Solvent Effects on Chemical Processes. Part 6. The Phenomenological Model Applied to the Solubility of Naphthalene and 4-Nitroaniline in Binary Aqueous–Organic Solvent Mixtures

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The phenomenological theory of solvent effects on solubility partitions the free energy of solution into contributions from solvent–solvent interactions (the general medium or solvophobic effect), solvent–solute interactions (the solvation effect), and solute–solute interactions (the intersolute effect). The theory relates the solvent effect on solubility to the mole fractions of the solvent components and the model parameters K_1 and K_2 (which are stepwise solvation exchange constants) and gA (the general medium parameter, where g is a curvature correction factor to the surface tension, and A is the nonpolar surface area of the solute). Solubility data for naphthalene and 4-nitroaniline are given over the entire composition range in aqueous–organic mixtures, the organic cosolvents being methanol, ethanol, propan-2-ol, propane-1,2-diol, ethylene glycol, acetone, dimethyl sulfoxide and acetonitrile. The data are quantitatively described by the model. Cosolvents are classified, on the basis of their polarities (as measured by their octan-1-ol–water partition coefficient P), into a less polar class whose solvation exchange constants increase with log P, and a more hydrophilic class with the opposite tendency. The gA parameter can be reasonably predicted with the empirical relationship $gA = -33.4 \log P_M + 13.4 \log P_R$ (Å^2 mol^{-1}), where M and R refer to the organic cosolvent and the solute, respectively. The product $g(\gamma_2 - \gamma_1)$, where γ_2 and γ_1 are the surface tensions of pure cosolvent and water, respectively, is close to the dispersion surface energy component of water and many other solvents.

Our laboratory has developed a phenomenological model of solvent effects that is based on the separation of the observed effect into contributions from solvent–solvent interactions (the general medium effect), solvent–solute interactions (the solvation effect) and solute–solute interactions (the intersolute effect).[1] This theory is capable of providing quantitative descriptions of solvent effects, in aqueous–organic solvent mixtures, on solubility,[1,2] surface tension,[3] molecular complex formation[4,5] and absorption spectra.[6] The parameters of the model, which are given physical meaning by the theory, are extracted by curve fitting to the experimental data; the parameter estimates appear to have chemically reasonable values. Our current work is directed toward a better understanding of the model parameters and to achieving an ability to predict these quantities. The present paper makes use of solubility data, which have the advantages of high precision and accessibility of the full range of mixed solvent composition.

Theory

Here we are concerned with the solubility of a solid nonelectrolyte in a binary solvent mixture. Let component 1 be water, component 2 an organic cosolvent and component 3 the solute. Experimentally we measure the equilibrium mole fraction solubility of the solute, x_3, as a function of the mole fraction of cosolvent, x_2, in the binary solvent mixture. The free energy of solution per molecule is calculated with eqn. (1), where

$$\Delta G^*_{\text{soln}} = -kT \ln x_3 \qquad (1)$$

k is Boltzmann's constant and T is the absolute temperature. Thermodynamically the standard free energy of solution is related to the solute activity by eqn. (2). It follows that ΔG^*_{soln}

$$\Delta G^\circ_{\text{soln}} = -kT \ln a_3 \qquad (2)$$

and $\Delta G^\circ_{\text{soln}}$ are related by eqn. (3), where f_3 is the solute activity

$$\Delta G^*_{\text{soln}} = \Delta G^\circ_{\text{soln}} + kT \ln f_3 \qquad (3)$$

coefficient. In the following we make no use of activity coefficients as measures of departure from ideal behaviour; rather we construct an explicit chemical model for ΔG^*_{soln} as a function of x_2.

In accord with the first sentence of the introduction, we write ΔG^*_{soln} as eqn. (4), where the subscripts identify the contributing

$$\Delta G^*_{\text{soln}} = \Delta G_{\text{gen med}} + \Delta G_{\text{solv}} + \Delta G_{\text{intersol}} \qquad (4)$$

effects. First we consider the solvation effect, which we model as a competitive stoichiometric equilibrium of solute R solvated by water (W) and cosolvent (M) as shown in the two-step (three-state) Scheme 1. The adequacy of a three-state solvation scheme has been discussed.[5] We postulate that the solvation free energy is a weighted average of contributions from the three states of R,

$$\Delta G_{\text{solv}} = \Delta G_{\text{WW}} F_{\text{WW}} + \Delta G_{\text{WM}} F_{\text{WM}} + \Delta G_{\text{MM}} F_{\text{MM}} \qquad (5)$$

where F_{WW}, F_{WM} and F_{MM} are fractions of solute in the RM_2, RWM and RM_2 forms, respectively. Further development[1] leads to eqn. (6), where x_1 and x_2 are the bulk mole fractions of

$$\Delta G_{\text{solv}} = \frac{(-kT \ln K_1) K_1 x_1 x_2 + (-kT \ln K_1 K_2) K_1 K_2 x_2^2}{x_1^2 + K_1 x_1 x_2 + K_1 K_2 x_2^2} + \Delta G_{\text{WW}} \qquad (6)$$

solvent components 1 and 2.

