Correlation of the rates of solvolysis of *n*-octyl fluoroformate and a comparison with *n*-octyl chloroformate solvolysis

2 PERKIN

Dennis N. Kevill * and Malcolm J. D'Souza †

Department of Chemistry and Biochemistry, Northern Illinois University, DeKalb, Illinois 60115-2862, USA

Received (in Cambridge, UK) 9th October 2001, Accepted 27th November 2001
First published as an Advance Article on the web 17th January 2002

The specific rates of solvolysis of *n*-octyl fluoroformate have been measured at 24.2 °C in 28 pure and binary solvents. For the 23 solvents for which both N_T (solvent nucleophilicity) and Y_{Cl} (solvent ionizing power) values are known, a correlation using the two-term Grunwald–Winstein equation leads to sensitivities towards changes in the two scales of 1.80 ± 0.13 (*l* value) and 0.79 ± 0.06 (*m* value), respectively. For seven solvents, a parallel study was made of *n*-octyl chloroformate solvolysis and F : Cl specific rate ratios were, in most instances, above unity, consistent with the association step of an association–dissociation (addition–elimination) pathway being rate-determining.

Recently, we have reported on the application of the extended (two-term) Grunwald–Winstein equation[1,2] [eqn. (1)] to the

$$\log (k/k_0) = lN_T + mY_{Cl} + C \qquad (1)$$

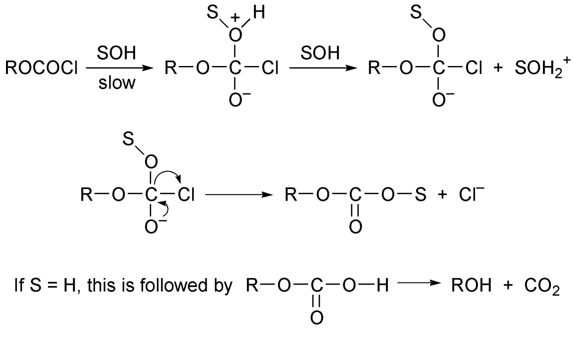
solvolyses of several chloroformate esters [eqn. (2)], including

$$\mathrm{ROCOCl} \xrightarrow{SOH/H_2O} \mathrm{ROCOOS + ROS + ROH + CO_2 + HCl} \qquad (2)$$

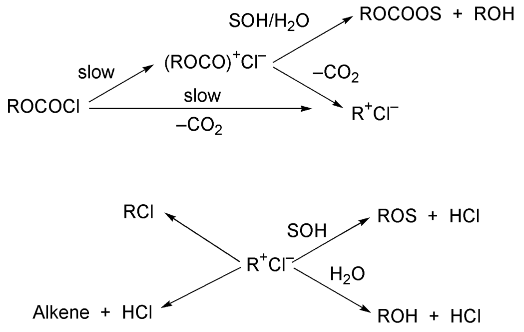
phenyl,[3] methyl,[4] ethyl,[5] isopropyl,[6] benzyl,[7] and 4-nitrobenzyl.[7] In eqn. (1), k and k_0 are the specific rates of solvolysis in a given solvent and in the standard solvent (80% ethanol), respectively; l is the sensitivity towards changes in solvent nucleophilicity (N_T); m is the sensitivity towards changes in solvent ionizing power (Y_x, for a leaving group X); c is a constant (residual) term. The eqn. (2) represents the most general form of the solvolysis reaction. The dialkyl or alkyl aryl carbonate is formed by nucleophilic attack of alcohol (SOH) at the acyl carbon. The alcohol or phenol product is formed either by a parallel attack by water to give the hydrogen carbonate ester, followed by loss of CO_2,[8] or by attack of water on R^+, formed by loss of CO_2 from an intermediate carboxylium ion $(ROCO)^+$. Capture of the R^+ by SOH leads to ester (ROS) and capture by the chloride ion formed in the ionization will lead to a decomposition pathway (for the chloroformate ester reactant) to give RCl. When feasible, an alternative decomposition pathway, involving extraction of a β-proton from the R group and alkene formation, can also occur.

