Enthalpies of Transfer from Methanol to Protic and Aprotic Solvents of the Transition State in the Reaction of Benzenesulphonyl Chloride with Imidazole

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Rates, activation parameters, and heats of solution of the reactants have been measured for the reaction of benzenesulphonyl chloride with imidazole in water, three alcohols, and six dipolar aprotic solvents. Enthalpies and entropies of activation are considerably lower in aprotic than in protic solvents. The corresponding changes in free energies are relatively small. Variations in activation parameters within each solvent group are small. Enthalpies of transfer from protic to aprotic solvents of reactants and transition state are endo- and exo-thermic respectively. These enthalpies of transfer are approximately constant and independent of the particular aprotic solvent.

In a previous study [1] of solvent effects on nucleophilic substitution at tetraco-ordinate sulphur, the kinetics of the reaction of imidazole with substituted benzenesulphonyl chlorides was investigated in methanol and acetonitrile. By measuring the heat of solution of the reactants, the solvent effect on the enthalpy of activation was separated into initial and transition state effects. This showed that the lower $\Delta H^{\ddagger}$ observed when changing solvent from methanol to acetonitrile (*ca.* 7 kcal mol^{-1}) is caused by an endothermic enthalpy of transfer of imidazole (*ca.* 3 kcal mol^{-1}) and an exothermic enthalpy of transfer of the transition state (*ca.* —4 kcal mol^{-1}). Thus the transition state in this reaction is considerably better solvated in acetonitrile than in methanol. To extend this study to other solvents, the activation parameters and heat of solution of the reactants have been determined for the reaction of imidazole with benzenesulphonyl chloride in a series of protic and dipolar aprotic solvents. This should give further information about transition state solvation, and should show to what extent the previous results depend upon the two particular solvents or are typical protic–aprotic solvent effects for this type of reaction.

TABLE 1

Rate constants and activation parameters for the reaction of benzenesulphonyl chloride with imidazole

	k/l mol^{-1} s^{-1}							$\Delta H^{\ddagger}$/	$\Delta S^{\ddagger}$/
Solvent	5 °C	10 °C	15 °C	20 °C	25 °C	30 °C	35 °C	kcal mol^{-1}	cal mol^{-1} K^{-1}
Sulpholan [a]					13·1 [b]	15·6	17·9	5·3	—36
Propylene carbonate	4·70	5·79	6·85	8·62	10·2			5·8	—34
Acetonitrile [c]	1·65	1·88	2·36		3·20	3·85		5·1	—39
Nitromethane		1·75	2·00	2·37	2·97	3·32		5·1	—39
Benzonitrile		0·970	1·15		1·60		2·19	5·1	—40
Butyronitrile	0·602	0·750	0·935		1·38	1·54		5·9	—38
Methanol [c]	0·0187	0·0275			0·0883	0·129		12·3	—22
Ethanol		0·0224	0·0328		0·0696	0·0964	0·136	11·9	—24
Propanol			0·0217	0·0324	0·0473	0·0665	0·0954	12·4	—23
96% Ethanol–H_2O (w/w)		0·0322	0·0454		0·0956	0·133	0·189	11·7	—24
Water [d]			0·800	1·21	1·91	2·88		14·3	—9

[a] k = 20·7 At 40 °C, 29·1 at 50 °C, 32·2 at 55 °C. [b] Extrapolated. [c] From ref. 1. [d] From O. Rogne, *J. Chem. Soc.* (*B*), 1970, 1056.

EXPERIMENTAL

Materials.—Benzenesulphonyl chloride was fractionally distilled at reduced pressure. Imidazole was recrystallized from benzene. Acetonitrile, benzonitrile, and butyronitrile were purified as described by Coetzee.[2] Methanol, absolute ethanol, and propanol were dried with molecular sieves and fractionally distilled. Nitromethane (Fluka puriss) was used as supplied as was the commercial 96% ethanol (w/w). All other solvents were fractionally distilled at reduced pressure. In addition to the above mentioned solvents, the following were also used: dimethylformamide, dimethyl sulphoxide, hexamethylphosphoramide, and 1-methyl-2-pyrrolidone. These solvents all reacted with benzenesulphonyl chloride and were therefore not used. Although water and alcohols also react with benzenesulphonyl chloride, these reactions are sufficiently slow compared with the reaction of the acid chloride with imidazole that the measurement and interpretation of the observed rate constants are not effected.

Rate and Calorimetric Measurements.—Rates and heats of solution were measured conductometrically and calorimetrically, respectively. The apparatus and procedure have been described.[1] The precision of the rate constants is ±5% or better, of $\Delta H^{\ddagger}$ *ca.* ±0·5 kcal mol^{-1}, of $\Delta S^{\ddagger}$ *ca.* ±2 cal mol^{-1} K^{-1}, and of the heats of solution ±0·1 kcal mol^{-1}

RESULTS AND DISCUSSION

Benzenesulphonyl chloride reacts with excess of imidazole in organic solvents to give 1 mol. equiv. of *N*-phenylsulphonylimidazole and 1 mol. equiv. of imidazole hydrochloride.[3,4] This reaction is a nucleophilic

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[1] O. Rogne, *J.C.S. Perkin II*, 1973, 823.

[2] J. F. Coetzee, *Pure Appl. Chem.*, 1966, **13**, 427.

[3] H. A. Staab and K. Wendal, *Chem. Ber.*, 1960, **93**, 2902.

