Effect of Sulpholan upon Dissociation of Phenols in Alkaline Solution

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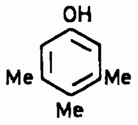
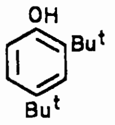
The degrees of ionisation of 3,4,5-trimethylphenol and 2,4-di-t-butylphenol have been measured in water–sulpholan mixtures containing hydroxide ion. The solubilities of 3,4,5-trimethylphenol and 2,4,6-trinitroaniline in dilute aqueous sulpholan solutions have also been determined and activity coefficients derived for the neutral compounds. It is shown that the decrease in the degree of ionisation of phenols that accompanies addition of sulpholan to water applies to both ordinary phenols and those containing bulky *ortho*-substituents. The cause of this decrease can be traced to the large decrease in activity of the neutral compound that accompanies addition of small amounts of sulpholan to water. The differing ionisation behaviour of phenols and aromatic amines is discussed in terms of activity coefficient changes.

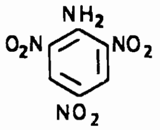
THE basicity towards feeble nitrogen and carbon acids of aqueous solutions of hydroxide ion can be dramatically increased by the addition of polar aprotic solvents such as dimethyl sulphoxide (DMSO), tetramethylene sulphone (sulpholan), or hexamethylphosphoramide (HMP).[1] We have recently shown, however, that the acidity of phenols containing bulky *ortho*-substituents is actually decreased by the addition of DMSO to water.[2] There is a minimum in the acidity function at *ca.* 10 mol % DMSO, beyond which point the basicity begins to increase; at high DMSO concentrations the systems become strongly basic towards phenols also. Since these results were obtained with hindered phenols (the only phenols weak enough to be but partially ionised in the systems of interest)[3] it was not known if their anomalous behaviour arose because of their phenolic character or because of the presence of bulky groups adjacent to the site of dissociation. Since we have found even deeper minima with sulpholan than with DMSO, we have examined the ionisation of a weak, unhindered phenol, 3,4,5-trimethylphenol (1), in aqueous sulpholan containing 0·0033M-tetramethylammonium hydroxide.



(1)



(2)



(3)

The lower concentration of base compared to the earlier work[2] and the lowered acidity of the phenol caused by the presence of alkyl groups in the ring permits the usual acidity function measurements to be made, without resort to the use of buffers in mixed solvents.

Figure 1 shows a plot of the degree of ionisation of (1) and 2,4-di-t-butylphenol (2) in aqueous sulpholan solutions containing 0·0033M-hydroxide ion as a function of sulpholan concentration. It can be seen that both types of phenolic indicator (one containing a bulky *ortho*-group and the other not) are substantially less ionised in solutions containing up to 35—50 mol % sulpholan than they are in water. It is clear that phenolic character is the primary cause of this anomalous behaviour, although the somewhat deeper minimum in the case of the hindered compound (2) suggests that the effect is enhanced by a bulky group next to the site of ionisation.

In an attempt to learn why phenols behave so differently from amines in this region we have measured the activity coefficients of compound (1) and of 2,4,6-trinitroaniline (3) in the region 0—7·5 mol % sulpholan. The results are shown in the Table. Measurements beyond 7·5 mol % sulpholan could not be made with the phenol because of emulsion formation. Attempts were made to determine the corresponding values for (2) but similar and, indeed, more serious difficulties were encountered with this compound.