$$RW_2 + M \xrightleftharpoons{K_1} RWM + W$$

$$RWM + M \xrightleftharpoons{K_2} RM_2 + W$$

Scheme 1

A cavity model is adopted as a means for expressing the general medium effect.[7] We write eqn. (7), where $g\gamma$ is the surface tension of the cavity created to hold the solute molecule, and A is the cavity surface area. (Actually we have proposed that A represents the essentially nonpolar portion of the surface of the molecule).[2] The quantity g accounts for the curvature effect on the surface tension; g is treated as an empirical parameter. The surface tension γ depends upon the solvation shell composition, and is given by eqn. (8), where $\gamma' = (\gamma_2 - \gamma_1)/2$, γ_1 and γ_2 being the surface tensions of pure component 1 and 2, respectively.

$$\Delta G_{\text{gen med}} = gA\gamma \qquad (7)$$

$$\gamma = \gamma_1 + \gamma'\left[\frac{K_1x_1x_2 + 2K_1K_2x_2^2}{x_1^2 + K_1x_1x_2 + K_1K_2x_2^2}\right] \qquad (8)$$

The number of parameters in this model can be reduced by relating all free energy changes to the fully aqueous solution according to eqn. (9). Applying eqn. (9) to eqn. (4) gives eqn. (10), where we have assumed that the intersolute effect is independent of composition. In the dissolution process the intersolute effect receives contributions from two sources: the solute crystal lattice energy, which is composition-independent provided the solid phase composition does not change with solvent composition; and solute–solute interactions in the solution phase, which will depend on solute concentration and solvent dielectric properties.

$$\delta_M\Delta G^*_{\text{soln}} = \Delta G^*_{\text{soln}}(x_2) - \Delta G^*_{\text{soln}}(x_2 = 0) \qquad (9)$$

$$\delta_M\Delta G^*_{\text{soln}} = \delta_M\Delta G_{\text{gen med}} + \delta_M G_{\text{solv}} \qquad (10)$$

Combining eqns. (6), (7), (8) and (10) provides eqn. (11), upon which the interpretations in the present paper are based. Eqn. (11) is used for fitting $\delta_M\Delta G^*_{\text{soln}}$, calculated from eqns. (1) and (9), to x_1 to x_2 by means of nonlinear regression analysis, which yields estimates of the model parameters K_1, K_2 and gA.

$$\delta_M\Delta G^*_{\text{soln}} = \frac{(gA\gamma' - kT\ln K_1)K_1x_1x_2 + (2gA\gamma' - kT\ln K_1K_2)K_1K_2x_2^2}{x_1^2 + K_1x_1x_2 + K_1K_2x_2^2} \qquad (11)$$

An earlier study[2] of the solubilities of a series of substituted biphenyls in water–methanol mixtures showed that A in gA represents the surface area of the essentially nonpolar portion of the solute molecule. In the present paper we turn our attention to the curvature correction factor g, which in other work had appeared to exhibit a dependence on cosolvent identity.[1,4] We have studied the solubilities of naphthalene and 4-nitroaniline in many aqueous–organic cosolvent systems. The solutes were chosen to represent nonpolar and semipolar solutes, and the cosolvents were selected to include a wide range of polarities and chemical types.

Experimental

Materials.—The organic cosolvents were HPLC or spectrophotometric grades. House distilled water was treated with a Sybron/Barnstead PCS water purification system. Naphthalene was recrystallized from acetone; 4-nitroaniline (Aldrich 99.9% purity) was used as received.

Apparatus.—4-Nitroaniline solubility measurements were made with a Hitachi U-3000 spectrophotometer. Naphthalene measurements in propan-2-ol–water systems were made with the Hitachi U-3000, and those in methanol–water with a Beckman DU-65 spectrophotometer. All other naphthalene studies were made by high performance liquid chromatography; the HPLC system consisted of a Waters 501 solvent system, Waters 484 variable wavelength detector and Rheodyne 7125 manual injector; the column was an Econosphere C-8, 5 μm, 150 × 4.6 mm cartridge column. Data acquisition and analysis were accomplished with a Macintosh SE-20 MB and Rainin Dynamax HPLC method manager program, version 1.1.

Solubility equilibration was carried out in a controlled-temperature water bath maintained at 25.00 ± 0.05 °C.

Procedures.—Solubility samples. Solvent mixtures of water and organic cosolvent were prepared by weight. An excess of solute was placed in 10 cm^3 or 20 cm^3 borosilicate ampoules, solvent mixture was added, the ampoules were chilled in a dry ice-acetone bath, and they were sealed with a torch. The ampoules were mounted on a rotor in the constant-temperature water bath and were rotated end-over-end for at least 48 h. The saturated solutions were filtered through Teflon® 22 μm filter membranes. Measured volumes of the filtered solutions were weighed in tared flasks for density determinations. Samples were appropriately diluted with solvent mixture for spectrophotometric analysis and with mobile phase for HPLC analysis.

Each reported value of solubility is the mean of 4–5 separate determinations (*i.e.*, 4–5 different ampoules) at that solvent composition.

