. The calculated product $g_2^{1/2} \times \mu_2^\dagger$ for cyclohexylsulfamic acid amounts to $g_2^{1/2} \times \mu_2^\dagger = (2.570 \pm 0.007) \times 10^{-29}$ C m. Since Onsager's electric dipole moment and Kirkwood's product are equal within experimental error, it may be assumed that the coupling between a given dipole and the dipoles surrounding it is small.

Because Kirkwood's theory is exact and Onsager's theory is approximate, the dipole moment μ_2^* calculated by Onsager's method (Eq. 16) is always at least somewhat approximate. μ_2^* is related to the exact value $\mu_2^\dagger$, given by Kirkwood's theory, by Eq. 19:

$$(\mu_2^*)^2 = g_2(\mu_2^\dagger)^2 + \frac{dg_1}{dc_2}\frac{(\mu_1^\dagger)^2}{V_1^0} \tag{19}$$

in which V_1^0 denotes the molar volume, $\mu_1^\dagger$ and g_1 are the molecular dipole moment and Kirkwood's correlation factor for the solvent, and c_2 is the concentration of solute in moles per cubic centimeter. For a nonpolar solvent, it follows from Eq. 19 that $(\mu_2^*)^2 = g_2(\mu_2^\dagger)^2$, while for a slightly polar solvent like 1,4-dioxane with $\mu_2 = 1.501 \times 10^{-30}$ C m [11], the product $(dg_1/dc_2)(\mu_1^*)^2/V_1^0$ for a dilute solution diminishes and Onsager's dipole moment is equal to the Kirkwood product.

Self-association of cyclohexylsulfamic acid

If association of solute species occurs, the volume polarization should increase less rapidly with increasing concentration than would be observed in the case of no interaction between the solute dipole moments. The decrease in the partial specific polarization of cyclohexylsulfamic acid with increasing mass ratio (Fig. 2) can be interpreted as being due to the association of polar solute species. When two polar molecules come into contact in a nonpolar solvent, dimer formation may be expected due to dipole attraction. Depending on the geometry of the molecule, the stable configuration would be formed with the dipole axes parallel or antiparallel [9]. An interaction of this sort could be described by [24]

$$2B_\mathrm{m} \leftrightarrow B_\mathrm{d} \tag{20}$$

and

$$K_\mathrm{D} = \frac{[B_\mathrm{d}]}{[B_\mathrm{m}]^2} = \frac{(1-\gamma)}{2\,c\gamma^2} \tag{21}$$

where B_m and B_d are the monomeric and dimeric species, K_D is the association constant, c is the concentration in mol dm^{-3}, and γ is the fraction of solute present as monomer. In Eq. 21 it is assumed that the activity coefficients of the monomer and dimer species can be approximated by unity.

In dilute solutions in a solvent of low electric permittivity, the volume polarization can be approximated by [9]

$$\frac{(\varepsilon-1)}{(\varepsilon+2)} = \frac{4\pi}{3}\sum n_i\alpha_i \tag{22}$$

where n_i is the number of molecules of species i per unit volume, and α_i is their polarization. The latter is given by

$$\alpha_i = \alpha_e + \mu_i^2/3kT \tag{23}$$

where α_e is the electronic polarization and μ_i is the dipole moment of species i. Subscripts are defined as 1 for solvent, m for monomer, and d for dimer. For a solute that dimerizes, Eq. 22 then becomes

$$\frac{(\varepsilon-1)}{(\varepsilon+2)} = \frac{4\pi n_1\alpha_1}{3} + \frac{4\pi N_\mathrm{A}}{3}(c_\mathrm{m}\alpha_\mathrm{m} + c_\mathrm{d}\alpha_\mathrm{d}) \tag{24}$$

where

$$c_\mathrm{m} = \gamma c = \frac{n_\mathrm{m}}{N_\mathrm{A}} \tag{25}$$

and

$$c_\mathrm{d} = \frac{(1-\gamma)c}{2} = \frac{n_\mathrm{d}}{N_\mathrm{A}} \tag{26}$$

are the concentrations (mol dm^{-3}) of monomer and dimer, respectively, and c is the stoichiometric concentration of polar solute. There is a procedure in [24] that shows how Eq. 24 can be transformed into a function of concentration and relative permittivity such that a linear plot results, with μ_m determined by the intercept at zero concentration and K_D by the slope of the line. The transformation essentially amounts to eliminating the properties of the solvent from Eq. 21, so that the properties of the solute can be seen directly. The result is