Two types of mechanism have been found to operate, postulated as an addition–elimination mechanism [eqn. (3)], with addition being rate determining, and an ionization mechanism [eqn. (4)]. Replacement of either or both oxygens by sulfur has been shown to lead to an increased tendency towards the ionization pathway.[5,9,10]

The solvolyses of 1-adamantyl chloroformate were found[11,12] to proceed almost entirely *via* the 1-adamantyl cation. Only in 100% ethanol was a trace of the mixed carbonate observed. However, replacement of chlorine by fluorine led to the reaction following the addition–elimination pathway in all but the most ionizing and weakly nucleophilic solvents.[13] Since the chloroformate and fluoroformate reacted in almost all solvents by different pathways, a consideration of the overall F : Cl specific rate ratios was not a useful mechanistic indicator. For other haloformate esters, a consideration of the F : Cl rate ratio has provided some of the best evidence in favor of the addition step within an association–dissociation (addition–elimination) mechanism being rate determining.



(3)



(4)

For solvolyses of ethyl haloformates, F : Cl specific rate ratios of 28.6 for 85% acetone at 0.0 °C[14] and of 1.1 for ethanol at 25.1 °C[15] have been reported. Since the C–F bond is much stronger than the C–Cl bond, ratios of well below unity would have been anticipated if the carbon–halogen bond was appreciably broken at the transition state of the rate-determining step. Since an extensive tabulation of the specific rates of solvolysis of ethyl chloroformate in a wide variety of solvents exists,[5] it was decided that a parallel study would be made of ethyl fluoroformate solvolyses. One could then see

---

† *Current address*: Department of Chemistry, Wesley College, 120 N. State Street, Dover, Delaware 19901-3875, USA.

DOI: 10.1039/b109169g

whether there was any appreciable variation in l and m values [eqn. (1)] from those obtained for the analysis of the chloroformate solvolyses. In addition, F : Cl specific rate ratios would be available for a wide range of solvent composition, such that it would be possible to see whether the previously observed[14,15] 26-fold variation in going from 85% acetone to ethanol can be extended when additional solvents are considered.

Initially, we attempted to follow the kinetics of the solvolyses of ethyl fluoroformate by the procedure developed by Queen and Nour[16] for solvolyses of aryl fluoroformates. This involved quenching in pentane and extracting the developed HF into water prior to titration. It was found that the ethyl ester, being less hydrophobic, was also to some degree extracted into the water, followed by relatively rapid hydrolysis and erratic and inaccurate titration values. To overcome this problem, we increased the hydrophobic character of the substrate by replacing the ethyl group by the *n*-octyl group [$CH_3(CH_2)_7OCOF$]. Also, to allow an unambiguous comparison, we determined for seven of the solvents the specific rate of solvolysis of the *n*-octyl chloroformate [$CH_3(CH_2)_7OCOCl$].

Results

The specific rates of solvolysis of *n*-octyl fluoroformate were determined in 28 solvents at 24.2 °C. The solvents consisted of ethanol and methanol, binary mixtures of water with ethanol, methanol, 2,2,2-trifluoroethanol (TFE), acetone, and 1,4-dioxane, and four binary mixtures of TFE and ethanol. The specific rates of solvolysis are reported in Table 1, together with the available N_T,[2,17] Y_{Cl},[18,19] and Y_{OTS}[18,20] values. Specific rates of solvolysis of *n*-octyl chloroformate were determined in seven solvents at the same temperature. These values are reported in Table 2, together with the F : Cl specific rate ratios (determined in conjunction with values from Table 1).

