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Effect of the leaving group solvation on solvolytic behavior of benzhydryl derivatives

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An effect of the leaving group (LG) solvation on reactivity of benzhydryl derivatives in S_N1 reactions has been investigated by using X,Y-substituted benzhydryl phenyl carbonates, methyl carbonates, 3,5-dinitrobenzoates (DNB), and the corresponding benzhydryl chlorides as reference compounds. Reaction constants (s_f) derived from LFER equation log k (25 °C) = $s_f(N_f + E_f)$ indicate that s_f parameters of carbonates and DNBs decrease as the fraction of the water in a given solvent/water mixture increases, while those of chlorides remain unchanged. This phenomenon is due to less important solvation and less charge separation in the TS. Effects of the solvents on the reaction rates were analyzed by Grunwald–Winstein correlations using various solvent-ionizing power scales. The *m* values obtained for carbonates and DNBs are considerably smaller than the *m* values for chlorides. Also, the solvolysis rate constants of substrates that have stronger electrofuges are less influenced by solvent (lower *m*) than those with weaker electrofuges. Values of *m* parameters obtained for a given substrate in a given binary solvent system correlate well with the electrofugality of the generated benzhydrylium ion. Abscissa at which $m = 0$ represents the extrapolated critical electrofugality E_f^{crit} of the substrates whose solvolysis rates should not depend on the water fraction in the aqueous/organic solvent mixtures. Similar values for the critical electrofugality have also been obtained from extrapolated log*k* *versus* E_f plots. Copyright © 2009 John Wiley & Sons, Ltd.

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Keywords: LFER reaction constant; electrofugality; nucleofugality; solvent effect; leaving group; benzhydryl derivatives; critical electrofugality; kinetics

INTRODUCTION

Nucleofugality of phenyl carbonate ($C_6H_5OCO_2^-$; PhCarb) and methyl carbonate ($CH_3OCO_2^-$; MeCarb) in S_N1 reactions have recently been examined thoroughly by studying the solvolysis rates of the substituted benzhydryl carbonates in numerous solvents and solvent mixtures.[1] It has been demonstrated that excellent correlations of log *k* *versus* E_f were obtained ($0.996 \leq r \leq 1.000$) if the special case of LFER was applied, which has been developed on the benzhydrylium system.[2–5] In this approach, solvolysis rate constants of benzhydrylium tosylates, bromides, chlorides, trifluoroacetates, 3,5-dinitrobenzoates, and 4-nitrobenzoates were subjected to the least-squares fit according to the correlation eqn (1)

$$\log k(25\,^\circ\mathrm{C}) = s_f(E_f + N_f) \qquad (1)$$

where k is the first order rate constant of the S_N1 reaction, s_f (slope of the correlation line) and N_f (negative intercept on the abscissa) are the nucleofuge specific parameters, and E_f is the electrofugality parameter. E_f is an independent parameter determined with the substituents on the benzhydryl system, while N_f and s_f are defined for a combination of the leaving group (LG) and the solvent. Predefined parameters are $s_f = 1.00$ for chloride nucleofuge in pure ethanol and $E_f = 0.00$ for dianisylcarbenium ion (**1**). The electrofugality parameters (E_f) of X,Y-substituted benzhydrylium ions are taken from Reference [2,3].

If one compares the Hammett–Brown correlation ($\log k = \rho^+\sigma^+ + \log k_0$) with eqn (1), it is evident that the fundamentals of E_f parameters are essentially the same as the fundamentals for σ^+ values, so it is not surprising that E_f correlates with σ^+ ($E_f = 4.39\ \Sigma\sigma^+ - 6.14$, $r^2 = 0.992$).[2,3] Consequently, slope parameters (ρ^+ and s_f) measure the same phenomenon.[6] Also, the origin of the substituent effects of E_f is the same as that which accounts for the magnitude of σ^+. However, the Hammett–Brown correlation is poor if it is applied to the unsymmetrically substituted benzhydryl and other α-R-diarylmethyl systems, due to nonadditivity and nonlinearity. Therefore, it is justified to use the s_f values instead of the ρ^+ for evaluation of the results obtained with benzhydryl substrates, particularly since excellent correlation have been obtained for all log*k* *versus* E_f plots studied.[1,2–5]

The outstanding feature of solvolysis of phenyl and methyl carbonates is that the slopes of the log *k* *versus* E_f plots (s_f) are generally lower than those of the corresponding chlorides, and they decrease as the fraction of the water in a given solvent/water mixture increases. Also, s_f parameters for the series of phenyl carbonates are lower than for the series of methyl carbonates (Table 1). On the other hand, correlations of numerous kinetic data for solvolysis of benzhydryl chlorides in different solvents give parallel linear plots with slopes of unity (Table 1) i.e., s_f

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Table 1. Solvolysis rate constants and activation parameters of some X,Y-substituted benzhydryl phenyl carbonates, methyl carbonates, 3,5-dinitrobenzoates, and chlorides in various solvents