Analytical methods. Naphthalene was analysed spectrophotometrically at 275 nm, 4-nitroaniline at 410 nm. For HPLC analyses of naphthalene, the mobile phase was methanol–water (1.5:1.0 v/v), with a flow rate of 1.0 cm^3 min^{-1}; detection was at 275 nm.

Surface area determination. Our foil-wrap technique was used.[1,2] A Corey–Pauling–Koltun (CPK) molecular model was tautly wrapped with the minimum extent of aluminium foil to yield a smooth envelope over all of the nonpolar surface of the molecule. (For naphthalene this is the entire molecule; for 4-nitroaniline it excludes the amino substituent and its immediate environs.) The foil was weighed. This weight was converted to an area by means of a calibration curve connecting known foil areas to their weights. The areas found in this way were 147(3) Å^2 molecule^{-1} for naphthalene and 106(4) Å^2 molecule^{-1} for the nonpolar surface area of 4-nitroaniline.

Calculations. The molar concentration of solute, c_3, found by analysis was converted to mole fraction of solute, x_3, by means of the saturated solution density ρ and the wt/wt percentage of organic cosolvent in the solvent mixture, w. The conversion is made with eqn. (12), where M_1, M_2 and M_3 are the molecular mass of water, organic cosolvent and solute, respectively. The free energy of solution, on a per molecule basis, was calculated with eqn. (1). $\delta_M\Delta G^*$ was then calculated with eqn. (9). Finally $\delta_M\Delta G^*$ was fitted to eqn. (11) and the experimental x_1 and x_2 values by nonlinear regression using Systat®, Version 5.2.

$$x_3 = \frac{c_3}{c_3 + (1000\rho - c_3M_3)\left(\dfrac{w}{M_2} + \dfrac{(1-w)}{M_1}\right)} \qquad (12)$$

Results

Tables 1 and 2 list solubility data for naphthalene and 4-nitroaniline in many aqueous–organic solvent mixtures. These data were analysed according to eqn. (11). [Some systems could be satisfactorily fitted with a one-step, two-state model, which generates a classical hyperbolic binding function, but others

Table 1 Solubility of naphthalene in aqueous–organic solvent mixtures at 25.0 °C[a]

x_2	ρ/g cm^{-3}	c_3/10^{-4} mol dm^{-3}	ΔG^*_{soln}/10^{-20} J molecule^{-1}
Methanol			
0.0	0.996	2.135(0.007)	5.13
0.0411	0.982	3.40(0.17)	4.92
0.0926	0.965	5.76(0.05)	4.68
0.1483	0.953	11.3(0.56)	4.38
0.2128	0.939	24.9(0.18)	4.03
0.2947	0.919	70.1(0.70)	3.58
0.4376	0.889	280(3.9)	2.96
0.4932	0.880	442(3.1)	2.75
0.6238	0.854	1 049(8)	2.35
0.7684	0.830	2 220(31)	1.99
0.8196	0.819	2 860(30)	1.87
0.8715	0.815	3 570(56)	1.76
0.9237	0.808	4 378(5)	1.66
1.0	0.803	5 720(45)	1.53
Ethanol			
0.0438	0.982	4.0(0.18)	4.84
0.0672	0.966	6.0(0.16)	4.64
0.1024	0.955	12.8(0.17)	4.31
0.1308	0.944	25.5(0.2)	4.01
0.1826	0.933	83.9(0.4)	3.49
0.2101	0.917	140(4)	3.25
0.2808	0.899	356(3)	2.83
0.3587	0.881	713(6)	2.50
0.4213	0.866	1 070(11)	2.30
0.5022	0.851	1 650(41)	2.08
0.6721	0.827	2 990(22)	1.76
0.7399	0.819	3 700(28)	1.65
0.9064	0.803	5 570(43)	1.42
1.0	0.800	6 750(40)	1.31
Propan-2-ol			
0.0302	0.980	4.0(0.11)	4.83
0.0821	0.958	25.3(0.23)	4.02
0.1024	0.943	63.5(0.6)	3.62
0.1600	0.917	316(3)	2.91
0.2123	0.898	541(2)	2.64
0.2831	0.883	981(4)	2.34
0.3405	0.865	1 348(10)	2.17
0.4281	0.847	1 880(31)	1.98
0.5615	0.828	2 810(12)	1.74
0.7610	0.801	3 900(140)	1.51
1.0	0.786	5 110(37)	1.32
Propane-1,2-diol			
0.0139	0.990	2.60(0.05)	5.03
0.0417	1.004	3.90(0.13)	4.83
0.0688	1.007	5.1(0.2)	4.70
0.1057	1.010	10.3 (0.3)	4.37
0.1354	1.019	16.7(0.1)	4.14
0.1751	1.013	30.3(0.3)	3.86
0.2037	1.020	44.2(0.5)	3.68
0.2564	1.024	83.9(0.5)	3.38
0.3513	1.020	195(2)	2.97
0.4082	1.023	290(4)	2.77
0.5749	1.015	632(7)	2.36
0.6413	1.013	816(7)	2.22
0.7982	1.000	1 215(31)	1.99
1.0	1.012	1 840(10)	1.76
Acetone			
0.0176	0.988	4.10(0.18)	4.84
0.0557	0.967	15.9(0.23)	4.24
0.0907	0.951	47(1.1)	3.76
0.1339	0.937	155(1.3)	3.23
0.1816	0.920	218(5)	3.05
0.2261	0.904	950(14)	2.41
0.2790	0.889	1 960(56)	2.07
0.3754	0.873	5 000(85)	1.61
0.4453	0.864	7 820(57)	1.37
0.5269	0.853	11 100(100)	1.17
0.6486	0.853	16 300(370)	0.946
0.7013	0.852	18 500(250)	0.865
0.8118	0.854	22 700(120)	0.729
1.0	0.861	28 900(120)	0.562
DMSO			
0.0144	0.998	3.20(0.14)	4.94
0.0254	1.002	4.6(0.2)	4.75
0.0555	1.020	9.7(0.2)	4.44
0.0732	1.020	12.3(0.4)	4.33
0.1054	1.032	22.5(0.6)	4.05
0.1239	1.033	30.8(0.4)	3.90
0.1656	1.040	59.4(0.8)	3.59
0.2081	1.058	110.6(0.8)	3.31
0.2401	1.056	169.6(1.0)	3.11
0.3092	1.074	408(3)	2.70
0.3977	1.076	1 063(7)	2.25
0.5116	1.078	2 740(24)	1.80
0.6156	1.078	5 280(4)	1.47
0.7696	1.072	11 000(320)	1.09
1.0	1.067	19 200(99)	0.767

