JOURNAL OF PHYSICAL ORGANIC CHEMISTRY, VOL. 6, 595–599 (1993)

STUDY OF INITIAL STATE AND TRANSITION STATE SOLVATION IN THE MENSCHUTKIN REACTION OF TRIETHYLAMINE WITH ETHYL IODIDE IN ALCOHOLS FROM INFINITE DILUTION ACTIVITY COEFFICIENTS

RAQUEL M. C. GONÇALVES*, ANTÓNIO R. T. CALADO, LÍDIA M. V. PINHEIRO AND
LÍDIA M. P. C. ALBUQUERQUE

CECUL (FCUL, FFUL), Cd. Bento da Rocha Cabral, 14, 1200 Lisboa, Portugal

AND

EUGÉNIA A. MACEDO

Laboratório de Processos de Separação e Reacção, Faculdade de Engenharia do Porto, Rua dos Bragas, 4099 Porto Codex, Portugal

The Gibbs energies of activation of the Menschutkin reactions of triethylamine with ethyl iodide in 10 monoalcohols and nine dialcohols, were dissected into contributions from the initial state and transition state. To perform this study, the infinite dilution activity coefficient values of the solutes in the solvents, γ^∞, were determined by the UNIFAC group-contribution method, using the modified Flory–Huggins equation in the combinatorial term. For triethylamine, the γ^∞ values were calculated using group-interaction parameters from the VLE Parameter Table, due to the non-availability of specific γ^∞ UNIFAC interaction parameters for the relevant groups. For ethyl iodide, the γ^∞ values were calculated using the group-interaction parameters from the specific γ^∞ UNIFAC Parameter Table, except for the solvents diethylene glycol and triethylene glycol, where VLE parameters were used for the same reasons as explained above for the triethylamine. The results were compared with those obtained for the unimolecular decomposition of *tert*-butyl halides. For the Menschutkin reaction, we conclude that solvent disruption and reorganization to a state appropriate to solvating the molecular species is a dominant interaction mechanisim.

INTRODUCTION

A variety of methods has been used in the investigation of reaction mechanisms, including not only the determination of reaction rates and orders but also the changes in these rates with changing conditions. One of the most powerful means for influencing reaction rates is through solvent variation.

Two main approaches for the examination of solvent effects on the rate constant, *k*, or on the Gibbs energy of activation, $\Delta^{\ddagger}G$, have been developed. In one of them, the kinetic data are correlated with solvent parameters using a multiple linear regression procedure, according to a consistent physico-chemical model.[1–4] In the other method, solvent effects on the kinetic values are dissected into contributions from the initial state and the transition state, from changes in the activation property and the corresponding change for the initial-state property.[5–8]

According to the second method, we need to calculate the transfer Gibbs energy of activation, $\delta\Delta^{\ddagger}G$, the transfer Gibbs energy of the reactants, δG_i, and the transfer Gibbs energy of the activated complex, δG_t. The three types of transfer Gibbs energies under study are related through the equation:

$$\delta G_t = \delta G_i + \Delta^{\ddagger}G_j - \Delta^{\ddagger}G_r = \delta G_i + \delta\Delta^{\ddagger}G \qquad (1)$$

where $\Delta^{\ddagger}G_j$ refers to the reaction in the solvent j and $\Delta^{\ddagger}G_r$ in the reference solvent r.

Values for $\delta\,\Delta^{\ddagger}G$ are determined from *k* values by making use of the transition state theory. Values for δG_i can be calculated using the following equation:

$$\delta G_i = RT\ \ln(\gamma_j^\infty/\gamma_r^\infty) \qquad (2)$$

---

* Author for correspondence.

0894–3230/93/100595–05$07.50

Received 5 May 1993
Revised 9 July 1993

where γ_j^{∞} and γ_r^{∞} are the infinite dilution activity coefficients of the solute in the solvent j and in a reference solvent r, respectively.

In a preceding paper, solvent effects on the Gibbs energies of transfer from ethanol for the initial state and transition state of the first-order unimolecular solvolysis of *tert*-butyl halides in mono- and dialcohols were analysed in terms of the contributions to the transfer Gibbs energy of the activated process.[9]

In the present study, we continue our analysis of solvent influences on the Gibbs functions of transfer for the second-order bimolecular Menschutkin reaction of triethylamine (Et_3N) with ethyl iodide (EtI), using mono- and dialcohols as solvents. A similar study has been carried out before, using some polar and aprotic solvents.[10] However, we are now in a position to extend this study to a larger variety of hydroxylic solvents, on account of the recently published *k* values, at 25 °C.[11,12]

To perform this analysis, we calculated the infinite dilution activity coefficients of triethylamine and of ethyl iodide in the alcohols, at 25 °C, using a predictive method: the UNIFAC group-contribution model.[13,14] The combinatorial activity coefficients were calculated using the modified Flory–Huggins equation in the Staverman–Guggenheim combinatorial expression, as suggested by Kikik *et al.*[15]

The group-interaction parameters from the γ^{∞} Parameter Table[16] and from the VLE Parameter Table[17–21] were used in the calculations carried out in this work.