$$\frac{(\varepsilon-\varepsilon_1^0)}{(\varepsilon+2)} = (\varepsilon_1^0-1)(\beta-M_2)\frac{c}{3\rho_1^0} + \frac{4\pi N_\mathrm{A}}{9}(\varepsilon_1^0+2)$$
$$(c_\mathrm{m}\alpha_\mathrm{m} + c_\mathrm{d}\alpha_\mathrm{d}) \tag{27}$$

where M_2 is the molecular weight of solute, and ρ_1^0 and β are coefficients in the empirical relation for the density of solution:

$$\rho = \rho_1^0 + \beta c \tag{28}$$

If we introduce the following function $F(\varepsilon)$ of the observed electric permittivity and concentration [24]:

$$F(\varepsilon) = \frac{9}{4\pi N_A(\varepsilon_1^0+2)}\left\{\frac{(\varepsilon-\varepsilon_1^0)}{(\varepsilon+2)} - \left[(\varepsilon_1^0-1)(\beta-M_2)\frac{c}{3\rho_1^0}\right]\right\}$$
$$= \frac{1.1893\times10^{-21}}{(\varepsilon_1^0+2)}[f_1(\varepsilon,\varepsilon_1^0)-f_2(\varepsilon_1^0,\beta,M_2,\rho_1^0)c] \tag{29}$$

it follows also that

$$F(\varepsilon) = c_\mathrm{m}\alpha_\mathrm{m} + c_\mathrm{d}\alpha_\mathrm{d} \tag{30}$$

Substituting for c_m and c_d from Eqs. 25 and 26 in 30 and then rearranging, we obtain the following relation:

$$\frac{F(\varepsilon)}{c} - \frac{\alpha_\mathrm{d}}{2} = \gamma\left(\alpha_\mathrm{m} - \frac{\alpha_\mathrm{d}}{2}\right) \tag{31}$$

Defining the quantity on the left side of Eq. 31 as $G(\varepsilon)$, defining the constant A via

$$\frac{1}{A} = \alpha_\mathrm{m} - \frac{\alpha_\mathrm{d}}{2} \tag{32}$$

so that $\gamma = AG(\varepsilon)$, and then using Eq. 21, the extrapolation function gives

$$\frac{1}{G(\varepsilon)} = A + 2K_\mathrm{D}A^2G(\varepsilon)c \tag{33}$$

For molecules which dimerize and have an antiparallel side-by-side configuration [9] μ_d is zero, so $\alpha_\mathrm{d} = \alpha_{\mathrm{d},e}$ (i. e., the electronic polarization of the dimer), which can simply be set equal to $2\alpha_{\mathrm{m},e}$. Then

$$G(\varepsilon) = \frac{F(\varepsilon)}{c} - \alpha_{\mathrm{m,e}} \tag{34}$$

and

$$\mu_\mathrm{m}^2 = \frac{3kT}{A} \tag{35}$$

When calculating $F(\varepsilon)$ and $G(\varepsilon)$ we used the electronic polarization of the monomer, as determined from the limiting partial molar refraction of solute multiplied by 1.05. The concentration of solute c in mol dm^{-3} was obtained from the mass ratio and the density of solution as $c = (\varsigma_2\rho\times10^3)/M_2(1+\varsigma_2)$. The parameter β was calculated from the linear plot of ρ (kg dm^{-3}) versus c (mol dm^{-3}) (see Eq. 28), and amounts to $\beta = (0.04601 \pm 0.00008)$ kg mol^{-1}. A plot of Eq. 33 is given in Fig. 3, from which it follows that the assumption of an antiparallel arrangement of monomeric units in the dimeric species is correct. The value of the slope of Eq. 33 amounts to $(3.39 \pm 0.03)\times10^{43}$, and the intercept to $(2.89 \pm 0.01)\times10^{21}$, from which dimerization constant and dipole moment of the monomeric species were calculated. They amount to $K_\mathrm{D} = 2.04 \pm 0.04$ and $\mu_\mathrm{m} = (2.18 \pm 0.01)\times10^{-29}$ C m.
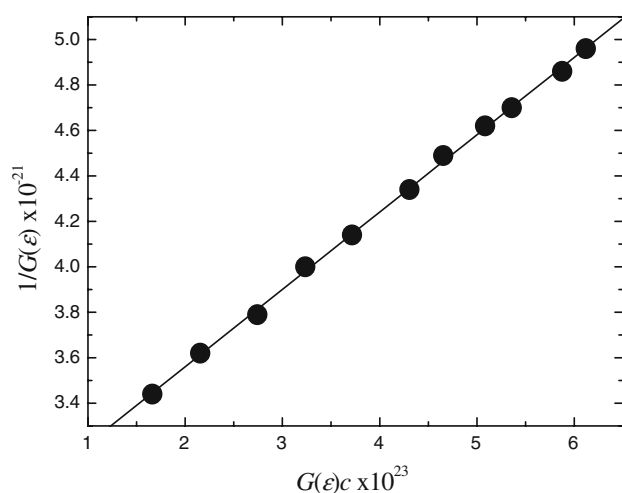
Fig. 3 Dependence of the function $1/G(\varepsilon)$ on $G(\varepsilon)c$ (see Eq. 33) for 1,4-dioxane solutions of cyclohexylsulfamic acid at 298.15 K

