

Solvent effects on reaction rates

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Abstract - Solvent effects on the rates of some well-known nucleophilic substitution reactions have been analysed in terms of initial-state and transition-state contributions. Where possible, the latter have been further analysed by the method of model solutes, on which solvent effects on a transition state are compared to solvent effects on a solute that might be a suitable model for the transition state. Solvent effects on reaction rates have also been analysed using the multiple linear regression procedure of Kamlet and Taft. It is shown that results from the two quite-different approaches are in good agreement with each other.

INTRODUCTION

Over the years, there have been developed two main methods for the examination of solvent effects on reaction rates. Firstly, rate constants, either as $\log k$ or as ΔG^\ddagger , may be correlated with a physical parameter characteristic of the solvent, for example, dielectric constant, solubility parameter, viscosity, etc., or with an empirical solvent parameter such as Y , Z , E_T , J , etc. (ref. 1-5). More recently, this type of analysis has been extended to multiple linear correlations with a number of solvent parameters, notably by Shorter et al. (ref. 6) on the reaction of diazodiphenylmethane and carboxylic acids, and more generally by Koppel and Palm (ref. 7) and by Kamlet and Taft and their coworkers (ref. 8-10). In the second method, the solvent effect on $\log k$ or ΔG^\ddagger is dissected into contributions from the reactants (initial-state) and the transition-state, followed, where possible, by a comparison of solvent effects on the transition-state with solvent effects on solutes that might function as suitable models for the transition-state. This method has been applied not only to a number of standard organic reactions (ref. 2, 11-18) but also to organometallic reactions (ref. 2, 19, 20) and to inorganic reactions (ref. 21). Although most dissections have been carried out in terms of Gibbs energy, there have been a number of studies using enthalpies of activation (ref. 2, 19-28). Of course, in principle, any thermodynamic parameter of activation can be dissected into initial-state and transition-state contributions, see for example the volumes of activation discussed in ref. 29.

The two methods outlined above have now been used extensively in discussions on solvent effects, but rather unfortunately, only few reactions have been studied by both methods (see ref. 2, 30), so that it has been difficult to compare results generally. Two pertinent reactions that have been so studied are the Menschutkin reaction of triethylamine with ethyl iodide, and the unimolecular decomposition of *t*-butyl chloride.

For the S_N2 reaction (1), plots of $\log k$ or of ΔG^\ddagger against various solvent parameters such as the dielectric constant function $Q = (\epsilon - 1)/(2\epsilon + 1)$, or the Hildebrand solubility parameter δ_H , yielded reasonable straight lines for a restricted range of solvents from which transition-state parameters z the charge separation, μ the dipole moment, and δ_H could be obtained (ref. 31), see Table 1.



Initial-state and transition-state contributions to $\delta\Delta G^\ddagger$, the change in ΔG^\ddagger with change in solvent, were calculated through eq (2), and the resulting Gibbs energies of transfer of the transition state, $\Delta G_t^{\circ}(\text{Tr})$, then compared to values for the model solute $\text{Et}_4\text{N}^+\text{I}^-$, as well as to the solvent functions Q and δ_H . Results, see Table 1, compared very well with those obtained using only $\log k$ or ΔG^\ddagger (ref. 31).

$$\Delta G_t^{\circ}(\text{Tr}) = \Delta G_t^{\circ}(\text{Et}_3\text{N}) + \Delta G_t^{\circ}(\text{EtI}) + \delta\Delta G^\ddagger \quad (2)$$

TABLE 1. Deduced properties of the Et₃N/EtI transition state in aprotic solvents.

Function plotted		Deduced property
ΔG^\ddagger	vs ΔG°	$z = 0.45$
ΔG^\ddagger	vs Q	$z = 0.43, \mu = 8.2$
ΔG^\ddagger	vs $f(\delta_H)$	$\delta_H = 12.2$
$\Delta G_t^\circ(\text{Tr})$	vs $\Delta G_t^\circ(\text{Et}_4\text{N}^+\text{I}^-)$	$z = 0.37$
$\Delta G_t^\circ(\text{Tr})$	vs Q	$z = 0.34, \mu = 6.5$
$\Delta G_t^\circ(\text{Tr})$	vs $f(\delta_H)$	$\delta_H = 11.5$
Electrostatic calculation		$z = 0.40, \mu = 7.6$

Two other approaches also gave similar values of z and μ for the transition state: a comparison of ΔG^\ddagger values for reaction (1) with ΔG° values for the model equilibrium (3), and an electrostatic calculation of solvent effects on ΔG^\ddagger for the related Menshutkin reaction of tripropylamine with methyl iodide (ref. 32), see Table 1. The net result of all these methods suggests the model shown in Fig. 1 for the Et₃N/EtI transition state.



