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The Effects of α-Substituents on the Kinetic and Thermodynamic Stability of 4-Methoxybenzyl Carbocations: Carbocation Lifetimes That Are Independent of Their Thermodynamic Stability

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The following new rate constants for reaction of α-substituted 4-methoxybenzyl carbocations, 4-MeOC$_6$H$_4$CR^1(R^2)$^+$, with a solvent of 50:50 (v/v) trifluoroethanol/water at 25 °C and ionic strength 0.50 (NaClO$_4$) are reported: 4-MeOC$_6$H$_4$CH(OMe)$^+$, $k_s = 2.2 \times 10^7$ s^{-1}; 4-MeOC$_6$H$_4$CH(N$_3$)$^+$, $k_s = 3.3 \times 10^5$ s^{-1}; 4-MeOC$_6$H$_4$C(CH$_3$)$_2^+$, $k_s = 1.3 \times 10^7$ s^{-1}; 4-MeOC$_6$H$_4$CH(CO$_2$Et)$^+$, $k_s = 1.4 \times 10^7$ s^{-1}; 4-MeOC$_6$H$_4$CCH$_3$(CF$_3$)$^+$, $k_s = 2.5 \times 10^7$ s^{-1}. The values of k_s for reaction of 4-MeOC$_6$H$_4$CR^1(R^2)$^+$ with 50:50 (v/v) trifluoroethanol/water are nearly independent of very large changes in the thermodynamic stability of these carbocations caused by the addition of a wide range of electron-withdrawing or electron-donating groups at the α-position. In the most extreme case, the change from an α-methoxy to two α-(trifluoromethyl) substituents leads to a 23 kcal/mol thermodynamic destabilization of 4-MeOC$_6$H$_4$CR^1(R^2)$^+$ relative to the neutral azide ion adducts but a 5-fold *decrease* in its reactivity toward solvent. The data show that the effects of α-substituents on the kinetic stability of 4-MeOC$_6$H$_4$CR^1(R^2)$^+$ are complex and do not parallel the thermodynamic stability of these carbocations. The results are explained by consideration of the polar and resonance effects of the α-substituents on both the thermodynamic driving force and the intrinsic barrier for capture of the carbocations by solvent. These reactions are a new example of the consequences of the "principle of nonperfect synchronization".[41]

Introduction

The correlation of rate constants for a reaction with equilibrium constants for the same or a related reaction forms the basis of linear free energy relationships.[1] These relationships constitute one of the most useful tools that physical organic chemists may use in order to characterize reaction transition states, and in particular *changes* in transition-state structure that may occur with changing reactant structure and/or the thermodynamic driving force for the reaction.[2] For example, there are good correlations of the heats of ionization of alkyl chlorides in solution,[3a] and of gas-phase heterolytic bond dissociation energies of tertiary alkyl bromides,[3b] with rate constants for the stepwise solvolyses of these compounds proceeding through the corresponding carbocation intermediates.[3] There is also a very large body of data which shows that changes in the thermodynamic stability of benzylic carbocations, XC$_6$H$_4$CR^1(R^2)$^+$, caused by ring-substituents (X) or additional aromatic rings in the benzylic position (R^1, R^2), lead to very large changes in the rate constants for reaction of the carbocations with solvent and other nucleophiles.[4–11] These results stand in sharp contrast with our, at first surprising, observation that the successive addition of β-fluorine substituents to 4-MeOC$_6$H$_4$CH(CH$_3$)$^+$, to give 4-MeOC$_6$H$_4$CH(CF$_3$)$^+$, causes large thermodynamic destabilizations of the carbocations relative to the neutral chloride ion adducts but leads to only very small changes in their reactivity toward a solvent of 50:50 (v/v) trifluoroethanol/water.[9,12] Further thermodynamic destabilization caused by the addition of a second α-CF$_3$ group to 4-MeOC$_6$H$_4$CH(CF$_3$)$^+$, to give 4-MeOC$_6$H$_4$C(CF$_3$)$_2^+$, leads to a 12-fold *decrease* in the reactivity of the carbocation toward solvent.[12]

We now present a full report of work which extends our studies to include not just fluorinated substitutents, but a wide variety of other α-substituents which are expected to either strongly stabilize (*e.g.*, α-OMe)[13] or strongly destabilize (*e.g.* α-CO$_2$Et)[14] the 4-methoxybenzyl carbocation (Chart I). We find that the rate constants for reaction of these carbocations with solvent are nearly independent of very large (up to 23 kcal/mol) changes in the thermo-

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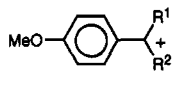
Chart I



$4\text{-}MeOC_6H_4CR^1(R^2)^+$

R^1, R^2 =
H, OMe
H, N_3
CH_3, CH_3
H, CH_3
H, H
H, CH_2F
H, CO_2Et
CH_3, CF_3
H, CHF_2
H, CF_3
CF_3, CF_3

dynamic stability of the carbocation caused by the addition of electron-withdrawing or electron-donating groups at the α-position. These results show that substituent effects on the kinetic stability of carbocations are complex and do not follow any simple "rule of thumb" such as the barrier to capture of carbocations by solvent decreases with their decreasing thermodynamic stability. However, the results *can* be explained by consideration of the effects of the α-substituents on both the thermodynamic driving force *and* the intrinsic barrier for capture of the carbocations by solvent.

Experimental Section

Materials. Pentafluorobenzoic acid, 4-nitrobenzoic acid, 1,3-dicyclohexylcarbodiimide (DCC), 4-pyrrolidinopyridine, 4-methoxybenzaldehyde, 4′-methoxyacetophenone, methylmagnesium iodide, trimethylsilyl azide, phosphorus tribromide, trifluoroethanol, and dry ether were purchased from Aldrich. 4-Methoxymandelic acid and 4-methoxybenzaldehyde dimethyl acetal were purchased from Lancaster Synthesis. Sodium azide was purchased from Fluka. All other chemicals obtained from commercial sources were reagent grade and were used without further purification. Water for the kinetic studies was distilled and then passed through a Milli-Q purification system.

2,2,2-Trifluoro-4′-methoxyacetophenone[9b] and 1-(4-methoxyphenyl)ethyl 3,5-dinitrobenzoate[7b] were prepared as described previously. 2-(4-Methoxyphenyl)-2-propanol was prepared by reaction of 4′-methoxyacetophenone with methylmagnesium iodide in dry ether: mp 37–38 °C; ^1H NMR ($CDCl_3$, 200 MHz) δ 7.42 (2H, d, J = 9 Hz, Ar), 6.88 (2H, d, J = 9 Hz, Ar), 3.81 (3H, s, OCH_3), 1.57 (6H, s, $(CH_3)_2$).

Ethyl 4-Methoxymandelate. 4-Methoxymandelic acid (9.1 g, 50 mmol) and p-toluenesulfonic acid (500 mg) were dissolved in ethanol (200 mL) and heated under reflux for 4 h. The solvent was evaporated, and the residue was dissolved in ether (50 mL). The ethereal solution was washed with $NaHCO_3$ (3 × 50 mL) and brine (1 × 50 mL), dried with $MgSO_4$, and evaporated. Recrystallization from ether/hexanes gave the ester (3.4 g, 32%) as a solid: mp 45 °C (lit.[15] mp 47–48 °C); ^1H NMR ($CDCl_3$, 200 MHz) δ 7.36 (2H, d, J = 9 Hz, Ar), 6.92 (2H, d, J = 9 Hz, Ar), 5.13 (1H, d, J = 6 Hz, CH), 4.24 (2H, m, CH_2), 3.44 (1H, d, J = 6 Hz, OH), 1.25 (3H, t, J = 7 Hz, CH_3).

Ethyl 4-methoxymandelate pentafluorobenzoate was prepared by adaptation of the esterification procedure of Hassner.[16a] Ethyl 4-methoxymandelate (2.5 g, 12 mmol) was dissolved in ether (100 mL), and to this was added pentafluorobenzoic acid (2.29 g, 10.8 mmol), DCC (2.23 g, 10.8 mmol), and 4-pyrrolidinopyridine (0.16 g, 1.1 mmol). The mixture was stirred at room temperature for 3 h and was then filtered. The filtrate was washed with 0.1 M HCl (2 × 100 mL), $NaHCO_3$ (2 × 100 mL), and brine (2 × 100 mL), dried with $MgSO_4$, and evaporated. Purification by column chromatography on silica gel (250 g) eluting with 1/4 ethyl acetate/hexanes gave the ester as a solid (2.6 g, 59%): mp 56 °C; ^1H NMR ($CDCl_3$, 200 MHz) δ 7.45 (2H, d, J = 9 Hz, Ar), 6.94 (2H, d, J = 9 Hz, Ar), 6.11 (1H, s, CH), 4.24 (2H, m, CH_2), 3.83 (3H, s, OCH_3), 1.25 (3H, t, J = 7 Hz, CH_3). Anal. ($C_{18}H_{13}F_5O_5$) C, H.

1-(4-Methoxyphenyl)-1-(trifluoromethyl)ethanol was prepared by adaptation of a literature procedure.[16b] To 2,2,2-trifluoro-4′-methoxyacetophenone (3 g, 15 mmol) in dry ether (30 mL) at 0 °C was added MeMgI (5.9 mL of a 3 M solution in ether). The solution was allowed to warm to room temperature, and stirring was continued for 1 h. Purification by column chromatography on silica gel (150 g) eluting with 1/1 ether/hexanes gave the alcohol (2.8 g, 87%) as a solid: mp 30 °C; ^1H NMR ($CDCl_3$, 200 MHz) δ 7.50 (2H, d, J = 9 Hz, Ar), 6.93 (2H, d, J = 9 Hz, Ar), 3.83 (3H, s, OCH_3), 2.38 (1H, s, OH), 1.77 (3H, s, CH_3).

1-(4-Methoxyphenyl)-1-(trifluoromethyl)ethyl bromide was prepared according to a literature procedure.[16b] 1-(4-Methoxyphenyl)-1-(trifluoromethyl)ethanol (0.82 g, 3.7 mmol) was cooled to 0 °C under argon. PBr_3 (0.53 mL, 5.6 mmol) was added, and the mixture was warmed to 40 °C and stirred for 25 h. The residue was dissolved in ether (10 mL), and the ethereal solution was washed with $NaHCO_3$ (10 mL, added dropwise) and water (10 mL), dried with $MgSO_4$, and evaporated. Purification by column chromatography on silica gel (50 g) eluting with 1/1 ether/hexanes gave the bromide (0.52 g, 50%) as an oil: ^1H NMR ($CDCl_3$, 200 MHz) δ 7.62 (2H, d, J = 9 Hz, Ar), 6.89 (2H, d, J = 9 Hz, Ar), 3.83 (3H, s, OCH_3), 2.30 (3H, s, CH_3).