The calculated dipole moment of the monomeric species is about 7×10^{-31} C m, which is higher than that calculated from the Debye procedure (see Eq. 15). The dimerization constant is of the expected order of magnitude for reasonably polar molecules in 1,4-dioxane [24]. The fraction of monomer γ, calculated from Eq. 21, is relatively high and amounts to 0.837 at the lowest and $\gamma = 0.798$ at the highest concentration studied. The relatively high value of γ may be ascribed to the strong association of molecules of cyclohexylsulfamic acid with molecules of 1,4-dioxane via hydrogen bonds between the acidic proton of cyclohexylsulfamic acid and the basic oxygen atoms of 1,4-dioxane.

A prominent feature of cyclohexylsulfamic acid is that it can exist in aqueous solution as a neutral molecule or in the zwitterionic form [4, 25]. Owing to the solubility of cyclohexylsulfamic acid in 1,4-dioxane, it may be concluded that it exists in a molecular form with a relatively high dipole moment [7]. The zwitterionic structure can be eliminated by considering the X-ray structure of the acid [13]. If we assume that the center of the positive charge is located on the nitrogen atom and the center of the negative charge is located on the oxygen atom O_1, the dipole distance r is found to be (0.298 ± 0.007) nm [13], which corresponds to a dipole moment of 4.77×10^{-29} C m. This value is considerably larger than those calculated by the Debye model (Eq. 15) or the Onsager model (Eq. 16). The nonpolar dimeric arrangement of cyclohexylsulfamic acid may be assumed to be a discrete arrangement of monomeric polar units in an antiparallel side-by-side configuration without further interactions. The same arrangement was also found in crystalline cyclohexylsulfamic acid [13].

Conclusion

The positive value of the partial molar excess volume and the ratio of molar volume or limiting partial molar volume to the van der Waals volume of cyclohexylsulfamic acid indicate that the empty space between the molecules of cyclohexylsulfamic acid in 1,4-dioxane solutions is practically the same as it is in the pure crystalline solute. The volumetric parameters of the McMillan–Mayer theory of solution clearly show that molecules of cyclohexylsulfamic acid are solvated with solvent molecules and that self-association of cyclohexylsulfamic acid molecules occurs in 1,4-dioxane. Onsager's electric dipole moment and the Kirkwood product of molecules of cyclohexylsulfamic acid in 1,4-dioxane are substantially lower than the electric dipole moment calculated from the X-ray structure of the acid. Based on these data, the zwitterionic structure of cyclohexylsulfamic acid was excluded and a highly polar molecular form was ascertained. In 1,4-dioxane, dipole–dipole association of cyclohexylsulfamic acid molecules involving an antiparallel arrangement of monomeric units occurs, just as in the pure crystalline state of cyclohexylsulfamic acid. The fraction of monomeric species is relatively high, which was ascribed to strongly hydrogen-bonded solvation of the molecules of cyclohexylsulfamic acid by 1,4-dioxane molecules.

Experimental

Chemicals

Commercially available cyclohexylsulfamic acid (HCy) was purchased from Sigma and 1,4-dioxane (p.a.) from Kemika. The compounds were used as delivered without further purification and stored in a desiccator over P_2O_5. The purity of the acid was checked by titration with sodium tetraborate and also by analysis of the elements C, H, and N (Perkin Elmer, 2400 Series II CHNS/O analyzer); it was found to be at least 99.9% pure. The purity of 1,4-dioxane was checked by comparing its experimental density and refractive index with data reported previously ($n_D = 1.42025$) [11], and the agreement was found to be within experimental uncertainty ($\pm 2 \times 10^{-5}$). The investigated solutions were prepared on a (solute/solvent) mass ratio ς_2 (i.e., grams of solute per gram of solvent [26]) by precise weighing using a digital balance (Mettler Toledo, model AT201, Switzerland), accurate to within $\pm 1 \times 10^{-5}$ g.

