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Solubility and Activity Coefficients of Acidic and Basic Nonelectrolytes in Aqueous Salt Solutions. 1. Solubility and Activity Coefficients of *o*-Phthalic Acid and L-Cystine in NaCl(aq), $(CH_3)_4NCl$(aq), and $(C_2H_5)_4NI$(aq) at Different Ionic Strengths and at $t = 25$ °C

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The solubility of *o*-phthalic acid and L-cystine was determined at following concentrations: NaCl(aq) (0.1 to 4.5) mol·L^{-1}, $(CH_3)_4NCl$(aq) (0.1 to 3) mol·L^{-1}, $(C_2H_5)_4NI$(aq) (0.1 to 1) mol·L^{-1} and in pure water. The solubility trend is $(C_2H_5)_4NI > (CH_3)_4NCl > NaCl$ for *o*-phthalic acid and $NaCl > (CH_3)_4NCl > (C_2H_5)_4NI$ for L-cystine. Setschenow constants and activity coefficients of neutral species were calculated from these data. The different trends shown by *o*-phthalic acid and L-cystine are discussed.

Introduction

Studies of the solubility of neutral species are of both theoretical and practical interest. In particular, as far as the thermodynamics of equilibria in solution are concerned, solubility investigations allow the determination of activity coefficients for nonelectrolyte solutes in aqueous solutions containing a large excess of salts.[1−3] In modeling the dependence of protonation and complex formation constants on medium using different approaches, such as Pitzer[4] and SIT (Specific Interaction Theory) equations,[5,6] it is often necessary to know the activity coefficients of neutral species, but data for nonelectrolytes are not so readily found as those for electrolytes.

In conjunction with colleagues in other laboratories, we have made the dependence on medium of equilibrium thermodynamic parameters the subject of many investigations.[7−9] The effect of tetralkylammonium salt on the protonation of low and high molecular weight ligands has been the focus of particular research interest since the tetralkylammonium cation can, in most cases, be considered to interact most weakly with both inorganic and organic anions.[10−14] We are currently involved in a study of the dependence on ionic strength of the thermodynamic protonation parameters of phthalate and S-containing carboxylic and aminocarboxylic ligands in different supporting electrolytes. To model the dependence of protonation constants on medium we must first derive the activity coefficients of neutral species from independent investigations (e.g., by solubility measurements). This work describes a solubility study of phthalate and L-cystine in NaCl(aq), Me_4NCl(aq), and Et_4NI(aq) at $t = 25$ °C.

Several studies of the solubility of both phthalate and L-cystine have been published,[15−23] but none at $C_{NaCl} > 3$ mol·L^{-1} and in Me_4NCl and Et_4NI. Only in an investigation by Bergen and Long[17] is the solubility of phthalate given in some other tetraalkylammonium salts.

Experimental Section

Chemicals. *o*-Phthalic acid and L-cystine (Fluka products) were used without further purification; their purity, checked alkalimetrically, was found to be >99 %. Sodium chloride solutions were prepared by weighing pure salt (Fluka, p.a.) previously dried in an oven at 110 °C. Tetramethylammonium chloride, Me_4NCl (Fluka), and tetraethylammonium iodide, Et_4NI (Fluka), were recrystallized from methanol. Tetraethylammonium hydroxide solutions were prepared from concentrated Et_4NOH (Fluka puriss. electrochemical grade) and standardized against potassium biphthalate. Hydrochloric acid solutions were prepared from concentrated ampules (Fluka) and standardized against sodium carbonate. All solutions were preserved from atmospheric CO_2 by means of soda lime traps. Grade A glassware and twice-distilled water were employed in the preparation of all the solutions.

Apparatus. The free hydrogen ion concentration was measured with a Metrohm model 713 potentiometer (resolution ± 0.1 mV, reproducibility ± 0.15 mV) connected to a Metrohm 665 automatic buret and to a model 8101 Ross-type Orion electrode, coupled with a standard calomel electrode. The potentiometer and the buret were connected to a personal computer, which using suitable software allows automatic data acquisition. The measurement cells were thermostated at (25 ± 0.1) °C. Purified N_2 was bubbled into the solutions in order to exclude the presence of CO_2 and O_2. To avoid systematic errors, some measurements were carried out using different apparatus (Metrohm model 809 titrando) and software (Metrohm TiAMO 1.0) for the automatic data acquisition.

Procedure. Saturated solutions of *o*-phthalic acid and L-cystine were prepared by adding an excess of *o*-phthalic acid or L-cystine to a solution of Et_4NI or Me_4NCl or NaCl at pre-established ionic strength values [NaCl: (0.5 to 4.5) mol·L^{-1}; Et_4NI: (0.15 to 0.9) mol·L^{-1}; Me_4NCl: (0.25 to 3.0) mol·L^{-1}]. Solutions were stirred at $t = 25$ °C for 24 h. Preliminary tests established that longer stirring times

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were unnecessary. A volume of 25 mL of the filtered solution was titrated with standard Et_4NOH. Separate titrations of HCl at the same ionic strength as the sample under study were carried out to determine the standard electrode potential E^0, and the junction potential coefficient j_a ($E_j = j_a[H^+]$). To avoid systematic errors, independent experiments were performed at least three times.