Compound[a]	Solvent[b]	t (°C)	k (s^{-1})[c]	$\Delta H^{\ddagger}$ (kJ mol^{-1})[d]	$\Delta S^{\ddagger}$ (J K^{-1} mol^{-1})[d]
3-PhCarb	90E10W	15	$(2.33 \pm 0.01) \times 10^{-3,e}$	78.3 ± 0.3	-23.2 ± 1.0
		25	$(7.17 \pm 0.13) \times 10^{-3,e,g}$		
		35	$(2.08 \pm 0.01) \times 10^{-2,e}$		
4-PhCarb	90E10W	20	$(7.08 \pm 0.08) \times 10^{-4,e}$	85.6 ± 0.6	-13.1 ± 1.9
		25	$(1.27 \pm 0.03) \times 10^{-3,e,g}$		
		35	$(4.06 \pm 0.07) \times 10^{-3,e}$		
		40	$(7.10 \pm 0.00) \times 10^{-3,e}$		
5-PhCarb	90E10W	25	$(7.22 \pm 0.17) \times 10^{-5e,g}$	95.3 ± 0.5	-4.6 ± 1.6
		35	$(2.58 \pm 0.01) \times 10^{-4,e}$		
		40	$(4.83 \pm 0.11) \times 10^{-4,e}$		
		45	$(8.59 \pm 0.09) \times 10^{-4,e}$		
4-PhCarb	70E30W	15	$(1.51 \pm 0.03) \times 10^{-3,e}$	82.5 ± 0.3	-12.2 ± 1.1
		25	$(5.00 \pm 0.15) \times 10^{-3,e,g}$		
		35	$(1.51 \pm 0.03) \times 10^{-2,e}$		
5-PhCarb	70E30W	15	$(1.12 \pm 0.01) \times 10^{-4,e}$	92.8 ± 0.8	$+1.7 \pm 2.7$
		25	$(4.17 \pm 0.10) \times 10^{-4,e,g}$		
		35	$(1.48 \pm 0.01) \times 10^{-3,e}$		
1-MeCarb	90E10W	10	$(1.68 \pm 0.01) \times 10^{-3,e}$	73.0 ± 1.2	-39.7 ± 4.1
		15	$(3.00 \pm 0.07) \times 10^{-3,e}$		
		25	$(8.46 \pm 0.06) \times 10^{-3,e,f}$		
1-MeCarb	70E30W	10	$(5.27 \pm 0.00) \times 10^{-3,e}$	71.3 ± 0.9	-36.3 ± 3.2
		15	$(9.30 \pm 0.00) \times 10^{-3,e}$		
		20	$(1.56 \pm 0.01) \times 10^{-2,e}$		
		25	$(2.55 \pm 0.05) \times 10^{-2,e,f}$		
3-MeCarb	70E30W	25	$(1.53 \pm 0.05) \times 10^{-3,e,f}$	85.0 ± 0.3	-13.6 ± 0.8
		35	$(4.84 \pm 0.10) \times 10^{-3,e}$		
		45	$(1.41 \pm 0.03) \times 10^{-2,e,f}$		
1-DNB	90E10W	25	$(2.39 \pm 0.06) \times 10^{-2,e}$		
2-DNB		25	$(3.11 \pm 0.06) \times 10^{-3,e}$		
3-DNB	90E10W	25	$(8.83 \pm 0.07) \times 10^{-4,e}$	86.7 ± 0.4	-12.7 ± 1.2
		35	$(2.86 \pm 0.08) \times 10^{-3,e}$		
		45	$(8.48 \pm 0.17) \times 10^{-3,e}$		
4-DNB	90E10W	25	$(1.54 \pm 0.02) \times 10^{-4,e}$	87.6 ± 0.1	-24.0 ± 0.4
		40	$(8.82 \pm 0.10) \times 10^{-4,e}$		
		50	$(2.57 \pm 0.09) \times 10^{-3,e}$		
3-DNB	80E20W	25	$(1.98 \pm 0.05) \times 10^{-3,f,h}$	83.6 ± 0.4	-16.3 ± 1.1
		35	$(6.16 \pm 0.00) \times 10^{-3,f}$		
		45	$(1.76 \pm 0.04) \times 10^{-2,f}$		
4-DNB	80E20W	25	$(3.50 \pm 0.10) \times 10^{-4,f,h}$	87.4 ± 0.9	-18.0 ± 2.9
		45	$(3.51 \pm 0.06) \times 10^{-3,f}$		
		55	$(9.59 \pm 0.17) \times 10^{-3,f}$		
5-DNB	80E20W	50	$(4.87 \pm 0.10) \times 10^{-4,f}$	95.8 ± 0.9	-12.5 ± 2.8
		60	$(1.49 \pm 0.01) \times 10^{-3,f}$		
		70	$(4.13 \pm 0.06) \times 10^{-3,f}$		
1-DNB	80A20W	15	$(8.87 \pm 0.01) \times 10^{-4,e}$	82.7 ± 1.0	-16.0 ± 3.4
		25	$(2.99 \pm 0.03) \times 10^{-3,h}$		
		35	$(8.91 \pm 0.01) \times 10^{-3,e}$		
3-DNB	80A20W	30	$(2.14 \pm 0.01) \times 10^{-4,e}$	93.0 ± 0.2	-8.6 ± 0.8
		35	$(3.95 \pm 0.03) \times 10^{-4,e}$		
		42	$(9.00 \pm 0.14) \times 10^{-4,e}$		
		50	$(2.24 \pm 0.02) \times 10^{-3,e}$		
4-DNB		35	$(6.62 \pm 0.16) \times 10^{-5,e,h}$	94.7 ± 0.2	-17.8 ± 0.5
		45	$(2.19 \pm 0.03) \times 10^{-4,e,h}$		

(*Continues*)

Table 1. (Continued)

