1604 *J. Org. Chem.* **1991**, *56*, 1604-1609

Distinguishing between Solvation Effects and Mechanistic Changes. Effects Due to Differences in Solvation of Aromatic Rings and Alkyl Groups

T. William Bentley,* In Sun Koo, and Simon J. Norman

Department of Chemistry, University College of Swansea, Singleton Park, Swansea SA2 8PP, U.K., and Department of Chemical Education, Gyeongsang National University, Chinju, Gyeongnam 660-701, Korea

Received July 3, 1990

Solvolytic rate constants at 25 °C are reported for *p*-methoxybenzyl chloride (1) in aqueous binary mixtures with acetone, acetonitrile, dioxane, dimethyl sulfoxide, ethanol, methanol, and 2,2,2-trifluoroethanol and for benzoyl chloride and *p*-methoxybenzoyl chloride (2) in aqueous acetonitrile and aqueous dioxane. Product selectivities are reported for solvolyses of 1 in aqueous ethanol and methanol. Logarithms of rate constants for solvolyses of 2 correlate linearly with solvolyses of 1 (unit slope and only a small "dispersion"—the tendency for the various binary mixtures to show separate correlations), showing that the solvation requirements of S_N1 reactions of aromatic carboxylic acid chlorides are very similar to those of benzylic chlorides. Similar good correlations are reported vs solvolyses of α-phenylethyl chloride and vs Z values. For S_N1 reactions of chlorides in binary mixtures having similar electrophilicities, the phenomenon of dispersion in Grunwald-Winstein plots (vs Y) and the poor correlation vs Y_{Cl} (reported previously) appears to be due to the differences in solvation between aromatic rings and alkyl groups; this difference is largest for binary aqueous mixtures with methanol > ethanol > aprotic solvents. The complex rate-rate profile for similar solvolytic reactions of benzoyl chloride is dissected quantitatively into contributions from two competing reaction channels, one of which shows only a small "dispersion" in a correlation with solvolyses of 2; these results are consistent with a mainly dissociative reaction channel for solvolyses of benzoyl chloride in highly aqueous media.

The phenomenon of "dispersion" in Grunwald-Winstein plots (eq 1) has, for many years, plagued quantitative interpretations of rate-rate profiles for solvolytic reactions in binary aqueous mixtures.[1,2a] When logarithms of rate

$$\log (k/k_0)_{RX} = mY \text{ (or } mY_X\text{)} \qquad (1)$$

constants (k) for solvolyses of any substrate (RX) relative to the rate constant in 80% ethanol/water (k_0) are plotted vs the solvent ionizing power Y, (based on $m = 1$ for solvolyses of *tert*-butyl chloride[3]), separate correlation lines (dispersion) are often observed (and sometimes curved plots) for different aqueous binary mixtures. Dispersion is even observed when correlations are restricted to compounds having the same leaving group (X), e.g., using an appropriate Y_X parameter (based on solvolyses of 1- and 2-adamantyl substrates[4,5]). In these circumstances, mechanistic changes are difficult to distinguish convincingly from solvation effects.

Large dispersion effects (corresponding to over a factor of 10 in rate) occur when substrates containing aromatic rings are studied[5f,6-9] and may also be observed for S_N2 solvolyses.[4d,5f] Possible reasons include solvation effects,[6b,c,8,9] which are particularly significant when correlations are not restricted to a common leaving group, and solvents of different electrophilicities such as acetic acid/water mixtures are studied.[6b,c] Dispersion may also be caused by mechanistic changes, such as ion pair return,[5g,6b,d] nucleophilic solvent assistance[5f,6b] variable extents of anchimeric assistance,[10] and general base catalysis.[11]

Nevertheless, large dispersion effects are not inevitable.[4,5f] Good correlations with small dispersion (corresponding to less than a factor of 2 in rate) have been observed for solvolyses of the aliphatic model substrates, e.g., *tert*-butyl chloride vs 1-adamantyl chloride[4a] and 1-adamantyl mesylate vs 2-adamantyl mesylate[4c] in aqueous binary mixtures with acetone, ethanol, and methanol. For aromatic systems, logarithms of rates of solvolyses of 2,6-dimethylbenzoyl chloride correlate well with solvolyses of *p*-methoxybenzoyl chloride (2) in aqueous binary mixtures with acetone, ethanol, and methanol (indicating similar mechanisms).[7b] Also, logarithms of rates of solvolyses of α-phenylethyl chloride correlate linearly with rates for neophyl chloride in aqueous dioxane, ethanol, and methanol (but dispersion was still observed for acetic acid/water mixtures).[6c]

Emphasizing earlier work,[6c] it has recently been suggested[8,9] that solvation of benzylic carbocations, involving charge delocalization to the benzene ring, may differ significantly from solvation of aliphatic substrates. We now

---

(1) Streitwieser, A., Jr. *Chem. Rev.* **1956**, *56*, 617–619.

(2) Reichardt, C. *Solvent Effects in Organic Chemistry*, 2nd. ed.; VCH: Weinheim, 1988; (a) p 353, (b) p 285, (c) p 372.

(3) (a) Grunwald, E.; Winstein, S. *J. Am. Chem. Soc.* **1948**, *70*, 846. (b) Fainberg, A. H.; Winstein, S. *J. Am. Chem. Soc.* **1956**, *78*, 2770.

(4) (a) Bentley, T. W.; Carter, G. E. *J. Am. Chem. Soc.* **1982**, *104*, 5741. (b) Bentley, T. W.; Carter, G. E. *J. Org. Chem.* **1983**, *48*, 579. (c) Bentley, T. W.; Llewellyn, G. *Prog. Phys. Org. Chem.* **1990**, *17*, 121. (d) Bentley, T. W.; Bowen, C. T.; Brown, H. C.; Chloupek, F. J. *J. Org. Chem.* **1981**, *46*, 38.