2-(4-Methoxyphenyl)-2-propyl 4-nitrobenzoate was prepared by esterification of 2-(4-methoxyphenyl)-2-propanol with 4-nitrobenzoic acid, as described above for ethyl 4-methoxymandelate pentafluorobenzoate: ^1H NMR ($CDCl_3$, 200 MHz) δ 8.28 (2H, d, J = 9 Hz, $ArNO_2$), 8.18 (2H, d, J = 9 Hz, $ArNO_2$), 7.38 (2H, d, J = 9 Hz, Ar), 6.89 (2H, d, J = 9 Hz, Ar), 3.80 (3H, s, OCH_3), 1.94 (6H, s, $(CH_3)_2$); MS found M^+ m/z 315.1105, $C_{17}H_{17}NO_5$ requires 315.1107. Anal. ($C_{17}H_{17}NO_5$) C, H, N.

Diazido(4-methoxyphenyl)methane was prepared from 4-methoxybenzaldehyde by a literature procedure,[17] except that the reaction was worked up by passage of the reaction mixture down a short column of basic alumina, eluting with CH_2Cl_2, followed by careful evaporation of the solvent. Column chromatography on silica gel eluting with 1/4 ether/hexanes gave the diazide (88%) as an oil: ^1H NMR ($CDCl_3$, 200 MHz) δ 7.34 (2H, d, J = 9 Hz, Ar), 6.92 (2H, d, J = 9 Hz, Ar), 5.69 (1H, s, CH), 3.80 (3H, s, OCH_3). **CAUTION!** Compounds of this class are explosive.[18]

Azidomethoxy(4-methoxyphenyl)methane was prepared by adaptation[19] of a general literature procedure for this class of compound.[20] 4-Methoxybenzaldehyde dimethyl acetal (13.7 g, 75 mmol) and trimethylsilyl azide (10 mL, 75 mmol) were cooled to −60 °C under argon, and $SnCl_4$ (0.15 mL) was added. The mixture was allowed to warm to room temperature, and stirring was continued for 24 h. Ether (150 mL) was added, and the solution was passed down a short column of basic alumina, followed by careful evaporation of the solvent. Purification by fractional distillation gave the azide (46%) as an oil, contaminated with the starting acetal (~10%): bp 97–98 °C (1.5 mmHg); IR (liquid film) 2100 cm^{-1} (N_3); ^1H NMR ($CDCl_3$, 200 MHz) δ 7.37 (2H, d, J = 9 Hz, Ar), 6.92 (2H, d, J = 9 Hz, Ar), 5.34 (1H, s, CH), 3.81 (3H, s, $ArOCH_3$), 3.54 (3H, s, OCH_3); ^{13}C NMR ($CDCl_3$, 50 MHz) δ 160.3, 129.2, 127.5, 114.0 (Ar), 93.7 (CH), 56.1 ($ArOCH_3$), 55.2 (OCH_3); MS found M^+ m/z 193.0851, $C_9H_{11}N_3O_2$ requires 193.0852. **CAUTION!** Compounds of this class are explosive.[20]

1-(4-Methoxyphenyl)ethyl azide and 2-(4-methoxyphenyl)-2-propyl azide were prepared as 10 mM solutions in trifluoroethanol/water by reaction of the corresponding 3,5-dinitrobenzoate and 4-nitrobenzoate esters, respectively, with sodium azide (20 mM). 1-(4-Methoxyphenyl)ethyl 3,5-dinitrobenzoate (3.5 mg) or 2-(4-methoxyphenyl)-2-propyl 4-nitrobenzoate (3.5 mg) were added to a mixture of trifluoroethanol (1 mL), 1 M NaN_3 (20 μL), 1 M NaOAc (10 μL), and water (20 μL). The solutions were allowed to stand at room temperature for 20 and 4 h, respectively, after which analysis by HPLC showed that reaction of the esters was complete. The products consisted of 95% and 74%, respectively, of the corresponding azide ion adducts and 5% and 26%, respectively, of the corresponding solvent adducts. The solutions were stored in the freezer and were used for kinetic studies within 5 days. Analysis by HPLC

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showed that there was no detectable reaction of the azide adduct during this time.

Kinetic Methods. Unless stated otherwise, all kinetic studies were carried out in 50:50 (v/v) trifluoroethanol/water at 25 °C and $I = 0.50$ ($NaClO_4$). Aqueous solutions containing sodium azide were adjusted to pH ≈ 7 with concentrated $HClO_4$ before use. Reactions were initiated by making a 100- to 300-fold dilution of a solution of substrate in acetonitrile into the reaction mixture, unless noted otherwise.

Rate constants for solvolysis of $4\text{-}MeOC_6H_4CH(N_3)_2$ (0.03 mM) were determined spectrophotometrically by following the appearance of 4-methoxybenzaldehyde at 285 nm. For reaction at $[NaN_3] = 1$ mM, the solution was buffered with acetate, 95% anion, which prevented protonation of N_3^- by trifluoroethanol. There was no change in the observed rate constant when the acetate buffer concentration was varied between 0.01 and 0.05 M. For the slower reactions in the presence of relatively high concentrations of NaN_3, there were slight upward drifts in the absorbance after 10 half-lives, which was shown to be due to decomposition of the trifluoroethanol substitution product, $4\text{-}MeOC_6H_4CH(N_3)OCH_2CF_3$. The latter is formed in low (<10%) yield, but in the absence of added azide ion it is 130-fold less reactive than $4\text{-}MeOC_6H_4CH(N_3)_2$.[21] For these reactions, good first-order kinetics were obtained using endpoints that were calculated by adding 3% to the absorbance change observed after 5 half-lives for the reaction of $4\text{-}MeOC_6H_4CH(N_3)_2$.[22]

Rate constants for solvolysis of $4\text{-}MeOC_6H_4CH(OMe)N_3$ (0.8 mM) at 20 °C were determined spectrophotometrically by following the appearance of 4-methoxybenzaldehyde at 305 nm. The solutions contained $CF_3CH_2O^-$ (0.001–0.010 M) which prevented acid-catalyzed breakdown of the 4-methoxybenzaldehyde dimethyl acetal present as an impurity (~10%, see above) in the substrate. For the very fast reactions in the absence of added azide ion, 20 μL of a solution of substrate in acetonitrile was placed in the bottom of an empty cuvette, and the reactions were initiated by the forceful addition of 3 mL of the appropriate reaction solution with an automatic pipet. The endpoints for these very fast reactions were subject to rather large uncertainties and so the first-order rate constants were obtained by nonlinear least-squares fit of the observed absorbance at 305 nm against time, using the NFIT program from Island Products.

Rate constants for solvolysis of $4\text{-}MeOC_6H_4CCH_3(CF_3)Br$ (0.2 mM) were determined spectrophotometrically by following the disappearance of the substrate at 260 nm. For reactions in the presence of N_3^-, the solutions were buffered with 5 mM cacodylate, 80% anion, which prevented protonation of N_3^- by trifluoroethanol.

Rate constants for solvolysis of $4\text{-}MeOC_6H_4CH(CO_2Et)OPFB$ (0.2 mM) were determined by following the disappearance of the substrate by HPLC, with 3-(4-methoxyphenyl)-1-propanol (0.09 mM) as an internal injection standard. The solutions were buffered with 5 or 10 mM acetate, 95% anion, which prevented protonation of N_3^- by trifluoroethanol.

Rate constants for solvolysis of $4\text{-}MeOC_6H_4C(CH_3)_2OPNB$ (0.12 mM) in the absence of azide ion were determined spectrophotometrically by following the disappearance of the substrate at 270 nm. For reactions in the presence of azide ion, the substrate concentration was 0.22 mM, and the reaction was followed by monitoring the appearance of 4-nitrobenzoate ion at 295 nm.

The rate constant for solvolysis of $4\text{-}MeOC_6H_4C(CH_3)_2N_3$ (0.1 mM) was determined by following the disappearance of the substrate by HPLC, with 2-(4-methoxyphenyl)ethanol (0.1 mM) as an internal injection standard. Reactions in a volume of 4 mL were initiated by injection of 40 μL of the final stock solution of the substrate in trifluoroethanol/water that was prepared as described above.[23]

The rate constant for solvolysis of $4\text{-}MeOC_6H_4CH(CH_3)ODNB$ (0.25 mM) was determined by following the disappearance of the substrate by HPLC in a discontinuous assay. Individual time points were obtained by the addition of 5 μL of a solution of substrate in acetonitrile to 1 mL of 50:50 (v/v) trifluoroethanol/water containing 3-(4-methoxyphenyl)-1-propanol (1 mM) as an internal injection standard. These mixtures were allowed to stand for determined times, after which the amount of substrate remaining was determined by HPLC analysis.

The rate constant for solvolysis of $4\text{-}MeOC_6H_4CH(CH_3)N_3$ (0.1 mM) was determined by following the disappearance of 20% of the substrate by HPLC, with 3-(4-methoxyphenyl)-1-propanol (0.1 mM) as an internal injection standard. Reactions in a volume of 4 mL were initiated by injection of 40 μL of the final stock solution of the substrate in trifluoroethanol/water that was prepared as described above.[23]

Pseudo-first-order rate constants, k_{obsd}, for these reactions were obtained from the slopes of linear semilogarithmic plots of reaction progress against time which covered at least 85% of the reaction, unless stated otherwise. The values of k_{obsd} were reproducible to within ±5%.

Procedures for Product Studies. Unless stated otherwise, product studies were carried out at room temperature, 22 ± 2 °C. There is no detectable difference between the product ratios obtained at room temperature and at 25 °C.[9]

Reactions of $4\text{-}MeOC_6H_4CCH_3(CF_3)Br$ (0.4 mM) were in the presence of 5 mM cacodylate buffer, 80% anion, which prevented protonation of N_3^- by trifluoroethanol, with 3-(4-methoxyphenyl)-1-propanol (0.2 mM) as an internal injection standard. Reactions of $4\text{-}MeOC_6H_4C(CH_3)_2OPNB$ (0.34 mM) were in the presence of 5 mM cacodylate buffer, 80% anion, which prevented acid-catalyzed breakdown of the solvent adducts, with 2-(4-methoxyphenyl)ethanol (0.43 mM) as an internal injection standard. Reactions of ethyl 4-methoxymandelate pentafluorobenzoate at 25 °C were carried out as described for the kinetic studies.