Quite similar studies have been carried out for the S_N1 unimolecular decomposition of *t*-butyl chloride (ref. 2, 16, 30, 33). Various plots involving ΔG^\ddagger as a function of solvent gave $z = 0.81$ in polar solvents, and z around 0.48-0.65 in purely aprotic solvents, Table 2. In addition, a study of kinetic salt effects by Clarke and Taft (ref. 34) yielded a value of 0.82 for z in aqueous solution. The separation of initial-state and transition-state contributions can be effected through eq (4), and the values of $\Delta G_t^\circ(\text{Tr})$ then compared with those for the model solute, $\Delta G_t^\circ(\text{Me}_4\text{N}^+\text{Cl}^-)$ as well as values calculated for $\Delta G_t^\circ(\text{t-Bu}^+\text{Cl}^-)$, and values obtained from plots of $\Delta G_t^\circ(\text{Tr})$ against Q or some function of δ_H . As seen in Table 2, results in terms of z , μ , and δ_H agree very well. The general conclusion of this work and of work on electrostatic calculations (ref. 35) is that the transition state can be represented by the model shown in Fig. 2 in polar solvents and by the model given in Fig. 3

$$\Delta G_t^\circ(\text{Tr}) = \Delta G_t^\circ(\text{t-BuCl}) + \delta \Delta G^\ddagger \quad (4)$$

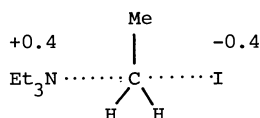
in the less polar aprotic solvents.

TABLE 2. Deduced properties of the *t*-BuCl transition state.

Function plotted	Deduced property	
	Polar solvents	Aprotic solvents
ΔG^\ddagger vs $\Delta G_t^\circ(\text{Me}_4\text{N}^+\text{Cl}^-)$	$z = 0.81$	$z = 0.48$
ΔG^\ddagger vs Q	-	$z = 0.65, \mu = 7.2$
ΔG^\ddagger vs $f(\delta_H)$	-	$\delta_H = 13$
Kinetic salt effects	$z = 0.82$	-
$\Delta G_t^\circ(\text{Tr})$ vs $\Delta G_t^\circ(\text{Me}_4\text{N}^+\text{Cl}^-)$	$z = 0.70$	$z = 0.45$
$\Delta G_t^\circ(\text{Tr})$ vs $\Delta G_t^\circ(\text{t-Bu}^+\text{Cl}^-)$	$z = 0.80$	-
$\Delta G_t^\circ(\text{Tr})$ vs Q	-	$z = 0.60, \mu = 6.6$
$\Delta G_t^\circ(\text{Tr})$ vs $f(\delta_H)$	-	$\delta_H = 15$
Electrostatic calculation	$z = 0.80, \mu = 8.8$	$\mu = 7.3$

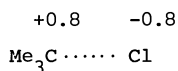
More detailed analyses have considered that values of $\Delta G_t^\circ(\text{Tr})$ for the *t*-butyl chloride reaction in aqueous or alcoholic solvents can themselves be dissected into electrostatic or interaction terms on the one hand, and nonelectrostatic or cavity terms on the other hand (ref. 36, 37). Results are exactly the same as obtained previously, namely values of z of around 0.81-0.84 units for the charge separation in the transition-state.

It has therefore been possible, for two particular reactions, to obtain certain transition-state properties by the two main methods involving solvent effects. However, there are other transition-state properties that are of considerable interest, such as the tendency of the transition-state to interact with hydrogen-bond donor solvents or with hydrogen-bond acceptor solvents. Since it is these properties that are involved in the Kamlet-Taft approach, an analysis involving dissection of ΔG^\ddagger into initial-state and transition-state contributions followed by application of the Kamlet-Taft equation to both ΔG^\ddagger and $\Delta G_t^\circ(\text{Tr})$ might lead to interesting and illuminating results.



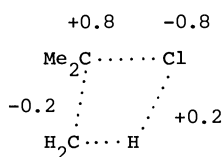
$$\mu = 7.6$$

Fig. 1



$$\mu = 8.8$$

Fig. 2



$$\mu = 7.3$$

Fig. 3

INITIAL-STATE AND TRANSITION-STATE EFFECTS

The Menshutkin reaction (1) has been extensively investigated by Abraham and Grellier (ref. 31) who determined solvent effects on the Gibbs energies of the reactants and then used eq (2) to obtain $\Delta G_t^\circ(\text{Tr})$, the change in Gibbs energy of the transition state on transfer from a reference solvent. In Table 3 is given a selection of results for aliphatic aprotic and

TABLE 3. Initial-state and transition-state effects in the $\text{Et}_3\text{N}/\text{EtI}$ reaction; values in kcal mol^{-1} at 298 K on the mol fraction scale.

Solvent	$\delta\Delta G^\ddagger$	ΔG_t°		
		Et_3N	EtI	Tr
Hexane	6.34	-1.28	-0.01	5.05
Cyclohexane	5.95	-1.26	-0.21	4.48
Ether	4.26	-1.06	0.10	3.30
Ethyl acetate	2.34	-0.74	-0.18	1.42
THF	2.05	-1.06	-0.43	0.56
Butanone	1.38	-0.68	-0.18	0.52
Cyclohexanone	1.21	-0.71	-0.31	0.19
Propanone	0.97	-0.30	0.05	0.72
Propionitrile	0.60	-0.42	0.17	0.35
DMF	0	0	0	0
Acetonitrile	-0.01	0.13	0.47	0.59
Nitromethane	-0.18	0.21	0.54	0.57
PC	-0.34	0.62	0.29	0.57
DMSO	-0.59	0.74	0.29	0.44
t-Butanol	2.70	-0.93	0.44	2.21
2-Propanol	2.78	-1.06	0.41	2.13
1-Butanol	3.18	-1.38	0.29	2.09
1-Propanol	3.00	-1.34	0.42	2.08
Ethanol	2.63	-1.14	0.57	2.06
Methanol	2.29	-1.29	0.84	1.84