Discussion

The comparisons of the specific rates of solvolysis of *n*-octyl fluoroformate and *n*-octyl chloroformate at 24.2 °C (Table 2) show only modest F/Cl leaving-group effects, with values ranging from 0.62 in 100% ethanol to 15.1 in 60% ethanol. In ethanol and methanol, the chloroformate, reacts marginally faster but, for all five of the comparisons in aqueous–organic solvents, the fluoroformate is somewhat faster, despite the stronger carbon–fluorine bond. Similar ratios have been observed previously for the solvolyses of other haloformate esters.[14–16] The small leaving-group effects have been ascribed[14–16,21] to the operation of an addition–elimination pathway in which the addition step is rate-determining [eqn. (3)]. The rate of attack by the solvent at the carbonyl carbon, to give a tetrahedral intermediate without the rupture of the carbon–halogen bond, would be expected to be only slightly dependent on the nature of the halogen. Due to the higher electronegativity of fluorine leading to an increase in the electron deficiency at the carbonyl carbon, it is reasonable to predict that the attack will be somewhat easier for the fluoroformate substrate. Parallel arguments have been applied to situations where small F : Cl leaving-group ratios have been found in nucleophilic aromatic substitutions.[22] After subsequent, or concurrent, deprotonation by a second solvent molecule (acting as a general base), regeneration of the carbonyl group, in a fast step, will now favor loss of halide ion.

Table 1 Specific rates of solvolysis of *n*-octyl fluoroformate[a] in a variety of pure and mixed solvents at 24.2 °C and the N_T, Y_{Cl}, and Y_{OTS} values for the solvents

Solvent[b]	10^5k/s^{-1} [c]	N_T [d]	Y_{Cl} [e]	Y_{OTS} [f]
100% EtOH	1.48 ± 0.03[g]	0.37	−2.52	−1.75
90% EtOH	14.3 ± 0.5	0.16	−0.94	−0.58
80% EtOH	59.6 ± 0.9	0.00	0.00	0.00
70% EtOH	93.9 ± 1.4	−0.20	0.78	0.47
60% EtOH[h]	141.8 ± 7.6	−0.38	1.38	0.92
50% EtOH[h]	197.7 ± 10.8	−0.58	2.02	1.29
40% EtOH[i]	256.1 ± 9.7	−0.74	2.75	2.08
100% MeOH	8.12 ± 0.08[j]	0.17	−1.17	−0.92
90% MeOH	78.7 ± 0.8	−0.01	−0.18	−0.17
80% MeOH[h]	160.8 ± 4.1	−0.06	0.67	0.47
70% MeOH[h]	271.9 ± 15.2	−0.40	1.46	1.02
95% Acetone	0.0409 ± 0.0013	−0.49	−3.19	−2.95
90% Acetone	0.322 ± 0.005	−0.35	−2.22	−1.99
80% Acetone	2.22 ± 0.04	−0.37	−0.83	−0.94
60% Acetone	16.9 ± 0.3	−0.52	0.95	0.66
95% Dioxane	0.192 ± 0.011			
90% Dioxane	0.999 ± 0.009			−2.06
80% Dioxane	2.97 ± 0.08	−0.46		−1.10
60% Dioxane	23.9 ± 0.7	−0.54		+0.30
40% Dioxane[i]	91.4 ± 1.2	−0.84		
90% TFE[k]	0.332 ± 0.011	−2.55	2.85	1.90
80% TFE[k]	2.21 ± 0.03	−2.19	2.90[l]	1.94
70% TFE[k]	4.30 ± 0.06	−1.98	2.96	2.00
50% TFE[k]	11.5 ± 0.8	−1.73	3.16	2.14
80T–20E[m]	0.117 ± 0.005	−1.76	1.89	0.98
60T–40E[m]	0.879 ± 0.009	−0.94	0.63	0.21
40T–60E[m]	1.65 ± 0.05	−0.34	−0.48	−0.44
20T–80E[m]	2.30 ± 0.08	0.08	−1.42	−1.18