HPLC Analyses. The products were separated by HPLC as described previously[7b,9] and were detected by their UV absorbance at 271 nm for $4\text{-}MeOC_6H_4CCH_3(CF_3)Y$, at 278 nm for $4\text{-}MeOC_6H_4CH(CH_3)Y$, and at 273 nm for all other compounds. These wavelengths are λ_{max} for the corresponding alcohols. The solvent and azide ion adducts were identified and their extinction coefficients at the above wavelengths shown to be identical, as described previously.[7b,9] Product ratios were determined over several half-lives of the reactions, in order to show that the products were stable to the reaction conditions.

Calculation of Rate Constant Ratios. Product rate constant ratios, k_{az}/k_s (M^{-1}), for the reactions of $4\text{-}MeOC_6H_4CCH_3(CF_3)Br$ and $4\text{-}MeOC_6H_4CH(CO_2Et)OPFB$ were calculated from the HPLC peak areas for the azide ion (A_{RNu}) and solvent (A_{ROS}) adducts using eq 1.

$$k_{az}/k_s = A_{RNu}/(A_{ROS}[N_3^-]) \qquad (1)$$

For the reactions of $4\text{-}MeOC_6H_4C(CH_3)_2OPNB$, the azide ion and trifluoroethanol adducts coeluted from the HPLC column. Therefore, k_{az}/k_s (M^{-1}) was calculated from the slope of a plot of the HPLC peak areas according to eq 2, where A is the area of

$$(A_{max} - A_0)/(A - A_0) = 1 + (k_s/k_{az})(1/[N_3^-]) \qquad (2)$$

the combined peaks for the azide ion and trifluoroethanol adducts, A_0 is the area of this peak at $[N_3^-] = 0$, and A_{max} is the area of this peak at $[N_3^-] = 0.50$ M, where the yield of RN_3 is essentially quantitative (>99%).

Results

All kinetic and product studies were carried out in 50:50 (v/v) trifluoroethanol/water at 25 °C and ionic strength 0.50 maintained with sodium perchlorate, unless noted otherwise.

Figure 1 shows that k_{obsd} for solvolysis of $4\text{-}MeOC_6H_4CH(N_3)_2$, determined spectrophotometrically by following the appearance of 4-methoxybenzaldehyde, decreases 300-fold as $[NaN_3]$ is increased from 0 to 20 mM. At the lowest concentration of NaN_3 (1 mM), the

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[23] The concentration of azide ion (*ca.* 0.1 mM) in the reaction mixture resulting from use of the substrate without its separation from the azide ion used in its preparation was insufficient to cause significant common ion depression of the rate constant for solvolysis.

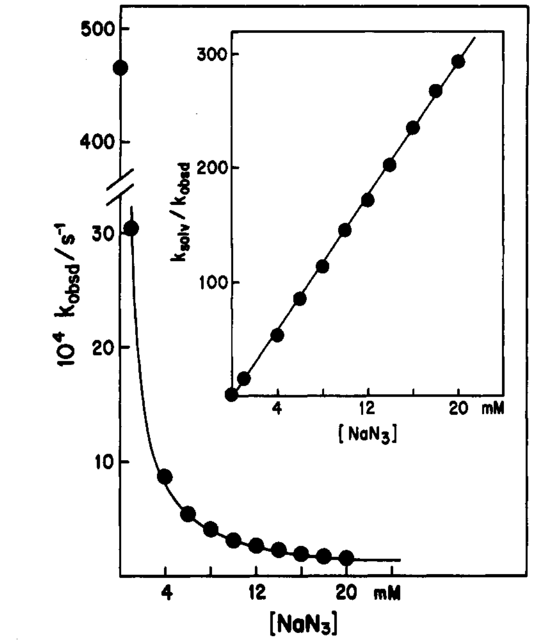

Figure 1. Dependence of k_{obsd} on the concentration of added sodium azide for the solvolysis of $4\text{-MeOC}_6H_4CH(N_3)_2$ in 50:50 (v/v) trifluoroethanol/water at 25 °C and ionic strength 0.50 ($NaClO_4$). The inset shows the linear reciprocal plot of the data according to eq 3 of the text ($Y^- = N_3^-$, $[CF_3CH_2O^-] = 0$ M); the slope of the line gives $k_{az}/k_s = 15\,000\ M^{-1}$.

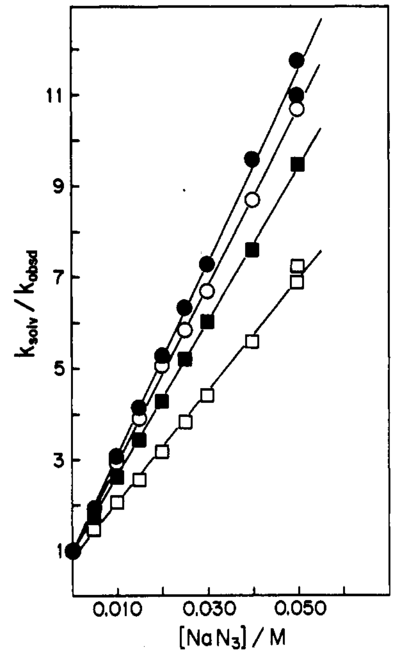

Figure 2. Linear reciprocal plots of the data for common ion inhibition of the solvolysis of $4\text{-MeOC}_6H_4CH(OMe)N_3$ by added sodium azide in 50:50 (v/v) trifluoroethanol/water at 20 °C and ionic strength 0.50 ($NaClO_4$) in the presence of increasing concentrations of $CF_3CH_2O^-$ according to eq 3 of the text ($Y^- = N_3^-$): (●) $[CF_3CH_2O^-] = 0.001$ M; (○) $[CF_3CH_2O^-] = 0.002$ M; (■) $[CF_3CH_2O^-] = 0.005$ M; (□) $[CF_3CH_2O^-] = 0.010$ M. The slopes of the lines give $k_{az}/(k_s + k_{TFE}[CF_3CH_2O^-]) = 210$, 194, 169, and 122 M^{-1}, respectively.

Scheme I

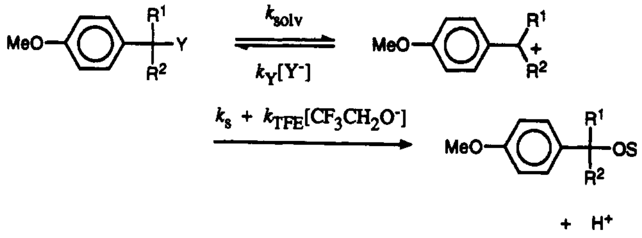

Table I. Partitioning Ratios, k_{az}/k_s (M^{-1}), for Reaction of α-Substituted 4-Methoxybenzyl Carbocations, $4\text{-MeOC}_6H_4CR^1(R^2)^+$, with Azide Ion and a Solvent of 50:50 (v/v) Trifluoroethanol/Water[a]

R^1	R^2	k_{az}/k_s,[b] M^{-1}	method[c]
H	OMe	230[d]	CI
H	N_3	15 000[e]	CI
CH_3	CH_3	380	PA[j]
H	CH_3	105[f]	PA
H	H	25[e,g]	PA
H	CH_2F	50[h]	PA
H	CO_2Et	350[e]	PA[k]
CH_3	CF_3	200	PA[j]
H	CHF_2	50[h]	PA
H	CF_3	95[i]	PA
CF_3	CF_3	1100[h]	PA

[a] Data from this work at room temperature (22 ± 2 °C) and I = 0.50 ($NaClO_4$) and determined as described in the Experimental Section, unless noted otherwise. [b] Rate constant ratio for partitioning of the carbocation between reaction with azide ion and with solvent. [c] Method by which k_{az}/k_s (M^{-1}) was determined: CI = common ion inhibition of the solvolysis of the azide ion adduct (see text); PA = HPLC product analysis of the azide ion and solvent adducts formed from reaction of derivatives with leaving groups other than azide ion. [d] At 20 °C. Determined from the intercept of a plot of $(k_s + k_{TFE}[CF_3CH_2O^-])/k_{az}$ against $[CF_3CH_2O^-]$ (Figure 3 and Results). [e] At 25 °C. [f] Reference 7b. [g] Reference 28. [h] Reference 12. [i] Reference 9. [j] Determined using five values of $[N_3^-]$ in the range 0–20 mM and in the presence of 5 mM cacodylate buffer, 80% anion. [k] Determined using three values of $[N_3^-]$ in the range 0–6 mM and in the presence of 10 mM acetate buffer, 95% anion. The value of k_{az}/k_s (M^{-1}) did not change when the concentration of acetate buffer was decreased to 5 mM.

rate decrease is 15-fold.[24,25] The inset to Figure 1 shows that the common azide ion inhibition data are fit by eq 3 ($Y^- = N_3^-$, $[CF_3CH_2O^-] = 0$ M) derived for stepwise

$$k_{solv}/k_{obsd} = 1 + [k_Y/(k_s + k_{TFE}[CF_3CH_2O^-])][Y^-] \quad (3)$$

solvolysis through a diffusionally-equilibrated carbocation intermediate that can be trapped by Y^- or solvent (Scheme I). The slope of the line in the inset to Figure 1 gives $k_{az}/k_s = 15\,000\ M^{-1}$ (Table I) for partitioning of $4\text{-MeOC}_6H_4\text{-}CH(N_3)^+$ between reaction with azide ion and with solvent.[24]

The rate constant for solvolysis of $4\text{-MeOC}_6H_4CH\text{-}(OMe)N_3$ at 20 °C, determined spectrophotometrically by following the appearance of 4-methoxybenzaldehyde, is independent of $[CF_3CH_2O^-]$ in the range 0.001–0.005 M. An average of 16 determinations gave $k_{solv} = 0.55\ s^{-1}$.[13,26] The reaction is subject to common ion inhibition by added azide ion, and the extent of inhibition by a given concentration of azide ion decreases as $[CF_3CH_2O^-]$ is increased in the range 0.001–0.010 M. Figure 2 shows the fit of the inhibition data to eq 3 ($Y^- = N_3^-$) derived for Scheme I. The slopes of the lines in Figure 2 give $k_{az}/(k_s + k_{TFE}[CF_3CH_2O^-]) = 210$, 194, 169, and 122 M^{-1} for partitioning of $4\text{-MeOC}_6H_4CH(OMe)^+$ between reaction with azide ion and with solvent in the presence of 0.001, 0.002, 0.005, and 0.010 M $CF_3CH_2O^-$, respectively. These

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[24] Amyes, T. L.; Richard, J. P. J. Am. Chem. Soc. 1991, 113, 1867–1869.