Compound[a]	Solvent[b]	t (°C)	k (s^{-1})[c]	$\Delta H^{\ddagger}$ ($kJ\,mol^{-1}$)[d]	$\Delta S^{\ddagger}$ ($J\,K^{-1}\,mol^{-1}$)[d]
		50	$(3.86 \pm 0.03) \times 10^{-4,e,h}$		
1-DNB	70A30W	25	$(6.35 \pm 0.08) \times 10^{-3,e}$		
2-DNB		25	$(7.25 \pm 0.10) \times 10^{-4,e}$		
3-DNB		25	$(2.82 \pm 0.03) \times 10^{-4,e}$		
4-DNB		25	$(5.60 \pm 0.02) \times 10^{-5,e}$		
1-DNB	60A40W	15	$(3.65 \pm 0.01) \times 10^{-3,e}$	82.5 ± 0.1	-5.0 ± 0.2
		25	$(1.20 \pm 0.02) \times 10^{-2,e}$		
		30	$(2.11 \pm 0.02) \times 10^{-3,e}$		
2-DNB	60A40W	25	$(1.52 \pm 0.03) \times 10^{-3,e}$		
3-DNB	60A40W	25	$(6.74 \pm 0.11) \times 10^{-4,e}$	87.1 ± 0.7	-13.5 ± 2.2
		35	$(2.14 \pm 0.01) \times 10^{-3,e}$		
		40	$(3.81 \pm 0.00) \times 10^{-3,e}$		
		45	$(6.66 \pm 0.08) \times 10^{-3,e}$		
		50	$(1.09 \pm 0.01) \times 10^{-2,e}$		
4-DNB	60A40W	25	$(1.38 \pm 0.02) \times 10^{-4,e}$	89.6 ± 0.0	-18.2 ± 0.1
		35	$(4.61 \pm 0.12) \times 10^{-4,e}$		
		45	$(1.43 \pm 0.00) \times 10^{-3,e}$		
5-Cl	90E10W	−10	$(3.65 \pm 0.01) \times 10^{-3}$	72.8 ± 0.6	-13.8 ± 2.2
		−7	$(5.23 \pm 0.00) \times 10^{-3}$		
		5	$(2.28 \pm 0.00) \times 10^{-2}$		
		8	$(3.27 \pm 0.09) \times 10^{-2}$		
5-Cl	80E20W	−15	$(7.17 \pm 0.01) \times 10^{-3}$	73.4 ± 0.5	-0.3 ± 2.0
		−5	$(2.64 \pm 0.04) \times 10^{-2}$		
		0	$(4.98 \pm 0.01) \times 10^{-2}$		
6-Cl				83.2 ± 0.5	-17.6 ± 1.8
5-Cl	80A20W	0	$(1.79 \pm 0.02) \times 10^{-3}$	72.1 ± 0.9	-32.9 ± 3.0
		10	$(5.53 \pm 0.15) \times 10^{-3}$		
		25	$(2.79 \pm 0.04) \times 10^{-2}$		

[a] Abbreviations defined in Scheme 1.

[b] Binary solvents are on a volume–volume basis at 25 °C. A = acetone, E = ethanol, W = water.

[c] Average rate constants from at least three runs at 25 °C and two runs at other temperatures. Errors shown are standard deviations.

[d] Errors shown are standard errors.

[e] Buffered with Proton sponge base [1,8-bis(dimethylamino)naphthalene].

[f] Buffered with 2,6-lutidine.

[g] From Reference [1].

[h] From Reference [2,3].

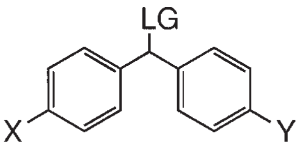
parameters seem independent of the solvent. Similarly, bromides also produce parallel log*k versus* E_f plots, but the slopes are slightly lower ($s_f = 0.95 \pm 0.03$; calculated from 12 entries).[4]

Generally a lower slope of Hammett plot in comparison to some reference S_N1 reaction has been rationalized in different ways: as an increase in the S_N2 character, as an earlier transition state due to relief of steric strain of tertiary derivatives, or as a neighboring group participation in the rate determining step.[7–13] Essentially, in all cases effects come from less positive charge on the reaction center in the transition state. According to above consideration, the same phenomena can account for lower s_f parameters.

The negative charge generated in heterolysis of phenyl and methyl carbonates is distributed almost equally over all three oxygen atoms because of the resonance and the negative (inverse) hyperconjugation effects.[1] Thus, for phenyl carbonate ion, the NBO charges at B3LYP/6-311++G(d,p) level are: −0.70, −0.73 for oxygen atoms involved in resonance, and −0.66 for that involved in inverse hyperconjugation (−0.80, −0.77, and −0.66 for methyl carbonate ion). Our first assumption was that lower slopes obtained in solvolysis of substituted benzhydryl phenyl and methyl carbonates than those of benzhydryl chlorides come from different solvation, due to dispersed negative charge generated in the transition state.

Finally, it should be mentioned that McLennan and Martin investigated the solvolytic behavior of various substituted benzhydryl *p*-nitrobenzoates in 50–80% aq. ethanol at 100 °C.[7] The corresponding ρ^+ values showed that the reaction constants were essentially invariant to the solvent change, i.e., almost parallel log *k versus* σ^+ plots were obtained (ρ^+ in the range between −3.18 and −3.11 in 80, 70, 60, and 50% aq. ethanol). Slight trends in decrease of ρ^+ values as the fraction of the water increases are in the limits of experimental error, so they cannot be taken as a valid prove of lack of the solvent influence.

In order to test systematically how the solvation of the LG influences the solvolytic behavior of substrates that produce carbocations which are highly stabilized by resonance, we carried out kinetic measurements with substituted benzhydryl phenyl carbonates, methyl carbonates, 3,5-dinitrobenzoates (DNB), and chlorides in various solvents. Also, our kinetic data obtained previously for substituted benzhydryl carbonates in numerous



LG = $C_6H_5OCO_2$ (PhCarb), CH_3OCO_2 (MeCarb), 3,5-dinitrobenzoate (DNB), chloride (Cl)

1: X = Y = MeO
2: X = MeO, Y = PhO
3: X = MeO, Y = Me
4: X = MeO, Y = H
5: X = Me, Y = Me
6: X = Y = H

Scheme 1.

solvents[1] were used to elucidate the influence of the LG on the reactivity of benzhydryl derivatives.

