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Nucleofugality of Pentafluorophenolate in Various Solvents: Solvolytic Behavior of Phenolates

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Abstract: The leaving group ability (nucleofugality) of the pentafluorophenolate anion has been determined from first order solvolytic rate constants (k) of X,Y-substituted benzhydryl pentafluorophenolates measured in a series of solvents, by using the three parameter LFER equation: log k = s1(Ef + Nf). Comparison with other leaving groups reveals that pentafluorophenolate is a moderate leaving group, whose nucleofugality (Nf value) is between the nucleofugalities of phenyl carbonate and 3,5-dinitrobenzoate leaving groups. However, due to its high reaction constant (s1 = 1.29 in 80 % aq. ethanol), relative reactivities of benzhydryl pentafluorophenolates and corresponding benzhydryl carbonates vary with the electrofugality of a carbocation formed in the heterolytic step, i.e., inversion of the reactivity of benzhydryl series with different leaving groups occurs. The plots of ΔG° vs. ΔG° for solvolysis of benzhydryl phenolates and carbonates reveal that phenolates solvolyzes over the lower Marcus intrinsic barrier than corresponding carbonates.

Keywords: nucleofugality, leaving group, LFER, phenolate, intrinsic barrier, solvolysis.

INTRODUCTION

The reactivity of leaving groups (nucleofugality) has a crucial influence on the rate of the heterolytic bond cleavage, which is the slow step of numerous organic reactions. Consequently, this topic is well-represented in most general textbooks on organic chemistry as well as of mechanistically oriented textbooks. For comparing the reactivities of various leaving groups, their abilities are, by a general qualitative rule of thumb, arranged in the same order as the acidities of their conjugate Brønsted acids. The basic shortcoming of such approach is that the variability of the intrinsic barriers in heterolysis of substrates with different types of leaving groups is neglected. Furthermore, such comparison does not have any practical application as the reactivity of leaving groups is not quantified.

In order to develop a comprehensive leaving group ability scale, which would be limited by using a single type of substrate, an electrofugality scale based on 39 benzhydrylium carbocations that covers 18 orders of magnitude in reactivity has been established. Employing that scale and Equation (1), which represents LFER, abilities of structurally diverse leaving groups have been determined in the range of 12 orders of magnitude in a particular solvent. In this equation, the contributions of an electrofuge (alkyl/aryl part of a substrate that in heterolytic process gives carbocation) and a nucleofuge to the overall solvolytic reactivity of a substrate are separated. This approach enables the main practical application of the scales, the estimation of reactivities of substrates constituted from any combination of an electrofuge and a nucleofuge in a given solvent at 25 °C.

Parameters in Equation (1) are: the solvolytic rate constant of a substrate at 25 °C (k), the nucleofugality-specific parameters Nf (nucleofugality; the negative intercept on the abscissa of the log k vs. Ef correlation line) and s1 (the slope of the correlation line), and the electrofugality parameter Ef (the independent variable that quantifies the solvolytic reactivity of a certain electrofuge). The nucleofugel-specific parameters for the certain combination of a leaving group and a solvent can be determined from the log k vs. Ef correlation line using solvolytic rate constants in a given solvent of a series of benzhydrylium derivatives and the reference Ef values.
In this LFER model, influences of solvation effects are associated to nucleofugality only, defined by two nucleofuge-specific parameters ($N_i$ and $s_i$), which specify the reactivity of some leaving group in a given solvent.\cite{9} In fact, the $N_i$ parameter determines the basic reactivity of the certain leaving group/solvent combination, while the reaction constant ($s_i$ parameter) varies within a limited range and slightly decreases as reactivity of leaving groups increases.\cite{10}

In our previous study, we have investigated the solvolytic behavior of the series of benzhydryl 2,4-dinitrophenolates and observed that the log $k/E_i$ lines that belong to 2,4-dinitrophenolate and phenyl carbonate are approaching each other as electrofugality decreases, and, finally intersect after a short extrapolation in experimental region of reactivity.\cite{3} This means that the relative reactivities of some pair of leaving groups depend on electrofuges, and more importantly, that inversion of their reactivities can occur. This case additionally demonstrate flaws in determining relative reactivities of leaving groups based on the rate constants for substrates with a common electrofuge. In this study we have examined the solvolytic behavior and nucleofugality of another phenolate leaving group, pentafluorophenolate, and compared the results with the ones obtained previously for carboxylates,\cite{11} in order to examine the inversion of relative reactivities of leaving groups with variation of the electrofuges and also to rationalize such phenomena.