(5) (a) Allard, B.; Casadevall, E. *Nouv. J. Chim.* **1983**, *7*, 569. (b) Kevill, D. N.; Bahari, M. S.; Anderson, S. W. *J. Am. Chem. Soc.* **1984**, *106*, 2895. (c) Creary, X.; McDonald, S. R. *J. Org. Chem.* **1985**, *50*, 474. (d) Takeuchi, K.; Ikai, K.; Shibata, T.; Tsugeno, A. *J. Org. Chem.* **1988**, *53*, 2852. (e) Lee, I.; Lee, B.; Sohn, S. C.; Lee, B. C. *Bull. Korean Chem. Soc.* **1985**, *6*, 19. (f) Fujio, M.; Goto, M.; Yoshino, T.; Funatsu, K.; Tsuji, Y.; Ouchi, S.; Tsuno, Y. *Mem. Fac. Science, Kyushi University, Ser. C* **1987**, *16*, 85; *Chem. Abstr.* **1988**, *109*, 148671j. (g) McManus, S. P.; Sedaghat-Herati, M. R.; Karaman, R. M.; Neamati-Mazraeh, N.; Cowell, S. M.; Harris, J. M. *J. Org. Chem.* **1989**, *54*, 1911.

(6) (a) Fainberg, A. H., Winstein, S. *J. Am. Chem. Soc.* **1957**, *79*, 1597. (b) Fainberg, A. H.; Winstein, S. *J. Am. Chem. Soc.* **1957**, *79*, 1602. (c) Fainberg, A. H.; Winstein, S. *J. Am. Chem.* **1957**, *79*, 1608. (d) Winstein, S.; Fainberg, A. H.; Grunwald, E. *J. Am. Chem. Soc.* **1957**, *79*, 4146.

(7) (a) Bentley, T. W.; Harris, H. C. *J. Chem. Soc., Perkin Trans. 2* **1986**, 619. (b) Bentley, T. W.; Harris, H. C.; Koo, I. S. *J. Chem. Soc., Perkin Trans. 2* 1988, 783.

(8) Bunton, C. A.; Mhala, M. M.; Moffatt, J. R. *J. Org. Chem.* **1984**, *49*, 3639.

(9) Liu, K. T.; Sheu, H. C.; Chen, H. I.; Chiu, P. F.; Hu, C. R. *Tetrahedron Lett.* **1990**, *31*, 3611.

(10) Laureillard, J.; Casadevall, A.; Casadevall, E. *Helv. Chim. Acta* **1984**, *67*, 352.

(11) Bentley, T. W.; Harris, H. C. *J. Org. Chem.* **1988**, *53*, 724.

(12) (a) da Roza, D. A.; Andrews, L. J.; Keefer, R. M. *J. Am. Chem. Soc.* **1973**, *95*, 7003. (b) Baddeley, G. Smith, N. H. P.; Vickars, M. A. *J. Chem. Soc.* **1956**, 2455.

(13) (a) Bohme, H.; Schurhoff, W. *Chem. Ber.* **1951**, *84*, 28. (b) Brown, D. A.; Hudson, R. F. *J. Chem. Soc.* **1953**, 3352. (c) Butler, A. R.; Gold, V. *J. Chem. Soc.* **1962**, 2212.

(14) Aronovitch, H.; Pross, A. *J. Chem. Soc., Perkin Trans. 2* **1978**, 540.

0022-3263/91/1956-1604$02.50/0

Table I. Rate Constants (s^{-1}) for Solvolyses of *p*-Methoxybenzyl Chloride (1) in Aqueous Binary Mixtures at 25 °C[a]

compstn (% v/v)	cosolvent		
	acetone	acetonitrile	dioxane
90	$(3.04 \pm 0.03) \times 10^{-6}$	$(4.02 \pm 0.08) \times 10^{-5}$	$(2.2 \pm 0.2) \times 10^{-6}$ [b]
80	$(6.61 \pm 0.11) \times 10^{-5}$	$(5.08 \pm 0.01) \times 10^{-4}$	$(2.69 \pm 0.02) \times 10^{-5}$
60	$(2.76 \pm 0.06) \times 10^{-3}$	$(7.22 \pm 0.01) \times 10^{-3}$	$(1.32 \pm 0.01) \times 10^{-3}$
50			$(7.98 \pm 0.01) \times 10^{-3}$
40	$(5.25 \pm 0.06) \times 10^{-2}$	$(6.26 \pm 0.05) \times 10^{-2}$	$(4.00 \pm 0.10) \times 10^{-2}$
30		$(2.13 \pm 0.01) \times 10^{-1}$	$(1.65 \pm 0.01) \times 10^{-1}$
20	$(7.35 \pm 0.09) \times 10^{-1}$	$(5.94 \pm 0.14) \times 10^{-1}$	$(5.89 \pm 0.05) \times 10^{-1}$
	DMSO	ethanol	methanol
100		1.67×10^{-5} [c]	$(2.86 \pm 0.03) \times 10^{-4}$
90		2.17×10^{-4} [d]	$(1.65 \pm 0.02) \times 10^{-3}$
80	$(8.11 \pm 0.10) \times 10^{-5}$	$(1.13 \pm 0.01) \times 10^{-3}$	$(7.37 \pm 0.06) \times 10^{-3}$
60	$(3.35 \pm 0.14) \times 10^{-3}$	$(1.15 \pm 0.03) \times 10^{-2}$	$(5.26 \pm 0.10) \times 10^{-2}$
40	$(9.87 \pm 0.13) \times 10^{-2}$	$(1.36 \pm 0.02) \times 10^{-1}$	$(3.70 \pm 0.04) \times 10^{-1}$
20[e]	$(8.54 \pm 0.22) \times 10^{-1}$	1.23 ± 0.08	1.37 ± 0.03
97%	w/w trifluoroethanol/water		
	$(1.94 \pm 0.04) \times 10^{-1}$		

[a] Determined conductimetrically in duplicate, except where stated otherwise; errors shown are average deviations. [b] Rate data at other temperatures, $k(T/°C)$: 1.05×10^{-5} (40.4), 1.35×10^{-4} (75.2), $\Delta H^{\ddagger} = 16.2$ kcal/mol, $\Delta S^{\ddagger} = -30$ cal/mol deg. [c] Data from ref 12a. [d] Data from ref 12b. [e] Rate data at other temperatures, $k(T/°C)$: for 20% DMSO, 0.182 (10.3), $\Delta H^{\ddagger} = 17.1$ kcal/mol, $\Delta S^{\ddagger} = -1.6$ cal/mol deg; for 20% ethanol, 0.0409 (−5.1), 0.0811 (0.0), $\Delta H^{\ddagger} = 17.3$ kcal/mol, $\Delta S^{\ddagger} = -0.2$ cal/mol deg; for 20% methanol, 0.049 (−5.2), 0.092 (−0.2), 0.15 (5.0), $\Delta H^{\ddagger} = 16.9$ kcal/mol, $\Delta S^{\ddagger} = -1.2$ cal/mol deg.