Density measurements

The density ρ (g cm^{-3}) of the 1,4-dioxane solution of cyclohexylsulfamic acid was measured by a vibrating-tube

density meter (Anton Paar, model DMA 60, Graz, Austria) equipped with a measuring cell (Anton Paar, type 602) and a digital thermometer (Anton Paar, DT 100-20) to a precision of ± 0.01 K. The temperature in the measuring cell was regulated to better than ± 0.01 K using an external bath circulator (Haake, DC3-B3, Karlsruhe, Germany). The uncertainty of the density measurements was $\pm 2 \times 10^{-5}$ g cm^{-3}. The density of pure 1,4-dioxane is 1.02792 g cm^{-3}.

Refractive index measurements

The refractive index was measured with a model DUR-W2 Schmidt–Haensch refractometer with an uncertainty of 1×10^{-5}. All measurements were performed at 298.15 K and at a wavelength of 589 nm.

Relative permittivity measurements

Electric permittivities were measured by a WTW dipole meter (model DM 01) using a DFL 1 cell at a constant frequency of 2 MHz. The cell was calibrated beforehand with standard pure liquids (i.e., carbon tetrachloride, benzene, and cyclohexane) [20]. The cell was thermostatted with a temperature stability of better than ± 0.01 K using an external bath circulator (Haake, DC3-B3, Karlsruhe, Germany), and the temperature was controlled by means of a digital thermometer (Anton Paar, DT 100-20) with a precision of ± 0.01 K. The uncertainty of the relative permittivity data was within ± 0.001 U. Since reliable determination of the electric dipole moment required a very low composition of solution where the difference between the solution and solvent permittivity is small, the composition range was selected according to the accuracy of the apparatus.

References

1. Nabors LO'B, Gelardi RC (1991) In: Nabors LO'B, Gelardi RC (eds) Alternative sweeteners. Marcel Dekker Inc., New York, p 1
2. Walters DE (1991) ACS Symp Ser 450:1
3. Shamil S, Birch GG, Mathlouhi M, Clifford MN (1987) Chem Senses 12:397
4. Klofutar C, Luci M, Abramović H (1999) Physiol Chem Phys Med NMR 31:1
5. Klofutar C, Rudan-Tasic D (2006) J Sol Chem 35:395
6. Klofutar C, Horvat J, Rudan-Tasic D (2007) J Mol Liq 131–132:87
7. Wyman J (1936) Chem Rev 3:213
8. Holt TW, Sears PG (1967) Trans Kentucky Acad Sci 28:1
9. Grunwald E, Highsmith S, Ting-Po I (1974) In: Szwarc M (ed) Ions and ion pairs in organic reactions. Wiley, New York, p 448
10. Klotz JM (1964) Chemical thermodynamics. Benjamin WA Inc., New York, p 241
11. Riddick JA, Bunger WB, Sakano TK (1986) Organic solvents: physical properties and methods of purification. Wiley, New York, p 312
12. Rudan-Tasic D, Klofutar C (2004) Food Chem 84:351
13. Leban I, Rudan-Tasic D, Lah N, Klofutar C (2007) Acta Cryst Sec B 63:418
14. Edward JT (1970) J Chem Educ 47:261
15. McMillan WG, Mayer JE (1945) J Chem Phys 13:276
16. Wurzburger S, Sartorio R, Guarino G, Nisi M (1988) J Chem Soc Faraday Trans 184:2279
17. Vogel AI (1948) J Chem Soc 1809
18. Vogel AI (1948) J Chem Soc 1820
19. Vogel AI (1948) J Chem Soc 1825
20. Oehme F, Wirth H. Die Bestimmung des molekularen Dipolmoments. Wissenschaftlich-Technische Werkstätten GmbH, Weilheim, Oberbayern 4/70
21. Böttcher C, Bordewijk P (1978) Theory of electric polarization, vol. 2, 2nd edn. Elsevier, Amsterdam, pp 285, 387
22. Oster G (1946) J Am Chem Soc 68:2036
23. Grunwald E, Effio A (1973) J Sol Chem 2:373
24. Treiner C, Skinner JF, Fuoss RM (1964) J Phys Chem 68:3406
25. Greenwood NN, Earnshaw A (1988) Chemie der Elemente. VCH, Weinheim, p 970
26. Eisenberg H (1976) Biological macromolecules and polyelectrolytes in solution. Clarendon, Oxford, p 29