## EXPERIMENTAL

### Substrate Preparation

4,4'-Dimethyldihydroxybenzyl (1.0 g; 4.4 mmol), potassium (0.17 g; 4.6 mmol), and hexafluorobenzene (0.87 g; 4.7 mmol); yield 0.98 g, 54.7 %; \textsuperscript{1}H NMR (300 MHz, CDCl\textsubscript{3}, 20 °C): $\delta$/ppm = 3.74 (s, 3H; ArOCH\textsubscript{3}); 6.30 (s, 1H; ArCH\textsubscript{3}); 6.81 (d, $J = 8.8$ Hz, 2H; ArH); 7.11–7.16 (m, 7H; ArH); \textsuperscript{13}C NMR (150 MHz, CDCl\textsubscript{3}, 20 °C): $\delta$/ppm = 122.9 (Ar); 135.1, 159.6, 163.8 (Ar); 68.0 (ArOCH\textsubscript{3}); 153.5, 154.8 (Ar); 131.2–137.4 (m, 3H; ArH); \textsuperscript{19}F NMR (282 MHz, CDCl\textsubscript{3}, 20 °C): $\delta$/ppm = −156.1 (t, $J_{FF}$ = 44.1 Hz, 1F; FAr); −163.6 (t, $J_{FF}$ = 41.0 Hz, 2F; FAr).

4-Methoxybenzhydryl Pentafluorophenyl Ether. It was prepared as pale-yellow oil, according to the procedure described for 4,4'-dimethyldihydroxybenzyl pentafluorophenyl ether, from 4-methoxybenzhydryl (1.0 g; 4.6 mmol), potassium (0.17 g; 4.6 mmol), and hexafluorobenzene (0.87 g; 4.7 mmol); yield 0.98 g, 54.7 %; \textsuperscript{1}H NMR (300 MHz, CDCl\textsubscript{3}, 20 °C): $\delta$/ppm = 3.74 (s, 3H; ArOCH\textsubscript{3}); 6.30 (s, 1H; ArCH\textsubscript{3}); 6.81 (d, $J = 8.8$ Hz, 2H; ArH); 7.11–7.16 (m, 7H; ArH); \textsuperscript{13}C NMR (150 MHz, CDCl\textsubscript{3}, 20 °C): $\delta$/ppm = 122.9 (Ar); 135.1, 159.6, 163.8 (Ar); 68.0 (ArOCH\textsubscript{3}); 153.5, 154.8 (Ar); 131.2–137.4 (m, 3H; ArH); \textsuperscript{19}F NMR (282 MHz, CDCl\textsubscript{3}, 20 °C): $\delta$/ppm = −156.1 (t, $J_{FF}$ = 44.1 Hz, 1F; FAr); −163.6 (t, $J_{FF}$ = 41.0 Hz, 2F; FAr).

4-Methoxy-4'-Methoxybenzhydryl Pentafluorophenyl Ether. It was prepared as pale-yellow oil, according to the procedure previously described, from 4-methoxy-4'-methyldihydroxybenzyl (1.0 g; 4.4 mmol), potassium (0.17 g; 4.4 mmol), and hexafluorobenzene (0.82 g; 4.4 mmol); yield 0.85 g, 57.6 %; \textsuperscript{1}H NMR (300 MHz, CDCl\textsubscript{3}, 20 °C): $\delta$/ppm = 3.74 (s, 3H; ArOCH\textsubscript{3}); 6.30 (s, 1H; ArCH\textsubscript{3}); 6.81 (d, $J = 8.8$ Hz, 2H; ArH); 7.11–7.16 (m, 7H; ArH); \textsuperscript{13}C NMR (150 MHz, CDCl\textsubscript{3}, 20 °C): $\delta$/ppm = 122.9 (Ar); 135.1, 159.6, 163.8 (Ar); 68.0 (ArOCH\textsubscript{3}); 153.5, 154.8 (Ar); 131.2–137.4 (m, 3H; ArH); \textsuperscript{19}F NMR (282 MHz, CDCl\textsubscript{3}, 20 °C): $\delta$/ppm = −156.1 (t, $J_{FF}$ = 44.1 Hz, 1F; FAr); −163.6 (t, $J_{FF}$ = 41.0 Hz, 2F; FAr).