[25] In ref 24, the decrease in k_{obsd} for reaction of $4\text{-MeOC}_6H_4CH(N_3)_2$ at $[N_3^-] = 1$ mM was reported erroneously as 20-fold.

[26] In our earlier paper,[13] $k_{solv} = 0.72\ s^{-1}$ for the solvolysis of $4\text{-MeOC}_6H_4CH(OMe)N_3$ at 20 °C was determined indirectly from analysis of the azide common ion inhibition data.

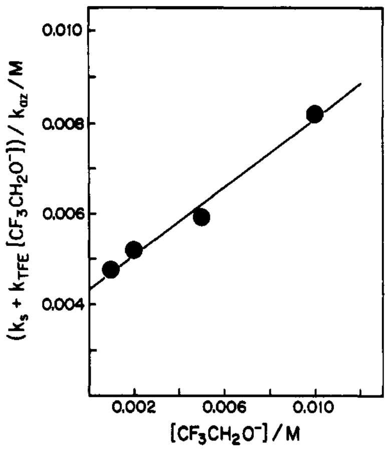

Figure 3. Plot of $(k_s + k_{TFE}[CF_3CH_2O^-])/k_{az}$ for partitioning of $4\text{-}MeOC_6H_4CH(OMe)^+$ between reaction with azide ion and with solvent in 50:50 (v/v) trifluoroethanol/water at 20 °C and ionic strength 0.50 ($NaClO_4$) against $[CF_3CH_2O^-]$. The intercept gives $k_{az}/k_s = 230\ M^{-1}$ for partitioning of $4\text{-}MeOC_6H_4CH(OMe)^+$ at $[CF_3CH_2O^-] = 0$ M.

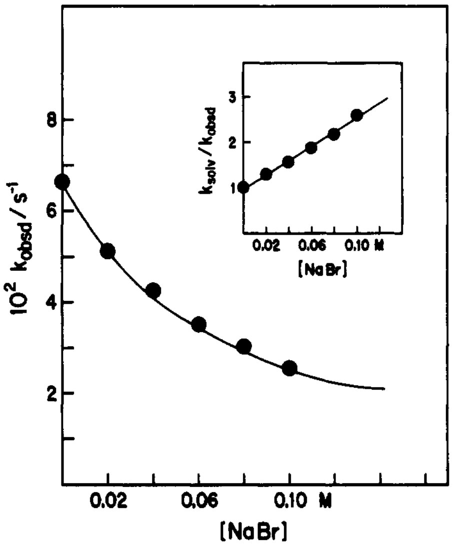

Figure 4. Dependence of k_{obsd} on the concentration of added sodium bromide for the solvolysis of $4\text{-}MeOC_6H_4CCH_3(CF_3)Br$ in 50:50 (v/v) trifluoroethanol/water at 25 °C and ionic strength 0.50 ($NaClO_4$). The inset shows the linear reciprocal plot of the data according to eq 3 of the text ($Y^- = Br^-$, $[CF_3CH_2O^-] = 0$ M); the slope of the line gives $k_{Br}/k_s = 16\ M^{-1}$.

decreases in nucleophilic selectivity are due to an increase in the reactivity of the bulk solvent toward the carbocation as the concentration of $CF_3CH_2O^-$, a solvent nucleophile, is increased. The intercept of the plot of $(k_s + k_{TFE}[CF_3CH_2O^-])/k_{az}$ against $[CF_3CH_2O^-]$ (Figure 3) gives $k_{az}/k_s = 230\ M^{-1}$ for partitioning of $4\text{-}MeOC_6H_4CH(OMe)^+$ between reaction with azide ion and with solvent at $[CF_3CH_2O^-] = 0$ M (Table I).[27]

Figure 4 shows that k_{obsd} for solvolysis of $4\text{-}MeOC_6H_4CCH_3(CF_3)Br$, determined spectrophotometrically by following the disappearance of the substrate, decreases 2.6-fold as [NaBr] is increased from 0 to 0.10 M. The data were fit to eq 3 ($Y^- = Br^-$, $[CF_3CH_2O^-] = 0$ M) derived for Scheme I (Figure 4, inset) to give $k_{Br}/k_s = 16\ M^{-1}$ for partitioning of $4\text{-}MeOC_6H_4CCH_3(CF_3)^+$ between reaction with bromide ion and with solvent. There is no change (±5%) in k_{obsd} for solvolysis of $4\text{-}MeOC_6H_4CCH_3(CF_3)Br$ in the presence of 5 mM cacodylate buffer, 80% anion, when $[NaN_3]$ is increased from 0 to 20 mM. At $[NaN_3] = 20$ mM the yield of the azide ion adduct is 80% ($k_{az}/k_s = 200\ M^{-1}$, Table I).

There is no change (±5%) in k_{obsd} for solvolysis of $4\text{-}MeOC_6H_4CH(CO_2Et)OPFB$ in the presence of 10 mM acetate buffer, 95% anion, when $[NaN_3]$ is increased from 0 to 6 mM. At $[NaN_3] = 6$ mM the yield of the azide ion adduct is 66%. The rate constant ratio $k_{az}/k_s = 350\ M^{-1}$ determined by product analysis (Table I) was constant over this range of $[NaN_3]$, but an increase to $[NaN_3] = 10$ mM led to a slight (~20%) decrease in this quantity to $k_{az}/k_s = 300\ M^{-1}$. This is attributed to N_3^--catalyzed attack of solvent at the carbonyl group of the substrate which gives $4\text{-}MeOC_6H_4CH(CO_2Et)OH$ as a product, resulting in an increase in the yield of the solvent adducts that is not related to capture of a carbocation intermediate.[7b,28]

There is no change (±5%) in k_{obsd} for solvolysis of $4\text{-}MeOC_6H_4C(CH_3)_2OPNB$ when $[NaN_3]$ is increased from 0 to 75 mM. At $[NaN_3] = 20$ mM the yield of the azide ion adduct is 85% ($k_{az}/k_s = 380\ M^{-1}$, Table I).

Table I summarizes the rate constant ratios k_{az}/k_s (M^{-1}) for partitioning of $4\text{-}MeOC_6H_4CR^1(R^2)^+$ between reaction with azide ion and with solvent reported previously[7b,9,12,28] and the new values determined in this work.

Table II gives the rate constants, k_{solv}, for solvolysis of $4\text{-}MeOC_6H_4CR^1(R^2)Y$ reported previously[9,12,28] and the values of k_{solv} for $4\text{-}MeOC_6H_4CH(OMe)N_3$, $4\text{-}MeOC_6H_4CH(N_3)_2$, $4\text{-}MeOC_6H_4C(CH_3)_2OPNB$, $4\text{-}MeOC_6H_4C(CH_3)_2N_3$, $4\text{-}MeOC_6H_4CH(CH_3)ODNB$, $4\text{-}MeOC_6H_4CH(CH_3)N_3$, $4\text{-}MeOC_6H_4CH(CO_2Et)OPFB$, and $4\text{-}MeOC_6H_4CCH_3(CF_3)Br$ determined in this work. Rate constants for solvolysis of the other $4\text{-}MeOC_6H_4CR^1(R^2)N_3$ in Table II, for which $k_{solv} < 1 \times 10^{-7}\ s^{-1}$, were estimated as described in the Discussion.

Discussion

Reaction Mechanisms and Lifetimes of Carbocation Intermediates. The inhibition of the solvolyses of $4\text{-}MeOC_6H_4CH(N_3)_2$ and $4\text{-}MeOC_6H_4CH(OMe)N_3$ by added azide ion shows that these compounds react by a $D_N + A_N$ mechanism[29] through diffusionally-equilibrated carbocation intermediates that can be trapped by azide ion and solvent (Scheme I).[13,24] The good fit of the experimental data to eq 3 ($Y^- = N_3^-$, Figures 1 and 2) derived for solvolysis through a carbocation intermediate (Scheme I) shows that the reactions of these carbocations with solvent can be completely inhibited by azide ion. Therefore, there is no significant reaction of the solvent with the neutral substrate or with carbocation-leaving group ion pairs,[30] and the rate constant ratios, k_{az}/k_s (M^{-1}), are for partitioning of the free carbocation intermediates between reaction with azide ion and with solvent (Table I). The inhibition of the solvolysis of $4\text{-}MeOC_6H_4CCH_3(CF_3)Br$ by added bromide ion (Figure 4) shows that the solvolysis of this compound also proceeds by a $D_N + A_N$ mechanism.

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[27] This differs from the value of $k_{az}/k_s = 163\ M^{-1}$ reported in our earlier work[13] for two reasons. (1) We have now determined the value of $k_{solv} = 0.55\ s^{-1}$ directly. (2) The earlier work was in the presence of 0.010 M $CF_3CH_2O^-$.

(28) Amyes, T. L.; Richard, J. P. *J. Am. Chem. Soc.* **1990**, *112*, 9507–9512.

(29) IUPAC Commission on Physical Organic Chemistry. *Pure Appl. Chem.* 1989, *61*, 23–56. Guthrie, R. D.; Jencks, W. P. *Acc. Chem. Res.* 1989, *22*, 343–349.

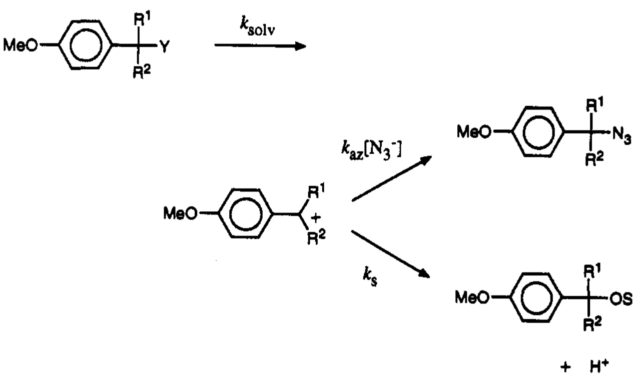
(30) Richard, J. P. *J. Org. Chem.* 1992, *57*, 625–629.