RESULTS

Electrofuges used here (**1**–**6**, Scheme 1) differ in reactivities up to six orders of magnitude (electrofugalities are as follow: $E_f(\mathbf{1}) = 0.00$, $E_f(\mathbf{2}) = -0.81$, $E_f(\mathbf{3}) = -1.29$, $E_f(\mathbf{4}) = -2.06$, $E_f(\mathbf{5}) = -3.47$, $E_f(\mathbf{6}) = -6.05$.[13] Benzhydryl DNBs were designed by selecting an appropriate benzhydryl electrofuge to enable measurements in the given solvents at 25 °C. Solvolysis rate constants of **1**–**5**-DNB were measured conductometrically at 25 °C in aqueous acetone and aqueous ethanol. Activation parameters of some substrates **1**–**5** with carbonates, DNB, and chloride as LGs in some solvents were determined from data collected at at least three different temperatures. Because of the problems with solubility of the substrates at lowered temperatures and with high reactivities at elevated temperatures, and also because of low solubility of the substrates in solvents with higher content of water, the activation parameters have not been determined for all possible combinations of the substrates and the solvents. The first order rate constants for solvolysis of substrates **1**–**5** and the corresponding activation parameters along with some reference data are presented in Table 2.

In order to calculate slope parameters (s_f) and the corresponding nucleofugality parameters (N_f) for DNB, the logarithms of the first-order rate constants (at 25 °C) measured here for **1**–**5**-DNB in a given solvent were plotted against E_f. Excellent linear correlations obtained in aqueous acetone and ethanol for DNB are presented in Fig. 1 ($r > 0.997$). In order to avoid overlaps, the plots measured in the least polar solvents are not presented in Fig. 1 (Supporting Information). The slopes of the log *k versus* E_f plots represent the s_f parameters of DNB in the given aqueous binary mixtures, while the negative intercepts on the abscissa correspond to its nucleofugality parameters, as defined in eqn (1). The nucleofuge specific parameters for DNB are presented in Table 1 along with some referent values obtained earlier with PhCarb, MeCarb, and chlorides.[1] The results show that the slope parameters s_f for DNB are decreased as the fraction of the water in the binary solvent increases in a similar manner as those for carbonates.

DISCUSSION

It has been demonstrated repeatedly that the different extent of solvation of the transition state, due to dispersal of a positive charge in the electrofuge[14–16] or a negative charge in the LG, influences the solvolytic behavior.[17–23] In order to study the

Table 2. Nucleofuge specific parameters (N_f and s_f) for 3,5-dinitrobenzoate (DNB), and s_f parameters for phenyl carbonate (PhCarb) and methyl carbonate (MeCarb) in various solvents at 25 °C

	DNB		PhCarb	MeCarb	Cl
Solvent[a]	s_f^b	N_f^b	s_f^c	s_f^c	s_f^c
100E	1.10 ± 0.03[c]	−2.04 ± 0.09[c]	0.98 ± 0.02	1.15 ± 0.04	1.00
90E10W	1.07 ± 0.02	−1.53 ± 0.06	0.93 ± 0.02	1.04 ± 0.02	0.98 ± 0.01
80E20W	0.99 ± 0.02[c]	−1.43 ± 0.04[c]	0.87 ± 0.02	0.99 ± 0.02	0.98 ± 0.01
70E30W			0.83 ± 0.02	0.94 ± 0.03	0.96 ± 0.04
60E40W			0.79 ± 0.02	0.90 ± 0.04	0.97 ± 0.06
50E50W			0.76 ± 0.06	0.87 ± 0.06	
90A10W	1.18 ± 0.02[c]	−2.57 ± 0.04[c]			0.99 ± 0.01
80A20W	1.07 ± 0.03[c]	−2.39 ± 0.11[c]	0.96 ± 0.00		1.02 ± 0.01
70A30W	0.99 ± 0.05	−2.27 ± 0.18	0.85 ± 0.02	0.97 ± 0.09	0.99 ± 0.01
60A40W	0.93 ± 0.05	−2.12 ± 0.18	0.80 ± 0.02	0.92 ± 0.01	0.98 ± 0.02

[a] Binary solvents are v/v; A = acetone, E = ethanol, W = water.
[b] Data from Reference [1].
[c] Data from Reference [2,3].

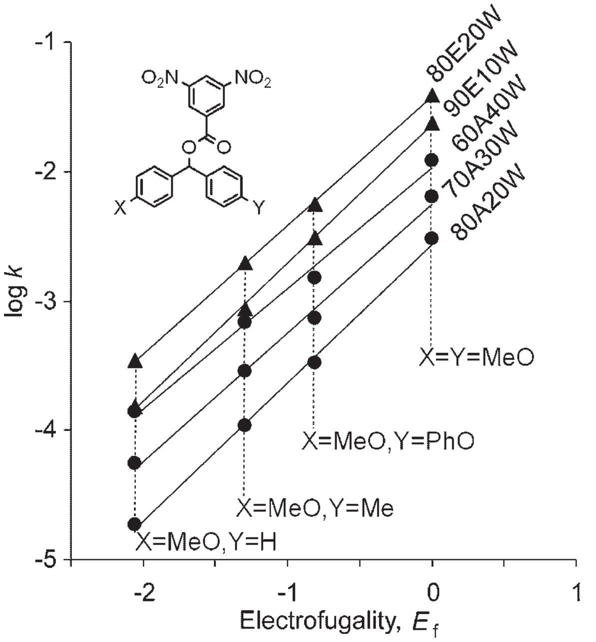


Figure 1. Plots of log*k* (25 °C, from Table 2) *versus* E_f for the solvolysis reactions of X,Y-substituted benzhydryl 3,5-dinirobenzoates in aqueous acetone and aqueous ethanol

effects of simultaneous solvation of the LG and the benzhydryl electrofuge, solvolytic behavior of benzhydryl chlorides have been compared with behavior of other benzhydryl derivatives. In chlorides the developed negative charge in the TS is concentrated only on chloride atom. In benzhydryl 3,5-dinitrobenzoates (**1**–**5**-DNB) the negative charge is delocalized to two carboxylate oxygen atoms by resonance, and to two nitro groups on the phenyl ring by negative inductive effect. In benzhydryl phenyl carbonate (**1**–**5**-PhCarb) and benzhydryl methyl carbonates (**1**–**5**-MeCarb), as mentioned above, intense charge delocalization occurs to three oxygen atoms.