We also focused our attention on solvent effects arising from the change of a first-order unimolecular reaction (the solvolysis of *tert*-butyl halides) to a second-order bimolecular reaction (the Menschutkin reaction of Et_3N with EtI).

RESULTS AND DISCUSSION

In Table 1 are shown the Gibbs energies of activation for the reaction of Et_3N with EtI in the various hydroxylic solvents, at 25 °C. These values were obtained from *k* data previously reported,[11,12] by using the thermodynamic equations associated with the transition state theory.

In Table 2 are summarized the γ^{∞} values for the substrates Et_3N and EtI in alcohols, at the same temperature. (Some values of γ^{∞} for the solvents under study have already been published.[22] However, we prefer to use only our γ^{∞} data in order to obtain a more coherent list.) In this work, the UNIFAC group-contribution method[13,14] was used. The model has already been used in a previous paper,[9] where a brief description and a presentation of the main equations is given.

Table 1. Gibbs energies of activation for the Menschutkin reaction of triethylamine with ethyl iodide in alcohols, at 25 °C (kJ mol^{-1})[a]

No.	Solvent	$\Delta^{\ddagger}G$
1	Methanol	95·85
2	Ethanol	97·50
3	Propan-1-ol	99·11
4	Propan-2-ol	98·07
5	Butan-1-ol	99·88
6	Butan-2-ol	98·65
7	Pentan-1-ol	100·97
8	2-Methylbutan-1-ol	101·45
9	3-Methylbutan-1-ol	100·67
10	Hexan-1-ol	102·06
11	Ethane-1,2-diol	94·28
12	Propane-1,2-diol	93·97
13	Propane-1,3-diol	91·88
14	Butane-1,2-diol	95·58
15	Butane-1,3-diol	94·58
16	Butane-2,3-diol	95·72
17	Pentane-1,5-diol	95·35
18	Diethylene glycol	91·61
19	Triethylene glycol	92·10

[a] Values calculated from data in refs (11) and (12).

Table 2. Infinite dilution activity coefficients for triethylamine and ethyl iodide in alcohols at 25 °C

No.[a]	γ^{∞} [b]	
	Et_3N	EtI
1	4·05	—
2	3·00	5·42
3	1·94	3·91
4	1·94	3·90
5	1·48	3·14
6	1·48	3·14
7	1·24	2·68
8	1·24	2·68
9	1·24	2·68
10	1·08	2·37
11	13·21	13·26
12	6·56	8·21
13	6·56	8·21
14	4·08	5·88
15	4·08	5·88
16	4·09	5·88
17	2·90	4·59
18	—	4·21
19	—	2·69

[a] Numbering of solvents as in Table 1.

[b] Values for alcohols 1 to 5 and 9, obtained from experiment, are available in ref. 22.

In the present work, for the combinatorial term we need the modified Flory–Huggins equation in the

Staverman–Guggenheim expression.[15] For the residual term we used group-interaction parameters from the UNIFAC–γ^∞ Parameter Table[16] for EtI, except for the solvents diethylene glycol and triethylene glycol. For EtI in these two solvents and for Et_3N we used UNIFAC-VLE[17–21] parameters, because no γ^∞ parameters were availiable for the relevant interactions.[16]

We were not able to calculate γ^∞ for Et_3N in diethylene glycol and in triethylene glycol because there are no available parameters. Regarding the γ^∞ values of the two solutes in ethane-1,2-diol, we used the interaction parameters for the alcohol group (OH), instead of considering this solvent as a single group, as is usually advised,[17,19] because relevant parameters for the diol group are not available.