4-Methoxy-4'-Phenoxymethyldihydroxybenzyl Pentafluorophenyl Ether. This compound was prepared according to the procedure previously described, from 4-methoxy-4'-methyldihydroxybenzyl (1.0 g; 4.4 mmol), potassium (0.17 g; 4.4 mmol), and hexafluorobenzene (0.82 g; 4.4 mmol); yield 0.85 g, 57.6 %; \textsuperscript{1}H NMR (300 MHz, CDCl\textsubscript{3}, 20 °C): $\delta$/ppm = 3.74 (s, 3H; ArOCH\textsubscript{3}); 6.30 (s, 1H; ArCH\textsubscript{3}); 6.81 (d, $J = 8.8$ Hz, 2H; ArH); 7.11–7.16 (m, 7H; ArH); \textsuperscript{13}C NMR (150 MHz, CDCl\textsubscript{3}, 20 °C): $\delta$/ppm = 122.9 (Ar); 135.1, 159.6, 163.8 (Ar); 68.0 (ArOCH\textsubscript{3}); 153.5, 154.8 (Ar); 131.2–137.4 (m, 3H; ArH); \textsuperscript{19}F NMR (282 MHz, CDCl\textsubscript{3}, 20 °C): $\delta$/ppm = −156.1 (t, $J_{FF}$ = 44.1 Hz, 1F; FAr); −163.6 (t, $J_{FF}$ = 41.0 Hz, 2F; FAr).
4,4'-Dimethoxybenzhydryl Pentafluorophenyl Ether. Freshly cut potassium (0.16 g; 4.1 mmol) was added to the previously prepared stirring solution of the 4,4'-dimethoxybenzhydryl (1.0 g, 4.1 mmol) in anhydrous tetrahydrofurane (15 ml), and the solution was heated 5 hours under an atmosphere of argon. After that, excess of the potassium was removed and the solution of hexafluorobenzene (0.76 g, 4.1 mmol) in tetrahydrofurane (10 ml) was added dropwise with vigorously stirring, and the reaction mixture was heated further for 30 min. A brown precipitate was filtered off and then 15 ml of benzene was added in the solution. The organic layer was then washed with water (3 x 15 ml) and dried over anhydrous sodium sulfate. The solvent was removed in vacuo and the residue was then left in a freezer with 10 ml of hexane for 12 h. After removal of white crystals, 0.90 g of pale-yellow oil was obtained (49.0 %); 1H NMR (400 MHz, CDCl3, 20 °C): δ/ppm = 3.79 (s, 6H; Ar–OCH3), 6.29 (1H; Ar–CH3), 6.86 (d, J = 8.8 Hz, 4H; ArH), 7.32 (d, J = 8.7 Hz, 4H; ArH); 13C NMR (150 MHz, CDCl3, 20 °C): δ/ppm = 55.4 (ArOCH3), 86.8 (Ar–CH3), 114.0, 128.8, 131.9, 159.8 (Ar); 19F NMR (282 MHz, CDCl3, 20 °C): δ/ppm = −154.4 (d, JFF = 25.4 Hz, 1F; F1Ar), −163.1 (t, JFF = 44.1 Hz, 1F; F1Ar), −163.8 (t, JFF = 40.1 Hz, 2F; F1Ar).

Kinetic Methods

Solvolysis rate constants were measured conductometrically. Freshly prepared solvents (30 ml) were thermostated (± 0.1 °C) at a given temperature for several minutes prior to addition of a substrate. 20–40 mg of a substrate was dissolved in 0.10 mL of dichloromethane and injected into a solvent. An increase of the conductivity during solvolysis was monitored automatically by means of the WTW LF 530 conductometer, using the Radiometer Z-pole Conductivity Cell (CDC641T). Individual rate constants were obtained by least-squares fitting of the conductivity data to the first-order kinetic equation for 3–4 half-lives. The rate constants were averaged from at least three measurements. In order to achieve a complete ionization of a liberated acid, the proton sponge base [1,8-bis(dimethylamino) naphthalene] was added. The typical molar ratio between the base and a substrate was between 3.0 and 40.

RESULTS AND DISCUSSION

Nucleofugality of Pentafluorophenolate

A series of benzhydryl pentafluorophenolates (1-PFPh-5-PFPh), which were prepared from corresponding benzhydrils, were subjected to solvolysis in pure ethanol, aqueous 90 %, 80 %, 70 % ethanol, aqueous 90 %, 80%, 70 %, 60 % acetone, and 60 % aqueous acetonitrile. The solvolysis rates were measured conductometrically at 25 °C (details are given in Kinetic methods). In a few cases the rates were measured at three different temperatures and extrapolated to 25 °C. First-order rate constants (measured and extrapolated) are presented in Table 1.

The logarithms of first-order rate constants in the given solvents were plotted against $E_f$, taken from the established electrofugality scale for benzhydryls, and nucleofugality parameters for pentafluorophenolate in the all mentioned solvents were determined ($N_f$ is the negative intercept on the abcissa, whereas $s_f$ is the slope of the plot). For the sake of clarity, only some of the plots are presented in Figure 1. However, all $N_f$ and $s_f$ values obtained along with corresponding standard errors and correlation coefficients, which confirm the high quality of the plots, are shown in Table 2.

The nucleofugalities obtained can be utilized for estimating the reactivities of pentafluorophenolates with different electrofuges according to Equation (1). Furthermore, nucleofugality of pentafluorophenolates can now be compared with nucleofugalities of a large number of other leaving groups, as it is presented in Figure 2. By analyzing the $N_f$ values presented in Figure 2, the shortcomings in using$pK_a$ values for qualitative predicting the reactivities of leaving groups can clearly be established. For instance, despite the lower acidity of p-toluenesulphonic acid than hydrochloric or hydrobromic acid, tosylate is noticeably better leaving group than both bromide and chloride. Furthermore, 2,4-dinitrophenolate and pentafluorophenolate leaving groups are in a middle of the scales despite the highest $pK_a$ values of their conjugate acids in the series presented.