Table II. Rate Constants (s^{-1}) for Solvolyses of Carboxylic Acid Chlorides in Aqueous Binary Mixtures at 25 °C[a]

	p-methoxybenzoyl chloride		benzoyl chloride	
compstn (% v/v)	acetonitrile	dioxane	acetonitrile	dioxane[b]
95	$(2.47 \pm 0.01) \times 10^{-4}$		$(3.87 \pm 0.11) \times 10^{-5}$	
90	$(1.53 \pm 0.01) \times 10^{-3}$	$(1.47 \pm 0.02) \times 10^{-4}$	$(1.25 \pm 0.02) \times 10^{-4}$	$(2.47 \pm 0.03) \times 10^{-4}$
80	$(1.30 \pm 0.01) \times 10^{-2}$	$(1.33 \pm 0.01) \times 10^{-3}$	$(5.15 \pm 0.03) \times 10^{-4}$	$(6.73 \pm 0.19) \times 10^{-4}$
60	$(1.24 \pm 0.03) \times 10^{-1}$	$(3.63 \pm 0.02) \times 10^{-2}$	$(3.38 \pm 0.05) \times 10^{-3}$	$(2.81 \pm 0.03) \times 10^{-3}$
50		$(1.67 \pm 0.03) \times 10^{-1}$		$(7.55 \pm 0.05) \times 10^{-3}$
40	1.3[d]	1.03 ± 0.02[e]	$(2.44 \pm 0.10) \times 10^{-2}$	$(2.25 \pm 0.01) \times 10^{-2}$
30	5.3[c,f]	3.0[c,g]	$(9.74 \pm 0.25) \pm 10^{-2}$	$(7.58 \pm 0.06) \times 10^{-2}$
20	19[c,h]	13[c,i]	$(2.92 \pm 0.05) \times 10^{-1}$	$(2.17 \pm 0.01) \times 10^{-1}$

[a] As for Table I. [b] Literature values (ref 13) for 90 and 80% dioxane vary, but two are ca. 20% lower than our values. [c] Calculated from data at other temperatures. [d] Also $k(T/°C)$: 0.059 (0.0), 0.225 (9.9), $\Delta H^{\ddagger} = 19.6$ kcal/mol, $\Delta S^{\ddagger} = 7.7$ cal/mol deg. [e] Also $k(T/°C)$: 0.058 (0.05), 0.186 (9.9), $\Delta H^{\ddagger} = 18.0$ kcal/mol, $\Delta S^{\ddagger} = 1.8$ cal/mol deg. [f] $k(T/°C)$: 0.147 (−6.0), 0.312 (0.0), $\Delta H^{\ddagger} = 17.7$ kcal/mol, $\Delta S^{\ddagger} = 4.3$ cal/mol deg. [g] $k(T/°C)$: 0.109 (−6.1), 0.243 (0.9), 0.48 (7.0), $\Delta H^{\ddagger} = 16.3$ kcal/mol, $\Delta S^{\ddagger} = -1.8$ cal/mol deg. [h] Calculated from $k = 0.41$ at −6.1 °C, assuming $\Delta H^{\ddagger} = 19$ kcal/mol. [i] $k(T/°C)$: 0.362 (−6.1), 0.558 (−2.1), 0.758 (0.2), 1.19 (3.2), $\Delta H^{\ddagger} = 18.0$ kcal/mol, $\Delta S^{\ddagger} = 7.0$ cal/mol deg.

Table III. Rate Constants and Kinetic Solvent Isotope Effects in Methanol at 25 °C[a]

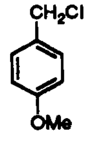
substrate	rate constant (MeOH)	rate constant (MeOD)	k.s.i.e.
p-methoxybenzyl chloride	$(2.86 \pm 0.05) \times 10^{-4}$	$(2.35 \pm 0.05) \times 10^{-4}$	1.22 ± 0.04
p-methoxybenzoyl chloride	$(1.13 \pm 0.01) \times 10^{-2}$	$(9.25 \pm 0.07) \times 10^{-3}$	1.22 ± 0.02

[a] Determined conductimetrically in duplicate in the order MeOH, MeOD, MeOD, MeOH.

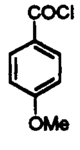
support this proposal with additional kinetic data and then show that a wide range of "dispersion" phenomena (including data for carboxylic acid chlorides) can now be rationalized quantitatively by differences in solvation between aromatic rings and alkyl groups. In an extension of these arguments, we show that solvolyses of benzoyl chloride also undergo mechanistic changes.

Results

Solvolytic rate constants for solvolyses of *p*-methoxybenzyl chloride (1) in seven aqueous binary mixtures are shown in Table I. Additional rate constants for solvolyses of benzoyl and *p*-methoxybenzoyl chlorides 2 are given in Table II, and solvent kinetic isotope effects in methanol are given in Table III. For solvolyses of 1 in ethanol/water and methanol/water mixtures (eq 2), product selectivities (eq 3) are calculated in Table IV.



1



2

$$ArCH_2Cl + ROH = ArCH_2OR + HCl \text{ (where R = H, Me, Et)} \quad (2)$$

$$S = [\text{ether product}][\text{water solvent}]/[\text{alcohol product}][\text{alcohol solvent}] \quad (3)$$

Table IV. Product Selectivities (S, eq 3) for Solvolyses of *p*-Methoxybenzyl Chloride (1) in Alcohol/Water Mixtures at 25 °C[a]

compstn (% v/v)	ethanol	(lit.[b])	methanol
90	1.7	(2.15)	3.6
80	2.0	(2.46)	3.8
60	2.7	(3.24)	4.8
40	3.6		5.8
20	4.4		6.4

[a] Determined by response-calibrated reverse-phase HPLC; values quoted are the averages of at least duplicate analyses on at least two independent samples; independent measurements were also made by J. Beaman (Swansea, 1990); estimated of combined errors ±5%. [b] Values in ethanol/water at 75 °C, determined by GC (ref 14).