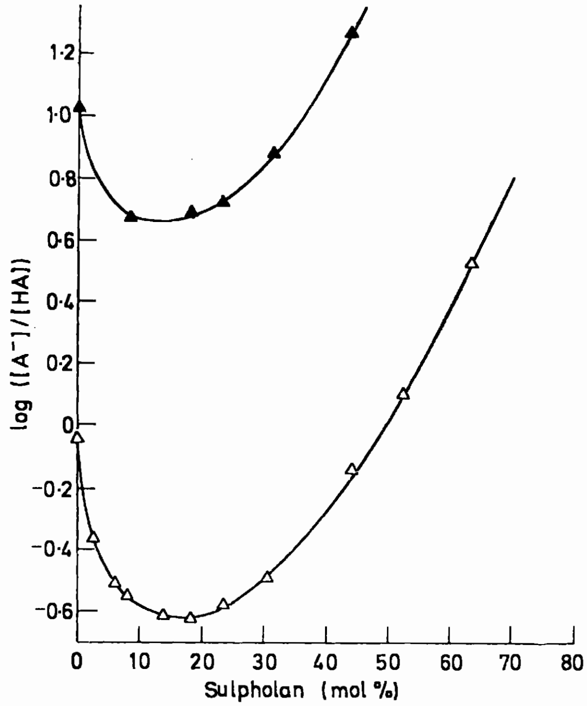


FIGURE 1 Ionisation ratios: (1) (upper curve); (2) lower curve)

Solubility and activity data for aqueous sulpholan mixtures

Sulpholan (mol %)	Solubility (10^3M)	f_{HA} *	$\log f_{HA}$	$\log a_{H_2O}$ †
		Compound (3)		
0	0·134	1·000	0	1·742
2·50	0·478	0·280	−0·533	1·693
5·00	1·35	0·099	−1·003	1·646
7·50	3·26	0·041	−1·389	1·603
		Compound (1)		
0	7·19	1·00	0	1·742
2·50	26·3	0·273	−0·563	1·693
5·00	66·4	0·108	−0·906	1·646
7·50	139	0·051	−1·289	1·603

* The activity coefficient f_{HA} is taken as the ratio of the compound's solubility in water to that in the solution in question.[9]
† Ref. 6.

The basis for the contrasting behaviour of phenols and aromatic amines can be traced to the activity coefficient changes that take place when sulpholan is added to water. Equations (3) and (4) can be derived from equations (1) and (2), which are different expressions for the acidity function H_-;[1] [ ] represents molarity, *a*

$$H_- = pK_{HA} + \log [A^-]/[HA] \qquad (1)$$

$$H_- = -\log (a_{H^+} . f_{A^-}/f_{HA}) \qquad (2)$$

$$\log f_{A^-}/f_{HO^-} = pK_W - pK_{HA} + \log [HO^-] - \log a_{H_2O} + \log f_{HA} - \log [A^-]/[HA] \qquad (3)$$

$$\log f_{A^-}/f_{HA}f_{HO^-} = pK_W - pK_{HA} + \log [HO^-] - \log a_{H_2O} - \log [A^-]/[HA] \qquad (4)$$

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[1] K. Bowden, *Chem. Rev.*, 1966, **66**, 119; C. H. Rochester, 'Acidity Functions,' Academic Press, London, 1970, ch. 7; J. R. Jones, *Quart. Rev.*, 1971, **25**, 365.

[2] A. Albagli, A. Buckley, A. M. Last, and R. Stewart, *J. Amer. Chem. Soc.*, 1973, **95**, 4711.

[3] C. H. Rochester, *J. Chem. Soc.*, 1965, 4603.

activity, and f activity coefficient, $K_W = a_{H^+}a_{HO^-}/a_{H_2O}$, and $K_{HA} = a_{H^+}a_{A^-}/a_{HA}$; HA is the weak acid whose degree of ionisation is being measured.

Equations (3) and (4) have been used to calculate the appropriate activity coefficient ratio terms, using molarity values for all activities and concentrations and using 15·74 for pK_W, 10·49 for the pK_{HA} of (1), and 12·20 for the pK_{HA} of (3).[4] Values of water activity, in molarity units, were derived from activity coefficient data given by Benoit and Choux for this solvent system.[5]

In Figure 2 a plot of log f_{A^-}/f_{HO^-} against solvent composition for (1) and (3) is shown. The negative slopes reflect the higher degree of solvation of hydroxide ion than of the organic anions. The smaller slope in the case of the phenol reflects, in turn, the expected higher degree of charge localisation on the oxygen atom of the phenoxide ion than on the nitrogen atom of the amide ion. If the activity coefficients of the neutral species are also considered the cause of the anomalous ionisation behaviour of phenols becomes apparent (Figure 2). The activity coefficients of the phenol and the amine drop sharply (and by comparable amounts) upon addition of sulpholan to water and, in the case of the phenols, this is sufficient to cause the term log $f_{A^-}/f_{HA}f_{HO^-}$ to become positive.