hydroxylic solvents (ref. 31, 38), with dimethylformamide (DMF) as the reference solvent. By-and-large, effects on ΔG^\ddagger are mainly due to transition-state effects, although the solvent effect on the reactants is not negligible. Indeed, the retarding effect of alcohols on the reaction rate (i.e. the increased value of ΔG^\ddagger in alcohols) by comparison to dipolar aprotic solvents is due both to stabilisation of Et_3N and destabilisation of the

transition state by alcohols. Abraham and Grellier (ref. 31) showed that the model ion-pair $\text{Et}_4\text{N}^+\text{I}^-$ is affected by change in solvent very much more than is the transition-state, and suggested the model shown in Fig. 1 for the transition-state. As mentioned in the Introduction, studies on solvent effects on $\log k$ (or ΔG^\ddagger) lead to exactly the same model for the transition-state, Fig. 1, as do results in terms of $\Delta G_t^0(\text{Tr})$, with respect to the important properties z (the charge separation) and μ (the dipole moment).

The unimolecular decomposition of *t*-butyl chloride has also been analysed by the method of initial-state and transition-state contributions, eq (4), and values for aliphatic aprotic and hydroxylic solvents are in Table 4 (ref. 2, 16, 38). Except for the outstanding case

TABLE 4. Initial-state and transition-state effects in the unimolecular decomposition of *t*-BuCl; values in kcal mol⁻¹ at 298 K on the mol fraction scale.

Solvent	$\delta\Delta G^\ddagger$	ΔG_t^0		π^*	Solvent parameters	
		<i>t</i> -BuCl	Tr		α	β
Ether	5.72	-0.41	5.31	0.27	0	0.47
Ethyl acetate	4.03	-0.55	3.48	0.55	0	0.45
Propanone	1.84	-0.29	1.55	0.71	0.08	0.48
NMP	0.58	0.04	0.62	0.92	0	0.77
Acetonitrile	0.18	0.15	0.33	0.75	0.19	0.37
DMF	0	0	0	0.88	0	0.69
Nitromethane	-0.58	0.36	-0.22	0.85	0.22	0.30
DMSO	-0.84	0.62	-0.22	1.00	0	0.76
<i>t</i> -Butanol	-0.38	0.08	-0.30	0.41	0.68	1.01
2-Propanol	-1.10	0.24	-0.86	0.48	0.76	0.95
1-Butanol	-1.40	0.08	-1.32	0.47	0.79	0.88
1-Propanol	-1.66	0.20	-1.46	0.52	0.78	0.84
Ethanol	-2.02	0.28	-1.74	0.54	0.83	0.77
Methanol	-3.34	0.54	-2.80	0.60	0.93	0.62
Water	-9.56	5.11	-4.45	1.09	1.17	0.18

of water, solvent effects on the reactant itself are much smaller than those on the transition state. (Although not considered here, aqueous organic solvents also give rise to substantial initial-state effects, see ref. 2). A difficulty with this particular reaction is that the transition-state in hydroxylic solvents for the "solvolysis" reaction cannot be the same as the transition state in the less polar aprotic solvents for the "elimination" reaction. Thus against the model solute $\text{Me}_4\text{N}^+\text{Cl}^-$, the transition-state in the hydroxylic solvents behaves as though it has a rather large charge separation of about 0.80 units, whereas in the aprotic solvents the effective charge separation declines to around 0.5-0.6 units similar values being obtained no matter whether $\delta\Delta G^\ddagger$ or $\delta\Delta G_t^0(\text{Tr})$ values are used. The two models shown in Fig. 2 and Fig. 3 help to resolve this difficulty, with the transition-state dipole moment decreasing from 8.8 D in hydroxylic to 7.3 D in the less polar aprotic solvents. However, since the leaving chloride on both models carries a partial charge of some -0.8 units, it is possible that the two transition states might behave similarly towards, for example, hydrogen-bond donor solvents.

An $\text{S}_{\text{N}}2$ reaction of different charge type to the Menshutkin reaction is the Finkelstein exchange reaction, for example eq (5). Parker et al. (ref. 12, 17, 39) have examined initial-state and transition-state effects on numerous examples of the Finkelstein reaction and have shown conclusively that the large solvent effects on $\log k$ or ΔG^\ddagger arise through solvation of the initial-state anion by hydroxylic solvents. The example given in Table 5



illustrates the analysis of Parker. Values for $\Delta G_t^0(\text{Cl}^-)$ are based on the assumption that $\Delta G_t^0(\text{Ph}_4\text{As}^+) = \Delta G_t^0(\text{Ph}_4\text{B}^-)$ and are from (ref. 17, 39-45); values for $\Delta G_t^0(\text{MeI})$ are from (ref. 17, 39, 46, 47). As a corollary of $\delta\Delta G^\ddagger \approx \Delta G_t^0(\text{Cl}^-)$, values of $\Delta G_t^0(\text{Tr})$ are quite small, and it has proved difficult to devise suitable transition-state model solutes, although species such as ClAgCl^- have been suggested (ref. 39). Parker et al. (ref. 17) have used eq (6) and eq (7) to correlate ΔG^\ddagger values for Finkelstein reaction, Y^-/RX , with $n = 1$ for the particular case of reaction (5). There seems no good reason why n should be exactly unity,