Table V. Correlations of Logarithms of Rate Constants (Relative to 80% Ethanol/Water) for Solvolyses of *p*-Methoxybenzoyl Chloride (2) with Solvolyses of *p*-Methoxybenzyl Chloride (1) in Aqueous Binary Mixtures at 25 °C[a]

cosolvent	slope	intercept	correl coeff
acetone	0.90 ± 0.03	0.17 ± 0.05	0.991
acetonitrile	0.99 ± 0.04	0.16 ± 0.07	0.997
dioxane	0.91 ± 0.01	0.21 ± 0.03	0.999
ethanol	0.94 ± 0.05	0.16 ± 0.08	0.995
methanol	0.97 ± 0.06	0.09 ± 0.10	0.993

[a] Kinetic data from Tables I and II, with additional data for solvolyses of 2 from refs 7 and 17; the number and range of solvent compositions are those given in Table I.

Discussion

Products of solvolyses of 2 in ethanol/water mixtures show a constant S (0.72 ± 0.04, eq 3) and the value less than unity is interpreted as evidence for product formation via a solvent-separated ion pair.[7b,15] Common ion rate depression was not observed for solvolyses of 2 in 90% v/v trifluoroethanol/water.[15] In contrast, solvolyses of 1 show common ion rate depression (indicating reaction via a free carbocation) in aqueous ethanol[16a] and aqueous trifluoroethanol,[16b] and S values follow the usual trend,[11,14] an increase as water is added to alcohol (Table IV). Similarly, solvolyses of *p*-methoxybenzyl bromide in 80% dioxane/water show rate increases with added perchlorate and rate decreases with added bromide.[16c]

Although the product-determining steps differ, the close similarity of the rate-determining step for solvolyses of 1 and 2 is shown by the identical solvent kinetic isotope effects in methanol (Table III) and by the very similar rate–rate profiles of solvent effects on reactivity (Table V). Extensive studies have been made of solvent isotope effects in water,[18] but relatively little has been published for methanol.[19] The value of 1.2 (Table III) is in the range expected for an S_N1 reaction, because the fractionation factor for bromide ion in methanol is 1.35 ± 0.05 (determined from solubility measurements[20]) and the value for chloride will be lower (e.g., as it is for water[21]). Also, similar solvent isotope effects in water and methanol have previously been obtained for solvolyses of acetic anhydride.[19]

Remarkable features of the correlations for the five aqueous binary mixtures (Table V) are the slopes close to unity and the small range of values for the intercepts. Detailed inspection of the plots (not shown) reveals only a small dispersion with the possibility of slight curvature; calculations of y at $x = -2$ for each of the five mixtures give values within the range 1.73 ± 0.12, confirming that dispersion is small. We had previously interpreted the dispersed correlations[7] of rate data for 2 and for 2,6-dimethylbenzoyl chloride with Y_{Cl} as evidence that the solvation requirements of carboxylic acid chlorides differed from those of alkyl chlorides. In effect, we had been treating the Cl in COCl as a different leaving group from Cl in alkyl chlorides, but the results (Table V) now show that the solvation requirements for dissociative reactions of these two functional groups are almost identical in aqueous mixtures of similar electrophilicities.

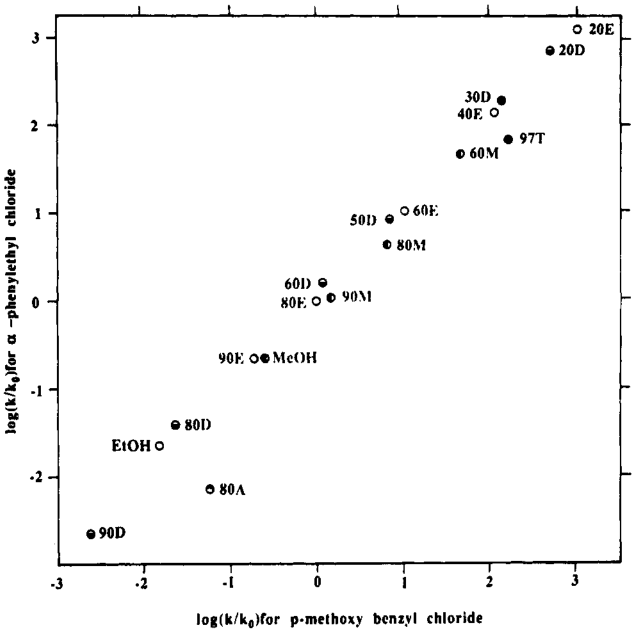


Figure 1. Correlation of logarithms of rate constants for solvolyses of α-phenethyl chloride (3) vs solvolyses of *p*-methoxybenzyl chloride (1) at 25 °C; for all data points except 80A, slope = 0.98 ± 0.02, intercept = 0.03 ± 0.04, correl coeff = 0.996; kinetic data for 1 from Table I and for 3 from refs 6a and 24. Solvent codes: A refers to acetone/water, An refers to acetonitrile/water, D refers to dioxane/water, E refers to ethanol/water, M refers to methanol/water, and T refers to trifluoroethanol/water.

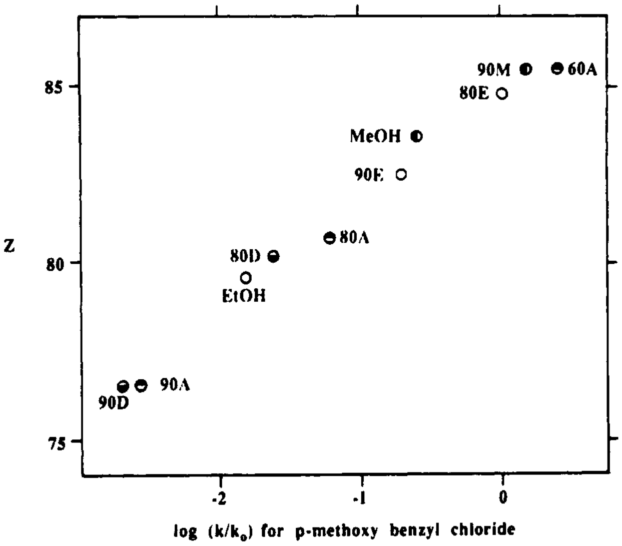


Figure 2. Correlation of Z values (data from ref 25) vs logarithms of rate constants for solvolyses of *p*-methoxybenzyl chloride (1) at 25 °C; slope 3.02 ± 0.12, intercept = 84.8 ± 0.17, correl coeff = 0.994; kinetic data for 1 from Table I.