Calculations. Calculations relative to the refinement of parameters for acid−base titrations were carried out by the computer program ESAB2M.[24] The general least squares computer program LIANA[25] was used for the refinement of solubility parameters. Conversion from molar to molal concentration scale was obtained from the equation:[26]

$$\frac{c/\text{mol}\cdot\text{L}^{-1}}{m/\text{mol}\cdot\text{kg}^{-1}} = d_0/\text{g}\cdot\text{cm}^{-3} + a\ c/\text{mol}\cdot\text{L}^{-1} + b\ (c/\text{mol}\cdot\text{L}^{-1})^2 \tag{1}$$

where d_0 is the density of pure water; a and b are empirical parameters (a = 0.017765, 0.10795, 0.18434; b = −0.0006525, 0.0004833, 0.0008112 for NaCl, Me_4NCl, and Et_4NI, respectively at t = 25 °C). The density of saturated solutions of *o*-phthalic acid and L-cystine are d = 1.0022/g·cm^{-3} and 0.9992/g·cm^{-3}, respectively, at t = 25 °C.

Data Analysis

Solubility data were fitted to the smoothing function:

$$S^T = S_0^T + \left[a_\infty + \frac{a_0 - a_\infty}{c_{MX} + 1}\right]c_{MX} \tag{2}$$

for molar concentration scales (eq 2 can be applied to the molal scale by substituting c_{MX} for m_{MX}). Owing to proton dissociation/association equilibria, the total solubility of the ligands under consideration is due to the neutral and deprotonated or protonated species. For a polyprotic acid H_nL, we have:

$$S^T = [H_nL^0] + [H_{n-1}L^-] + [H_{n-2}L^{2-}] + ... + [L^{n-}] \tag{3}$$

$$S^T = S^0 + \sum_0^{n-1}[H_iL^{(n-i)-}] \tag{3a}$$

$$S^T = S^0[1 + \sum_0^{n-1}(\prod_i^n K_i^H[H^+]^{n-i+1})^{-1}] \tag{4}$$

and for a polyamine with n amino groups:

$$S^T = [A^0] + [AH^+] + [AH_2^{\ 2+}] + ... + [AH_n^{\ n+}] \tag{5}$$

$$S^T = S^0 + \sum_1^n[AH_i^{\ i+}] \tag{5a}$$

$$S^T = S^0\ (1 + \sum_1^n(\beta_i^{\ H}[H^+]^i) \tag{6}$$

For *o*-phthalic acid and L-cystine, the above equations reduce to

$$S^T = S^0\left(1 + \frac{1}{K_2^{\ H}[H^+]} + \frac{1}{K_1^{\ H}K_2^{\ H}[H^+]^2}\right) \tag{7}$$

$$S^T = S^0\left(1 + \frac{1}{K_2^{\ H}[H^+]} + \frac{1}{K_1^{\ H}K_2^{\ H}[H^+]^2} + K_3^{\ H}[H^+] + K_3^{\ H}K_4^{\ H}[H^+]^2\right) \tag{8}$$

respectively. According to Long and McDevit,[1] the solubility of a neutral species is related to activity coefficients by the equations:

$$\log\frac{y}{y_0} = \log\frac{S_0^0}{S^0} = k_c c_{MX} \tag{9}$$

and

$$\log\frac{\gamma}{\gamma_0} = \log\frac{S_0^0}{S^0} = k_m m_{MX} \tag{9a}$$

where k_c and k_m are known as Setschenow coefficients, in the molar and molal concentration scales, respectively (see also Symbols and Abbreviations). The general equation for the salt effect on activity coefficients is[1]

$$\log\frac{S_0^0}{S^0} = \log\frac{y}{y_0} = k_c c_{MX} + k_i(S^0 - S_0^0) \tag{10}$$

where c_{MX} is the molarity of the salt solution, y and y_0 are the activity coefficients of the neutral species in the salt solution and in the reference state, and k_i is the nonelectrolyte self-interaction parameter. If the values of S^0 and S_0^0 are low, the last term of eq 10 can be neglected, even if k_i is often of the same order of magnitude as k_c. When the solubility of the nonelectrolyte is high (generally for solubility >0.2 mol·L^{-1} the self-interaction term represents >10 % of the total salt effect), eq 10 must be used instead of eq 9. The same observation also holds for activity coefficients and solubilities in the molal concentration scale. Generally the terms *salting out* and *salting in* are used to denote an increase and a decrease in the activity coefficient of the nonelectrolyte with increasing electrolyte concentration.