Table 3 gives the calculated Gibbs energies of transfer for the activation process, $\delta\,\Delta^\ddagger G$, the initial state, δG_i, and the transition state, δG_t, based on ethanol as the reference solvent. Equations (1) and (2) were used to obtain these results, taking into account that $\delta G_i = \delta G_i(Et_3N) + \delta G_i(EtI)$. Values for $\delta G_i(Et_3N)$ in solvents diethylene glycol and triethylene glycol and for $\delta G_i(EtI)$ in methanol (Table 3, in parentheses) were obtained by the following linear correlation analysis:

$$\delta G_i(Et_3N) = 0\cdot35224 + 1\cdot4964\ \delta G_i(EtI)$$
$$(N = 16, r = 0\cdot997, \sigma = 0\cdot16)$$

where N is the number of pairs of points, r the correlation coefficient and σ the standard deviation of the fit.

Table 3. Gibbs energy of transfer from ethanol to other solvents of the Et_3N with EtI reaction in alcohols at 25 °C (kJ mol^{-1})

No.[a]	$\delta\,\Delta^\ddagger G$	$\delta G_i(Et_3N)$	$\delta G_i(EtI)$	δG_i	δG_t
1	−1·65	0·75	(0·26)[b]	(1·00)	(−0·64)
2	0	0	0	0	0
3	1·61	−1·08	−0·81	−1·90	−0·29
4	0·57	−1·09	−0·81	−1·90	−1·33
5	2·38	−1·75	−1·35	−3·10	−0·72
6	1·15	−1·75	−1·35	−3·10	−1·95
7	3·47	−2·20	−1·74	−3·94	−0·47
8	3·95	−2·20	−1·74	−3·94	0·01
9	3·17	−2·20	−1·74	−3·94	−0·77
10	4·56	−2·53	−2·05	−4·57	−0·01
11	−3·22	3·67	2·22	5·89	2·67
12	−3·53	1·94	1·03	2·97	−0·56
13	−5·62	1·94	1·03	2·97	−2·66
14	−1·92	0·76	0·20	0·96	−0·96
15	−2·92	0·76	0·20	0·96	−1·96
16	−1·78	0·76	0·20	0·97	−0·82
17	−2·15	−0·09	−0·41	−0·50	−2·65
18	−5·89	(−0·58)[b]	−0·62	(−1·21)	(−7·10)
19	−5·40	(−2·25)[b]	−1·74	(−3·99)	(−9·39)

[a] Numbering of solvents as in Table 1.
[b] Estimated value from linear regression analysis between $\delta G_i(Et_3N)$ and $\delta G_i(EtI)$.

It is generally accepted that alcohols are self-associated structures, stabilized by hydrogen bonds consisting of linear and/or cyclic polymers. Along the set of normal alcohols, the aliphatic group size increases and the concentration associated with linear hydrogen-bonded chain polymers over the alcohol gross concentration also increases. This structural nature of the alcohols is consistent with the $\delta\,\Delta^\ddagger G$ increase.

Also, the chain branching and the position and the number of OH groups in the solvent molecule play an important role. For instance, in monoalcohols, when the hydroxyl group moves from the end to the middle of the carbon chain, the formation of linear multimers decreases and consequently $\delta\,\Delta^\ddagger G$ decreases.

The results, shown in the two last columns in Table 3, suggest that, in general, solvent initial state effects are usually greater than transition state effects, when ethanol is used as reference solvent. We can point out four exceptions: butane-1,3-diol, pentane-1,5-diol, diethylene glycol and triethylene glycol.

If mono- and dialcohols are considered separately, we may say that, for solvent changes from ethanol, there is a decrease (negative values) of the Gibbs energy of the initial state for monoalcohols, except for methanol, and, conversely, the Gibbs energy of the initial state for dialcohols 11 to 17 shows an increase (positive values), except for pentane-1,5-diol. The mentioned stabilization for monoalcohols, as well as the destabilization for dialcohols, can be explained in terms of the disruption of hydrogen bonding in the solvents, which is quite relevant for the highly structured alcohols (methanol and dialcohols).

As to the Gibbs energy of the activated complex, mono- and dialcohols show a similar behaviour: in both cases, the Gibbs energy of the activated complex shows negative values. The only exception is ethane-1,2-diol (δG_t value for solvent 2-methylbutan-1-ol is too small to deserve special mention). The behaviour of diethylene glycol and triethylene glycol, solvents 18 and 19 in Table 3, is somewhat different. Compared with the other dialcohols, δG_i and especially δG_t are strongly negative.