$$\delta\Delta G^\ddagger = n\Delta G_t^0(\text{Y}^-) \quad (6)$$

$$\delta\Delta G^\ddagger = n\Delta G_t^0(\text{Y}^- - \text{RX}) \quad (7)$$

TABLE 5. Initial-state and transition-state effects in the Cl^-/MeI reaction; values in kcal mol^{-1} at 298 K on the mol fraction scale.

Solvent	$\delta\Delta G^\ddagger$	Cl^-	ΔG_t° MeI	Tr
Methanol	7.7	-7.6	1.1	1.2
Water	7.2	-10.2	3.5	0.5
Formamide	5.9	-7.4	1.7	0.2
Nitromethane	2.1	-0.8	0.6	1.9
Acetonitrile	1.5	-0.8	0.4	1.1
DMF	0	0	0	0
Propanone	0.0	2.2	0.1	2.3
DMA	-0.6	2.9	-0.2	2.1
NMP	-1.3	2.0	-0.4	0.3

and linear correlations for the data in Table 5 suggests that n should be somewhat less than unity, eq (8) and eq (9).

$$\delta\Delta G^\ddagger = -0.70 \Delta G_t^\circ(\text{Cl}^-) + 0.98 \quad r = 0.972 \quad (8)$$

$$\delta\Delta G^\ddagger = -0.90 \Delta G_t^\circ(\text{Cl}^-/\text{MeI}) + 1.22 \quad r = 0.975 \quad (9)$$

CORRELATION ANALYSIS

A large number of parameters of "solvent polarity" have been suggested for the correlation of reaction rates. Reichardt (ref. 1) in 1965 discussed 7 empirical parameters, but by 1979 was able to list no fewer than 24 such parameters (ref. 4) for use in single linear regressions, eq (10).

$$\log k \text{ or } \Delta G^\ddagger = mP + c \quad (10)$$

However, $\log k$ or ΔG^\ddagger values for the two simple $\text{S}_{\text{N}}2$ reactions (1) and (5) are not well related; for 6 common solvents the correlation constant, r , is only 0.605, using a value of $\delta\Delta G^\ddagger = 0.50$ for reaction (1) in water (ref. 31).⁺ Thus if $\log k$ for reaction (1) is not linearly related to $\log k$ for reaction (5), it follows that there is no possible solvent parameter that will be linearly related to both sets of $\log k$ values. It is therefore quite futile to search for any further general solvent parameters to use in eq (10), although solvent parameters for use in multiple linear regressions still need to be investigated.

Two groups of workers have set out general equations for the correlation of solvent effects through multiple regression analysis. Koppel and Palm (ref. 7) use the four-parameter eq (11), in which $f(\epsilon)$ is a dielectric constant function, usually $Q = (\epsilon-1)/(2\epsilon+1)$, $f(\eta)$ is a refractive index function $(\eta^2-1)/(\eta^2+2)$, and E and B are measures of electrophilic solvation ability and nucleophilic solvation ability of the solvent, respectively. Koppel and Palm (ref. 7) and, later, Shorter et al. (ref. 6) have applied eq (11) to a variety of reaction types quite successfully.

$$\log k = \log k_0 + g.f(\epsilon) + p.f(\eta) + e.E + b.B \quad (11)$$

The Kamlet and Taft group of workers (ref. 10) have used the alternative eq (12), in which π^* is a measure of solvent polarity, α and β refer to the hydrogen-bond acidity and hydrogen-bond basicity of the solvent, and δ_{H}^2 (or sometimes δ_{H}) is used as a measure of the work required to form a cavity in the solvent; δ_{H} is the Hildebrand solubility parameter. For polychlorinated or aromatic solvents, a polarisability correction term, $\pi^* + d\delta$, is required, but this will not be needed for the solvents considered here. Eq (12) applies not only to rate constants, where $\text{XYZ} = \log k$ or ΔG^\ddagger , but to a very large variety of other processes. For the correlation of $\log k$ values it is expected that the δ_{H}^2 term will cancel out between initial-state and transition-state, unless there are special circumstances. Some values of π^* , α , and β are in Table 4, see also ref. 10.

⁺ An even better example is the correlation of $\log k$ for the $\text{Br}^-/\text{methyl tosylate}$ reaction (ref. 48) with $\log k$ for the $\text{Pr}_3\text{N}/\text{MeI}$ reaction, the so-called J-parameter (ref. 49-51). For 11 common solvents, r is only 0.130.

$$XYZ = (XYZ)_O + s.\pi^* + a.\alpha + b.\beta + h.\delta_H^2/100 \quad (12)$$

Both eq (11) and eq (12) are general enough to be applied to almost any type of reaction. However, as will be shown later, there are considerable advantages to be gained by use of eq (12). As examples, three types of nucleophilic substitution reactions dealt with above will be examined through eq (12). It is immaterial whether $\log k$ or ΔG^\ddagger values are used in eq (12), but for comparisons with model solutes, the use of ΔG^\ddagger values is more helpful. In the following correlations, $\delta\Delta G^\ddagger$ values will be expressed in kcal mol⁻¹ on the mol fraction scale, with DMF as the reference solvent.