[a] Substrate concentration of 0.0100 mol dm^{-3}, unless otherwise indicated. [b] Unless otherwise indicated, binary solvents are on a volume–volume basis at 25.0 °C. [c] With associated standard deviation; average of all integrated first-order rate coefficients from duplicate runs, except for 90% TFE, where the average of initial values obtained by extrapolation of plots versus extent of reaction is reported. [d] From refs. 2 and 17. [e] From refs. 18 and 19. [f] Values from refs. 18 and 20*a*, except those values based on solvolyses of 1-adamantyl toluene-*p*-sulfonate are adjusted as described in ref. 20*b*. [g] Value of 1.53 (± 0.03) × 10^{-5} s^{-1} at 25.0 °C. [h] Substrate concentration of 0.0050 mol dm^{-3}. [i] Substrate concentration of 0.0033 mol dm^{-3}. [j] Value of 8.53 (± 0.05) × 10^{-5} s^{-1} at 25.0 °C. [k] On a weight–weight basis. [l] From ref. 7. [m] T–E are TFE–EtOH mixtures.

Table 2 Specific rates of solvolysis of *n*-octyl chloroformate[a] in pure and mixed solvents at 24.2 °C and the F : Cl specific rate ratios

solvent[b]	10^5 k/s^{-1} [c]	F : Cl[d]
100% EtOH	2.39 ± 0.03[e]	0.62 ± 0.02
80% EtOH	7.37 ± 0.09	8.09 ± 0.12
60% EtOH	9.42 ± 0.19	15.1 ± 0.9
100% MeOH	8.51 ± 0.12	0.95 ± 0.02
80% Acetone	0.775 ± 0.012	2.86 ± 0.07
80% Dioxane	1.56 ± 0.06	1.90 ± 0.09
80% TFE[f]	0.217 ± 0.008	10.2 ± 0.4

[a] Substrate concentration of 0.0100 mol dm^{-3}, unless otherwise indicated. [b] See footnotes in Table 1. [c] See footnotes in Table 1. [d] The specific rates of solvolysis of *n*-octyl fluoroformate are from Table 1. [e] Value of 2.70 (± 0.04) × 10^{-5} s^{-1} at 25.0 °C. [f] Substrate concentration of 0.0200 mol dm^{-3}.

In contrast, nucleophilic substitution reactions in which the carbon–halogen bond is believed to be broken in the rate-determining step have considerably lower values for the F/Cl leaving-group effect. For S_N1 reactions, values of about 10^{-5} for *tert*-butyl halide solvolyses,[23] 10^{-6} for triphenylmethyl halide solvolyses,[23] and 10^{-7} for 4-(*N*,*N*-dimethylamino)benzoyl halide solvolyses[21] have been reported. The values are higher, but still well below unity, for S_N2 reactions, with values for reactions of methyl halides of 3 × 10^{-2} for hydrolysis,[24] 9 × 10^{-2} for reaction with hydroxide ion,[25] and 1.2 × 10^{-3} for reaction with iodide ion.[26] It is of interest that acetyl halides undergoing solvolysis in 75% acetone[23] show a very low F/Cl leaving-group effect of 1.3 × 10^{-4}, supporting the concept[27] of an appreciable difference in mechanism for these solvolyses, relative to that for haloformate solvolyses in similar solvents; for example, in the very similar solvent 80% acetone, the *n*-octyl haloformates

Table 3 Coefficients from extended Grunwald–Winstein correlations of the solvolyses of *n*-octyl fluoroformate and a comparison with corresponding values for the solvolyses of three chloroformate esters