Comparison with *tert*-butyl halide solvolysis

Despite the great number of experimental and interpretative studies of nucleophilic displacement reactions, published after the landmark study of Menschutkin about solvent effects,[23] only in recent years have the deep mechanistic implications received considerable attention.[24–27] For the Menschutkin reaction of triethylamine with ethyl iodide, which can be seen as a creation of two charges of opposite sign from uncharged reactants followed by their subsequent separation, there is no doubt that the reaction is favoured by the presence of polar solvents. The same is also true for the unimolecular decomposition of *tert*-butyl halides, for which the dominant step is the formation of an intermediate with a significant charge separation.[3,9,25,28–30] There are good reasons to believe that the high charge separation of the transition state and the tendency of the transition state to interact with hydrogen-bond donor solvents, cause the electrostriction of the surrounding solvent. Accordingly, the polarization effect of the substrate molecules, the disruption of hydrogen bonding in the solvent and the interaction of solvent with the ion-pair-like structures of the activated complexes may be expected to play the active role. Therefore, solvent effects can be quite different when the contributions from the initial state and from the transition state are compared.

In our preceding study of the initial and transition state solvation of the solvolysis of *tert*-butyl halides in 16 mono- and dialcohols, also based on ethanol as the reference solvent, we reached the following main conclusions: (i) values of δG_i are small and negative for mono-alcohols (except for methanol) and small and positive for dialcohols; (ii) values of δG_t for monoalcohols tend to be small and positive but for dialcohols are always high and negative (the solvation of the activated complex in dialcohols is much more important than the solvation of the substrate); (iii) for dialcohols, the solvent structure and its particular interaction with the substrate and with the activated complex dominate over the polarization effect of these molecular species and, conversely, for monoalcohols the effect of the substrate and activated complex polarization have a marked influence on the solvent–solvent–solute interaction mechanisms.

The similar investigation of the initial and transition state contributions to the solvent effects on the reaction of Et_3N with EtI in almost the same set of alcohols led to different conclusions: (i) although δG_i shows negative values for monoalcohols (except for methanol) and tends to be positive for dialcohols, solvent effects in the initial state always dominate over solvent effects in the transition state; (ii) δG_t is almost always negative and, consequently, no difference can be ascribed to the behaviour of mono- and dialcohols.

From these results, it seems that the participation of solvent in the Menschutkin reaction comes 'earlier' than in the solvolytic reaction. Solà *et al.*,[26] from *ab initio* studies in the gas phase and in solution stated that 'whereas solvent reorganization may be considered to follow the chemical process, the opposite view may be also considered: the chemical process can be induced by solvent fluctuations'. This is what Hwang *et al.*[31] call a solvent-driven process. In this way, the reorganization of the solvent to a state appropriate to solvating the molecular species in the reaction of triethylamine with ethyl iodide, which takes place before the charge distributions on the reactants begin to change, is a dominant influence on the solvent–solvent–solute interaction mechanisms.

Another feature corroborates this interpretation. In fact, if correlation analysis through equation (3),[3]

$$XYZ = XYZ_0 + a_1\pi^* + a_2\alpha + a_3\beta + a_4C \qquad (3)$$

is applied to the transfer Gibbs energy of activation and of the initial state, the statistically preferred equations are:

$$\delta\,\Delta^{\ddagger}G = 13{\cdot}5900 - 18{\cdot}0091\pi^* - 3{\cdot}93347 \times 10^{-3}C$$

$$(N = 19, r = 0{\cdot}933, \sigma = 1{\cdot}27)$$

$$\delta G_i = -13{\cdot}2122 + 4{\cdot}92428\pi^* + 14{\cdot}7531 \times 10^{-3}C$$

$$(N = 19, r = 0{\cdot}910, \sigma = 1{\cdot}29)$$

These equations show that the specific solute–solvent interactions, represented by the parameters α (acidity) and β (basicity), are not relevant. Conversely, not only the non-specific solute–solvent interactions, represented by π^* (polarity/polarizability), but also the solvent–solvent interactions, denoted by C (disruption/reorganization), are the dominant interaction mechanisms. (The same treatment applied to δG_t gives poor correlations that do not allow us to obtain reliable quantitative information. However, from a qualitative point of view, we observe that parameter C is not relevant.)

ACKNOWLEDGEMENTS

Financial support from the Instituto Nacional de Investigação Científica is gratefully acknowledged.