[a] Quantities in parentheses are standard deviations.

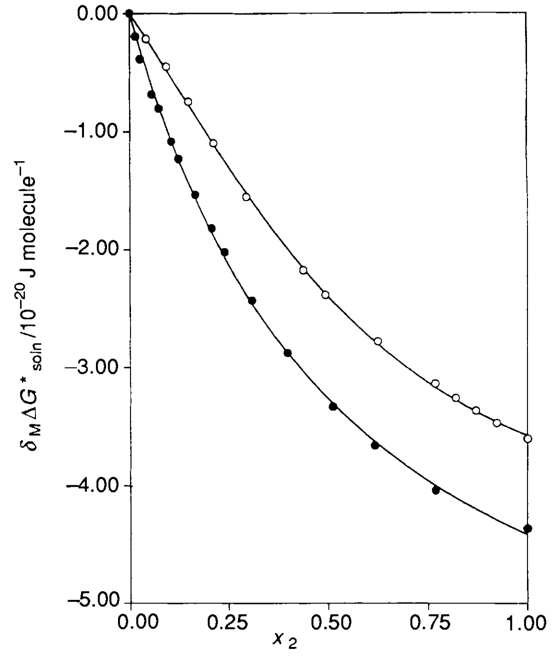

Fig. 1 Solubility curves for naphthalene in water–methanol (open circles) and water–DMSO (filled circles). The points are experimental (Table 1) and the curve is drawn with eqn. (11) and the parameter values from Table 3.

required the two-step model embodied in eqn. (11). For consistency, and because it is chemically reasonable to expect the involvement of an intermediate mixed-solvate species, eqn. (11) was applied to all systems.] The curve-fits were excellent, the standard deviation of the points about the fitted line lying in the range 0.2 to 2%. Fig. 1 shows the curves for naphthalene in the methanol and dimethyl sulfoxide (DMSO) systems.

Table 3 gives the parameter values K_1, K_2 and gA. These gA values can be converted to nominal g values with the nonpolar area estimates 147 Å^2 molecule^{-1} for naphthalene and 106 Å^2 molecule^{-1} for 4-nitroaniline. The mean g values are, for naphthalene, 0.51 (range 0.29–0.86) and, for 4-nitroaniline, 0.41 (range 0.11–0.81).

Table 2 Solubility of 4-nitroaniline in aqueous–organic solvent mixtures at 25.0 °C[a]