It now appears that the major cause of the dispersions reported previously[7] is a difference in solvation between aromatic rings and alkyl groups. The effect may be due to π-conjugation between the aromatic ring and the carbocation center in the transition state.[9] Dispersion is largest in methanol > ethanol > aprotic solvents.[7] Studies of enthalpies of solution show that the relatively large differences in solvation between aryl and alkyl groups in water are reduced in methanol,[22] although this initial-state

---

(15) Song, B. D.; Jencks, W. P. *J. Am. Chem. Soc.* **1989**, *111*, 8470.

(16) (a) Queen, A. *Can. J. Chem.* **1979**, *57*, 2646. (b) Amyes, T. L.; Richard, J. P. Submitted for publication. (c) Vitullo, V. P.; Grabowski, J.; Sridharan, S. *J. Chem. Soc., Chem. Commun.* **1981**, 737.

(17) Bentley, T. W.; Koo, I. S. *J. Chem. Soc., Perkin Trans. 2* **1989**, 1385.

(18) (a) Gold, V. *Adv. Phys. Org. Chem.* **1969**, *7*, 259. (b) Schowen, R. L. *Prog. Phy. Org. Chem.* **1972**, *9*, 275. (c) Alvarez, F. J.; Schowen, R. L. *Isot. Org. Chem.* **1987**, *7*, 1. (d) Kresge, A. J.; More O'Ferrall, R. A.; Powell, M. F. *Isot. Org. Chem.* **1987**, *7*, 177.

(19) Gold, V.; Grist, S. *J. Chem. Soc. B* **1971**, 2285.

(20) Ruasse, M. F.; Motallebi, S. *Bull. Chem. Soc. Fr.* **1988**, 349.

(21) Thornton, E. K.; Thornton, E. R. in *Isotope Effects in Chemical Reactions*; Collins, C. J., Bowman, N. S., Eds.; Van Nostrand Reinhold: New York, 1970; p 251.

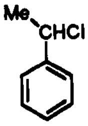
solvation alone could not account for our observations. Acid chlorides react rapidly with pure dimethyl sulfoxide (DMSO[23a]) and solvolytic reactions in aqueous DMSO are complex.[23b] Hence, these results are excluded from Table V.

Good correlations showing negligible dispersion (but possibly slight curvature[6a]) can also be seen for solvolyses of α-phenylethyl chloride (**3**) vs solvolyses of **1** (Figure 1), except that there is a significant deviation for 80% acetone/water (studied by four laboratories[24a–d]). Even the solvatochromic parameter Z,[2b,25] a scale of solvent polarity based on the solvent dependence of the intermolecular charge-transfer transition in the pyridinium salt (**4**), shows a good correlation with solvolyses of **1** (Figure 2); only data for the less aqueous media are available, but these solvents are the most likely to show dispersion.

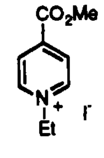
A key feature of **1**, **3**, and **4** is that they contain one aromatic ring, in which a positive charge can be delocalized. Curved plots and dispersion are observed when the model compounds are not aromatic, e.g., plots of Z vs Y[25a] (the model compound is *tert*-butyl chloride) and of Z vs Y_I[26] (the model compound is 1-adamantyl iodide). Because the solvent mixtures considered here have similar electrophilicities, differences in anions (I^- for Z and Cl^- for **1**) are not important in this case (Figure 2).

A revision of the accepted Z value for pure water is required. It is currently based on a long extrapolation vs Y values for 95–60% aqueous binary mixtures with acetone, ethanol, and methanol, but the assumption[25a] of linearity is not consistent with a more extensive plot of Z vs Y.[25b] A short extrapolation of logarithms of rate constants for solvolyses of **1** vs Y gives $\log (k/k_0) = 3.51 \pm 0.03$ for water, and a long extrapolation of Figure 2 gives a predicted Z value of 95.4 ± 0.7, compared with the original value[25a] of 94.6 ± 0.1 (for which we calculate an uncertainty of at least 1.0).

As expected, dispersion is observed (plot not shown) for $E_T(30)$ and related solvatochromic scales of solvent polarity.[27] The betaine dyes on which these scales are based contain several aromatic rings,[27] and preferential solvation effects are observed.[2c] Also the correlation with diphenylmethyl chloride (**5**) shows significant but not large



3



4

Ph_2CHCl

5

dispersion (Figure 3), and comparisons with Y or Y_{Cl} show that the effect of two aromatic rings, is not twice as large as the effect of one aromatic ring. This complex situation

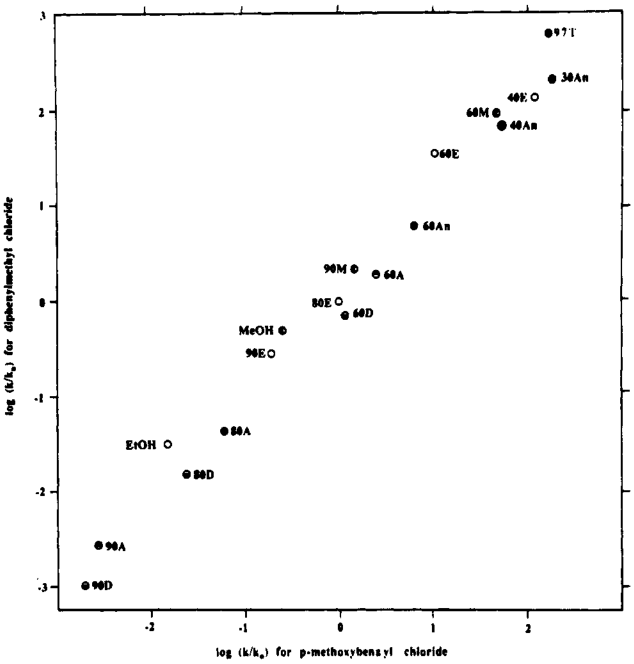


Figure 3. Correlation of logarithms of rate constants for solvolyses of diphenylmethyl chloride (**5**) vs solvolyses of *p*-methoxybenzyl chloride (**1**) at 25 °C; kinetic data for **1** from Table I and for **5** from refs 3, 6d, and 8.