Substrate	Scales	n^a	l^b	m^b	c^c	l/m	R^d	F^e
OctOCOF	N_T, Y_{Cl}	23	1.80 ± 0.13	0.79 ± 0.06	0.13 ± 0.34	2.28	0.959	114
OctOCOF	N_T, Y_{Cl}	19^f	1.67 ± 0.07	0.76 ± 0.03	−0.08 ± 0.18	2.20	0.988	325
PhOCOCl[g]	N_T, Y_{Cl}	21	1.68 ± 0.10	0.57 ± 0.06	0.12 ± 0.41	2.95	0.973	159
MeOCOCl[h]	N_T, Y_{Cl}	19	1.59 ± 0.09	0.58 ± 0.05	0.16 ± 0.07	2.74	0.977	
EtOCOCl[i]	N_T, Y_{Cl}	28	1.56 ± 0.09	0.55 ± 0.03	0.19 ± 0.24	2.84	0.967	179
4-NO_2BzOCOCl[j]	N_T, Y_{Cl}	19	1.61 ± 0.09	0.46 ± 0.04	0.04 ± 0.22	3.50	0.975	157
OctOCOF	N_T, Y_{OTS}	25	1.56 ± 0.13	0.96 ± 0.08	−0.08 ± 0.38	1.63	0.944	91
OctOCOF	N_T, Y	26	1.31 ± 0.10	0.88 ± 0.06	−0.18 ± 0.31	1.49	0.962	143

[a] Number of solvents included in the correlation. [b] From eqn. (1), with associated standard error. [c] From eqn. (1), accompanied by the standard error of the estimate. [d] Correlation coefficient. [e] The F-test value. [f] Omitting the four TFE–ethanol solvents (see text). [g] Values from ref. 3. [h] Values from ref. 4. [i] Values from ref. 5. [j] For 4-nitrobenzyl chloroformate; values from ref. 7.

show an F : Cl ratio of 10.2 (Table 2), higher by almost five orders of magnitude.

Due to both a low reactivity (consistent with the very low F : Cl ratios for S_N1 reactions) and a strong autocatalysis by the acid developed,[13,28] it has not been possible to use 1-adamantyl fluoride to develop a Y_F scale. However, if the currently considered mechanism is as in eqn. (3), with the association step rate determining, this is not necessarily a handicap to the present investigation. The ideal Y_X scale would be based on a solvolysis which mimics the movement of the π electrons of the carbonyl group onto the oxygen. In several studies of chloroformate esters reacting by this mechanism, the Y_{Cl} scale was found to be appropriate for use within the extended Grumwald–Winstein equation (Table 3) and it is reasonable to predict that this scale will also be appropriate for use within analyses, when eqn. (3) applies, of the specific rates of solvolysis of other haloformate esters.

It is found (Table 3 and Fig. 1) that the use of N_T values in conjunction with Y_{Cl} values leads to acceptable correlations, with l and m values similar to those obtained in analyses of the specific rates of solvolysis of phenyl,[3] methyl,[4] and ethyl[5] chloroformates. The major difference is a somewhat larger m value for the *n*-octyl fluoroformate solvolyses, possibly reflecting the need for increased solvation of the developing negative charge on the carbonyl oxygen in the presence of the more electronegative fluorine attached at the carbonyl carbon. Visual inspection of Fig. 1 indicates that the measures of goodness of fit would probably be considerably improved if the four solvolyses in TFE–ethanol mixtures were omitted from the correlation. Also in earlier correlations of other haloformate esters, it was found that the data points for these solvent systems usually lay below the correlation line.[3–5,7] When these data points are omitted from the correlation (Table 3), the l and m values are only very slightly reduced but considerably improved values for the correlation coefficient (0.988 relative to 0.959) and for the F-test value (325 relative to 114) are observed.

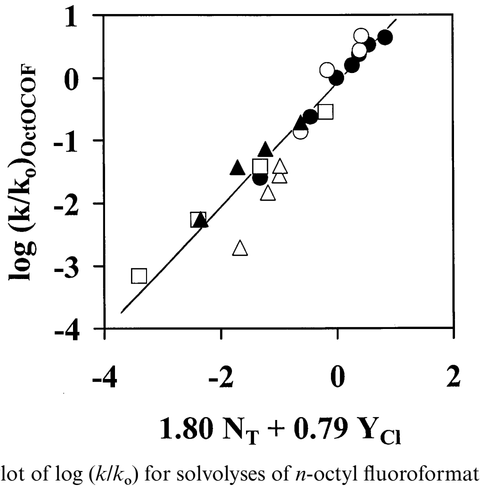


Fig. 1 Plot of log (k/k_o) for solvolyses of *n*-octyl fluoroformate at 24.2 °C against (1.80N_T + 0.79Y_{Cl}); ● EtOH (aq), ○ MeOH (aq), □ Acetone (aq), ▲ TFE (w/w; aq), △ TFE–EtOH.