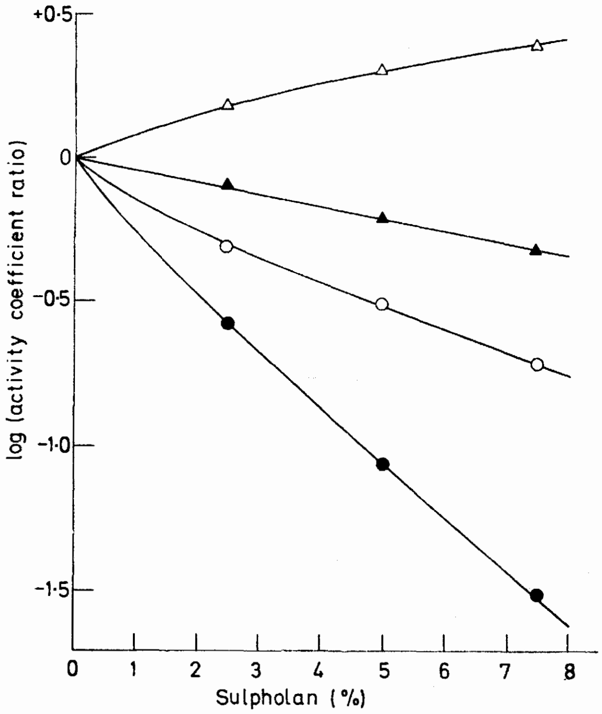

FIGURE 2 Variation of the logarithm of activity coefficient ratios as a function of sulpholan concentration: two upper curves, log $f_{A^-}/f_{HA}f_{HO^-}$; two lower curves, log f_{A^-}/f_{HO^-}; open symbols (1); closed symbols, (3)

The increase in the basicity of the medium towards phenols that occurs at higher concentrations of sulpholan can be traced to two factors. First, there is evidence indicating that at higher concentrations the activity coefficient of the neutral compound will level off.[5] This would allow the activity coefficient ratio f_{A^-}/f_{HO^-} to become the dominant factor in determining solution basicity towards phenols, as it is for aromatic amines throughout the whole solvent range. Secondly, the effect of the decrease in water activity begins to be felt at high sulpholan concentrations. [The acidity function can be expressed in the form $H_- = \log (a_{H_2O}K_W/a_{HO^-} \cdot f_{A^-}/f_{HA})$, and a decrease in a_{H_2O} will be reflected in an increase of solution basicity towards all solutes.] In the case of sulpholan, but not DMSO, this effect is of minor importance in solutions containing more than 40 mol % water.

EXPERIMENTAL

Sulpholan was distilled under vacuum from sodium hydroxide pellets and redistilled from calcium hydride.

The ionisation ratios were measured as previously described[4] and the method of Hine and Hine[6] was used to obtain the extinction coefficients of the phenoxide ions at each solvent composition studied.

The pK_{HA} of (1) was measured in phosphate and glycine buffers at 25° and was found to be 10·49 ± 0·03. The literature values are 10·51 at 20°[7] and 10·25 at 25°.[8]

Solubilities were determined by equilibrating an excess of the solid with the solvent mixture under study at 25° for 24 h, to give saturated solutions. These were filtered and the solute concentrations determined spectrophotometrically, after dilution if necessary, and after making any necessary allowances for solvent effects on extinction coefficients. Activity coefficients (f) were obtained using the expression $f' = f(c/c')$, where c is solubility and primed and unprimed symbols refer to the solvent composition under study and water, respectively.[9]

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[8] H. C. Ko, W. F. O'Hara, T. Hu, and L. G. Hepler, *J. Amer. Chem. Soc.*, 1964, **86**, 1003.

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