was anticipated in pessimistic predictions about dispersion.[8] Rates of solvolyses of **5** in 60% aqueous solvents (Figure 3) show the order expected from the polarities (e.g., based on E_T values[27]) of the cosolvents (methanol > ethanol > acetonitrile > acetone > dioxane). Rates of solvolyses of dimethylsulfonium ions are almost insensitive to solvent ionizing power, but solvolyses of benzhydryldimethylsulfonium ions show the same order of dispersion effects as for **5** (aqueous methanol > aqueous ethanol > aqueous acetone > aqueous dioxane).[28] It has been proposed[29] that **5** is a suitable model compounds for S_N1 solvolytic reactivity, but extra solvation of aromatic rings must be taken into account.

Data points for the weakly nucleophilic solvent 97% trifluoroethanol/water in Figures 1 and 3 are within a factor of 2 of the main correlation lines—too small to warrant interpretation.

Further progress can now be made on the mechanistic interpretation of solvolytic reactions of benzoyl chloride, for which two competing reaction channels have been proposed.[15,17] One of these reaction channels is predominantly dissociative in character and the rate depends sharply on the solvent polarity, whereas the competing reaction channel is much less sensitive to changes in solvent polarity. As aqueous binary mixtures cover a wide range of solvent polarities, a mechanistic change from one reaction channel to the other can be seen as the solvent composition is varied. Solvent effects on the dissociative reaction channel for solvolyses of benzoyl chloride are similar to those for solvolyses of **2**, and it has been possible to quantify ("dissect") the contribution of this reaction channel to the overall solvolysis.[17]

The observed (undissected) rate constants, including the new data (Table II), plotted in Figure 4 against logarithms of rate constants for solvolyses of **2**, show curvature and

---

(22) Krishnan, C. V.; Friedman, H. L. *J. Phys. Chem.* **1971**, *75*, 388.

(23) (a) Michelot, R.; Tchoubar, B. *Bull. Chem. Soc. Fr.* **1966**, 3039. (b) Kivinen, A. In *Chemistry of Acyl Halides*; Patai, S., Ed.; Wiley: New York, 1972, p 186.

(24) (a) Berliner, E.; Shieh, N. *J. Am. Chem. Soc.* **1957**, *79*, 3849. (b) Anantaraman, R.; Saramma, K. *Tetrahedron* **1965**, *21*, 535. (c) Harris, J. M.; Becker, A.; Clark, D. C.; Fagan, J. F.; Kennan, S. L. *Tetrahedron Lett.* **1973**, 3813. (d) Tsuno, Y.; Kusuyama, Y.; Sawada, M.; Fujui, T.; Yukawa, Y. *Bull. Chem. Soc. Jpn.* **1975**, *48*, 3337. (e) Shiner, V. J., Jr.; Dowd, W.; Fisher, R. D.; Hartshorn, S. R.; Kessick, M. A.; Milakofsky, L.; Rapp, M. W. *J. Am. Chem. Soc.* **1969**, *91*, 4838.

(25) (a) Kosower, E. M. *J. Am. Chem. Soc.* **1958**, *80*, 3253. (b) Kosower, E. M. *J. Am. Chem. Soc.* **1958**, *80*, 3267.

(26) Bentley, T. W.; Carter, G. E.; Roberts, K. *J. Org. Chem.* **1984**, *49*, 5183.

(27) Dimroth, K.; Reichardt, C.; Siepmann, T.; Bohlmann, F. *Justus Liegigs Ann. Chem.* **1963**, *661*, 1. (b) Krygowski, T. M.; Wrona, P. K.; Zielkowska, U.; Reichardt, C. *Tetrahedron* **1985**, *41*, 4519.

(28) Kevill, D. N.; Anderson, S. W.; Ismail, N. HJ.; Fujimoto, E. K. *Stud. Org. Chem.* **1986**, *31*, 311.

(29) Dvorko, G. F.; Ponomareva, E. A.; Kulik, N. I. *Russ. Chem. Rev.* **1984**, *53*, 547.

(30) Bentley, T. W.; Carter, G. E.; Harris, H. C. *J. Chem. Soc., Perkin Trans. 2* **1985**, 983.

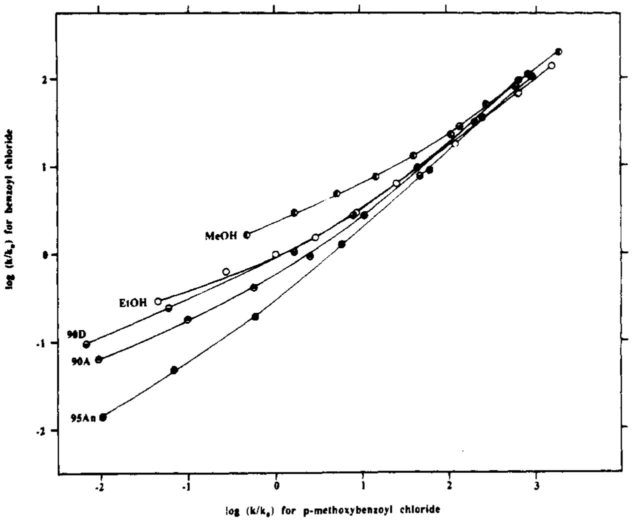


Figure 4. Correlation of logarithms of rate constants for solvolyses of benzoyl chloride vs solvolyses of *p*-methoxybenzoyl chloride (2) at 25 °C; kinetic data from Table II and refs 7, 17, and 30; solvent codes as for Figure 1.