Analysis of the log *k* versus E_f plots

The major factor controlling variation of rate with solvent composition of the reference chlorides is the solvation of the developing chloride ion, regardless of the barrier of the heterolysis reaction, i.e., shifts of transition states toward reactants in faster reactions do not diminish the importance of the solvation. Since the chloride solvation is much more important than the solvation of the substituted benzhydrylium ion because of the charge delocalization in the latter, the changes of the water content have a similar effect on the reactivity for all substrates, so parallel log *k versus* E_f plots are obtained, i.e., same s_f parameters in all solvents used.[4]

Even though consistent explanation of dependence between the solvent polarity and s_f is lacking, two major factors can be considered to influence the reaction constant (s_f): the degree of the charge separation (earlier or later transition state) and the degree of the charge delocalization which mainly determines the importance of solvation. Clear differentiation between those two influences is difficult, since the net effect is combination of both. As mentioned above, the negative charge in carbonate anions and in DNB anion is delocalized, so the charge delocalization occurs simultaneously in both parts of the activated complex, an electrofuge and a nucleofuge, while in chlorides only the generating positive charge is delocalized, and the negative is concentrated on relatively small chloride ion. Because of less pronounced solvation, the solvolysis rate constants of carbonates and DNBs increase less with increasing electrofugality than those of chlorides. The net effect is lower s_f in all solvents (the exceptions are the s_f values for methyl carbonate and DNB in the least polar solvents).

Why would the log *k versus* E_f slopes (s_f) decrease when the fraction of the water in the binary solvent increases? While for the series of benzhydryl chlorides small differences in solvation of the electrofuge are negligible due to strong solvation of the chloride ion, for the series of substrates in which delocalization occurs also in the nucleofuge, different solvation of the electrofuge is important. Increasing electrofugality in the series of given benzhydryl derivatives (carbonates or DNBs) comes from more extensive positive charge delocalization and thus less stabilization of the activated complex by more polar solvent. On the other hand, in the case of benzhydryl substrates with weaker electrofuges, the solvation has more influence on the reactivity since the positive charge is less dispersed. Thus, in the solvent with a higher fraction of water (more polar solvent) rate enhancement becomes less strong if the substrate have a stronger electrofuge than that with a weaker electrofuge, and the result is a lower log *k versus* E_f slope (s_f) in a more polar solvent. This consideration is in accord with experimental findings. For example, the ratio between the solvolysis rates constants of benzhydryl carbonate **5**-PhCarb ($E_f = -3.46$) in 60% aq. ethanol and 90% aq. ethanol is 11.8, while that of **3**-PhCarb ($E_f = -1.29$) in the same solvents is only 5.7.[1]

Because of similar structures of phenyl and methyl carbonates, the influence of the charge delocalization and of charge separation on s_f values may be analyzed separately. The reaction constants shown in Table 1 indicate that the s_f values for the series of phenyl and methyl carbonates decrease for almost the same amount if the water content increases. For example, if

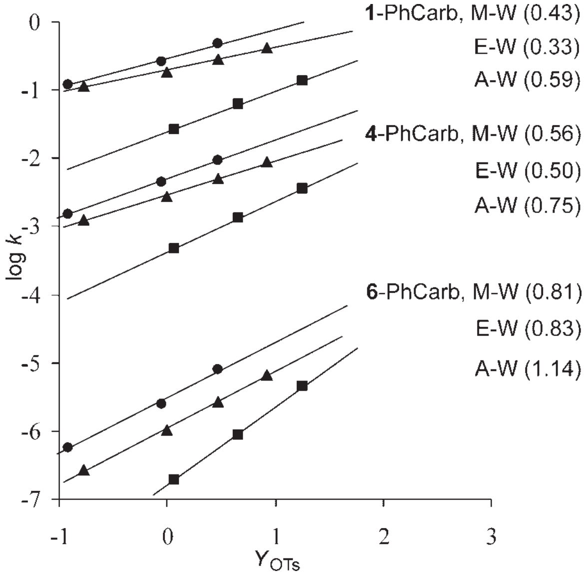


Figure 2. Correlation plots of log *k versus* Y_{OTs} for solvolysis of (a) benzhydryl phenyl carbonates **1**-Phcarb, **4**-PhCarb, and **6**-PhCarb and in binary aqueous solvents (v/v); solvents: W = water, E = ethanol, M = methanol, A = acetone; *m* values are given in parentheses (abbreviations defined in Scheme 1)

Table 3. Values of *m* parameters from Grunwald–Winstein correlations for solvolysis of X,Y-substituted benzhydryl phenyl carbonates (PhCarb), methyl carbonates (MeCarb), 3,5-dintirobenzoates (DNB), and chlorides, and the corresponding critical electrofugalities E_f^{crit}