Table II. Experimental and Estimated Rate Constants, k_{solv} (s^{-1}), for Solvolysis of α-Substituted 4-Methoxybenzyl Derivatives, 4-MeOC$_6$H$_4$CR^1(R^2)Y, in 50:50 (v/v) Trifluoroethanol/Water at 25 °C and I = 0.50 (NaClO$_4$)[a]

		leaving group, Y$^-$						
R^1	R^2	OTs$^-$	Br$^-$	Cl$^-$	OPFB[b]	ODNB[c]	OPNB[d]	N$_3^-$
H	OMe							0.86[e]
H	N$_3$							0.047
CH$_3$	CH$_3$						0.090	3.4×10^{-5}
H	CH$_3$					4.6×10^{-4}	1.3×10^{-4} [f]	1.3×10^{-7}
H	H			0.67[g]	2.3×10^{-5} [g]	1.3×10^{-6} [g]		3.7×10^{-10} [j]
H	CH$_2$F			0.32[h]	1.1×10^{-5} [h]			1.8×10^{-10} [k]
H	CO$_2$Et				5.5×10^{-7}			8.8×10^{-12} [k]
CH$_3$	CF$_3$		0.066					1.8×10^{-12} [l]
H	CHF$_2$			9.1×10^{-4} [h]				5.0×10^{-13} [m]
H	CF$_3$	0.087[i]	6.2×10^{-4} [i]	3.0×10^{-5} [h]				1.7×10^{-14} [m]
CF$_3$	CF$_3$	0.034[h]	3.6×10^{-7} [h]					9.9×10^{-18} [l]

[a] Data are from this work, determined as described in the Experimental Section, unless noted otherwise. [b] Pentafluorobenzoate ion leaving group. [c] 3,5-Dinitrobenzoate ion leaving group. [d] 4-Nitrobenzoate ion leaving group. [e] Estimated from k_{solv} = 0.55 s^{-1} at 20 °C (average of 16 determinations, Results) using a temperature correction of 1.56-fold obtained from the values of k_{solv} for 4-MeOC$_6$H$_4$CH(N$_3$)$_2$ determined at 20 and 25 °C: Amyes, T. L. Unpublished results. [f] Calculated from the data in Figure 1 of ref 7b. [g] Reference 28. [h] Reference 12. [i] Reference 9. [j] Estimated from k_{solv} for the ODNB leaving group and the ratio of k_{solv} values for 4-MeOC$_6$H$_4$CH(CH$_3$)Y with Y = ODNB and N$_3$. [k] Estimated from k_{solv} for the OPFB leaving group and the ratio of k_{solv} values for 4-MeOC$_6$H$_4$CH$_2$Y with Y = OPFB and N$_3$. [l] Estimated from k_{solv} for the bromide ion leaving group and the ratio of k_{solv} values for 4-MeOC$_6$H$_4$CH(CF$_3$)Y with Y = Br and N$_3$. [m] Estimated from k_{solv} for the chloride ion leaving group and the ratio of k_{solv} values for 4-MeOC$_6$H$_4$CH$_2$Y with Y = Cl and N$_3$.

Scheme II



The reactions of 4-MeOC$_6$H$_4$C(CH$_3$)$_2$OPNB, 4-MeOC$_6$H$_4$CH(CO$_2$Et)OPFB, and 4-MeOC$_6$H$_4$CCH$_3$(CF$_3$)Br are zero order in [N$_3^-$] up to concentrations of the latter that give 97%, 66%, and 80% yields of the azide ion adducts, respectively, which shows that these compounds react with azide ion by a D$_N$ + A$_N$ mechanism (Scheme II).[10a,14] It has been shown previously[7b,9,12,28] that all the other 4-MeOC$_6$H$_4$CR^1(R^2)Y in Table II (Y$^-$ ≠ N$_3^-$) also react with azide ion by a D$_N$ + A$_N$ mechanism. Therefore, the rate constant ratios determined by product analysis correspond to partitioning ratios, k_{az}/k_s (M^{-1}, Table I), for reaction of the free carbocation intermediates with azide ion and with solvent (Scheme II).

The reaction of azide ion with unstable α-substituted benzyl carbocations is diffusion limited, with $k_{az} = 5 \times 10^9$ M^{-1} s^{-1}.[6-10] Therefore, the partitioning ratios k_{az}/k_s (M^{-1}, Table I) can be combined with this value for k_{az} to give rate constants, k_s (s^{-1}), for reaction of 4-MeOC$_6$H$_4$CR^1(R^2)$^+$ with a solvent of 50:50 (v/v) trifluoroethanol/water (Table III).[31]

Equilibrium Constants for Formation of α-Substituted 4-Methoxybenzyl Carbocations. Table III gives equilibrium constants for formation of 4-MeOC$_6$H$_4$CR^1(R^2)$^+$ from the neutral azide ion adducts, calculated as $K_{eq} = k_{solv}/k_{az}$ (M), where k_{solv} is the first-order rate constant for solvolysis of the azide ion adduct, 4-MeOC$_6$H$_4$CR^1(R^2)N$_3$, and $k_{az} = 5 \times 10^9$ M^{-1} s^{-1} for the diffusion-limited reaction of azide ion with unstable benzyl carbocations (Scheme III).[6-10,31]

Values of k_{solv} for 4-MeOC$_6$H$_4$CH(OMe)N$_3$, 4-MeOC$_6$H$_4$CH(N$_3$)$_2$, 4-MeOC$_6$H$_4$C(CH$_3$)$_2$N$_3$, and 4-MeOC$_6$H$_4$CH(CH$_3$)N$_3$ were determined experimentally (Table II). Values of k_{solv} for the other 4-MeOC$_6$H$_4$CR^1(R^2)N$_3$ were estimated from values of k_{solv} for compounds of the same R^1 and R^2 with other leaving groups Y$^-$, with the assumption that the ratios of k_{solv} values for stepwise solvolysis of the azide ion adducts and other Y$^-$ adducts are independent of R^1 and R^2 (see Table II).

This procedure for estimation of k_{solv} for the very stable 4-MeOC$_6$H$_4$CR^1(R^2)N$_3$ in Table II ($k_{solv} < 1 \times 10^{-7}$ s^{-1}) does not take into account specific differences in the ground-state energies of 4-MeOC$_6$H$_4$CR^1(R^2)Y arising from factors that are a function of Y$^-$, R^1, and R^2, such as steric strain and/or stabilizing or destabilizing electronic geminal interactions[33] between the leaving groups and the α-substituents. There is good evidence that the benzylic position of 4-MeOC$_6$H$_4$C(CF$_3$)$_2$Y is highly congested,[12,34a,b] so the solvolysis of these compounds may be accelerated by the relief of ground-state strain.[12,34] Therefore, the use of the values of k_{solv} for 4-MeOC$_6$H$_4$C(CF$_3$)$_2$Br and 4-MeOC$_6$H$_4$CCH$_3$(CF$_3$)Br, both of which have bulky leaving groups at crowded tertiary centers, probably leads to overestimates of the values of k_{solv} for the corresponding azide ion adducts, which are less congested, and hence also to overestimates of the thermodynamic stabilities of 4-MeOC$_6$H$_4$C(CF$_3$)$_2^+$ and 4-MeOC$_6$H$_4$CCH$_3$(CF$_3$)$^+$.

There are no data that would allow the estimation of the effects of electronic geminal interactions at the benzylic

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[31] There is only a small (*ca.* 1.5-fold) uncertainty in the choice of $k_{az} = 5 \times 10^9$ M^{-1} s^{-1} for the diffusion-limited reaction of carbocations with azide ion: see footnote 35 of ref 10b. Therefore, the values of k_s obtained indirectly by use of this value for k_{az} are well within a factor of 2 of the true values. It has also been shown that the rate constant for reaction of azide ion with carbocations is within 2-fold of the diffusion limited value when $k_{az}/k_s \approx 10^5$ M^{-1}.[32]

[32] McClelland, R. A.; Kanagasabapathy, V. M.; Banait, N. S.; Steenken, S. *J. Am. Chem. Soc.* **1991**, *113*, 1009–1014.

[33] Schleyer, P. v. R.; Kos, A. J. *Tetrahedron* **1983**, *39*, 1141–1150. Schleyer, P. v. R.; Jemmis, E. D.; Spitznagel, G. W. *J. Am. Chem. Soc.* **1985**, *107*, 6393–6394. More O'Ferrall, R. A.; Murray, B. A. *J. Chem. Soc., Chem. Commun.* **1988**, 1098–1099. Kirmse, W.; Goer, B. *J. Am. Chem. Soc.* **1990**, *112*, 4556–4557. Wu, Y.-D.; Kirmse, W.; Houk, K. N. *J. Am. Chem. Soc.* **1990**, *112*, 4557–4559.

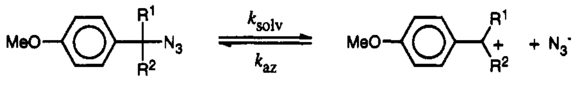
[34] (a) Allen, A. D.; Kanagasabapathy, V. M.; Tidwell, T. T. *J. Am. Chem. Soc.* **1983**, *105*, 5961–5962. *J. Am. Chem. Soc.* **1986**, *108*, 3470–3474. (b) Kanagasabapathy, V. M.; Sawyer, J. F.; Tidwell, T. T. *J. Org. Chem.* **1985**, *50*, 503–509. (c) Tidwell, T. T. *Angew. Chem., Int. Ed. Engl.* **1984**, *23*, 20–32. (d) Tidwell, T. T. *Adv. Chem.* **1987**, *215*, 315–328. (e) Allen, A. D.; Tidwell, T. T. In *Advances in Carbocation Chemistry*; Creary, X., Ed.; JAI Press, Inc.: Greenwich, CT, 1989; Vol. 1, pp 1–44.