x_2	ρ/g cm^{-3}	$c_3/10^{-3}$ mol dm^{-3}	$\Delta G^*_{\text{soln}}/10^{-20}\,J$molecule^{-1}
Methanol			
0.0	0.985	3.80(0.5)	3.94
0.011 5	0.977	4.30(0.5)	3.88
0.019 9	0.964	6.90(0.5)	3.68
0.045 5	0.974	6.03(0.5)	3.73
0.089 5	0.963	6.96(0.02)	3.66
0.131 7	0.959	9.50(0.02)	3.51
0.176 0	0.947	13.50(0.1)	3.35
0.236 5	0.917	30.7(1.4)	2.98
0.307 2	0.915	45.5(0.5)	2.80
0.382 2	0.895	82.3(0.4)	2.53
0.522 7	0.866	184.3(1)	2.14
0.588 8	0.865	170.2(0.9)	2.16
0.646 8	0.855	205(1.5)	2.06
0.785 3	0.822	344(4)	1.80
0.896 5	0.818	363(2)	1.75
1.0	0.808	555(3)	1.54
Ethanol			
0.008 08	0.990	4.73(0.03)	4.10
0.015 8	0.983	4.97(0.09)	3.82
0.032 6	0.975	5.71(0.07)	3.75
0.062 1	0.962	8.50(0.08)	3.56
0.088 6	0.958	10.99(0.10)	3.44
0.163 3	0.931	42.4(0.3)	2.83
0.222 2	0.916	73.6(0.8)	2.57
0.258 4	0.904	97.8(9)	2.43
0.337 7	0.886	165.5(1.5)	2.16
0.396 3	0.877	189(2)	2.08
0.515 2	0.855	253(2)	1.90
0.616 8	0.836	290(3)	1.80
0.740 7	0.820	316(3)	1.71
0.903 4	0.798	336(3)	1.63
1.0	0.792	337(2)	1.60
Propan-2-ol			
0.005 72	0.987	4.71(0.02)	3.85
0.012 8	0.975	5.10(0.06)	3.80
0.025 2	0.979	5.93(0.06)	3.73
0.049 9	0.967	9.43(0.07)	3.52
0.092 2	0.950	26.8(0.11)	3.04
0.109 8	0.943	41.1(0.3)	2.85
0.182 6	0.913	102(1.1)	2.40
0.211 4	0.903	123(1.6)	2.30
0.237 6	0.896	143(2)	2.22
0.361 8	0.866	211(2)	1.97
0.471 4	0.848	245(1.4)	1.85
0.576 6	0.816	264(2)	1.76
0.578 4	0.831	262(1)	1.76
0.692 8	0.794	232(5)	1.75
0.718 6	0.813	250(1)	1.72
0.846 0	0.791	226(1.7)	1.71
0.855 3	0.799	222(2)	1.72
1.0	0.782	192(3)	1.73
Ethylene glycol			
0.006 01	0.995	4.60(0.10)	3.86
0.011 5	0.990	4.80(0.10)	3.84
0.024 2	0.999	5.17(0.05)	3.80
0.051 5	1.006	6.11(0.03)	3.71
0.082 9	1.013	7.40(0.2)	3.60
0.117 6	1.020	9.50(0.1)	3.48
0.161 7	1.038	13.1(0.1)	3.32
0.210 7	1.047	18.3(0.3)	3.15
0.268 2	1.054	26.2(0.1)	2.97
0.340 1	1.060	40.1(0.4)	2.75
0.426 4	1.090	59.8(0.7)	2.55
0.545 5	1.076	96.0(2.0)	2.30
0.677 5	1.080	138(5)	2.09
0.872 5	1.092	223(10)	1.83
1.0	1.091	308(21)	1.66
Acetone			
0.006 28	0.975	11.0(0.2)	3.49
0.012 65	0.973	11.9(0.2)	3.45
0.025 6	0.966	17.2(0.2)	3.29
0.054 1	0.970	18.0(0.4)	3.25
0.073 7	0.960	28.5(0.5)	3.04
0.125 6	0.942	98.1(2.7)	2.48
0.158 7	0.953	184(3.2)	2.20
0.214 7	0.925	436(6.7)	1.78
0.302 5	0.916	934(2.3)	1.39
0.340 1	0.915	977(9)	1.35
0.456 1	0.914	1406(24)	1.12
0.501 0	0.912	1495(13)	1.07
0.714 6	0.907	1947(15)	0.857
0.839 8	0.907	2075(11)	0.788
1.0	0.896	2018(16)	0.756
DMSO			
0.004 8	0.969	4.97(0.1)	3.82
0.009 6	0.990	5.60(0.1)	3.77
0.020 2	0.984	7.00(0.2)	3.66
0.042 2	0.998	10.3(0.3)	3.48
0.067 5	1.004	15.5(0.5)	3.29
0.097 2	1.027	24.8(0.4)	3.07
0.134 5	1.041	43.6(0.5)	2.81
0.175 8	1.053	86.4(1.3)	2.49
0.225 7	1.067	203(2)	2.10
0.286 3	1.081	577(7)	1.61
0.370 0	1.099	1400(20)	1.17
0.478 5	1.128	2480(30)	0.843
0.623 7	1.149	3390(10)	0.630
0.803 4	1.164	4130(30)	0.474
1.0	1.153	3830(90)	0.464
Acetonitrile			
0.007 7	0.988	4.96(0.2)	3.83
0.017 5	0.975	8.64(0.1)	3.59
0.036 0	0.976	8.52(0.1)	3.59
0.060 3	0.962	22.0(1.1)	3.18
0.104 5	0.946	64.8(1.1)	2.70
0.170 2	0.913	234.0(24)	2.12
0.189 4	0.896	204.9(0.9)	2.17
0.287 2	0.896	459(6)	1.78
0.336 4	0.886	574(6)	1.65
0.430 7	0.875	994(9)	1.37
0.567 5	0.863	1081(17)	1.28
0.710 4	0.862	1161(10)	1.20
0.717 8	0.856	1186(11)	1.19
0.866 3	0.840	1218(4)	1.13
1.0	0.833	1054(6)	1.16

[a] Quantities in parentheses are standard deviations.