			m						
Leaving group	Solvent[a]	Scale	**1**	**2**	**3**	**4**	**5**	**6**	E_f^{crit} [b]
PhCarb	E-W	Y_{Cl}	0.24[d]		0.33	0.36	0.46	0.60[d]	4.1
		Y_{OTs}	0.33[d]		0.45	0.50	0.64	0.83[d]	4.0
									4.0 ± 0.0[c] (≈4.0)
	A-W	Y_{Cl}	0.45[d]		0.53	0.57	0.70	0.87[d]	6.2
		Y_{OTs}	0.59[d]		0.70	0.74	0.92	1.14[d]	6.2
									6.2 ± 0.0[c] (≈6.0)
MeCarb	E-W	Y_{Cl}	0.29	0.30	0.39	0.41		0.65[d]	4.7
		Y_{OTs}	0.40	0.42	0.53	0.55		0.89[d]	4.7
									4.7 ± 0.0[c] (≈4.7)
	A-W	Y_{Cl}	0.52		0.59			0.93[d]	7.6
		Y_{OTs}	0.69		0.78			1.22[d]	7.6
									7.5 ± 0.1[c] (≈7.5)
DNB	E-W	Y_{Cl}	0.34	0.35	0.41	0.42	0.48	0.58	(≈2.9)
		Y_{OTs}	0.43	0.45	0.53	0.53	0.62	0.75	
	A-W	Y_{Cl}	0.33	0.36	0.44	0.48	0.59[f]	0.79[f]	4.2
		Y_{OTs}	0.37	0.40	0.49	0.54	0.66[f]	0.88[f]	4.2
									4.2 ± 0.0[c] (≈4.2)
Cl	E-W	Y_{Cl}	0.53[e]					0.59[e]	
		Y_{OTs}	0.72[e]					0.79[e]	
	A-W	Y_{Cl}	0.91[e]					0.92[e]	

[a] Binary solvents are v/v at 25 °C; A = acetone, E = ethanol, W = water.

[b] Abscissa of the *m versus* E_f plot where $m = 0$.

[c] Value of the average E_f^{crit} ± SD obtained from seven different scales (Supporting Information); the approximative values E_f^{crit} given in parentheses are derived from intersections of log *k versus* E_f plots in given binary mixture.

[d] Rate constants employed in Grunwald–Winstein correlations were calculated from eqn (1) by using N_fs and s_f for carbonates given in Reference [1] and E_fs given in References [2,3].

[e] Rate constants employed in Grunwald–Winstein correlations were calculated by using N_fs and s_f for chlorides given in Reference [4].

[f] Rate constants employed in Grunwald–Winstein correlations were calculated from eqn (1) by using N_fs and s_f for 3,5-dinitrobenzoates (Table 1).

switching from 90% aq. ethanol to 60% aq. ethanol, s_f is decreased for the same value for both series of carbonates ($\Delta s_f = 0.14$; $\Delta s_f = 0.10$ and 0.11, respectively when switching from 80% to 60% aq. acetone). This phenomenon could be the consequence of negative charge delocalization, since in both LGs the charge is mainly distributed to three oxygen atoms.[1] On the other hand, consistently smaller s_f values for phenyl carbonates than for methyl carbonates for each solvent is likely to come from less charge separation in the TS, which is in accord with greater reactivity of phenyl carbonates.

Even though the influence of the negative charge delocalization and the charge separation in TS on the importance of solvation cannot be differentiated for the series of benzhydryl DNBs, the trends in s_f values in the series of a given organic solvent with various water contents, indicate that diminished solvation occurs in the TS in a similar manner as for benzhydryl methyl carbonates.

The above conclusions have been drawn by analyzing the kinetic data for the series of benzhydryl derivatives in a given solvent. In order to provide further support about the importance of solvation in the LG for benzhydryl substrates, we used a different approach and analyzed the solvolytic behavior of a single substrate separately in the series of organic solvents/water mixtures.

Analysis of the logk versus Y plots

Using various solvent ionizing power scales we plotted log *k* of **1**–**6**-LG *versus* *Y* values from various ionizing power scales (Y_{Cl}, Y_{Br}, Y_{OTs}, Y_{BnCl}, Y_{xBnCl}, Y_{xBnBr}, Y)[24–28] (Supporting Information). It should be pointed out that all kinetic data are obtained in the organic-rich solvents in which linear relationship between log *k* and *Y* exists.[29]

It has been reported repeatedly that kinetic data obtained in different types of solvents cannot be treated with a single line expressed by the Grunwald–Winstein equation because of dispersion of the data, but the rates in each binary aqueous solvent pair should be treated separately.[17–19,25,30–32] This phenomenon was proposed to be mainly a consequence of differential solvation, electrophilic solvent assistance, and also of different extent of ion-pair return in different binary systems.[18,30–33] Figure 2 shows the lines obtained by plotting the logarithms of solvolysis rates constants (experimental or calculated by eqn 1) of **1**-Phcarb, **4**-PhCarb, and **6**-PhCarb against Y_{OTs} (for correlation parameters for carbonates and DNBs refer to Supporting Information). Basically equally good correlations for separated lines were obtained regardless which solvent ionizing power scale was used. Table 3 presents the *m* values for methyl and phenyl carbonates, DNBs, and chlorides derived log *k versus* Y_{Cl} and log *k versus* Y_{OTs} plots (for complete correlation analyses and other details refer to Supporting Information).

As expected, all *m* values for benzhydryl carbonates and DNBs with better electrofuges are lower than those for chlorides (Table 3), indicating lower sensitivity of these substrates for the solvent change.

Low *m* values have usually been coupled with relatively positive $\Delta S^{\ddagger}$, as was demonstrated for 2-adamantyl perchlorate and 1-adamantyl picrate.[20–22] However, $\Delta S^{\ddagger}$ values obtained with benzhydryl carbonates and DNBs are not considerable more positive than those for chlorides. This might be due to more restricted internal motion in the transition states than in the ground state of the benzhydryl system, which is not the case with, for example, the rigid adamantyl system. The reaction rates of carbonates and DNBs are mostly determined with the magnitude of $\Delta H^{\ddagger}$, while no obvious correlations between the reaction rates and $\Delta S^{\ddagger}$ could be found. The same was observed earlier for solvolysis of substituted benzhydryl chlorides.[34–37]

Table 3 shows that the *m* values for carbonates and DNBs decrease as the electron donating ability of the substituted benzhydryl ring increases, while those of chlorides are essentially the same. The lower sensitivity of the substrates with better electrofuges toward solvent polarity is consistent with the above conclusions based on the log *k versus* E_f plots.