Another outstanding feature of the PFPh leaving group is that it produces the highest $s_f$ value in the series (parentheses in Figure 2). Therefore, expectedly, its log $k/k_E$ correlation line intersects the lines of other leaving groups that are close enough in nucleofugality. Figure 3 demonstrates such intersections in the region of kinetic
Table 1. Solvolysis Rate Constants of X,Y-substituted Benzydrol Pentafluorophenolates in Various Solvents at 25 °C

| Solvent | Substrate (X, Y) | $k_2$ | $\Delta S^{+}$ [J mol$^{-1}$ K$^{-1}$] |
|---------|----------------|-------|--------------------------------------|
| 100E    | 1 (4-OMe, 4'-OMe) | 0.00  | (3.47 ± 0.02) × 10$^{-3}$            |
|         | 2 (4-OMe, 4'-OPh) | -0.86 | (2.89 ± 0.02) × 10$^{-3}$            |
|         | 3 (4-OMe, 4'-Me)  | -1.32 | (5.24 ± 0.03) × 10$^{-4}$            |
|         | 4 (4-OMe, H)      | -2.09 | 5.41 × 10$^{-4}$ (14)                |
| 90E10W  | 1 (4-OMe, 4'-OMe) | 0.00  | (2.24 ± 0.06) × 10$^{-2}$            |
|         | 2 (4-OMe, 4'-OPh) | -0.86 | (1.88 ± 0.02) × 10$^{-3}$            |
|         | 3 (4-OMe, 4'-Me)  | -1.32 | (3.65 ± 0.06) × 10$^{-4}$            |
|         | 4 (4-OMe, H)      | -2.09 | (4.01 ± 0.04) × 10$^{-5}$            |
| 80E20W  | 1 (4-OMe, 4'-OMe) | 0.00  | (5.44 ± 0.01) × 10$^{-3}$            |
|         | 2 (4-OMe, 4'-OPh) | -0.86 | (4.92 ± 0.09) × 10$^{-3}$            |
|         | 3 (4-OMe, 4'-Me)  | -1.32 | (1.08 ± 0.01) × 10$^{-3}$            |
|         | 4 (4-OMe, H)      | -2.09 | (1.15 ± 0.02) × 10$^{-4}$            |
| 70E30W  | 2 (4-OMe, 4'-OPh) | -0.86 | (7.42 ± 0.10) × 10$^{-3}$            |
|         | 3 (4-OMe, 4'-Me)  | -1.32 | (2.19 ± 0.04) × 10$^{-3}$            |
|         | 4 (4-OMe, H)      | -2.09 | (2.29 ± 0.05) × 10$^{-4}$            |
| 90A10W  | 1 (4-OMe, 4'-OMe) | 0.00  | (8.91 ± 0.11) × 10$^{-4}$            |
|         | 2 (4-OMe, 4'-OPh) | -0.86 | (6.05 ± 0.03) × 10$^{-5}$            |
|         | 3 (4-OMe, 4'-Me)  | -1.32 | 1.52 × 10$^{-5}$ (14)                |
| 80A20W  | 1 (4-OMe, 4'-OMe) | 0.00  | (5.78 ± 0.09) × 10$^{-3}$            |
|         | 2 (4-OMe, 4'-OPh) | -0.86 | (4.22 ± 0.04) × 10$^{-3}$            |
|         | 3 (4-OMe, 4'-Me)  | -1.32 | (9.76 ± 0.07) × 10$^{-4}$            |
|         | 4 (4-OMe, H)      | -2.09 | 9.13 × 10$^{-4}$ (14)                |
| 70A30W  | 1 (4-OMe, 4'-OMe) | 0.00  | (1.74 ± 0.02) × 10$^{-2}$            |
|         | 2 (4-OMe, 4'-OPh) | -0.86 | (1.38 ± 0.03) × 10$^{-3}$            |
|         | 3 (4-OMe, 4'-Me)  | -1.32 | (3.45 ± 0.08) × 10$^{-4}$            |
|         | 4 (4-OMe, H)      | -2.09 | (4.08 ± 0.02) × 10$^{-5}$            |
| 60A40W  | 1 (4-OMe, 4'-OMe) | 0.00  | (4.44 ± 0.07) × 10$^{-2}$            |
|         | 2 (4-OMe, 4'-OPh) | -0.86 | (4.10 ± 0.07) × 10$^{-3}$            |
|         | 3 (4-OMe, 4'-Me)  | -1.32 | (1.12 ± 0.02) × 10$^{-3}$            |
|         | 4 (4-OMe, H)      | -2.09 | (1.30 ± 0.04) × 10$^{-4}$            |
| 60A40W  | 2 (4-OMe, 4'-OPh) | -0.86 | (9.82 ± 0.14) × 10$^{-3}$            |
|         | 3 (4-OMe, 4'-Me)  | -1.32 | (2.43 ± 0.09) × 10$^{-3}$            |
|         | 4 (4-OMe, H)      | -2.09 | (2.50 ± 0.07) × 10$^{-4}$            |
| 5 (Me, 4'-Me) | -3.44 | 3.46 × 10$^{-6}$ (14)                |