Discussion

The Solvation Exchange Constants.—Since naphthalene and 4-nitroaniline are substantially less polar than water, we anticipate that the organic cosolvents, which are also less polar than water, will tend to displace water from the solvation shell, and therefore we expect the exchange constants K_1 and K_2 to be greater than unity. On the other hand, these cosolvents are all infinitely miscible with water—that is, they are to this extent 'water-like'—so the exchange constants are not expected to be very large. As Table 3 shows, most of the values fall in the range 1–10.

We had earlier made correlations of the surface tension of binary aqueous–organic solvent mixtures,[3,8] and our results led to the conjecture that these organic cosolvents fall into two classes. One of these, comprised of solvents having log P values greater than about -1 (P is the octan-1-ol–water partition

Table 3 Model parameters for the solubility of naphthalene and 4-nitroaniline in aqueous–organic solvents[a]

Cosolvent	K_1	K_2	gA/Å^2 molecule^{-1}
Naphthalene			
Methanol	2.52(0.07)	1.19(0.09)	63(0.8)
Ethanol	3.6(0.4)	3.5(0.6)	54(1.5)
Propan-2-ol	7.0(1.1)	6.0(1.5)	43(2.3)
Propane-1,2-diol	4.0(0.1)	2.2(0.2)	71(1.3)
Ethylene glycol[b]	3.04(0.03)	1.21(0.04)	102(1.0)
Acetone	6.5(0.5)	2.9(0.4)	69(1.6)
DMSO	4.8(0.2)	1.3(0.1)	127(2.2)
4-Nitroaniline			
Methanol	2.7(0.4)	1.5(0.5)	35(3.0)
Ethanol	4.2(0.3)	5.1(0.6)	21.2(0.9)
Propan-2-ol	5.9(0.5)	10.4(1.1)	11.0(0.5)
Ethylene glycol	3.9(0.2)	0.65(0.21)	84(7.2)
Acetone	9.5(1.8)	3.5(1.3)	37(4.0)
DMSO	3.9(0.5)	3.8(0.8)	86(3.5)
Acetonitrile	8.1(0.9)	5.6(1.0)	29(1.8)

[a] Quantities in parentheses are standard deviations. [b] From ref. 1.

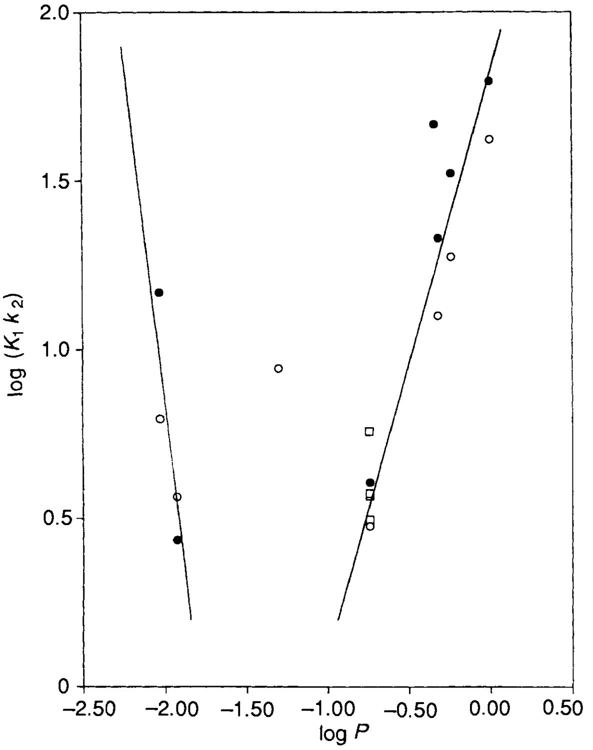

Fig. 2 Plot of log K_1K_2 against log P of the organic cosolvents: ○, naphthalene; ●, 4-nitroaniline; □, substituted biphenyls;[2] the lines have no theoretical significance

coefficient) behaves 'normally' in that the surface activity of the solvent increases with its hydrophobicity (as measured by log P). The other class showed anomalous behaviour, its surface activity increasing with solvent hydrophilicity. It was proposed that two separate effects operate in these systems, and it was suggested that the phenomenon might also be found in solvation phenomena.[3]

The results in the present paper allow us to examine this issue. Fig. 2 is a plot of log K_1K_2 (from Table 3) against log P values of the cosolvents.[9] The plot also includes four points for substituted biphenyls in methanol–water.[2] Except for the anomalous behaviour of propane-1,2-diol, the results are consistent with the surface tension analyses;[3,8] there are two classes of cosolvent, distinguished by their polarity. Similar behaviour is seen in a plot of log K_1 against log P, though with more scatter. These plots offer a means for the approximate prediction of K_1 and K_2 values. The mechanistic implication of this biphasic behaviour of the exchange constants is that there are two independent interaction mechanisms in the solvation process; those solvents having log P greater than −1 act through a nonpolar interaction, whereas those with log P less than −1 operate through a polar interaction.