In order to provide independent support that the substrates are less sensitive to change of the solvent polarity if the charge is more delocalized, we plotted the *m* parameters obtained for the series of phenyl carbonates (**1**–**6**-PhCarb), methyl carbonates (**1**–**6**-MeCarb), and 3,5-dinitrobenzaotes (**1**–**5**-DNB) in a given aqueous binary solvent series, against the corresponding electrofugalities (E_f), since for benzhydryl system the charge delocalization is closely related to electrofugality. Correlations of *m versus* E_f have been performed with *m* parameters derived from seven different solvent-ionizing power scales.

Lines (*m vs.* E_f) show good correlations regardless to the ionizing power scale used for calculating the *m* parameter. Figure 3 presents the m_{OTs} *versus* E_f correlation lines for phenyl carbonates and DNBs in aqueous ethanols and/or aqueous acetones (for other correlations refer to Supporting Information).

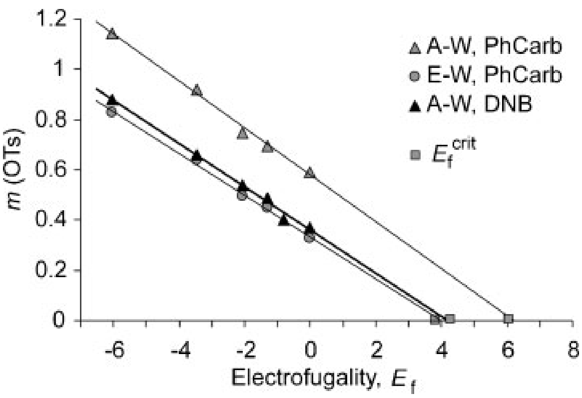


Figure 3. Correlation plots of *m* (obtained in log *k vs.* Y_{OTs} correlation) *versus* E_f in binary aqueous solvents (solvents: W = water, E = ethanol, M = methanol, A = acetone)

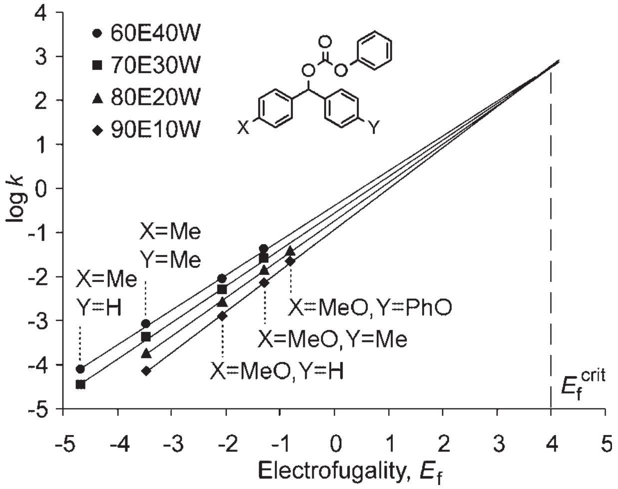


Figure 4. Extrapolated log *k* (25 °C) *versus* E_f correlation plots for the solvolysis of phenyl carbonates in aqueous ethanol (v/v; W = water, E = ethanol)

At one point the extrapolated *m versus* E_f plots reach $m = 0$. Abscissa at that point indicates the critical electrofugality value E_f^{crit} at which the solvolysis rate of a given benzhydryl derivative in a given series binary solvent mixture should not depend on the water content. Such derivatives are those with highly stabilized electrofuges.

Extrapolated critical electrofugality values from two *m versus* E_f correlations (*m* derived from log *k versus* Y_{Cl} and log *k versus* Y_{OTS} plots) are summarized in Table 3 (for others refer to Supporting Information). Regardless which ionizing power scale has been used for derivation of the *m* parameter, essentially the same results for the extrapolates critical electrofugality are obtained.

To verify the existence of the extrapolates critical electrofugality established by analyzing *m versus* E_f plots, we have returned to analyze log *k versus* E_f plots based on eqn (1). The extrapolated log *k versus* E_f plots constructed for a given LG (PhCarb, MeCarb, or DNB) in a given binary solvent system intersect in a certain interval of E_f. Assuming that log *k versus* E_f plots are still linear in the extrapolated region, abscissa above this interval indicates that the solvolysis of a benzhydryl substrate with a given electrofugality in a given binary solvent mixture series system should not depend on the water content, which concept corresponds to above-established critical electrofugality E_f^{crit} based on the intersection of the extrapolated *m versus* E_f lines. Figure 4 shows the extrapolated plots that correspond to phenyl carbonates in aqueous ethanol. Extrapolates E_f^{crit} derived from extrapolated *k versus* E_f plots for phenyl and methyl carbonates and DNBs in all series of solvents measured are presented in Table 3 (for the extrapolated plots refer to Supporting Information). It is rather outstanding that the extrapolated E_f^{crit} derived from *m verus* E_f plots and that derived from log *k versus* E_f plots are practically the same (Table 3 and the Supporting Information). It should be mentioned that if instead of assuming the model with linear behavior of log *k versus* E_f plots in the region of high electrofugality, the curved plots that approach an asymptote are considered (also for *m vs.* E_f plots), the concept of existance of critical electrofugality is unchanged, only the values of E_f^{crit} may be slightly shifted toward higher values.

The values of the critical electrofugalities for phenyl carbonate are consistently lower than for methyl carbonate in all aqueous binary mixture systems. The lowest E_f^{crit} is obtained for DNB in aqueous acetone.