The molal Setschenow coefficient is, in turn, related to coefficient λ of the Pitzer model by the equation (for a 1:1 electrolyte):

$$\lambda = \frac{\ln 10k_m}{2} \tag{11}$$

Results and Discussion

Total solubilities for *o*-phthalic acid and L-cystine are reported in Tables 1 and 2, respectively. The same tables also show some literature data to be in good agreement with our own. S^T values were smoothed using eq 2, and the relative results are given in Tables 3 and 4. The behavior of *o*-phthalic acid and L-cystine as a function of different supporting electrolytes is quite dissimilar, with total solubility for *o*-phthalic acid being

$$Et_4NI > Me_4NCl > NaCl$$

Table 1. Experimental Data on the Solubility[a] of *o*-Phthalic Acid in Different Ionic Media at Different Ionic Strengths at $t = 25$ °C

c_{MX} mol·L^{-1}	m_{MX} mol·kg^{-1}	S_c^T	S_m^T	S_c^0	S_m^0
		(± 0.0015)[b]			
0.000	0.000	0.0479	0.0482	0.0411	0.0414
0.000	0.000	0.0479	0.0482	0.0411	0.0414
0.000	0.000	0.0421	0.0423	0.0362	0.0364
0.000	0.000	0.0422	0.0425	0.0362	0.0365
0.000	0.000	0.0424	0.0427	0.0364	0.0367
0.000	0.000	0.0418	0.0421	0.0355	0.0357
		Et_4NI			
		(± 0.0010)[b]			
0.150	0.155	0.0552	0.0569	0.0462	0.0478
0.150	0.155	0.0532	0.0549	0.0444	0.0460
0.950	1.157	0.1206	0.1468	0.1096	0.1356
0.950	1.157	0.1209	0.1472	0.1097	0.1359
0.251	0.263	0.0667	0.0701	0.0568	0.0602
0.251	0.263	0.0668	0.0703	0.0570	0.0604
0.501	0.553	0.0866	0.0957	0.0759	0.0849
0.501	0.553	0.0861	0.0951	0.0755	0.0844
1.005	1.237	0.1339	0.1648	0.1229	0.1536
1.005	1.237	0.1329	0.1636	0.1219	0.1524
0.263	0.277	0.0592	0.0624	0.0499	0.0530
0.552	0.617	0.0743	0.0829	0.0643	0.0728
0.872	1.042	0.0939	0.1122	0.0852	0.1033
		Me_4NCl			
		(± 0.0015)[b]			
0.252	0.260	0.0527	0.0543	0.0434	0.0450
0.252	0.260	0.0524	0.0541	0.0431	0.0447
0.791	0.867	0.0611	0.0669	0.0513	0.0570
0.791	0.867	0.0612	0.0671	0.0514	0.0572
1.636	1.991	0.0853	0.1037	0.0753	0.0936
2.596	3.605	0.1116	0.1550	0.1029	0.1461
0.251	0.259	0.0497	0.0512	0.0407	0.0422
0.752	0.821	0.0565	0.0617	0.0471	0.0521
1.499	1.793	0.0733	0.0877	0.0639	0.0780
1.993	2.542	0.0762	0.0972	0.0675	0.0883
3.012	4.453	0.1070	0.1582	0.0987	0.1497
		NaCl			
		(± 0.0008)[b]			
0.127[c]	0.128	0.0411	0.0413	0.0331	0.0333
0.244[c]	0.246	0.0398	0.0401	0.0316	0.0319
0.493[c]	0.499	0.0368	0.0373	0.0286	0.0290
0.947	0.966	0.0343	0.0350	0.0264	0.0271
0.970[c]	0.990	0.0314	0.0321	0.0239	0.0245
1.601[c]	1.655	0.0247	0.0256	0.0185	0.0192
1.955	2.037	0.0248	0.0258	0.0187	0.0197
2.203[c]	2.307	0.0199	0.0209	0.0147	0.0156
2.978[c]	3.173	0.0152	0.0162	0.0112	0.0121
3.056	3.262	0.0141	0.0150	0.0103	0.0112
3.789	4.116	0.0107	0.0116	0.0069	0.0077
4.268	4.693	0.0088	0.0097	0.0060	0.0068
4.268	4.693	0.0084	0.0093	0.0056	0.0063

[a] Solubilities are given as mol·L^{-1} or mol·kg^{-1}. [b] ± SD. [c] Ref 15.