[4] T. C. Bruice, ' Methods in Enzymology,' eds. S. P. Colowick and N. O. Kaplan, *Academic Press*, New York, 1963, vol. VI, p. 606.

displacement on sulphur.[1] The second-order rate constants and activation parameters are summarized in Table 1. The activation parameters fall in two groups according to solvent type. Thus the aprotic solvents give consistently lower $\Delta H^\ddagger$ and $\Delta S^\ddagger$ values. Since $\Delta H^\ddagger$ is different in the two solvent types, the relative rates are temperature dependent. The reaction is, however, generally faster in aprotic solvents at ordinary temperatures, but since the solvent effects on $\Delta H^\ddagger$ and $\Delta S^\ddagger$ tend to compensate, the effect on $\Delta G^\ddagger$ is relatively small. The variation of $\Delta H^\ddagger$ and $\Delta S^\ddagger$ within each solvent type is small and does not justify any discussion. An exception is water which gives significantly higher $\Delta H^\ddagger$ and $\Delta S^\ddagger$ values than the alcohols. The heats of solution, ΔH_s, and the enthalpies of transfer for benzenesulphonyl chloride and imidazole, $\delta\Delta H_s$, from methanol to the various solvents, are in Table 2. The enthalpies of transfer of the reactants, $\delta\Delta H_s{}^r$, the difference in activation enthalpy $\delta\Delta H^\ddagger$, and the enthalpies of transfer of the transition state from methanol, $\delta\Delta H^t = \delta\Delta H_s{}^r + \delta\Delta H^\ddagger$,[5] are in Table 3. The enthalpy of transfer of the transition state from methanol to dipolar aprotic solvents is exothermic, showing that the transition state is well solvated by aprotic solvents. The effect is also approximately constant (*ca.* —4 kcal mol^{-1}). Thus there is no large variation in the enthalpy of transfer of the transition state, and hence in its solvation, with properties of the solvents such as dielectric constants, solvent polarity parameters, donor numbers, *etc.*[6-8] In the case of the dielectric constant, this is clearly seen when comparing propylene carbonate and butyronitrile where $\delta\Delta H^t$ is almost identical although the dielectric constants differ by 50. Exothermic enthalpies of transfer of similar magnitude to the one observed here are also seen in the transfer of various S_N2 and S_NAr transition states from methanol to dipolar aprotic solvents.[9-11] The similarity of enthalpies of transfer in S_N2 and S_NAr reactions was suggested [9] as being due to the small importance of hydrogen bonding compared to dipole–dipole and dispersion interactions between transition state and solvent. The same probably applies in the present case also. The endothermic enthalpy of transfer observed for substitutions at a carbonyl carbon atom,[12,13] where the transition state is a good hydrogen bond acceptor,[7] is consistent with this.

TABLE 2

Heats of solution and enthalpies of transfer from methanol for imidazole and benzenesulphonyl chloride at 25 °C

Solvent	Imidazole ΔH_s/ kcal mol^{-1}	Imidazole $\delta\Delta H_s$/ kcal mol^{-1}	$PhSO_2Cl$ ΔH_s/ kcal mol^{-1}	$PhSO_2Cl$ $\delta\Delta H_s$/ kcal mol^{-1}
Sulpholan [a]	4·16	2·40	0·28	−0·37
Propylene carbonate	4·38	2·62	0·24	−0·41
Acetonitrile	4·79	3·03	0·67	0·02
Nitromethane	4·73	2·97	0·95	0·30
Benzonitrile	4·61	2·85	0·05	−0·60
Butyronitrile	4·46	2·70	−0·12	−0·77
Methanol	1·76	0	0·65	0
Ethanol	2·30	0·54	0·79	0·14
Propanol	2·29	0·53	1·24	0·59
96% Ethanol–H_2O (w/w)	2·20	0·44	1·16	0·51
Water	3·07	1·31		

[a] At 35 °C.

TABLE 3

Enthalpies of transfer from methanol to various solvents of reactants and transition state for the reaction of benzenesulphonyl chloride with imidazole

Solvent	$\delta\Delta H_s{}^r$/ kcal mol^{-1}	$\delta\Delta H^\ddagger$/ kcal mol^{-1}	$\delta\Delta H^t$/ kcal mol^{-1}
Sulpholan	2·0	−7·0	−5·0
Propylene carbonate	2·2	−6·5	−4·3
Acetonitrile	3·0	−7·2	−4·2
Nitromethane	3·3	−7·2	−3·9
Benzonitrile	2·3	−7·2	−4·9
Butyronitrile	1·9	−6·4	−4·5
Methanol	0	0	0
Ethanol	0·7	−0·4	0·3
Propanol	1·1	0·1	1·2
96% Ethanol–H_2O (w/w)	0·9	−0·6	0·3
Water	>1·3	2·0	>3·3

Few protic solvents could be studied due to their high reactivity towards benzenesulphonyl chloride. In water the low solubility of benzenesulphonyl chloride made it impossible to measure its heat of solution accurately with our apparatus. The enthalpy of solution is, however, positive so the $\delta\Delta H^t$ value given is a minimum value. In alcoholic solvents, the transition state is increasingly better solvated in the series PrOH–EtOH–MeOH, *i.e.* with increasing dielectric constant and polarity. Water, however, in spite of its polarity and high dielectric constant, is not a good solvent. The relatively large endothermic enthalpy of transfer to water could reflect the unfavourable process of placing the transition state in such a highly structured liquid. The more positive $\Delta S^\ddagger$ for water, which could reflect breaking of the solvent structure, is consistent with this although initial state effects also need to be considered.

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