The General Medium Parameter.—The parameter gA enters the theory as a determiner of the general medium effect, which is the hydrophobic effect (the solvophobic effect in general). We have established[2] that A represents the nonpolar surface area of the solute. The curvature correction factor g is treated as an empirical parameter because the geometry of the cavity may be very complex, being determined by the structure of the solute and the nature of the solvent. A goal of this work was to examine the solvent dependence of g; the inclusion of two solutes also permitted the solute dependence to be studied.

We observe that gA is reasonably correlated with log P of the cosolvents:

$$\text{Naphthalene: } gA = -32.1\,(\pm 6.5)\log P + 45.5\,(\pm 7.8) \quad (r = 0.91)$$

$$\text{4-Nitroaniline: } gA = -34.7\,(\pm 3.5)\log P + 15.5\,(\pm 3.9) \quad (r = 0.97)$$

The slopes are not significantly different, whereas the intercepts differ. We conjecture that the slopes measure the sensitivity of gA to the solvent polarity, and the intercepts measure the sensitivity of gA to the solute polarity; we therefore write eqn. (13), where P_M and P_R are the octan-1-ol–water partition

$$gA = M \log P_M + R \log P_R \qquad (13)$$

coefficients of the cosolvent and the solute, respectively. From the empirical correlations we set $M = -33.4$. We then estimate the R quantities with eqn. (13) and the experimental gA values, finding $R = 13.8(3.9)$ for naphthalene and $R = 12.9(4.4)$ for 4-nitroaniline. Thus eqn. (13) constitutes an empirical means for the prediction of gA values, with $M = -33.4$ Å^2 molecule^{-1} and $R = 13.4$ Å^2 molecule^{-1}. For naphthalene, log $P_R = 3.20$, and for 4-nitroaniline, log $P_R = 1.39$. Table 4 shows the results, which are quite satisfactory. It appears that gA, and therefore g, depends upon the polarity of both the cosolvent and the solute.

A sense of the reasonableness of the magnitude of M and R can be obtained by plotting the areas of some aromatic hydrocarbons[11] against their log P values;[9] the slope is about 42 Å^2 molecule^{-1}, which, multiplied by typical g values, gives quantities comparable to the experimental estimates of M and R.

An interesting consequence of eqn. (13) is that gA can be negative. A test of this is provided by literature data[12] on the solubility of sucrose in water–ethanol solutions. For sucrose log $P_R = -3.67$, and eqn. (13) predicts $gA = -37$ Å^2 molecule^{-1}. The curve-fit to eqn. (11) is shown in Fig. 3; the derived parameters are $K_1 = 0.3(0.12)$, $K_2 = 3.0(1.2)$, $gA = -40.1(0.8)$ Å^2 molecule^{-1}. A negative gA, which does not seem physically plausible, may require definition of a hypothetical nonpolar area for a polar solute.

Throughout the development and application of this phenomenological theory it has been assumed that g is a constant within a given experimental study, in which the solute and cosolvent identities are fixed, and the cosolvent composition may be varied from $x_2 = 0$ to $x_2 = 1$. We have found that g can take different values depending upon the identity of the cosolvent. This creates a possible inconsistency in the model, for, if g is constant throughout any given study, yet has different

Table 4 The general medium effect parameter

Cosolvent	log P	gA^a/Å^2 molecule^{-1} Calc.	Obs.	$\gamma_2{}^b$/erg cm^{-2}	$-g(\gamma_2 - \gamma_1)^b$/erg cm^{-2}
Naphthalene					
Methanol	−0.74	68	63	22.4	21.2
Ethanol	−0.32	54	54	21.8	18.5
Propan-2-ol	0.00	43	43	20.8	14.8
Propane-1,2-diol	−1.35	88	71	37.1^a	16.7
Ethylene glycol	−1.93	107	102	48.1	16.4
Acetone	−0.24	51	69	22.9	23.0
DMSO	−2.03	111	127	42.9	24.9
4-Nitroaniline					
Methanol	−0.74	43	35	22.4	16.3
Ethanol	−0.32	29	21	21.8	10.0
Propan-2-ol	0.00	19	11	20.8	5.1
Ethylene glycol	−1.93	83	84	48.1	18.7
Acetone	−0.24	27	37	22.9	17.1
DMSO	−2.03	86	86	42.9	23.4
Acetonitrile	−0.34	30	29	28.5	11.7

[a] From ref. 10.

Table 5 Thermodynamic data for nonpolar solutes

Compound	T_m/K	Δ_fH/cal mol$^{-1\,a}$	Δ_fS/cal mol^{-1} K^{-1}	ΔG^*_{soln} ($x_2 = 0$)/10^{-20} J molecule^{-1}	Refs.
Naphthalene	353.4	4536	12.8	5.13	15
Biphenyl	488	4440	9.1	5.83	2, 16
1,4-Dichlorobenzene	326.1	4370	13.4	4.87	17, 18
1,4-Dibromobenzene	360.3	4870	13.5	5.65	17, 18
1,4-Diiodobenzene	404	5340	13.2	6.87	18–20

[a] 1 cal = 4.184 J.