- $^{(a)}$ Binary solvents are v/v at 25 °C. A = acetone, AN = acetonitrile, E = ethanol, W = water.
- $^{(b)}$ Electrofugality parameters are taken from Ref. [5].
- $^{(c)}$ Average rate constants from at least three runs at 25 °C. Errors shown are standard deviations.
- $^{(d)}$ Extrapulated from data at higher temperatures by using the Eyring equation.
- $^{(e)}$ $\Delta H^\ddagger = 87.1 ± 1.7$ kJ mol$^{-1}$, $\Delta S^\ddagger = 53.7 ± 0.5$ JK$^{-1}$ mol$^{-1}$.
- $^{(f)}$ $\Delta H^\ddagger = 78.9 ± 1.1$ kJ mol$^{-1}$, $\Delta S^\ddagger = 72.5 ± 3.4$ JK$^{-1}$ mol$^{-1}$.
- $^{(g)}$ $\Delta H^\ddagger = 86.6 ± 1.1$ kJ mol$^{-1}$, $\Delta S^\ddagger = 51.0 ± 3.5$ JK$^{-1}$ mol$^{-1}$.
- $^{(h)}$ $\Delta H^\ddagger = 109.0 ± 5.6$ kJ mol$^{-1}$, $\Delta S^\ddagger = 16.3 ± 1.7$ JK$^{-1}$ mol$^{-1}$.

Table 2. Nucleofugality parameters $N_f$ and $s_f$ for pentafluorophenolate in various solvents

| Solvent | $N_f$ | $s_f$ | $R^2$ |
|---------|-------|-------|-------|
| 70E30W  | -0.91 ± 0.04 | 1.20 ± 0.02 | 1.0000 |
| 80E20W  | -0.97 ± 0.04 | 1.29 ± 0.02 | 0.9995 |
| 90E10W  | -1.23 ± 0.06 | 1.33 ± 0.03 | 0.9995 |
| 100E    | -1.79 ± 0.09 | 1.36 ± 0.04 | 0.9990 |
| 60A40W  | -1.12 ± 0.01 | 1.21 ± 0.01 | 1.0000 |
| 70A30W  | -1.40 ± 0.03 | 1.26 ± 0.02 | 1.0000 |
| 80A20W  | -1.66 ± 0.01 | 1.34 ± 0.01 | 1.0000 |
| 90A10W  | -2.28 ± 0.03 | 1.34 ± 0.01 | 1.0000 |
| 60A40W  | -0.63 ± 0.03 | 1.34 ± 0.02 | 1.0000 |

- $^{(a)}$ Binary solvents (v/v) at 25 °C. A = acetone, AN = acetonitrile, E = ethanol, W = water.
- $^{(b)}$ Errors shown are standard errors.
- $^{(c)}$ Correlation coefficient.

Figure 1. Plots of log $k$ (25 °C) vs. $E_f$ for solvolysis of substituted benzydrol pentafluorophenolates in ethanol (E) and aqueous ethanol (E) and acetone (A).

Table 3. Nucleofugity of Pentafluorophenolate in Various Solvents

- Measurements, indicating that for numerous pairs of nucleofuges, relative reactivities can vary with variation of the electrofuges. Such behavior is not surprising when comparing electrofuges with various steric demands adjacent to the carbocation center,$^{[11]}$ but it is quite unexpected with the benzydrol series, since only electronic effects determine their relative reactivities in a certain solvent. Figure 3 further demonstrates the intersection of the line for dintrinophenolate (DNPh)$^{[8]}$ with the line for dichloroacetate (DCAc)$^{[7]}$ after a short extrapolation. The same has been observed for pentafluorobenzoate (PFB)$^{[6]}$ but that line is not shown in Figure 3 as it completely overlaps with the line for DCAc. Accordingly, beside the basic application of Equation (1) to estimate solvolytic reactivities of various substrates,$^{[3]}$ the model can also be used for predicting variations of relative reactivities of leaving groups with electrofugality.
Influences of Intrinsic Barriers on Relative Reactivities

In order to investigate the effect of an electrofuge on solvolytic behavior, we correlated in Figure 4 activation free energies for solvolysis of 4,4'-dimethoxybenzhydryl carboxylates (X = Y = MeO) and phenolates in 80 % ethanol with the benzhydrylium cation (Scheme 2a). It is not possible to predict exactly which of the given carboxylates recombine with the six orders of magnitude more reactive benzhydrylium cation ($E = 5.90$)$^{[13]}$ without a barrier, but a fair estimation can be done. If acetate reacts with 3.5 orders of magnitude more reactive 4,4'-dimethoxybenzhydryl cation ($E = 3.63$) without a barrier (diffusion controlled process),$^{[13]}$ as the chloride anion does,$^{[12a]}$ then, based on nucleophilicities in acetonitrile,$^{[12c]}$ it can be presumed that 3,5-dinitrobenzoate and more reactive anions (Figure 4a) recombine with the benzhydrylium cation without a barrier. Accordingly, most of the substrates (higher activation free energies given on the abscissa in Figure 4a), with exception of the fastest ones, undoubtedly solvolyze without a barrier according to the principle of microscopic reversibility (Scheme 2b).$^{[5]}$ Activation free energies for those substrates correspond to their heterolytic free energies.$^{[5]}$ This assumption is supported with the slope of the correlation line in Figure 4a which reveals a noticeably stronger ion-pair character of transition states for solvolysis of benzhydryl carboxylates than of those for solvolysis of 4,4'-dimethoxybenzhydryl carboxylates. Consequently, the range of solvolysis activation free energies in the case of the weaker benzhydrylium electrofuge is closer to the range of Lewis basicity of the given series of carboxylates, i.e. better describes the relative stabilities of the anions than the range of reactivities when the 4,4'-dimethoxybenzhydryl electrofuge is employed.