REFERENCES

1. I. A. Koppel and V. A. Palm, *Reakts. Sposobnost. Org. Soedin.* **8**, 291 (1971).
2. M. J. Kamlet, J.-L. Abboud and R. W. Taft, *J. Am. Chem. Soc.* **99**, 6027, 8325 (1977).
3. M. H. Abraham, R. M. Doherty, M. J. Kamlet, J. M. Harris and R. W. Taft, *J. Chem. Soc., Perkin Trans. 2* 913 (1987).
4. C. Reichardt, *Solvents and Solvent Effects in Organic Chemistry*, 2nd ed., VCH, Weinheim, (1988).
5. E. M. Arnett, J. J. Burke and P. McC. Duggleby, *J. Am. Chem. Soc.* **85**, 1350 (1963).
6. E. M. Arnett, W. G. Bentrude, J. J. Burke and P. McC. Duggleby, *J. Am. Chem. Soc.* **87**, 1541, 2048 (1965).
7. M. H. Abraham, *J. Chem. Soc. B* 299 (1971).
8. M. H. Abraham, *J. Chem. Soc., Perkin Trans. 2* 1343 (1972).
9. R. M. C. Gonçalves, A. M. N. Simões, L. M. P. C. Albuquerque and E. A. Macedo, *J. Phys. Org. Chem.* **6**, 133 (1993).
10. M. H. Abraham, *Pure Appl. Chem.* **57**, 1055 (1985).
11. C. A. N. Viana, A. R. T. Calado and L. M. V. Pinheiro, *J. Chem. Res.* (*M*) 173 (1992); (*S*) 6 (1992).
12. A. R. T. Calado, L. M. V. Pinheiro, L. M. P. C. Albuquerque, R. M. C. Gonçalves, M. Rosés, C. Ràfols and E. Bosch, *Collect. Czech. Chem. Commun.*, submitted for publication.

13. Aa. Fredenslund, R. Jones and J. M. Prausnitz, *AIChE J.* **21**, 1086 (1975).
14. Aa. Fredenslund, J. Gmehling and P. Rasmussen, *Vapor–Liquid Equilibria Using UNIFAC*, Elsevier, Amsterdam (1977).
15. I. Kikic, P. Alessi, P. Rasmussen and Aa. Fredenslund, *Can. J. Chem. Eng.* **58**, 253 (1980).
16. J. C. Bastos, M. E. Soares and A. G. Medina, *Ind. Eng. Chem. Res.* **27**, 1269 (1988).
17. S. Skjold-Jørgensen, B. Kolbe, J. Gmehling and P. Rasmussen, *Ind. Eng. Chem., Process Des. Dev.* **18**, 714 (1979).
18. J. Gmehling, P. Rasmussen and Aa. Fredenslund, *Ind. Eng. Chem., Process Des. Dev.* **21**, 118 (1982).
19. E. A. Macedo, U. Weidlich, J. Gmehling and P. Rasmussen, *Ind. Eng. Chem., Process Des. Dev.* **22**, 676 (1983).
20. D. Tiegs, J. Gmehling, P. Rasmussen and Aa. Fredenslund, *Ind. Eng. Chem. Res.* **26**, 159 (1987).
21. H. K. Hansen, P. Rasmussen, Aa. Fredenslund, M. Schiller and J. Gmehling, *Ind. Eng. Chem. Res.* **30**, 2352 (1991).
22. M. H. Abraham and P. L. Grellier, *J. Chem. Soc., Perkin Trans 2* 1735 (1976).
23. N. Menschutkin, *Z. Phys. Chem.*, **5**, 589 (1890); **6**, 41 (1890).
24. E. M. Arnett and R. Reich, *J. Am. Chem. Soc.* **102**, 5892 (1980).
25. M. H. Abraham, P. L. Grellier, J.-L. M. Abboud, R. M. Doherty, and R. W. Taft, *Can. J. Chem.* **66**, 2673 (1988).
26. M. Solà, A. Lledós, M. Duran, J. Bertrán and J.-L. M. Abboud, *J. Am. Chem. Soc.* **113**, 2873 (1991).
27. J.-L. M. Abboud, R. Notario, J. Bertrán and R. W. Taft, *J. Am. Chem. Soc.* **113**, 4738 (1991).
28. R. M. C. Gonçalves, A. M. N. Simões and L. M. P. C. Albuquerque, *J. Chem. Soc., Perkin Trans. 2* 1379 (1990).
29. R. M. C. Gonçalves, A. M. N. Simões and L. M. P. C. Albuquerque, *J. Chem. Soc., Perkin Trans.* 2 825 (1991).
30. R. M. C. Gonçalves, A. M. N. Simões, R. A. S. E. Leitão and L. M. P. C. Albuquerque, *J. Chem. Res.* (*S*) 330 (1992); (*M*) 2701 (1992).
31. J.-K., Hwang, G. King, S. Creighton and A. Warshel, *J. Am. Chem. Soc.* **110**, 5297 (1988).