Values of $\delta\Delta G^\ddagger$ for the Menshutkin reaction (1), denoted as $\delta\Delta G^\ddagger(\text{Et}_3\text{N}/\text{EtI})$, are those given in Table 3. For this reaction the parameter β is not significant in any of the correlations to be considered, and eq (12) then reduces (ref. 52) to a three-parameter eq (13).

$$\delta\Delta G^\ddagger(\text{Et}_3\text{N}/\text{EtI}) = 6.04 - 6.58 \pi^* + (0.64 \alpha) - (0.33 \delta_H^2/100) \quad (13)$$

$n = 20, \quad sd = 0.38, \quad r = 0.984$

The number of solvents is n , the standard deviation is sd , and the overall correlation constant is r . In eq (13) the terms in α and $\delta_H^2/100$ are not significant, and hence eq (13) can be replaced by the one-parameter eq (14), for the solvents listed in Table 3. Thus the

$$\delta\Delta G^\ddagger(\text{Et}_3\text{N}/\text{EtI}) = 6.04 - 6.98 \pi^* \quad (14)$$

$n = 20, \quad sd = 0.40, \quad r = 0.980$

only factor that substantially affects the reaction rate in the 20 given solvents is the solvent dipolarity as measured by π^* . This is not surprising for a reaction that proceeds via a very dipolar transition state, Fig. 1, but the lack of dependence on the solvent hydrogen-bond acidity, α , is unexpected. Although it may be presumed that there is some cancellation in α between initial-state and transition-state, this cannot be deduced from eq (13). It is, of course, an inherent property of ΔG^\ddagger that only differences between initial-state and transition-state may be evaluated.

The *t*-butyl chloride reaction can be analysed in an exactly similar way. For the 15 listed solvents in Table 4 the β parameter is not significant in any correlation, although for a more detailed analysis using an expanded data set see (ref. 53). The correlation equation for $\delta\Delta G^\ddagger(\text{t-BuCl})$ is shown as eq (15). The two major effects that influence ΔG^\ddagger , and hence

$$\delta\Delta G^\ddagger(\text{t-BuCl}) = 8.36 - 8.76 \pi^* - 6.87 \alpha - (0.07 \delta_H^2/100) \quad (15)$$

$n = 15, \quad sd = 0.34, \quad r = 0.996$

$\log k$, are the solvent dipolarity, π^* , and the solvent hydrogen-bond acidity, α . Inspection of transition-states, Fig. 2 and Fig. 3 shows considerable dipolar character, and a leaving chlorine atom with a charge of -0.8 units, capable of interacting strongly with hydrogen-bond donor (HBD) acids.

It is not possible to analyse solvent effects on ΔG^\ddagger for the Finkelstein reaction (5) by the full equation (12), because values are available for only 9 solvents, Table 5. Usually, as a rough guide, the minimum number of solvents necessary is taken as 5N, where N is the number of explanatory variables, so that two explanatory variables, at the most, could be used. In practice, however, the only significant term in eq (12) is the one in α , the resulting one-parameter equation being eq (16). The sign of the α -term in eq (16) is

$$\delta\Delta G^\ddagger(\text{Cl}^-/\text{MeI}) = -0.25 + 7.56 \alpha \quad (16)$$

$n = 9, \quad sd = 0.87, \quad r = 0.973$

positive, unlike the term in eq (15), so that hydrogen-bond donor solvents now increase ΔG^\ddagger and hence reduce the rate, no doubt by lowering the Gibbs energy of the reactant, Cl^- , as suggested by Parker et al. (ref. 12, 17). It should be noted that eq (16), although valid for the 9 solvents in Table 5, cannot be generally correct because it implies that $\delta\Delta G^\ddagger$ reaches a limiting value of -0.25 kcal mol⁻¹ for all solvents with $\alpha = 0$. A larger selection of solvents is needed for a detailed analysis of reaction (5).

CORRELATION ANALYSIS, TRANSITION-STATES, AND MODEL SOLUTES

The application of general equations such as eq (11) and eq (12) to solvent effects on $\log k$ or ΔG^\ddagger values is straightforward, and yields interesting information on differential solvent influences between initial-states and transition-states. To further analyse solvent

effects, it is necessary to deal, not with differences between initial-states and transition-states, but with the separate terms that refer to single solutes. Solvent effects on the Gibbs energy of solutes are usually expressed in terms of Gibbs energies of transfer, $\Delta G_{\text{t}}^{\circ}$, from some standard or reference solvent to other solvents. Correlation of these $\Delta G_{\text{t}}^{\circ}$ values with solvent properties requires a slightly different approach to correlations of ΔG^{\ddagger} values. The $\Delta G_{\text{t}}^{\circ}$ values will depend not only on various solute-solvent interaction terms, but also on a term that is related to the so-called "cavity effect". On dissolution of a solute in a solvent, work is required to form a cavity in the solvent, and so on transfer of a solute from one solvent to another, there will be a resultant cavity effect due to the difference in the energy of cavity formation in the two solvents. The cavity form will not depend on solute-solvent interactions, but is purely dependent on solvent-solvent interactions. Hence any general equation for the correlation of $\Delta G_{\text{t}}^{\circ}$ values must include not only terms that refer to solute-solvent interactions but also a term that refers to solvent-solvent interactions.