Table 2. Experimental Data on the Solubility[a] of L-Cystine in Different Ionic Media at Different Ionic Strengths at $t = 25$ °C

c_{MX} mol·L^{-1}	m_{MX} mol·kg^{-1}	S_c^T	S_m^T	S_c^0	S_m^0
		(± 0.04)[b]			
0.000	0.000	0.692	0.694	0.689	0.691
0.000	0.000	0.654	0.656	0.652	0.654
		Et_4NI			
		(± 0.03)[b]			
0.150	0.155	0.533	0.549	0.531	0.547
0.150	0.155	0.516	0.532	0.514	0.530
0.246	0.259	0.561	0.589	0.559	0.587
0.492	0.544	0.463	0.511	0.461	0.509
0.770	0.900	0.355	0.415	0.354	0.414
0.893	1.071	0.317	0.380	0.316	0.379
0.950	1.154	0.296	0.360	0.294	0.358
0.950	1.154	0.337	0.410	0.336	0.408
		Me_4NCl			
		(± 0.02)[b]			
0.292	0.302	0.561	0.580	0.559	0.578
0.598	0.641	0.507	0.543	0.505	0.542
1.251	1.449	0.325	0.377	0.324	0.375
1.500	1.793	0.267	0.319	0.265	0.317
1.500	1.793	0.297	0.355	0.295	0.353
1.730	2.132	0.244	0.301	0.243	0.300
3.000	4.427	0.077	0.113	0.076	0.112
3.000	4.427	0.078	0.115	0.078	0.115
		NaCl			
		(± 0.04)[b]			
0.498	0.504	0.800	0.809	0.797	0.807
1.998	2.083	0.973	1.014	0.970	1.011
2.998	3.196	1.109	1.182	1.107	1.180
4.521	5.004	1.296	1.434	1.295	1.433
3.000[c]	3.198	1.621	1.728	1.619	1.726
2.000[c]	2.085	1.230	1.282	1.228	1.280
1.000[c]	1.022	1.174	1.200	1.171	1.197
0.500[c]	0.506	0.955	0.966	0.952	0.964
0.150[c]	0.151	0.832	0.836	0.830	0.834
1.000[d]	1.022	0.832	0.850	0.830	0.848
3.000[d]	3.198	1.096	1.168	1.094	1.167

[a] Solubilities are given as mmol·L^{-1} or mmol·kg^{-1}. [b] ± SD. [c] Ref 22. [d] Ref 21.

and for L-cystine being

$$\mathrm{NaCl} \gg \mathrm{Me_4NCl} > \mathrm{Et_4NI}$$

As an example, S^T values for *o*-phthalic acid in Me_4NCl and NaCl versus concentration of supporting electrolyte are shown in Figure 1. Tables 1 and 2 also show solubilities S^0 for neutral species obtained by eqs 7 and 8. The protonation constants needed to calculate S^0 at each ionic strength value using eqs 7 and 8 were obtained from log K^{H0} (infinite dilution) together with parameters (C) for dependence on ionic strength using the equation:

$$\log K^{H} = \log K^{H0} - 0.51z^* \frac{\sqrt{I}}{1 + 1.5\sqrt{I}} + CI \qquad (12)$$

where

$$z^* = \sum (\text{charge})^2_{\text{reactants}} - \sum (\text{charge})^2_{\text{products}}$$

In the Supporting Information, we have included some information on the protonation data used in this investigation. S^0 values were smoothed in the same way as for total solubilities. Empirical parameters a_0 and a_∞ are reported in Table 5. We used these data to obtain Setschenow coefficients:

$$k_m = \left(\frac{a_\infty - a_0}{m_{MX} + 1} - a_\infty\right) \qquad (13)$$

$$k_c = \left(\frac{a_\infty - a_0}{c_{MX} + 1} - a_\infty\right) \qquad (13a)$$

and activity coefficients:

$$\log \gamma = m_{MX}\left(\frac{a_\infty - a_0}{m_{MX} + 1} - a_\infty\right) \qquad (14)$$

$$\log y = c_{MX}\left(\frac{a_\infty - a_0}{c_{MX} + 1} - a_\infty\right) \qquad (14a)$$

Activity coefficients are reported in Tables 6 and 7.

Table 3. Smoothed Total Solubility[a] of *o*-Phthalic Acid in Different Ionic Media at Different Ionic Strengths at t = 25 °C in both Molar and Molal Scales