Due to the barrierless reverse combination reaction of most carboxylates with the benzhydrylium electrofuge, the slope of the correlation plot presented in
Figure 4a is close in magnitude to the Hammond-Leffler $\alpha$-parameter. Its value as well as the high quality of the correlation confirms the applicability of the Hammond postulate$^{[14]}$ and the Bell-Evans-Polanyi principle$^{[15]}$ for carboxylates, i.e., the series of substrates with the same class of leaving groups, which are stabilized in both transition states and free anions with the same type of electronic effects.

The two points on the correlation plot shown in Figure 4a that correspond to phenolates, appreciably deviate from the line, indicating that if 4,4'-dimethoxybenzhydryl carboxylate and phenolate produce anions of the similar relative stability (the abscissa), the solvolysis of a carboxylate occurs over a higher free energy barrier (the ordinate), that is, carboxylates have the higher Marcus intrinsic barrier$^{[16]}$ than phenolates for both heterolysis and the reversible recombination reaction (Scheme 2c). Also, when carboxylate and phenolate solvolyze via the same free energy barrier, the former generates the more stable anion, confirming its higher intrinsic barrier (Scheme 2d).

The correlation of the activation free energies for solvolysis of 4,4'-dimethoxybenzhydryl carboxylates and phenolates in 80 % ethanol with standard free energies for heterolysis of corresponding Brönsted acids in water (obtained from literature $pK_a$ values given in Supplementary Materials), which represent the relative stabilities of the anions toward a proton, qualitatively confirms the above given relations in energies. The slope of the correlation larger than unity with the substrates that solvolyze over barriers is attributed to an appreciably wider energy range of the Lewis basicity of both carboxylate and phenolate anions toward benzhydrylium carbocations than in the case of their Brönsted basicity.$^{[7a]}$

In general, relative reactivities in the series of carboxylate leaving groups are determined with the stabilities of the free anions produced in solvolysis. The same phenomenon can also be observed with the two phenolates. However, the Hammond postulate and the Bell-Evans-Polanyi principle cannot be applied for interpretation of reactivity-stability relationships for the two classes of substrates, carboxylates and phenolates, due to different stabilization effects that occur in both transition states and free anions. The higher intrinsic barriers and more reactant-like transition states for carboxylates might be rationalized with a lag of resonance in the carboxylate moiety, leaving the polar effects from the aryl/alkyl moiety to dominate and determine the relative stabilities of the transition states. The Hammond postulate is still valid for
carboxylates because the stabilizing contribution of resonance in a series of free carboxylate anions is the same. The nonsynchronized onset of the resonance and the polar substituent effects in the TS has already been observed for benzoates\cite{7a} as well as for other substrates.\cite{17} On the other hand, the resonance in both transition states of phenolates and free phenolate anions is a dominant effect, whose contribution in stabilizing free anions determines their relative stabilities and consequently relative solvolytic reactivities of the series of phenolates.

Comparison of the activation free energies on the diagram given in Figure 4a indicates that in the series of the 4,4′-dimethoxybenzhydrylium electrofuge (the ordinate), pentafluorophenolate (PFPh) is a better leaving group than 3,5-dinitrobenzoate (DNB), monosubstituted fluoro-, chloro- and bromoacetates (Fac, ClAc and BrAc), and formate (Form). On the contrary, PFPh is a poorer leaving group than the mentioned carboxylates in the series of substrates with the benzhydrylum electrofuge (the abscissa). Available data presented in the same correlation (Figure 4a) reveal a similar behavior of 2,4-dinitrophenolate (DNPh). It is indicative that the enhancement of the solvolytic reactivity of the phenolates in comparison to some carboxylates occurs in the combination with a better electrofuge, i.e. in the series of substrates that solvolyze via a barrier. Obviously, the higher intrinsic barrier is the rate determining variable for carboxylates, so phenolates solvolyze faster despite a higher relative stability of the free carboxylate anions (up to 2.5 kcal mol\(^{-1}\)). On the other hand, for the series of benzhydryl substrates, solvolysis is either barrierless or close to be barrierless, and consequently, the impact of the intrinsic barrier at carboxylates is minimized. In this case, the carboxylates that yield more stable anions than phenolates, also solvolyze faster than the phenolates, i.e., the relative stabilities of anions control the kinetics.