Table III. Rate and Equilibrium Constants for Formation of α-Substituted 4-Methoxybenzyl Carbocations, $4\text{-MeOC}_6\text{H}_4\text{CR}^1(\text{R}^2)^+$, from the Corresponding Azide Ion Adducts and Rate Constants for Their Capture by Solvent[a]

R^1	R^2	k_{solv},[b] s^{-1}	$K_{eq} = k_{solv}/k_{az}$,[c] M	k_s,[d] s^{-1}
H	OMe	0.86	1.7×10^{-10}	2.2×10^{7}
H	N_3	0.047	9.4×10^{-12}	3.3×10^{5}
CH_3	CH_3	3.4×10^{-5}	6.8×10^{-15}	1.3×10^{7}
H	CH_3	1.3×10^{-7}	2.6×10^{-17}	4.8×10^{7}
H	H	3.7×10^{-10}	7.4×10^{-20}	2.0×10^{8}
H	CH_2F	1.8×10^{-10}	3.6×10^{-20}	1.0×10^{8}
H	CO_2Et	8.8×10^{-12}	1.8×10^{-21}	1.4×10^{7}
CH_3	CF_3	1.8×10^{-12}	3.6×10^{-22}	2.5×10^{7}
H	CHF_2	5.0×10^{-13}	1.0×10^{-22}	1.0×10^{8}
H	CF_3	1.7×10^{-14}	3.4×10^{-24}	5.3×10^{7}
CF_3	CF_3	9.9×10^{-18}	2.0×10^{-27}	4.5×10^{6}

[a] In 50:50 (v/v) trifluoroethanol/water at 25 °C and $I = 0.50$ ($NaClO_4$). [b] Rate constants for solvolysis of the azide ion adducts taken from Table II. [c] Equilibrium constants for formation of the carbocations from the neutral azide ion adducts (Scheme III) calculated using $k_{az} = 5 \times 10^9$ M^{-1} s^{-1} for the diffusion-limited reaction of azide ion with benzyl carbocations (see text). [d] First-order rate constants for capture of the carbocations by solvent calculated from the values of k_{az}/k_s (M^{-1}) in Table I and $k_{az} = 5 \times 10^9$ M^{-1} s^{-1} for the diffusion-limited reaction of azide ion with benzyl carbocations (see text).

Scheme III



carbon of $4\text{-MeOC}_6\text{H}_4\text{CR}^1(\text{R}^2)\text{N}_3$, so that an assessment of the possible effects of these on the ground-state energies, and hence rate constants for solvolysis,[35] of $4\text{-MeOC}_6\text{H}_4\text{CR}^1(\text{R}^2)\text{N}_3$ cannot be made. Despite these limitations, the estimated values of k_{solv} for the stable azide ion adducts (Table III) decrease as $\Sigma\sigma^*$ for the α-substituents increases.[36] This shows that the uncertainties in the estimates of k_{solv} are not sufficiently large to change the *relative* order of the thermodynamic stabilities of $4\text{-MeOC}_6\text{H}_4\text{CR}^1(\text{R}^2)^+$ implied by the data in Table III.

Rate–Equilibrium Correlations for Reactions of α-Substituted 4-Methoxybenzyl Carbocations. The correlation between the rate constants for the reaction of $4\text{-MeOC}_6\text{H}_4\text{CR}^1(\text{R}^2)^+$ with solvent, k_s (s^{-1}), and equilibrium constants for formation of these carbocations from $4\text{-MeOC}_6\text{H}_4\text{CR}^1(\text{R}^2)\text{N}_3$, K_{eq} (M), is shown in Figure 5 (filled circles). These data show that *the value of k_s for reaction of $4\text{-MeOC}_6\text{H}_4\text{CR}^1(\text{R}^2)^+$ with 50:50 (v/v) trifluoroethanol/water is nearly independent of very large changes (up to 23 kcal/mol) in the thermodynamic stability of these carbocations relative to the neutral azide ion adducts.* These results stand in very sharp contrast with the large body of data which shows that changes in the thermodynamic stability of benzylic carbocations $\text{XC}_6\text{H}_4\text{CR}^1(\text{R}^2)^+$ lead to very large changes in the rate constants for their reaction with solvent and other nucleophiles.[4-11] Therefore, the intuitive idea, developed on the basis earlier work, that more thermodynamically stable carbocations will have greater kinetic stabilities is clearly an oversimplification. Two explanations which might be thought to account for the remarkable insensitivity of the reactivity of $4\text{-MeOC}_6\text{H}_4\text{CR}^1(\text{R}^2)^+$ to very large changes in the thermodynamic stability of these carbocations can be excluded as follows.

Early Transition State. The transition state for the addition of solvent to $4\text{-MeOC}_6\text{H}_4\text{CR}^1(\text{R}^2)^+$ is early and very carbocation-like so that *none* of the substituent effect on the equilibrium constant for formation of the carbocations is expressed in the rate constant for their reaction with solvent. The following observations show that this cannot account for our results:

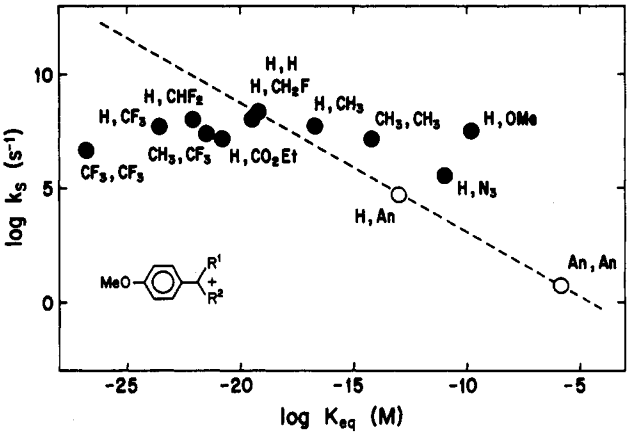


Figure 5. Correlation between rate constants for the reaction of α-substituted 4-methoxybenzyl carbocations with solvent (k_s, s^{-1}) and equilibrium constants for their formation from the corresponding neutral azide ion adducts (K_{eq}, M) in 50:50 (v/v) trifluoroethanol/water at 25 °C and ionic strength 0.50 ($NaClO_4$): (●) data from Table III; (○) data from Table IV. The dashed line drawn through the points for the α-(4-methoxyphenyl) (An = 4-methoxhphenyl) derivatives and the unsubstituted 4-methoxybenzyl carbocation has a slope of −0.57.

(1) Thermodynamic destabilization of $4\text{-MeOC}_6\text{H}_4\text{CH}(\text{CH}_3)^+$ by the addition of an electron-withdrawing 3-nitro substituent leads to a 60-fold increase in the reactivity of this carbocation toward solvent,[7b] which shows that there is significant carbon–solvent bond formation in the transition state for capture of $4\text{-MeOC}_6\text{H}_4\text{CH}(\text{CH}_3)^+$ by solvent. Thus, the destabilization of this carbocation by the successive addition of β-fluorine substituents, to give $4\text{-MeOC}_6\text{H}_4\text{CH}(\text{CF}_3)^+$, should also result in the expression of these substituent effects in the transition state for capture of this carbocation by solvent.

(2) Plots of rate constants for the reactions of ring-substituted cumyl carbocations,[10a,37] 1-phenylethyl carbocations,[7b] and acetophenone oxocarbenium ions[38] with water against the equilibrium constants for the same reaction have slopes of 0.50, 0.47, and 0.53, respectively. This shows that approximately 50% of the substituent effect on the equilibrium constant for formation of the neutral solvent adducts from the carbocations is expressed in the transition state for this reaction.

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(3) The increases in the rate constants for the reaction of acetate ion and solvent with $XC_6H_4CH(CF_3)^+$ when X is made less electron-donating,[9b] and the value of $\beta_{nuc} = 0.32$ for the reaction of alcohols with $4\text{-}MeOC_6H_4CH(CF_3)^+$,[10b] show that there is considerable bonding between the nucleophile and the benzylic carbon in the transition state for capture of these highly unstable carbocations.

Steric Effects. The expected differences in the reactivity of $4\text{-}MeOC_6H_4CR^1(R^2)^+$ with different α-substituents toward solvent are offset by differing steric effects of the α-substituents. The following show that the essentially constant reactivity of $4\text{-}MeOC_6H_4CR^1(R^2)^+$ toward solvent cannot be explained by increasing steric retardations accompanying decreasing thermodynamic stability of these carbocations:

(1) The carbocations $4\text{-}MeOC_6H_4CH(OMe)^+$ and $4\text{-}MeOC_6H_4CH(CO_2Et)^+$ have similar steric bulk at the benzylic position, but they differ in stability by 15 kcal/mol, relative to the neutral azide ion adducts (Table III). Despite this, they show very similar reactivities toward solvent, with the *less stable* $4\text{-}MeOC_6H_4CH(CO_2Et)^+$ reacting 1.6-fold *slower* than $4\text{-}MeOC_6H_4CH(OMe)^+$ (Table III).

(2) The addition of three β-fluorine substituents leads to a 2-fold increase in the reactivity of $4\text{-}MeOC_6H_4C(CH_3)_2^+$ toward solvent, whereas the same substitution leaves the reactivity of $4\text{-}MeOC_6H_4CH(CH_3)^+$ unaltered (Table III). The polar effects of the addition of three β-fluorine substituents to $4\text{-}MeOC_6H_4C(CH_3)_2^+$ to give $4\text{-}MeOC_6H_4CCH_3(CF_3)^+$ and to $4\text{-}MeOC_6H_4CH(CH_3)^+$ to give $4\text{-}MeOC_6H_4CH(CF_3)^+$ should be similar. If steric effects were important, then the addition of β-fluorines should lead to a smaller increase in the reactivity of $4\text{-}MeOC_6H_4C(CH_3)_2^+$ than of $4\text{-}MeOC_6H_4CH(CH_3)^+$ because the former is already more crowded at the benzylic carbon.

(3) We have shown previously[12] that the steric effects of the increasing numbers of β-fluorines along the series $4\text{-}MeOC_6H_4CH(CH_3)^+$, $4\text{-}MeOC_6H_4CH(CH_2F)^+$, $4\text{-}MeOC_6H_4CH(CHF_2)^+$, and $4\text{-}MeOC_6H_4CH(CF_3)^+$ on k_s for the capture of these carbocations by solvent are small.