c_{MX} / mol·L^{-1}	S_c^T	m_{MX} / mol·kg^{-1}	S_m^T
0.00	0.0426 ± 0.0004[b]	0.00	0.0429 ± 0.0004[b]
		Et_4NI	
0.05	0.0462 ± 0.0004	0.05	0.0467 ± 0.0004
0.10	0.0500 ± 0.0006	0.10	0.0507 ± 0.0004
0.25	0.0617 ± 0.0010	0.25	0.0631 ± 0.0008
0.50	0.0821 ± 0.0011	0.50	0.0851 ± 0.0010
0.75	0.1034 ± 0.0007	0.75	0.1082 ± 0.0008
1.00	0.1251 ± 0.0005	1.00	0.1320 ± 0.0006
		1.25	0.1563 ± 0.0007
		Me_4NCl	
0.05	0.0439 ± 0.0004	0.05	0.0444 ± 0.0004
0.10	0.0451 ± 0.0004	0.10	0.0458 ± 0.0004
0.25	0.0488 ± 0.0005	0.25	0.0501 ± 0.0006
0.50	0.0546 ± 0.0007	0.50	0.0570 ± 0.0008
0.75	0.0603 ± 0.0008	0.75	0.0638 ± 0.0009
1.00	0.0658 ± 0.0008	1.00	0.0705 ± 0.0010
1.50	0.0765 ± 0.0010	1.50	0.0837 ± 0.0011
2.00	0.0871 ± 0.0014	2.00	0.0968 ± 0.0013
2.50	0.0975 ± 0.0020	2.50	0.1098 ± 0.0017
3.00	0.1079 ± 0.0027	3.00	0.1228 ± 0.0021
		3.50	0.1357 ± 0.0027
		4.00	0.1486 ± 0.0033
		4.50	0.1615 ± 0.0039
		NaCl	
0.05	0.0418 ± 0.0004	0.05	0.0421 ± 0.0004
0.10	0.0410 ± 0.0003	0.10	0.0414 ± 0.0003
0.25	0.0390 ± 0.0003	0.25	0.0394 ± 0.0003
0.50	0.0360 ± 0.0003	0.50	0.0366 ± 0.0003
0.75	0.0335 ± 0.0004	0.75	0.0342 ± 0.0003
1.00	0.0312 ± 0.0004	1.00	0.0321 ± 0.0003
1.50	0.0271 ± 0.0004	1.50	0.0282 ± 0.0004
2.00	0.0232 ± 0.0004	2.00	0.0248 ± 0.0004
2.50	0.0196 ± 0.0003	2.50	0.0215 ± 0.0004
3.00	0.0161 ± 0.0003	3.00	0.0184 ± 0.0004
4.00	0.0093 ± 0.0003	4.00	0.0124 ± 0.0006
4.50	0.0060 ± 0.0004	4.50	0.0094 ± 0.0007

[a] Solubilities are given as mol·L^{-1} or mol·kg^{-1}. [b] ± SD.

Table 4. Smoothed Total Solubility[a] of L-Cystine in Different Ionic Media at Different Ionic Strengths at t = 25 °C in both Molar and Molal Scales

c_{MX} / mol·L^{-1}	S_c^T	m_{MX} / mol·kg^{-1}	S_m^T
0.00	0.677 ± 0.012[b]	0.00	0.678 ± 0.011[b]
		Et_4NI	
0.05	0.642 ± 0.012	0.05	0.651 ± 0.011
0.10	0.610 ± 0.015	0.10	0.627 ± 0.014
0.25	0.529 ± 0.024	0.25	0.565 ± 0.023
0.50	0.430 ± 0.022	0.50	0.491 ± 0.026
0.75	0.359 ± 0.011	0.75	0.439 ± 0.018
1.00	0.306 ± 0.023	1.00	0.400 ± 0.013
		1.25	0.371 ± 0.029
		Me_4NCl	
0.05	0.654 ± 0.010	0.05	0.658 ± 0.009
0.10	0.632 ± 0.009	0.10	0.641 ± 0.007
0.25	0.574 ± 0.007	0.25	0.594 ± 0.005
0.50	0.497 ± 0.008	0.50	0.532 ± 0.006
0.75	0.434 ± 0.010	0.75	0.484 ± 0.008
1.00	0.381 ± 0.011	1.00	0.443 ± 0.010
1.50	0.290 ± 0.010	1.50	0.377 ± 0.011
2.00	0.212 ± 0.009	2.00	0.321 ± 0.011
2.50	0.142 ± 0.010	2.50	0.273 ± 0.010
3.00	0.076 ± 0.013	3.00	0.228 ± 0.009
		3.50	0.186 ± 0.009
		4.00	0.146 ± 0.010
		4.50	0.108 ± 0.012
		NaCl	
0.05	0.708 ± 0.012	0.05	0.709 ± 0.011
0.10	0.736 ± 0.013	0.10	0.737 ± 0.012
0.25	0.806 ± 0.020	0.25	0.809 ± 0.020
0.50	0.894 ± 0.030	0.50	0.901 ± 0.030
0.75	0.959 ± 0.035	0.75	0.970 ± 0.036
1.00	1.008 ± 0.038	1.00	1.025 ± 0.039
1.50	1.081 ± 0.039	1.50	1.109 ± 0.040
2.00	1.134 ± 0.036	2.00	1.174 ± 0.038
2.50	1.175 ± 0.033	2.50	1.227 ± 0.035
3.00	1.208 ± 0.032	3.00	1.273 ± 0.033
4.00	1.262 ± 0.041	4.00	1.353 ± 0.038
4.50	1.284 ± 0.050	4.50	1.389 ± 0.044
		5.00	1.423 ± 0.053

[a] Solubilities are given as mmol·L^{-1} or mmol·kg^{-1}. [b] ± SD.