CONCLUSION

Benzhydryl derivatives in which substantial simultaneous delocalization of the positive charge in the benzhydryl moiety and the negative charge in the LG occur in the TS, generally have lower reaction constants (s_f) than the compounds that lack the LG which can delocalize the evolving negative charge. For such substrates the reaction rate is enhanced less strong if the polarity of the solvent of the given binary mixture is increased (higher fraction of water), causing decrease of s_f values. Compounds that show the above phenomena are X,Y-substituted benzhydryl phenyl and methyl carbonates and X,Y-substituted benzhydryl 3,5-dinitrobenzoate.

Because of the decreasing slopes of log *k versus* E_f plots with increasing water content in the binary organic/aqueous solvent, the extrapolated plots intersect in the narrow range and the abscissa of that extrapolated intersection indicates the critical electrofugality E_f^{crit}. It seems that if the electrofugality of benzhydryl derivative is above the critical electrofugality E_f^{crit}, its solvolysis rate may be independent on the water content, at least in solvents rich in organic component. To design such substrates, the extended electrofugality scale is needed and also the critical E_f^{crit} for a given LG. Nevertheless, it might be predicted that the ethanolysis rate of benzhydryl phenyl carbonate with $E_f \approx 3$ depends only marginally on the fraction of water, while that of the corresponding benzhydryl DNB still reacts with unchanged rate in all ethanol/water mixtures.

EXPERIMENTAL SECTION

Substrate preparation

4,4′-Dimethoxybenzhydryl 3,5-dinitrobenzoate (**1**-DNB), 4-methoxy-4′-phenoxybenzhydryl 3,5-dinitrobenzoate (**2**-DNB), 4-methoxy-4′-methylbenzhydryl 3,5-dinitrobenzoate (**3**-DNB), 4-methoxybenzhydryl 3,5-dinitrobenzoate (**4**-DNB), and 4,4′-dimethylbenzhydryl 3,5-dinitrobenzoate (**2**-DNB) were prepared from the parent benzhydrols and 3,5-dinitrobenzoyl chloride in the presence of pyridine in dry benzene solution according to procedure presented in details in Reference [2,3]. ^{1}H NMR and ^{13}C NMR spectra are presented in the Supporting Information.

4-Methoxy-4′-methylbenzhydryl phenyl carbonate (**3**-PhCarb), 4-methoxybenzhydryl phenyl carbonate (**4**-PhCarb), and 4,4′-dimethylbenzhydryl phenyl carbonate (**5**-PhCarb) were prepared from the parent benzhydrol and phenyl chloroformate in the presence of pyridine in dry benzene. 4,4′-Dimethoxy--Dimethoxybenzhydryl methyl carbonate (**1**-MeCarb) and methoxy-4′-methylbenzhydryl methyl carbonate (**3**-MeCarb) were prepared from the parent benzhydrol and methyl chloroformate. Detailed procedures are given in Reference [1].

Kinetic methods

Solvents were purified and dried according to the standard procedures. Solvolysis rate constants at various temperatures (±0.05 °C) were measured conductometrically. Typically, 10–40 mg of substrate was dissolved in 0.10 ml of dichloromethane and injected into the fresh mixed aqueous solvent. Increase of conductivity during solvolysis was monitored automatically by means of WTW LF 530 conductometer using Pt electrode LTA 1/NS. Individual rate constant were obtained by the least squares fitting of the conductivity to the first order kinetic equation for 3–4 half-lives. Rate constants at 25 °C were averaged from at least three measurements, while the rate constants at higher and lower temperatures are obtained from at least two measurements.

Liberated weak acids (3,5-dinitrobenzoic, phenyl carbonic, and methyl carbonic) were ionized by addition of the proton sponge base [1,8-bis-(dimethylamino)naphthalene]. Calibration showed a linear response of the conductivity toward concentrations of liberated 3,5-dinitrobenzoic acid in the presence of a base. The ranges of concentrations for each given aqueous binary mixture for DNBs are presented in Table 4.

Some rate constants for solvolysis DNBs in 80% ethanol were taken from the Reference [2,3]. In order to keep experimental conditions unchanged, kinetic measurements with DNBs in 80% ethanol in this work were also performed in the presence of 2,6-lutidine. Test measurement with the proton sponge base conformed that in 80% ethanol the rate constants obtained in the presence of 2,6-lutidine and those obtained in the presence of the proton sponge base were all within the range of the experimental error. However, it turned out that in less polar solvents, 2,6-lutidine did not dissociate the liberated 3,5-dinitobenzoic acid completely. Therefore, solvolysis rates of DNBs in other solvents were measured in the presence of the proton sponge base. Test measurements were carried out

Table 4. Experimental initial concentrations of the substrates and the bases for solvolysis of the substituted 3,5-dinitrobenzoates

Solvent[a]	Base[b]	c_0(DNB), (mM)	c_0(Base), (mM)	c_0(Base)/c_0(DNB)
90E10W	PSB	2.3–3.8	15.6–31.2	5.0–10.0
80E20W	Lutidine	1.6–3.5	8.0–12.0	3.0–7.0
80A10W	PSB	1.6–2.7	10.9–15.6	4.5–6.8
70A30W	PSB	1.9–2.5	12.5–18.7	5.0–8.0
60A40W	PSB	1.5–2.5	3.1–6.2	2.0–4.0

[a] Binary solvents are on a volume–volume basis at 25 °C. A = acetone, E = ethanol, W = water.
[b] PSB = proton sponge base [1,8-bis(dimethylamino)naphthalene].

titrimetrically. Details and ranges of base concentration for phenyl and methyl carbonates are given in Reference [1], Table 6.

SUPPORTING INFORMATION

Correlation analyses of solvolyses of substituted benzhydryl carbonates and chlorides, correlations of *m* values with electrofugality parameters E_f, corresponding critical electrofugality values.

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