The variability in contributions of the intrinsic barrier and the relative stabilities of free anions (produced in solvolysis) on relative reactivities of leaving groups with electrofugality accounts for the intersections of the log \(k/\epsilon_1\) lines shown in Figure 3. The intersections represent the points of the inversion in relative reactivity of two leaving groups. The line for PFPh intersects the three lines for carboxylate at different values of electrofugality in the experimental range. On the right side from an intersection of the lines is the region in which the intrinsic barrier for a certain carboxylate is the rate determining variable, causing that phenolates solvolyze faster than carboxylates. On the left side from the intersections, the intrinsic barrier for the carboxylates is not a dominant variable anymore and the stability of the corresponding anions determine their reactivities; so the carboxylates solvolyze faster than the phenolates, producing more stable anions. Analogously, the log \(k/\epsilon_1\) values for phenyl carbonate and DNPh intersect in the experimental region (\(\epsilon_1 = -6, \log k = -6\)), i.e., inversion in relative reactivities occurs.\cite{1,18} Figure 4 also demonstrates approaching and intersecting the lines for DCICac and DNPh almost identically as it occurs in the previous case with phenyl carbonate. Expectedly, the inversion in reactivity of the DNPh leaving group occurs with more reactive carboxylates, whose free anions are also closer in stability with DNPh anion.

**Importance of the Reaction Constant**

In our previous study we showed that the foundations of the \(s_t\) and Hammett \(\rho\) parameters are the same, i.e. both represent the reaction constants.\cite{18} It has also been demonstrated that \(s_t\) parameter increases with decreasing reactivity of the leaving group which is in the line with the Hammond postulate.\cite{7a} In the series of leaving groups of the same type, having the same stabilization effects that occur in TS and free anions, a decrease in nucleofugality is followed by an increase of both endergonicity and \(s_t\) parameter. Comparison of the two phenolate leaving groups validates the trend; the pentafluorophenolate leaving group has a larger \(s_t\) value than more reactive 2,4-dinitrophenolate for a certain solvent in all the cases.

It has already been mentioned that the Hammond postulate cannot be applied to a series of different types of substrates which can be proved by comparison of \(s_t\) values of phenolates and carboxylates of similar reactivity. Thus, PFPh in a certain solvent has an appreciably higher \(s_t\) value than any carbonate, including the least reactive ones (Table 2, Figure 2). Similarly, the \(s_t\) value for DNPh in a given solvent is larger than \(s_t\) values of carboxylates that are several orders of magnitude less reactive (Figure 2). These differences arise from the variability in intrinsic barriers between the two classes of substrates, that is, unusual high \(s_t\) values indicate noticeably lower intrinsic barriers for phenolates. Consequently, unusual high \(s_t\) values give rise to intersections of the phenolate and carboxylate log \(k/\epsilon_1\) correlation lines (Figure 3), i.e. relative reactivities of some leaving groups vary with electrofugality. This behavior clearly indicates that reactivities of leaving groups, i.e. nucleofugalities, cannot be correctly defined with solvolysis rate constants obtained from a series of substrates with a common electrofuge. Along with technical difficulties for collecting experimental data due to limited range of reactivity of such substrates, the results do not give information on variability in intrinsic barriers of different types of leaving groups. On the other hand, this information is preserved in \(s_t\) parameters in Equation (1), rendering this method appropriate for both determining the nucleofugality of any type of leaving group and estimating heterolytic reactivity.

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SUPPLEMENTARY MATERIALS

Nucleofugality of Pentafluorophenolate in Various Solvents: Solvolytic Behavior of Phenolates

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Table S1. Rate Constants and Corresponding Activation Free Energies for Solvolysis of some Benzhydryl Carboxylates and Phenolates in 80 % Ethanol at 25 °C Estimated Using Equation (1)\(^{(a)}\) and Corresponding Electrofugality and Nuclefugality Parameters

| Substrate | \(E_f\) \(^{(b)}\) | \(N_f\) | \(s_f\) | \(k/s^{-1}\) estimated | \(\Delta^\circ G^o/kcal \text{ mol}^{-1}\) estimated | Reference for \(N_f\) and \(s_f\) |
|-----------|---------------------|--------|--------|--------------------------|---------------------------------------------|-----------------------------|
| 1-HFB     | 0.00                | 1.80   | 0.88   | 3.84 × 10^1              | 15.29                                       | 1                           |
| 1-TFAc    | 0.00                | 1.42   | 0.82   | 1.46 × 10^1              | 15.86                                       | 1                           |
| 1-TClAc   | 0.00                | 1.21   | 0.90   | 1.23 × 10^1              | 15.97                                       | 2                           |
| 1-DClAc   | 0.00                | −0.59  | 0.91   | 2.90 × 10^{-1}           | 18.19                                       | 2                           |
| 1-PFB     | 0.00                | −0.68  | 0.90   | 2.44 × 10^{-1}           | 18.29                                       | 3                           |
| 1-DNPh    | 0.00                | 0.22   | 1.03   | 1.69                     | 17.14                                       | 4                           |
| 8-DClAc   | −6.03               | −0.59  | 0.91   | 9.46 × 10^{-7}           | 25.67                                       | 2                           |
| 8-FAc     | −6.03               | −1.72  | 1.00   | 1.78 × 10^{-8}           | 28.03                                       | 2                           |
| 8-ClAc    | −6.03               | −1.95  | 1.01   | 8.71 × 10^{-9}           | 28.45                                       | 2                           |
| 8-BrAc    | −6.03               | −1.93  | 1.02   | 7.60 × 10^{-9}           | 28.53                                       | 2                           |
| 8-Form    | −6.03               | −2.13  | 1.04   | 3.26 × 10^{-9}           | 29.03                                       | 2                           |
| 8-Ac      | −6.03               | −3.61  | 1.12   | 1.60 × 10^{-11}          | 32.18                                       | 2                           |
| 8-PFB     | −6.03               | −0.68  | 0.90   | 9.14 × 10^{-7}           | 25.69                                       | 3                           |
| 8-DNB     | −6.03               | −1.43  | 0.98   | 4.89 × 10^{-8}           | 27.43                                       | 1                           |
| 8-DNPh    | −6.03               | 0.22   | 1.03   | 1.04 × 10^{-6}           | 25.62                                       | 4                           |
| 8-PFPh    | −6.03               | −0.97  | 1.29   | 9.33 × 10^{-10}          | 29.77                                       | this work                   |