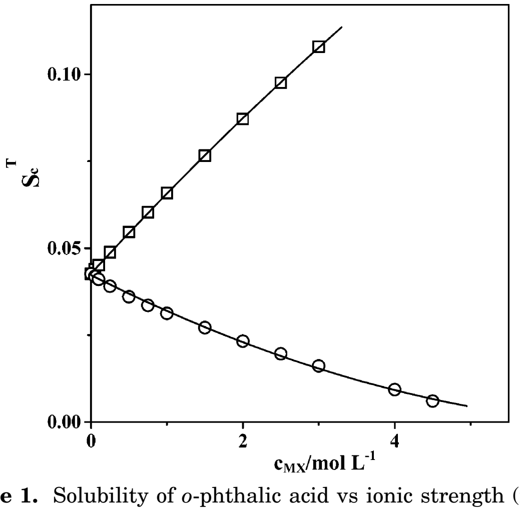

Figure 1. Solubility of *o*-phthalic acid vs ionic strength (molar scale) in Me_4NCl (□) and NaCl (○).

Setschenow coefficients have been reported by various authors to be true constants; the activity coefficients of neutral species are therefore linearly dependent on the concentration of the supporting electrolyte. The results of the present study show that, in the concentration range investigated, this is strictly true only for phthalate in NaCl(aq) in the molal concentration scale. By using the simple linear function, we calculated the Setschenow parameters reported in Table 8, which also indicates differences in the standard deviation of the fit (linear-nonlinear); although these differences can be considered significant, the figures in Table 8 are of interest for purposes of comparison. The parameter λ of the widely used Pitzer equations can be obtained from eq 11, using data from Tables 5 or 8 (i.e., using nonlinear or linear Setschenow coefficients, λ values are reported in Supporting Information Table 3S).

The trend shown by *o*-phthalic acid solubility has been discussed by Bergen and Long.[17] They observed that the Setschenow coefficient increases regularly from CsCl (k_c = 0.001) to LiCl (k_c = 0.224) and decreases from tetramethylammonium bromide (k_c = −0.160) to tetrapropylammonium bromide (k_c = −0.647), concluding that the size of the supporting electrolyte ion plays a fundamental role in determining the solubility and activity coefficients of nonelectrolytes. Our data are consistent with this statement. Another way of interpreting the reduced solubility of *o*-phthalic acid in NaCl is to consider the formation of little soluble Na^+-pht species, as reported for 1,2,4,5-benzenetetracarboxylic acid.[27] The same authors discussed the dependence of salt effects on the acidic or basic character of the nonelectrolyte and proposed that acidic substances may be more salted than basic ones in aqueous

Table 5. Empirical Parameters of the Smoothing Equationss 13−13a for *o*-Phthalic Acid and L-Cystine in both Molar and Molal Scales

	molar scale			molal scale		
	$-\log S_0^0$	a_∞	a_0	$-\log S_0^0$	a_∞	a_0
			o-Phthalic Acid			
Et_4NI	-1.443 ± 0.002^a	0.231 ± 0.059^a	0.774 ± 0.056^a	-1.439 ± 0.002	0.189 ± 0.041	0.850 ± 0.047
Me_4NCl		0.114 ± 0.011	0.255 ± 0.011		0.099 ± 0.008	0.338 ± 0.015
NaCl		-0.196 ± 0.007	-0.134 ± 0.020		-0.158 ± 0.001	-0.158 ± 0.001
			L-Cystine			
Et_4NI	-3.178 ± 0.008	-0.264 ± 0.152	-0.425 ± 0.125	-3.174 ± 0.008	-0.099 ± 0.106	-0.353 ± 0.103
Me_4NCl		-0.394 ± 0.015	-0.061 ± 0.041		-0.180 ± 0.007	-0.146 ± 0.033
NaCl		0.002 ± 0.012	0.344 ± 0.051		0.011 ± 0.010	0.340 ± 0.048

[a] ± SD on the parameter.