We have also carried out the analyses (Table 3) with the Y_{Cl} values replaced by Y_{OTS} values. In the establishment of the Y_{OTS} scale negative charge is developing on oxygen, but it is dispersed over the three oxygens of the developing toluene-4-sulfonate anion (4-$CH_3C_6H_4SO_3^-$). The goodness of fit is slightly inferior, indicating that the development on one atom (the incipient chloride ion) is preferable, as a similarity model, to the development on oxygen—but spread over three atoms. Surprisingly, since it contains a nucleophilic component,[2,19a,b] the original Y scale, based on *tert*-butyl chloride solvolysis,[29] in conjunction with the N_T scale gives reasonable correlations (Table 3). However, due to the nucleophilic contribution to the solvent ionizing power scale, a low l value is associated with this analysis.

Conclusions

A mechanism for the solvolyses of *n*-octyl fluoroformate involving an association–dissociation (addition–elimination) pathway, with the association step being rate determining [eqn. (3)], is supported by two types of evidence obtained in this study. Firstly, the F : Cl specific rate ratios obtained in a comparison with the corresponding solvolysis of *n*-octyl chloroformate are close to unity with, in most cases, the fluoroformate reacting slightly faster and, secondly, the l and m values obtained from an extended Grunwald–Winstein equation [eqn. (1)] treatment are very similar to those previously observed for the solvolyses of several chloroformate esters which have been shown to solvolyze with the association step of an association–dissociation pathway being rate determining.

The correlations are best carried out using the N_T scale in conjunction with the Y_{Cl} scale. Use of the Y_{OTS} scale gives slightly inferior correlations. Use of the original Y scale gives surprisingly good correlations but the l values are low. These low l values result from a component governed by solvent nucleophilicity being incorporated into the *tert*-butyl chloride based Y scale.

Experimental

The *n*-octyl chloroformate (Aldrich) was purified by fractional distillation at reduced pressure. The *n*-octyl fluoroformate was prepared by the stirred reaction for four days, under nitrogen and at room temperature, of *n*-octyl chloroformate (5.0 g, 0.026 mol), potassium fluoride (2.8 g, 0.048 mol), and 18-crown-6 (0.34 g, 0.0013 mol).[30] Fractional distillation gave 1.20 g (26%) *n*-octyl fluoroformate, bp 51–53 °C/2.5 mmHg. Anal. Calcd. for $C_9H_{17}O_2F$: C, 61.39; H, 9.65; F, 10.79. Found: C, 61.42; H, 9.93; F, 10.21.

The solvents were purified as previously described.[17] The kinetic runs for the chloroformate[17] and fluoroformate[13,16] esters were also carried out as previously described.

The multiple regression analyses were carried out using the ABSTAT statistical package (Anderson-Bell, Arvada, Colorado, USA).