The general equation of Koppel and Palm, eq (11), was set up specifically for the correlation of rate constants, and all four terms in the equation refer to solute-solvent effects. Since there is no term in eq (11) that could arise from solvent-solvent effects, eq (11) is not suitable for the general correlation of $\Delta G_{\text{t}}^{\circ}$ values. However, the general equation of the Kamlet-Taft group, eq (12), includes a cavity term in the Hildebrand solubility parameter, either as δ_{H} or better as δ_{H}^2 . Use of $\delta_{\text{H}}^2/100$ in eq (12) is merely to scale the coefficient of the cavity term to the other coefficients. As pointed out before, the cavity term in eq (12) is expected to be very small or zero when eq (12) is applied to ΔG^{\ddagger} values, see for example eq (13). But this is not so when eq (12) is applied to $\Delta G_{\text{t}}^{\circ}$ values (ref. 54, 55). Thus for transfer of the solute nitromethane from the gas phase to a variety of (non-hydrogen-bonding) solvents, a term in δ_{H} was found to be very significant (ref. 55):

$$\Delta G_{\text{t}}^{\circ}(\text{MeNO}_2) = -1.54 - 3.44 \pi^* + 0.21 \delta_{\text{H}} \quad (17)$$

$n = 18 \quad r = 0.991$

Since it is possible to use the same general equation, eq (12), for the correlation of ΔG^{\ddagger} and $\Delta G_{\text{t}}^{\circ}$ values, it is also possible to combine the two main approaches to the study of solvent effects on reaction rates into one unified approach. Hitherto, see Introduction, either ΔG^{\ddagger} values have been correlated with solvent parameters, or ΔG^{\ddagger} values have been separated into initial-state and transition-state values and the latter compared with $\Delta G_{\text{t}}^{\circ}$ values for model solutes.

In a unified approach, ΔG^{\ddagger} values are separated into initial-state and transition-state values, and then the ΔG^{\ddagger} values themselves, together with $\Delta G_{\text{t}}^{\circ}$ values for reactants, transition-state, and possible model solutes, may be analysed through eq (12) or some other similar general equation. Thus not only is the overall solvent effect separated into initial-state and transition-state contributions, but the various factors making up the overall solvent effect can also be separated into initial-state and transition-state contributions. Provided that enough solvents, and the correct type of solvents, have been studied, it should be possible, for instance, to determine the effect of HBD solvents on values of ΔG^{\ddagger} , through the α -term in eq (12), and then to break this α -term down into contributions from the initial-state and the transition-state. The transition-state α -term could then also be compared to α -terms for various model solutes to which the solvent might act as an HBD acidic solvent.

This unified method may be applied to the $\text{Et}_3\text{N}/\text{EtI}$ reaction, for which transition-state values are available, by the correlation of $\Delta G_{\text{t}}^{\circ}$ for the transition-state, denoted as $\Delta G_{\text{t}}^{\circ}(\text{Et}_3\text{N}/\text{EtI})^{\ddagger}$, by eq (12). In addition, $\Delta G_{\text{t}}^{\circ}$ values for the model $\text{Et}_4\text{N}^+\text{I}^-$ ion-pair solute may be similarly analysed. The resulting equations are eq (18) and eq (19); the solvent set for the latter regression is similar, but not identical to, the solvent set in Table 3, (ref. 54).

$$\Delta G_{\text{t}}^{\circ}(\text{Et}_3\text{N}/\text{EtI})^{\ddagger} = 3.77 - 6.14 \pi^* - 0.51 \alpha + 1.21 \delta_{\text{H}}^2/100 \quad (18)$$

$n = 20 \quad sd = 0.34 \quad r = 0.975$

$$\Delta G_{\text{t}}^{\circ}(\text{Et}_4\text{N}^+\text{I}^-) = 10.4 - 14.9 \pi^* - 6.8 \alpha + 2.42 \delta_{\text{H}}^2/100 \quad (19)$$

$n = 18 \quad sd = 0.7 \quad r = 0.997$

Comparison of eq (18) with eq (13) shows conclusively that the π^* term in eq (13) is a transition-state effect, whilst the lack of dependence of $\delta \Delta G^{\ddagger}$ on α and $\delta_{\text{H}}^2/100$ is due to cancellation of effects between initial-state and transition-state. A comparison of eq (18) with eq (19) is also instructive. Both equations contain unfavourable cavity terms in

$\delta_{\text{H}}^2/100$, as expected, but the size of the π^* and α terms in eq (19) are much larger than the terms in eq (18). Hence the ion-pair $\text{Et}_4\text{N}^+\text{I}^-$ is not a good model for the transition state, with $\pi^*(\text{Tr})/\pi^*(\text{Ion-pair}) = 0.41$ and $\alpha(\text{Tr})/\alpha(\text{Ion-pair}) \approx 0.08$. Interaction of the leaving iodide ion in the transition-state, Fig. 1, with HBD solvents is very much less than the similar interaction of I^- in the ion-pair.