Table 6. Activity Coefficient of *o*-Phthalic Acid in Different Ionic Media and at Different Ionic Strengths at $t = 25$ °C

$\frac{c_{MX}}{mol \cdot L^{-1}}$	y_c	$\frac{m_{MX}}{mol \cdot kg^{-1}}$	γ_m
	Et_4NI		
0.05	0.917 ± 0.006^a	0.05	0.910 ± 0.005^a
0.10	0.846 ± 0.009	0.10	0.834 ± 0.007
0.25	0.682 ± 0.012	0.25	0.662 ± 0.011
0.50	0.505 ± 0.010	0.50	0.484 ± 0.010
0.75	0.393 ± 0.005	0.75	0.376 ± 0.006
1.00	0.314 ± 0.004	1.00	0.302 ± 0.003
		1.25	0.249 ± 0.003
	Me_4NCl		
0.05	0.972 ± 0.005	0.05	0.963 ± 0.004
0.10	0.946 ± 0.004	0.10	0.930 ± 0.004
0.25	0.878 ± 0.004	0.25	0.846 ± 0.005
0.50	0.787 ± 0.003	0.50	0.743 ± 0.007
0.75	0.714 ± 0.002	0.75	0.666 ± 0.007
1.00	0.654 ± 0.003	1.00	0.605 ± 0.006
1.50	0.555 ± 0.006	1.50	0.510 ± 0.006
2.00	0.476 ± 0.009	2.00	0.439 ± 0.006
2.50	0.411 ± 0.012	2.50	0.381 ± 0.007
3.00	0.357 ± 0.014	3.00	0.334 ± 0.008
		3.50	0.293 ± 0.009
		4.00	0.258 ± 0.010
		4.50	0.228 ± 0.010
	NaCl		
0.05	1.016 ± 0.006	0.05	1.018 ± 0.004
0.10	1.033 ± 0.006	0.10	1.037 ± 0.004
0.25	1.088 ± 0.010	0.25	1.095 ± 0.004
0.50	1.195 ± 0.015	0.50	1.199 ± 0.005
0.75	1.320 ± 0.020	0.75	1.313 ± 0.005
1.00	1.462 ± 0.023	1.00	1.438 ± 0.006
1.50	1.807 ± 0.027	1.50	1.725 ± 0.008
2.00	2.242 ± 0.029	2.00	2.068 ± 0.011
2.50	2.791 ± 0.031	2.50	2.480 ± 0.016
3.00	3.480 ± 0.040	3.00	2.974 ± 0.023
4.00	5.427 ± 0.103	4.00	4.277 ± 0.044
4.50	6.784 ± 0.166	4.50	5.129 ± 0.060
		5.00	6.151 ± 0.081

[a] ± SD.

Table 7. Activity Coefficient of L-Cystine in Different Ionic Media and at Different Ionic Strengths at $t = 25$ °C

$\frac{c_{MX}}{mol \cdot L^{-1}}$	y_c	$\frac{m_{MX}}{mol \cdot L^{-1}}$	γ_m
	Et_4NI		
0.05	1.049 ± 0.020^a	0.05	1.040 ± 0.019^a
0.10	1.099 ± 0.026	0.10	1.079 ± 0.023
0.25	1.253 ± 0.046	0.25	1.190 ± 0.039
0.50	1.533 ± 0.052	0.50	1.362 ± 0.047
0.75	1.849 ± 0.026	0.75	1.524 ± 0.031
1.00	2.210 ± 0.089	1.00	1.682 ± 0.027
		1.25	1.839 ± 0.086
	Me_4NCl		
0.05	1.009 ± 0.017	0.05	1.017 ± 0.017
0.10	1.021 ± 0.017	0.10	1.035 ± 0.017
0.25	1.076 ± 0.020	0.25	1.092 ± 0.018
0.50	1.219 ± 0.028	0.50	1.198 ± 0.023
0.75	1.421 ± 0.037	0.75	1.319 ± 0.029
1.00	1.688 ± 0.045	1.00	1.455 ± 0.035
1.50	2.461 ± 0.059	1.50	1.776 ± 0.044
2.00	3.681 ± 0.075	2.00	2.174 ± 0.050
2.50	5.587 ± 0.111	2.50	2.664 ± 0.054
3.00	8.558 ± 0.220	3.00	3.268 ± 0.058
		3.50	4.011 ± 0.066
		4.00	4.926 ± 0.085
		4.50	6.051 ± 0.124
	NaCl		
0.05	0.963 ± 0.017	0.05	0.963 ± 0.017
0.10	0.930 ± 0.017	0.10	0.931 ± 0.016
0.25	0.853 ± 0.019	0.25	0.854 ± 0.019
0.50	0.767 ± 0.025	0.50	0.767 ± 0.024
0.75	0.711 ± 0.027	0.75	0.709 ± 0.026
1.00	0.671 ± 0.028	1.00	0.667 ± 0.027
1.50	0.619 ± 0.026	1.50	0.611 ± 0.025
2.00	0.586 ± 0.023	2.00	0.574 ± 0.023
2.50	0.564 ± 0.019	2.50	0.547 ± 0.020
3.00	0.547 ± 0.016	3.00	0.526 ± 0.016
4.00	0.524 ± 0.013	4.00	0.494 ± 0.012
4.50	0.515 ± 0.015	4.50	0.481 ± 0.012
		5.00	0.470 ± 0.014

[a] ± SD.

salts that promote disordering of the water structure. This may, in part, account for the different trends observed for *o*-phthalic acid and L-cystine.