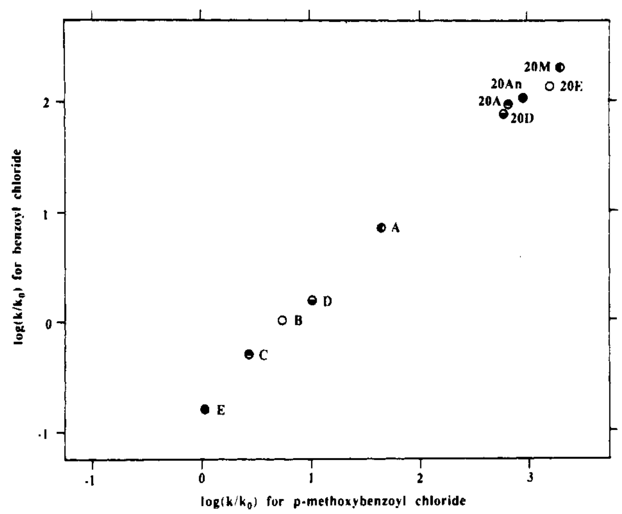


Figure 5. Logarithms of dissected rate constants (A–E) (see text) and observed rate constants in 20% solvent compositions for the dissociative reaction channel for solvolyses of benzoyl chloride vs solvolyses of *p*-methoxybenzoyl chloride (2) at 25 °C: points A–E are calculated for aqueous methanol, aqueous ethanol, aqueous acetone, aqueous dioxane, and aqueous acetonitrile, respectively. For the ten points shown, slope = 0.93 ± 0.02, intercept = −0.73 ± 0.04, correl coeff = 0.998; for points A–E only, slope = 0.99 ± 0.05, intercept = −0.77 ± 0.04, correl coeff = 0.997.

substantial dispersion. Points for methanol, ethanol, and 90% dioxane are dispersed by a 10-fold factor in rate from the corresponding acetonitrile/water data. For each binary mixture, the solvent composition at which the two reaction channels contribute equally to the observed rate can be estimated from the intersection point of the two approximately linear regions at the extremities of the curves.[17] Assuming that there are two competing reaction channels, half of the observed rate constant in this solvent composition (obtained by interpolation) gives the rate constant for reaction by the dissociative reaction channel. In this way, points labeled A–E (Figure 5) were calculated for the various aqueous binary mixtures. A correlation line through these five points and the observed rate data for 20% aqueous media shows negligible dispersion (Figure 5). Because of the small change in slopes of the correlations for aqueous acetonitrile, there is more uncertainty in the dissection for this solvent, and the calculated point E deviates slightly from the correlation line previously reported (Figure 2, ref 17).

A line through dissected points A–E (Figure 5) passes very close to the undissected rate constants for 20% solvent compositions, so these rate–rate profiles strongly support recent proposals[15,17] that solvolyses of benzoyl chloride occur by competing reaction channels, in agreement with studies of substituent effects[7a,15] and of product selectivities.[17] In Figure 4, the order of dispersion of the aprotic solvents (aqueous dioxan > aqueous acetone > aqueous acetonitrile) is the reverse of their order of polarity (see above). The large dispersions for ethanol and methanol are consistent with water acting as a general base catalyst for attack by alcohol.[11] Hence, we have now refined the procedures for distinguishing between solvation effects and mechanistic changes, procedures that began when the microscopic parameter *Y* value was shown to provide a superior alternative to bulk solvation properties such as dielectric constant or mole fraction of water.[3,31]

Conclusions

The precision of Grunwald–Winstein plots (eq 1) can be improved considerably by taking account of specific solvation effects. In addition to specific solvation of the leaving group,[4,5] there are also significant differences in solvation between aryl and alkyl groups.[4d,6c,8,9] When allowance is made for these effects (e.g., by comparing substrates having one aromatic ring), solvent effects for dissociative reactions of carboxylic acid chlorides in aqueous binary mixtures are very similar to those for benzylic chlorides (Table V). Logarithms of rates of solvolyses of 1 in aqueous acetone, ethanol, and methanol (solvents of similar electrophilicity) also correlate with the recently proposed Y_{BnCl} scale, based on solvolyses of 2-aryl-2-adamantyl chlorides.[9] Hence, after a period in which solvolyses of various compounds have been explored to model the solvolytic reactions of chlorides,[7-9,17,29] a significant new factor (>10-fold in rate and caused by differences in solvation of aromatic rings and alkyl groups) has emerged to rationalize a wide range of kinetic data. In principle, the diversity of *Y* scales could now be reduced, but in practice it will be convenient to continue to employ a variety of model compounds.

Furthermore, the correlation with *Z* values (Figure 2) greatly strengthens the link between kinetic and solvatochromic measures of solvent polarity. Previously, there has not been such direct evidence that solvolysis rates and charge-transfer transitions would respond in the same way to the microscopic events associated with rapid changes in solvation, and it has been suggested that interpretation of *Z* values may be complicated by destabilization of the excited state of 4 in more polar solvents.[33]

With appropriate choice of model compound, rate–rate profiles of solvent effects provide quantitative dissections of competing reaction channels, e.g., for solvolyses of benzoyl chloride (Figures 4 and 5). An important feature of this work is that only one solvent parameter (or rate data for only one model compound) is employed, and deviations from expected behavior can be recognized readily. In contrast, when multiparameter equations are employed, novel effects may not be detected because there is a

---

(31) There is a more recent analysis of solvent effects in binary mixtures, emphasizing the molar concentration of the more polar component.[32]

(32) Langhals, H. *Angew. Chem., Int. Ed. Engl.* **1982**, *21*, 724.

(33) Larsen, J. W.; Edwards, A. G.; Dobi, P. *J. Am. Chem. Soc.* **1980**, *102*, 6780.

tendency to correlate all of the data moderately successfully.

Experimental Section

p-Methoxybenzyl chloride (Aldrich) was separated from a calcium carbonate stabilizer before use (the purified product contained traces of *p*-methoxybenzaldehyde). Corresponding ethyl and methyl ethers were prepared by standard methods and were shown to give the same HPLC response at 266 nm as *p*-methoxybenzyl alcohol.