Acknowledgements

D. N. K. thanks Professor H. Mayr (Universität München) for his hospitality whilst this manuscript was being prepared.

References

1 S. Winstein, E. Grunwald and H. W. Jones, *J. Am. Chem. Soc.*, 1951, **73**, 2700.
2 D. N. Kevill, in *Advances in Quantitative Structure-Property Relationships*, ed. M. Charton, JAI Press, Greenwich, CN, 1996, vol. 1, pp. 81–115.
3 D. N. Kevill and M. J. D'Souza, *J. Chem. Soc., Perkin Trans. 2*, 1997, 1721.
4 D. N. Kevill, J. C. Kim and J. B. Kyong, *J. Chem. Res. (S)*, 1999, 150.
5 D. N. Kevill and M. J. D'Souza, *J. Org. Chem.*, 1998, **63**, 2120.
6 J. B. Kyong, Y.-G. Kim, D. K. Kim and D. N. Kevill, *Bull. Korean Chem. Soc.*, 2000, **21**, 662.
7 J. B. Kyong, B.-C. Park, C.-B. Kim and D. N. Kevill, *J. Org. Chem.*, 2000, **65**, 8051.
8 C. Faurholt and J. C. Gjaldbaek, *Dansk. Tids. Farm.*, 1945, **19**, 255; C. Faurholt and J. C. Gjaldbaek, *Chem Abstr.*, 1946, **40**, 513.
9 D. N. Kevill, M. W. Bond and M. J. D'Souza, *J. Org. Chem.*, 1997, **62**, 7869.
10 D. N. Kevill and M. J. D'Souza, *Can. J. Chem.*, 1999, **77**, 1118.
11 D. N. Kevill, J. B. Kyong and F. L. Weitl, *J. Org. Chem.*, 1990, **55**, 4304.
12 D. N. Kevill and F. L. Weitl, *Tetrahedron Lett.*, 1971, 707.
13 D. N. Kevill and J. B. Kyong, *J. Org. Chem.*, 1992, **57**, 258.
14 M. Green and R. F. Hudson, *J. Chem. Soc.*, 1962, 1055.
15 S. I. Orlov, A. L. Chimishkyan and M. S. Grabarnik, *J. Org. Chem. USSR (Engl. Transl.)*, 1983, **19**, 1981.
16 A. Queen and T. A. Nour, *J. Chem. Soc., Perkin Trans. 2*, 1975, 935.
17 D. N. Kevill and S. W. Anderson, *J. Org. Chem.*, 1991, **56**, 1845.
18 T. W. Bentley and G. Llewellyn, *Prog. Phys. Org. Chem.*, 1990, **17**, 121.
19 (*a*) T. W. Bentley and G. E. Carter, *J. Am. Chem. Soc.*, 1982, **104**, 5741; (*b*) D. N. Kevill and M. J. D'Souza, *J. Chem. Res. (S)*, 1993, 174; (*c*) J. S. Lomas, M. J. D'Souza and D. N. Kevill, *J. Am. Chem. Soc.*, 1995, **117**, 5891.
20 (*a*) F. L. Schadt, T. W. Bentley and P. v. R. Schleyer, *J. Am. Chem. Soc.*, 1976, **98**, 7667; (*b*) B. Allard and E. Casadevall, *Nouv. J. Chim.*, 1985, **9**, 565.
21 B. D. Song and W. P. Jencks, *J. Am. Chem. Soc.*, 1989, **111**, 8470.
22 (*a*) J. Miller, *Nucleophilic Aromatic Substitution*, Elsevier, Amsterdam, 1968; (*b*) J. F. Bunnett, E. W. Garbish, Jr. and K. M. Pruitt, *J. Am. Chem. Soc.*, 1957, **79**, 385.
23 C. G. Swain and C. B. Scott, *J. Am. Chem. Soc.*, 1953, **75**, 246.
24 I. Fells and E. A. Moelwyn Hughes, *J. Chem. Soc.*, 1959, 398.
25 D. N. Glew and E. A. Moelwyn Hughes, *Proc. R. Soc. London*, 1952, **A211**, 254.
26 R. H. Bathgate and E. A. Moelwyn Hughes, *J. Chem. Soc.*, 1959, 2642.
27 T. W. Bentley, G. Llewellyn and J. A. McAlister, *J. Org. Chem.*, 1996, **61**, 7927.
28 (*a*) C. G. Swain and R. E. T. Spalding, *J. Am. Chem. Soc.*, 1960, **82**, 6104; (*b*) C. A. Bunton and J. H. Fendler, *J. Org. Chem.*, 1966, **31**, 2307.
29 E. Grunwald and S. Winstein, *J. Am. Chem. Soc.*, 1948, **70**, 846.
30 J. Cuomo and R. A. Olofson, *J. Org. Chem.*, 1979, **44**, 1016.