There is quite an abundance of literature reports on the solubility of *o*-phthalic acid.[15−19,23] Rivet and Rosemblum[15] studied the effect of salt on solubility in several electrolytes (alkali and alkaline earth metal cations—chloride, bromide, iodide, sulfate anions, and others) generally at $I < 3$ mol·L^{-1}, and their data in water and in NaCl are in accordance with those presented here. Bergen and Long[17] reported data on solubility in tetralkylammonium bromide. McMaster et al.[16] gave solubilities in water and in 10 % and 15 % Na_2SO_4. Viçoso et al.[19] obtained $S_0 = 0.0427$ mol·kg^{-1} in water at 25 °C, which is in very good agreement with our results. Nanyin et al.[18] reported several solubility data in the temperature range 25−155 °C. Few data are reported in the literature on the solubility of cystine.[20−23] Apruzzese et al.[22] reported the solubility of cystine in NaCl in the concentration range 0.15 to 3 mol·L^{-1} and their data are fairly consistent with ours (see Table 2). Carta and Tola[20] studied the same system in the same experimental conditions, and again we found there to be good accordance with data reported here. From these reports we have log $S_0^T = -3.10$ [22] and −3.16,[20] which is very close to our value log $S_0^0 = -3.178$ (molal concentration scale).

Table 8. Linear Setschenow Coefficients for *o*-Phthalic Acid and L-Cystine in Different Ionic Media at t = 25 °C

concn scale	electrolyte	$k_{c,m}$	$(10^2(\sigma_{fit}/\lvert k_{c,m}\rvert))_{linear}$[a]	$(10^2(\sigma_{fit}/\lvert k_{c,m}\rvert))_{nonlinear}$[a]
		o-Phthalic Acid		
c_{MX}/mol·L^{-1}	Et_4NI	−0.507	8.5	7.4
	Me_4NCl	−0.156	6.5	6.0
	NaCl	0.186	5.8	4.8
m_{MX}/mol·kg^{-1}	Et_4NI	−0.489	9.9	7.4
	Me_4NCl	−0.157	9.4	6.0
	NaCl	0.163	5.8	4.6
		L-Cystine		
c_{MX}/mol·L^{-1}	Et_4NI	0.399	9.7	6.2
	Me_4NCl	0.307	10.4	4.8
	NaCl	−0.070	16.3	13.1
m_{MX}/mol·kg^{-1}	Et_4NI	0.251	9.2	6.2
	Me_4NCl	0.174	4.1	3.2
	NaCl	−0.078	17.5	13.1
			9.4[b]	6.9[b]

[a] σ_{fit} = SD on the fit for the linear and nonlinear equations used for calculating Setschenow coefficients. [b] Mean values.

For the dependence of k_c on log K_{ow} (K_{ow} = water−octanol partition coefficient), Ni and Yalkowsky[23] proposed the empirical equation (for NaCl):

$$k_c = 0.039K_{ow} + 0.117$$

Using this equation (K_{ow} = 0.73 and −5.08 for phthalate and cystine, respectively[28,29]), we obtain k_c (pht) = 0.145 and k_c (cy) = −0.08. This is quite an interesting result which encourages us to further investigate these empirical relationships. In particular, similar expressions would be very useful for other salts, and to this end we are investigating the solubility of several other acidic and basic substances in different supporting electrolytes.

Supporting Information Available:

Additional text and tables. This material is available free of charge via the Internet at http://pubs.acs.org.

Symbols and Abbreviations

a_∞, a_0	empirical parameters used in smoothing functions
AH_n^{n+}	n-protonated polyamine
c	molar concentration
c_{MX}, m_{MX}	concentration of supporting electrolyte
cy	L-cystine
Et_4NI	$(C_2H_5)_4NI$
Et_4NOH	$(C_2H_5)_4NOH$
H_nL	n-protic acid
k_c, k_m	Setschenow coefficient in the molar and molal scale, respectively
k_i	nonelectrolyte self-interaction parameter
K_i^H	stepwise protonation constant (stoichiometric)
K_i^{H0}, β_i^{H0}	protonation constant at infinite dilution
m	molal concentration
Me_4NCl	$(CH_3)_4NCl$
MX	supporting electrolyte
pht	*o*-phthalic acid
S_0^T	total solubility in pure water
S_0^0	solubility of neutral species in pure water
S^0	solubility of neutral species
S^T	total solubility
X_m, X_c	parameter X in the molal and molar concentration scales, respectively
y	activity coefficient (molar)
z^*	difference in the square of the charge on species for protonation reactions
β_i^H	overall protonation constant (stoichiometric)
γ	activity coefficient (molal)
λ	parameter for the activity coefficient of a neutral species (Pitzer model)

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