Resonance and Transition-State Imbalance. A. Electron-Withdrawing α-Substituents. The effects of electron-withdrawing α-substituents on the reactivity of $4\text{-}MeOC_6H_4CR^1(R^2)^+$ can be understood by considering both the polar and the resonance effects of these α-substituents, which have opposing effects on both the rate and the equilibrium constants for the reaction of these carbocations with solvent.[9,12,14] The addition of an electron-withdrawing α-substituent to the 4-methoxybenzyl carbocation will destabilize this carbocation by a polar effect, but this will be offset to some extent by increased resonance electron donation from the 4-methoxybenzyl ring to the benzylic carbon. The increased resonance electron delocalization is "driven" by the stabilization that is obtained upon movement of the center of positive charge away from the positive end of the dipole of the electron-withdrawing α-substituent. There is good evidence that α-CF_3 substituents at $4\text{-}MeOC_6H_4CR^1(R^2)^+$ greatly increase the extent of resonance electron delocalization of the charge at the benzylic carbon onto the 4-methoxybenzyl ring and hence the charge density at C-4 of the aromatic ring.[9,12,34,39] For example, $4\text{-}MeOC_6H_4CH(CF_3)^+$ undergoes nucleophilic aromatic substitution with primary and secondary amines to give $4\text{-}(R^3,R^4N)C_6H_4CH(CF_3)^+$,[39] while the reaction of $4\text{-}MeOC_6H_4C(CF_3)_2^+$ with 50:50 (v/v) trifluoroethanol/water gives a 33% yield of a quinone methide.[12]

Equation 4 divides the overall effect of electron-withdrawing α-substituents on the rate constant for capture of $4\text{-}MeOC_6H_4CR^1(R^2)^+$ by solvent into expression

$$\log (k/k_o) = \alpha^P \log (K/K_o)^P + \alpha^R \log (K/K_o)^R \qquad (4)$$

of the polar substituent effect $[\alpha^P \log (K/K_o)^P]$ and of the resonance substituent effect $[\alpha^R \log (K/K_o)^R]$, where α^P and α^R are the fractions of the *equilibrium* polar and resonance substituent effects, respectively, that are expressed in the transition state. Since electron-withdrawing α-substituents lead to overall thermodynamic *destabilization* of $4\text{-}MeOC_6H_4CR^1(R^2)^+$ (Table III and Figure 5), then $|\log (K/K_o)^P| > |\log (K/K_o)^R|$. However, we observe that the reactivity of $4\text{-}MeOC_6H_4CR^1(R^2)^+$ is essentially independent of electron-withdrawing α-substituents, *i.e.*, $\log (k/k_o) \approx 0$. Thus, the almost complete cancellation of the two terms on the right-hand side of eq 4 requires $\alpha^R > \alpha^P$. That is, there is a greater fractional *loss* of resonance than of polar interactions on moving from the ground to the transition state for capture of $4\text{-}MeOC_6H_4CR^1(R^2)^+$ by solvent. Such "imbalance"[2a,40] or "nonperfect synchronization"[41] between the loss of resonance and polar interactions has been noted previously for the capture by solvent of oxocarbenium ions[19,38] and 1-arylethyl[7b] and triarylmethyl[6c] carbocations and for a number of reactions involving the formation and/or destruction of resonance-stabilized carbanions.[40-42] This imbalance can be understood by considering a hypothetical transition state for *formation* of a carbocation from a neutral adduct in which 50% of the carbon-leaving group bond is broken. In such a transition state, the extent of sp^2 hybridization, and hence degree of planarity, of the central carbon will, to a first approximation, be only 50% that of the fully-formed carbocation, so that the "efficiency" of resonance delocalization at the central carbon will be only 50% of that in the fully-formed carbocation.[7b,19,40,41c,d] Thus the fractional development of polar interactions in the transition state, as measured by the extent of bond-breaking and/or charge development, is 0.50, but the fractional development of resonance interactions is only (0.50 × 0.50) = 0.25.[7b,19,40,41c,d] The "lag" in the development of resonance interactions in the transition state for formation of the carbocation corresponds to an "early" loss of these interactions in the transition state for the reverse reaction, *i.e.*, the reaction of a carbocation with a nucleophile.[7b,19,40,41]

Resonance and Transition-State Imbalance. B. Electron-Donating α-Substituents. The effects of electron-donating α-substituents that interact with the charge at the benzylic carbon by resonance delocalization (eq 5) on the reactivity of $4\text{-}MeOC_6H_4CR^1(R^2)^+$ are complex. The successive addition of α-(4-methoxyphenyl) (α-anisyl) substituents or of an α-azido substituent leads to large decreases in k_s for the reaction of $4\text{-}MeOC_6H_4$-

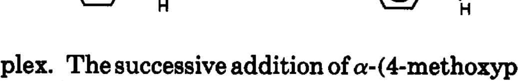

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Table IV. Rate and Equilibrium Constants for Formation of α-(4-Methoxyphenyl)-Substituted 4-Methoxybenzyl Carbocations, $4\text{-MeOC}_6\text{H}_4\text{CR}^1(\text{R}^2)^+$, from the Corresponding Azide Ion Adducts and Rate Constants for Their Capture by Solvent[a]

R^1	R^2	k_{solv},[b] s^{-1}	$K_{eq} = k_{solv}/k_{az}$,[c] M	k_s,[d] s^{-1}
H	H	3.7×10^{-10} [e]	7.4×10^{-20} [e]	2.0×10^{8} [e]
H	An[f]	5.5×10^{-4} [g]	1.1×10^{-13}	5×10^{4} [h]
An[f]	An[f]	28[i]	1.9×10^{-6} [j]	5[k]

[a] In 50:50 (v/v) trifluoroethanol/water at 25 °C. [b] Rate constants for solvolysis of the azide ion adducts. [c] Equilibrium constants for formation of the carbocations from the neutral azide ion adducts (Scheme III) calculated using $k_{az} = 5 \times 10^9$ M^{-1} s^{-1} for the diffusion-limited reaction of azide ion with benzyl carbocations, unless noted otherwise. [d] First-order rate constants for reaction of the carbocations with solvent. [e] Data from Table III. [f] An = 4-methoxyphenyl. [g] Estimated from k_{solv} for the chloride ion leaving group and the ratio of k_{solv} values for $4\text{-MeOC}_6\text{H}_4\text{CH}_2\text{Y}$ with Y = Cl and N_3 (Table II). $k_{solv} = 1 \times 10^6$ s^{-1} for $4\text{-MeOC}_6\text{H}_4\text{CH(An)Cl}$ in 50:50 (v/v) trifluoroethanol/water was estimated from k_{solv} for this compound in 80% acetone (ref 46) with the assumption that the effect of the change in solvent is the same as that observed for the solvolysis of $4\text{-MeOC}_6\text{H}_4\text{CH}_2\text{Cl}$ (ref 28). [h] Estimated from $k_s = 1.0 \times 10^5$ s^{-1} in 1:4 acetonitrile/water (ref 6b) with the assumption that the effect of the change in solvent (2-fold) is the same as that for the reaction of $4\text{-MeOC}_6\text{H}_4\text{CH(CF}_3)^+$ (ref 39). [i] Estimated from k_{solv} for the chloride ion leaving group and the ratio of k_{solv} values for $4\text{-MeOC}_6\text{H}_4\text{CH}_2\text{Y}$ with Y = Cl and N_3 (Table II). $k_{solv} = 5 \times 10^{10}$ s^{-1} for $4\text{-MeOC}_6\text{H}_4\text{C(An)}_2\text{Cl}$ in 50:50 (v/v) trifluoroethanol/water was estimated from k_{sov} for this compound in 80% acetone (ref 46) with the assumption that the effect of the change in solvent is the same as that observed for the solvolysis of $4\text{-MeOC}_6\text{H}_4\text{CH}_2\text{Cl}$ (ref 28). [j] Calculated using $k_{az} = 1.5 \times 10^7$ M^{-1} s^{-1} for reaction of this carbocation with azide ion (ref 32). [k] Estimated from $k_s = 10$ s^{-1} in 1:2 acetonitrile/water (ref 6c) with a 2-fold correction for the change in solvent (footnote *h*). The reactivities of carbocations towards 1:2 acetonitrile/water and 1:4 acetonitrile/water are very similar (ref 6c).

$\text{CR}^1(\text{R}^2)^+$ with solvent (Tables III, IV and Figure 5). However, the successive addition of α-methyl substituents or of an α-methoxy substituent does *not* lead to significant decreases in the reactivity of the carbocation toward solvent (Table III and Figure 5).

The α-anisyl and α-azido substituents stabilize positive charge at the benzylic carbon of $4\text{-MeOC}_6\text{H}_4\text{CR}^1(\text{R}^2)^+$ by charge delocalization onto the additional 4-methoxyphenyl ring or the terminal diazo group,[43] respectively. This leads to a decrease in, or attenuation of, the contribution of resonance electron donation from the *original* 4-methoxyphenyl ring but results in an overall increase in the *total* resonance stabilization and hence thermodynamic stability of the carbocation (Table III and Figure 5). The accompanying increases in the kinetic stability of the carbocation represent the "normal" expression of substituent effects, with more stable species reacting more slowly. The line drawn through the points for $4\text{-MeOC}_6\text{H}_4\text{CH}_2^+$, $4\text{-MeOC}_6\text{H}_4\text{CH(An)}^+$, and $4\text{-MeOC}_6\text{H}_4\text{C(An)}_2^+$ in Figure 5 has a slope of –0.57 and is consistent with a *ca.* 60% loss of the resonance stabilization of these carbocations by the α-anisyl substituents in the transition state for their capture by solvent.