Dry solvents were either Fisons commercial grade (acetone, dioxane, methanol) or were freshly dried and distilled before use: acetonitrile (from P_2O_5); dimethyl sulfoxide (from CaH_2); ethanol (from $Mg(OEt_2)$) and trifluoroethanol (from P_2O_5). MeOD (99.5+ %D) was from Aldrich.

Chromatographic and kinetic methods were as described previously.[7b]

Acknowledgment. We are grateful to the SERC (U.K.) for the award of a studentship to (S.J.N.) and for an equipment grant, to the British Council in Seoul for a travel grant (I.S.K.), to K. T. Liu and J. P. Richard for preprints, to M. F. Ruasse and R. A. More O'Ferrall for comments on the interpretation of the data on solvent isotope effects, and to H. C. Harris, D. N. Kevill, and H. Langhals for helpful discussions.

Substituent Effects upon the Peak Potentials and Reductive Cleavage Rate Constants of Hydroxy- and Methoxy-Substituted 9,10-Anthraquinones in 50% Aqueous CH_3CN: Do They Correlate?

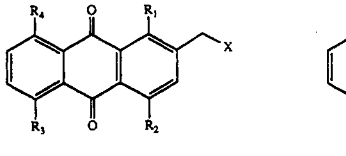
Ronald L. Blankespoor,* Elise L. Kosters, Alan J. Post, and Derek P. VanMeurs

Department of Chemistry, Calvin College, Grand Rapids, Michigan 49546

Received July 9, 1990

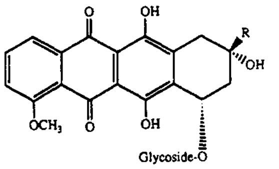
A variety of hydroxy- and methoxy-substituted 2-(acetoxymethyl)-9,10-anthraquinones (**2a–7a**) were reduced electrochemically and with dithionite ($S_2O_4^{2-}$) in 50% aqueous CH_3CN buffers over a wide pH range. Good to excellent yields of their corresponding reductive cleavage products, the substituted 2-methyl-9,10-anthraquinones **2b–7b**, were obtained from most of these anthraquinone acetates, but only at higher pH. Rate constants for the reaction of 2-(acetoxymethyl)-9,10-anthraquinone (**1a**) with excess dithionite ranged from $1.0 \times 10^{-4}\ s^{-1}$ at pH values less than 7 to $4.0 \times 10^{-4}\ s^{-1}$ at a pH of 10, demonstrating that loss of acetate occurs in the rate-determining step and that cleavage occurs slower via the anthrahydroquinone of **1a** than the conjugate base of the anthrahydroquinone. Substituent effects upon the reductive cleavage process were determined by measuring rate constants for those acetates that react cleanly with dithionite at pH 8. These effects, which are rationalized on the basis of resonance theory and intramolecular H bonding, correlate fairly well with the peak potentials (E_p) of the reductive cleavage products of these acetates. Thus, electron-donating substituents on an anthraquinone acetate not only make it more difficult to reduce resulting in a more negative E_p but also enhance the rate of acetate cleavage in the corresponding anthrahydroquinone.

We recently reported that the electroreduction of 2-(acetoxymethyl)-9,10-anthraquinone (**1a**) and its methoxy derivatives **2a**, **4a**, and **6a** to their corresponding 2-methyl-9,10-anthraquinones **1b**, **2b**, **4b**, and **6b**, respectively, in aqueous media is pH dependent.[1] Since much higher conversions were obtained at higher pH (> 7), we concluded that this electroreductive cleavage process proceeds through the sequence of reactions shown in Scheme I for **1a**. Reduction of acetate **1a** leads to its anthrahydroquinone **8**, which at pH < 7, undergoes cleavage slowly to give the protonated, vinylogous quinone methide **9**. At higher pH, equilibrium shifts toward the conjugate base **10**, which is converted to the quinone methide **11** at a higher rate.



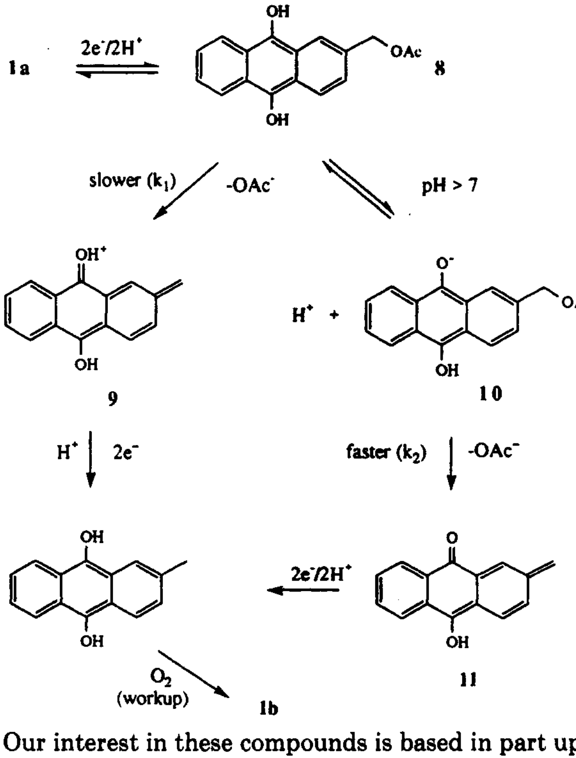
1: $R_1 = R_2 = R_3 = R_4 = H$
2: $R_1 = OCH_3, R_2 = R_3 = R_4 = H$
3: $R_1 = OH, R_2 = R_3 = R_4 = H$
4: $R_1 = R_4 = OCH_3, R_2 = R_3 = H$
5: $R_1 = R_4 = OH, R_2 = R_3 = H$
6: $R_1 = R_4 = H, R_2 = R_3 = OCH_3$
7: $R_1 = R_4 = H, R_2 = R_3 = OH$

a: X = OAc
b: X = H
c: X = OH
d: X = Br



12 a: R = $COCH_3$
b: R = $COCH_2OH$

Scheme I



Our interest in these compounds is based in part upon their structural similarity to anthracyclines such as dau-

---

[1] Blankespoor, R. L.; Hsung, R.; Schutt, D. L. *J. Org. Chem.* **1988**, *53*, 3032.

0022-3263/91/1956-1609$02.50/0 © 1991 American Chemical Society