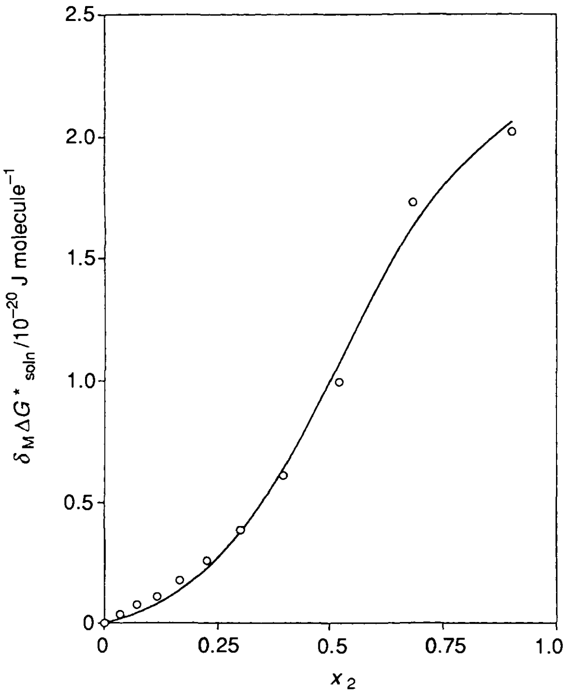

Fig. 3 Solubility curve for sucrose in water–ethanol. The data points are from ref. 12 and the smooth curve is drawn with eqn. (11).

values in different solvent systems, how can it assume a unique value in water, the common reference solvent? Here we address this problem.

Two factors seem to act in minimizing the difficulty. One of these is that the g value in pure water, for naphthalene and similar nonpolar solutes, is estimated to be 0.41 ± 0.03 (see the Appendix). As it happens, this is the median of the 14 g values contained in Table 3. Thus the maximum excursion of g as x_2 goes from 0 to 1 is never as large as might have been expected.

The second factor damping the variability in g appears in eqn. (11), where it is seen that g always appears as the product $g(\gamma_2 - \gamma_1)$. Table 4 lists values of $-g(\gamma_2 - \gamma_1)$, which undergoes less variation than does g itself. The value of $-g(\gamma_2 - \gamma_1)$ is itself of some interest. For naphthalene this quantity is 19.4 ± 3.8 erg cm^{-2}, and for 4-nitroaniline it is 17.0 ± 5.5 erg cm^{-2}. These are interesting because they are close to the smallest values of surface tension of any liquids, and because they are quite close to the estimated dispersion energy component (21.8 erg cm^{-2}) of the surface tension of water.[13] It is also possible that the variation in g is an artefact of the data analysis; in particular, the assumption that $\delta_M\Delta G_{intersol} = 0$ may not be acceptable in all solvents.

Appendix

Estimation of g in the Fully Aqueous Solution.—When $x_2 = 0$, the equation for free energy of solution is as shown in eqn. (14),

$$\Delta G^*_{soln} = gA\gamma_1 + \Delta G_{cryst} + \Delta G_{solvation} \qquad (14)$$

where ΔG_{cryst} is the crystal lattice energy of the solid solute. For very nonpolar solutes in water, we make the assumption that the solvation contribution to ΔG^*_{soln} is negligible relative to the general medium ($gA\gamma_1$) and intersolute (ΔG_{cryst}) contributions. To find ΔG_{cryst}, we begin with the proposition that a dissolved

Table 6 *gA* and *g* values calculated for nonpolar solutes in water[a]

Compound	A/Å^2 molecule^{-1}	gA/Å^2 molecule^{-1}	g
Naphthalene	147(3)	64.6	0.44
Biphenyl	179(3)	64.4	0.36
1,4-Dichlorobenzene	152(7)	64.3	0.42
1,4-Dibromobenzene	172(3)	70.5	0.41
1,4-Diiodobenzene	192(4)	82.2	0.43

[a] Quantities in parentheses are standard deviations.

solute is in the supercooled liquid state.[14] From experimental estimates of the solute melting point T_m and heat of fusion $\Delta_f H$, the entropy of fusion at the melting point is calculated from $\Delta_f S = \Delta_f H/T_m$. With the assumptions that $\Delta_f H$ and $\Delta_f S$ are temperature-independent and that the heat capacities of the solid and liquid are equal, the free energy of fusion, which we equate with ΔG_{cryst}, is estimated at the experimental temperature from $\Delta G_{cryst} = \Delta_f H - T\Delta_f S$. Then g is found from eqn. (15)

$$g = \frac{\Delta G^*_{soln}(x_2 = 0) - \Delta G_{cryst}}{A\gamma_1} \qquad (15)$$

Table 5 gives the thermodynamic data needed to apply eqn. (15) for five nonpolar solutes. For these compounds the nonpolar surface area was taken to be equal to the total area. Table 6 gives the results of the calculation. The mean value of g is 0.41 with a standard deviation of 0.03.

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