\(^{(a)}\) log \(k\) (25 °C) = \(s_f(E_f + N_f)\). \(^{(b)}\) Values are taken from reference 1.

Table S2. Rate Constants and Corresponding Activation Free Energies for Solvolysis of some Benzhydryl Carboxylates Measured in 80 % Ethanol at 25 °C

| Substrate | \(k/s^{-1}\) | \(\Delta^\circ G^o/kcal \text{ mol}^{-1}\) | Reference |
|-----------|--------------|------------------------------------------|-----------|
| 1-FAc     | 1.93 × 10^{-2} | 19.79                                    | 2         |
| 1-ClAc    | 1.06 × 10^{-2} | 20.15                                    | 2         |
| 1-BrAc    | 1.07 × 10^{-2} | 20.14                                    | 2         |
| 1-Form    | 6.11 × 10^{-3} | 20.47                                    | 2         |
| 1-Ac      | 9.06 × 10^{-5} | 22.97                                    | 5         |
| 1-DNB     | 3.93 × 10^{-2} | 19.37                                    | 6         |
| 8-HFB     | 1.70 × 10^{-4} | 22.60                                    | 7         |
Table S3. Literature pKₐ Values and Corresponding Standard Free Energies for heterolysis of some Brønsted Acids

| Acid                        | pKₐ  | ΔrG° (kcal/mol) | Reference |
|-----------------------------|------|----------------|-----------|
| Heptafluorobutyric (HFB) acid | 0.10 | 0.14           | 8         |
| Trifluoroacetic (TFAc) acid  | 0.23 | 0.31           | 9         |
| Trichloroacetic (TCIAc) acid | 0.66 | 0.90           | 10        |
| Dichloroacetic (DCIAc) acid  | 1.35 | 1.84           | 10        |
| Fluoroacetic (FAc) acid      | 2.59 | 3.53           | 10        |
| Chloroacetic (ClAc) acid     | 2.87 | 3.92           | 10        |
| Bromoacetic (BrAc) acid      | 2.90 | 3.96           | 10        |
| Formic (Form) acid           | 3.75 | 5.12           | 10        |
| Acetic (Ac) acid             | 4.76 | 6.49           | 10        |
| 3,5-Dinitrobenzoic (DNB) acid| 2.80 | 3.82           | 11        |
| 2,4-Dinitrophenol (DNPh) acid| 4.09 | 5.58           | 12        |
| Pentafluorophenol (PFPh) acid| 5.41 | 7.38           | 13        |

Table S4. Experimental Concentrations (cₒ) of 1,8–bis(dimethylamino)naphthalene (Proton Sponge Base) and Substrates in Kinetic Measurements of Solvolysis Rate Constants for Substituted Benzhydryl Pentafluorophenolates

| Solvent (a) | cₒ(PSB)/ mmol dm⁻³ (b) | cₒ(PSB)/cₒ(S) (b) |
|-------------|-------------------------|-------------------|
| 100E        | 52.9–101.4              | 25.0–40.0         |
| 90E10W      | 25.4–87.6               | 15.0–30.0         |
| 80E20W      | 14.1–39.4               | 10.0–15.0         |
| 70E30W      | 7.1–25.4                | 5.0–10.0          |
| 90A10W      | 52.9–88.8               | 25.0–35.0         |
| 80A20W      | 31.7–85.3               | 15.0–35.0         |
| 70A30W      | 8.8–60.9                | 5.0–25.0          |
| 60A40W      | 4.2–20.3                | 3.0–10.0          |
| 60AN40W     | 8.5–20.3                | 5.0–12.0          |
Binary solvents are v/v at 25 °C; A = aceton, AN = acetonitrile, E = ethanol, W = water.

PSB = 1,8-bis(dimethylamino)naphthalene (Proton Sponge Base); S = substrate (substituted benzhydryl pentafluorophenolates)

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