For the t-butyl chloride reaction, correlations may be carried out for the transition-state transfer quantity, $\Delta G_{\text{t}}^{\circ}(\text{t-BuCl})^{\ddagger}$, and for a model ion-pair, $\text{Me}_4\text{N}^+\text{Cl}^-$, (ref. 54), leading to eq (20) and eq (21). Now, a comparison of eq (20) with eq (15) shows that the π^* and α terms in eq (15) are mainly due to transition-state effects, whilst a comparison of eq (20)

$$\Delta G_{\text{t}}^{\circ}(\text{t-BuCl})^{\ddagger} = 7.39 - 9.63 \pi^* - 7.36 \alpha + 1.30 \delta_{\text{H}}^2/100 \quad (20)$$

$n = 15 \quad sd = 0.34 \quad r = 0.991$

$$\Delta G_{\text{t}}^{\circ}(\text{Me}_4\text{N}^+\text{Cl}^-) = 14.8 - 20.0 \pi^* - 13.3 \alpha + 2.90 \delta_{\text{H}}^2/100 \quad (21)$$

$n = 17 \quad sd = 0.5 \quad r = 0.998$

and eq (21) shows that the t-BuCl transition-state is much nearer an ion-pair than is the $\text{Et}_3\text{N}/\text{EtI}$ transition-state. Both solvent dipolarity and HBD acidity lower $\Delta G_{\text{t}}^{\circ}(\text{t-BuCl})^{\ddagger}$ and $\Delta G_{\text{t}}^{\circ}(\text{Me}_4\text{N}^+\text{Cl}^-)$ in value, with $\pi^*(\text{Tr})/\pi^*(\text{Ion-pair}) = 0.48$ and $\alpha(\text{Tr})/\alpha(\text{Ion-pair}) = 0.55$; note that the solvent set for eq (21) is not quite the same as that for eq (20), see (ref. 54).

Only a very rough analysis can be made for the Cl^-/MeI reaction, but the one-parameter eq (16) for $\delta\Delta G^{\ddagger}$ may be compared to eq (22) for transfer of Cl^- . The correlation equation is

$$\Delta G_{\text{t}}^{\circ}(\text{Cl}^-) = 1.67 - 10.59 \alpha \quad (22)$$

$n = 9 \quad sd = 1.13 \quad r = 0.976$

very poor, and cannot be at all general, but does show that for the 9 solvents in Table 5, the increase in ΔG^{\ddagger} in HBD solvents is entirely due to initial-state effects, in agreement with the results given in Table 5. It would be very interesting to treat the $\Delta G_{\text{t}}^{\circ}$ values for the transition-state through the full eq (12), but this is not yet possible.

In conclusion, application of eq (12) to $\Delta G_{\text{t}}^{\circ}$ values for transition-states and model solutes reveals new, important information not available by just correlating values of ΔG^{\ddagger} for reactions.

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REFERENCES

1. C. Reichardt, *Angew. Chem., Int. Ed.*, **4**, 29-40 (1965).
2. M.H. Abraham, *Progr. Phys. Org. Chem.*, **11**, 1-87 (1974).
3. E.F. Caldin, *Pure Appl. Chem.*, **51**, 2067-2086 (1979).
4. C. Reichardt, *Angew. Chem., Int. Ed.*, **18**, 98-110 (1979).
5. C. Reichardt, *Pure Appl. Chem.*, **54**, 1867-1884 (1982).
6. D. Mather and J. Shorter, *J. Chem. Soc., Perkin Trans. II*, 1179-1183 (1983), and previous papers.
7. I.A. Koppel and V.A. Palm in *Advances in Linear Free Energy Relationships*, eds. N.B. Chapman and J. Shorter, Plenum Press, London (1972).
8. M.J. Kamlet, J.L.M. Abboud, and R.W. Taft, *Progr. Phys. Org. Chem.*, **13**, 485-630 (1981).
9. M.H. Abraham, R.W. Taft, and M.J. Kamlet, *J. Org. Chem.*, **46**, 3053-3056 (1981).
10. M.J. Kamlet, J.L.M. Abboud, M.H. Abraham, and R.W. Taft, *J. Org. Chem.*, **48**, 2877-2887 (1983).
11. E.M. Arnett and D.R. McKelvey, *Record. Chem. Progr.*, **26**, 185-190 (1965).
12. A.J. Parker, *Chem. Revs.*, **69**, 1-32 (1969).

13. M.H. Abraham, *Chem. Comm.*, 1307-1308 (1969).
14. K.F. Wong and C.A. Eckert, *Trans. Faraday Soc.*, 66, 2313-2319 (1970).
15. M.H. Abraham, *J. Chem. Soc. (B)*, 299-308 (1971).
16. M.H. Abraham, *J. Chem. Soc., Perkin Trans. II*, 1343-1357 (1972).
17. A.J. Parker, U. Mayer, R. Schmid, and V. Gutmann, *J. Org. Chem.*, 43, 1843-1854 (1978).
18. E.S. Rudakov and V.P. Tretyakov, *Org. React.*, 2(4), 142-176 (1965).
19. M.H. Abraham, *J. Chem. Soc. (A)*, 1061-1068 (1971).
20. M.H. Abraham, J. Andonian-Haftvan, and M.R. Sedaghat-Herati, *J. Organometallic Chem.*, 172, 31-38 (1979).
21. M.J. Blandamer and J. Burgess, *Co-ord. Chem. Revs.*, 31, 93-121 (1980).
22. M.H. Abraham, R.J. Irving, and G.F. Johnston, *J. Chem. Soc. (A)*, 199-202 (1970).
23. P. Haberfield, A. Nudelman, A. Bloom, R. Romm, and H. Ginsberg, *J. Org. Chem.*, 36, 1792-1795 (1971).
24. P. Haberfield, *J. Am. Chem. Soc.*, 93, 2091-2093 (1971).
25. P. Haberfield and J. Pessin, *J. Am. Chem. Soc.*, 105, 526-528 (1983).
26. R. Fuchs and L.L. Cole, *J. Am. Chem. Soc.*, 95, 3194-3197, (1973).
27. V.D. Kiselev, G.V. Mavrin and A.I. Konovalov, *J. Org. Chem. USSR*, 16, 1233-1238 (1980).
28. V.A. Breus, S.A. Neklyudov, B.N. Solomonov, and A.I. Konovalov, *J. Org. Chem. USSR*, 19, 1426-1429 (1983).
29. H.S. Golinkin, I. Lee, and J.B. Hyne, *J. Am. Chem. Soc.*, 1307-1312 (1967).
30. M.H. Abraham in *Advances in Solution Chemistry*, eds, I. Bertini, L. Lunazzi, and A. Dei, Plenum Pub. Co. (1981).
31. M.H. Abraham and P.L. Grellier, *J. Chem. Soc., Perkin Trans. II*, 1735-1741 (1976).
32. M.H. Abraham and R.J. Abraham, *J. Chem. Soc., Perkin Trans. II*, 1677-1681 (1975).
33. M.H. Abraham, *J. Chem. Soc., Perkin Trans. II*, 1028-1031 (1977).
34. G.A. Clarke and R.W. Taft, *J. Am. Chem. Soc.*, 84, 2295-2303 (1962).
35. M.H. Abraham and R.J. Abraham, *J. Chem. Soc., Perkin Trans. II*, 47-52 (1974).
36. M.H. Abraham and G.F. Johnston, *J. Chem. Soc. (A)*, 1610-1615 (1971).
37. M.H. Abraham, A. Nasehzadeh, J.J. Moura Ramos, and J. Reisse, *J. Chem. Soc., Perkin Trans. II*, 854-859 (1980).
38. M.H. Abraham and A. Nasehzadeh, unpublished work.
39. R. Alexander, E.C.F. Ko, A.J. Parker, and T.J. Broxton, *J. Am. Chem. Soc.*, 90, 5049-5069 (1968).
40. B.G. Cox, G.R. Hedwig, A.J. Parker, and D.W. Watts, *Aust. J. Chem.*, 27, 477-501 (1974).
41. A.J. Parker and W.E. Waghorne, *Aust. J. Chem.*, 31, 1181-1187 (1978).
42. M.H. Abraham, *J. Chem. Soc., Faraday Trans. I*, 69, 1375-1388 (1973).
43. M.H. Abraham and A.F. Danil de Namor, *J. Chem. Soc. Faraday Trans. I*, 74, 2101-2110 (1978).
44. M.H. Abraham, *Monat. Chem.*, 110, 517-524, (1979).
45. M.H. Abraham, T. Hill, H.C. Ling, R.A. Schulz, and R.A.C. Watt, *J. Chem. Soc. Faraday Trans. I*, 80, 489-505 (1984).
46. D.N. Glew and E.A. Noelwyn-Hughes, *Disc. Faraday Soc.*, 15, 150-161 (1953).
47. E.R. Thomas, B.A. Newman, T.C. Long, D.A. Wood, and C.A. Eckert, *J. Chem. Eng. Data*, 27, 399-405 (1982).
48. P. Muller and B. Siegfried, *Helv. Chim. Acta*, 55, 2400-2406 (1972).
49. C. Lassau and J.-C. Jungers, *Bull. Soc. Chim. France*, 2678-2685 (1968).
50. Y. Drougard and D. Decroocq, *Bull. Soc. Chim. France*, 2972-2983 (1969).
51. G. Berrebi and D. Decroocq, *J. Chim. Phys.*, 71, 673-688 (1974).

52. J.M.L. Abboud, M.H. Abraham, M.J. Kamlet, R.M. Doherty, and R.W. Taft, unpublished work.
53. M.J. Harris, M.H. Abraham, M.J. Kamlet, R.M. Doherty, and R.W. Taft, unpublished work.
54. R.W. Taft, M.H. Abraham, R.M. Doherty, and M.J. Kamlet, *J. Am. Chem. Soc.*, in the press.
55. M.H. Abraham, M.J. Kamlet, and R.W. Taft, *J. Chem. Soc. Perkin Trans. II*, 923-928 (1982).