The very small effect of the strongly electron-donating α-methoxy group on the reactivity of $4\text{-MeOC}_6\text{H}_4\text{CR}^1(\text{R}^2)^+$ is unexpected. Like the α-anisyl and α-azido substituents, the α-methoxy substituent also leads to an increase in the total resonance stabilization and hence thermodynamic stability of the carbocation, but this stabilization is not reflected in the rate constant k_s for capture of the carbocation by solvent (Table III and Figure 5). This result can be rationalized by reference to eq 6 which separates

$$\log (k/k_o) = \alpha^{R1,R2} \log (K/K_o)^{R1,R2} + \alpha^{4\text{-MeOAr}} \log (K/K_o)^{4\text{-MeOAr}} \quad (6)$$

the overall effect of electron-donating α-substituents on the rate constant for capture of $4\text{-MeOC}_6\text{H}_4\text{CR}^1(\text{R}^2)^+$ by solvent into two parts: (1) Expression of the direct resonance stabilization of the carbocation by the added α-substituent(s) [$\alpha^{R1,R2} \log (K/K_o)^{R1,R2}$] and (2) expression of the *attenuation* of this resonance stabilization by the accompanying decreased resonance electron donation from the original 4-methoxyphenyl ring [$\alpha^{4\text{-MeOAr}} \log (K/K_o)^{4\text{-MeOAr}}$]. Thus, $\alpha^{R1,R2}$ and $\alpha^{4\text{-MeOAr}}$ are the fractions of the *equilibrium* resonance substituent effect of the added α-substituents and the offsetting attenuation of this effect by decreased resonance electron donation from the original 4-methoxyphenyl ring, respectively, that are expressed in the transition state for capture of $4\text{-MeOC}_6\text{H}_4\text{CR}^1(\text{R}^2)^+$ by solvent. Electron-donating α-substituents lead to an overall increase in the *total* resonance stabilization and hence thermodynamic stability of $4\text{-MeOC}_6\text{H}_4\text{CR}^1(\text{R}^2)^+$ (Table III and Figure 5), so that $|\log (K/K_o)^{R1,R2}| > |\log (K/K_o)^{4\text{-MeOAr}}|$. The "normal" expression of the stabilizing effects of the α-anisyl and α-azido substituents in the transition state for capture of $4\text{-MeOC}_6\text{H}_4\text{CR}^1(\text{R}^2)^+$ by solvent suggests that for these substituents $\alpha^{R1,R2} \geq \alpha^{4\text{-MeOAr}}$. For $R^1 = R^2$ = anisyl ($4\text{-MeOC}_6\text{H}_4$) there is no distinction between the original 4-methoxyphenyl ring and the added α-substituents so that $\alpha^{R1,R2} = \alpha^{4\text{-MeOAr}}$ and there can be no imbalance between the expression of the two substituent effects. However, for the α-methoxy and α-methyl substituents, there is almost complete cancellation of the two terms on the right-hand side of eq 6, which requires $\alpha^{4\text{-MeOAr}} > \alpha^{R1,R2}$. That is, on moving from the ground to the transition state for capture of $4\text{-MeOC}_6\text{H}_4\text{CR}^1(\text{R}^2)^+$ by solvent, the fractional expression of the attenuation of the effects of the α-methoxy or α-methyl substituents by decreased resonance electron donation from the original 4-methoxyphenyl ring is larger than the fractional expression of the direct stabilizing resonance interactions of these substituents themselves. This imbalance suggests that overlap of the lone pair(s) of electrons on the α-methoxy group and of hyperconjugation of the hydrogens of the α-methyl groups with the empty *p* orbital at the benzylic carbon is effective at greater extents of pyramidalization of this center than is overlap of the π orbitals of a 4-methoxyphenyl ring or of an azido group.

The introduction of a second α-methoxy group to $4\text{-MeOC}_6\text{H}_4\text{CH(OMe)}^+$ *does* lead to a substantial decrease in reactivity to $k_s = 1.7 \times 10^4$ s^{-1} for the reaction of $4\text{-MeOC}_6\text{H}_4\text{C(OMe)}_2^+$ with 100% water.[44] This is consistent with a much smaller absolute effect of the attenuation of the stabilization due to the added α-substituent because the resonance stabilization of the carbocation provided by the 4-methoxyphenyl ring has already been reduced considerably by the addition of the first α-methoxy group.

Reactions of α-Substituted 4-Methoxybenzyl Carbocations. The remarkable almost complete insensitivity of the rate constants for capture of $4\text{-MeOC}_6\text{H}_4\text{CR}^1(\text{R}^2)^+$ by solvent to changes in the thermodynamic stability of

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Table V. First-Order Rate Constants, k_s (s^{-1}), for Capture of α-Substituted 4-Methylbenzyl Carbocations, $4\text{-MeC}_6H_4CR^1(R^2)^+$, by Solvent[a]

R^1	R^2	k_s, s^{-1}
CH_3	OMe	1.3×10^7 [b]
CH_3	CH_3	1.0×10^9 [c]
H	CH_3	6×10^9 [d]
H	CF_3	1×10^{10} [e]

[a] In 50:50 (v/v) trifluoroethanol/water at 25 °C and $I = 0.50$ ($NaClO_4$), unless noted otherwise. [b] Calculated from $k_s = 5 \times 10^7\ s^{-1}$ for reaction of this carbocation with 100% water ($I = 1.00$, KCl), determined by diffusion-limited trapping with sulfite dianion (ref 38), with a 2-fold correction for the difference in the rate constants that are obtained by sulfite dianion and by azide ion trapping (ref 19). An additional correction for the difference in solvent was estimated from the 2-fold lower reactivity of $4\text{-MeOC}_6H_4CH(CH_3)^+$ toward 50:50 (v/v) trifluoroethanol/water than toward 100% water (ref 7b). [c] Determined from $k_{az}/k_s = 5\ M^{-1}$ for this carbocation (ref 10a) with $k_{az} = 5 \times 10^9\ M^{-1}\ s^{-1}$ for the diffusion-limited reaction of azide ion with benzyl carbocations (see text). [d] Reference 7b. [e] Reference 9.

this carbocation caused by the addition of electron-withdrawing or electron-donating α-substituents is a result of the balance between the destabilizing or stabilizing effects of the added α-substituents and the attenuation of these effects by increased or decreased resonance electron donation from the original 4-methoxyphenyl ring, as described by eqs 4 and 6. A change from a 4-MeO to a 4-Me or a 4-H substituent at $XC_6H_4CR^1(R^2)^+$ will result in a decrease in the stabilization of the carbocation by resonance electron donation from the aromatic ring and hence to smaller absolute attenuations of the effects of added α-substituents, *i.e.*, smaller values of log $(K/K_o)^R$ (eq 4) and log $(K/K_o)^{4\text{-MeOAr}}$ (eq 6). This prediction is born out by the data in Table V which gives rate constants for capture of α-substituted 4-methylbenzyl carbocations by solvent. These data show that substitution of a 4-MeO by a 4-Me substituent at $XC_6H_4CR^1(R^2)^+$ results in carbocations whose reactivities show much larger responses to changes in their thermodynamic stability caused by the addition of electron-withdrawing or electron-donating α-substituents.

The expression of "normal" substituent effects on the reactivity of $XC_6H_4CR^1(R^2)^+$ with ring-substituents, X, that are less electron-donating than 4-MeO corresponds to Hammett ρ values for capture of these carbocations by solvent that increase as the α-substituent is made more electron-withdrawing. This is illustrated by the substantially smaller $\rho^+ \approx 2.1$ for the capture of $XC_6H_4CH(OMe)^+$ by 50:50 (v/v) trifluoroethanol/water[45] compared with $\rho^+ > 4.8$ for the capture of $XC_6H_4CH(CF_3)^+$ by the same solvent.[9b] The nearly constant reactivity of $4\text{-MeOC}_6H_4R^1(R^2)^+$ with a wide range of α-substituents toward solvent shows that the point of intersection of the Hammett plots of log k_s for different α-substituents R^1 and R^2 lies close to the σ^+ value for the 4-MeO substituent.

Intrinsic Barriers to Carbocation Capture. The large loss of resonance interactions of the 4-methoxyphenyl ring with the charge at the benzylic carbon in the transition state for capture of $4\text{-MeOC}_6H_4CR^1(R^2)^+$ by solvent involves extensive electronic reorganization and changes in bond lengths and angles. The *imbalance* between the loss of this resonance interaction and the polar or resonance interactions of the added α-substituents makes a very large contribution to the intrinsic barrier for this reaction.[41] The intrinsic barrier, a purely kinetic factor, is the barrier for the reaction in the absence of a thermodynamic driving force ($\Delta G^\circ = 0$).[41] This provides a qualitative explanation for the observations that the addition of electron-withdrawing α-substituents (*e.g.*, α-CF_3 or α-CO_2Et) to $4\text{-MeOC}_6H_4CR^1(R^2)^+$, which tend to increase resonance electron delocalization from the 4-methoxybenzyl ring, and hence the intrinsic barrier, leads to carbocations which appear to react "too slowly", while electron-donating α-substituents (*e.g.*, α-OMe or α-CH_3), which tend to decrease resonance electron delocalization and hence the intrinsic barrier, lead to unexpectedly reactive carbocations. These reactions are a new example of the consequences of the "principle of nonperfect synchronization".[41]

Conclusions

The effects of substituents on the thermodynamic and kinetic stability of benzylic carbocations are a result of both the direct stabilizing or destabilizing interactions due to the substituent and the attenuating effects of the substituents on other interactions. There are four general cases:

(1) Electron-withdrawing α-substituents lead to thermodynamic destabilization of benzylic carbocations, but this may be attenuated by increases in resonance electron donation from the original aromatic ring(s). They result in increases in the intrinsic barrier that *oppose* the increases in k_s due to the increases in the thermodynamic driving force.

(2) Electron-donating α-methoxy and α-methyl substituents lead to thermodynamic stabilization of benzylic carbocations, but this may be attenuated by decreases in resonance electron donation from the original aromatic ring(s). They result in decreases in the intrinsic barrier that *oppose* the decreases in k_s due to the decreases in the thermodynamic driving force.

(3) Electron-donating α-anisyl and α-azido substituents lead to thermodynamic stabilization of benzylic carbocations which is attenuated by decreases in resonance electron donation from the original aromatic ring(s). They result in increases in the intrinsic barrier that *reinforce* the decreases in k_s due to the decreases in the thermodynamic driving force.

(4) Electron-withdrawing *meta* substituents lead to thermodynamic destabilization of benzylic carbocations but they do not change the intrinsic barrier to carbocation capture. They lead to "normal" changes in k_s that parallel the increases in the thermodynamic driving force.

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(45) Estimated using $k_s = 2.2 \times 10^7\ s^{-1}$ for the capture of $4\text{-MeOC}_6H_4CH(OMe)^+$ in 50:50 (v/v) trifluoroethanol/water (Table III) and $k_s = 2 \times 10^9\ s^{-1}$ for the capture of $4\text{-HC}_6H_4CH(OMe)^+$ in 100% H_2O (ref 19), assuming that the effect of the change in solvent on k_s for the latter carbocation is the same as that determined for capture of $4\text{-MeOC}_6H_4CH(CH_3)^+$ (2-fold, ref 7b).

(46) Ta-Shma, R.; Rappoport, Z. *J. Am. Chem. Soc.* 1983, *105*, 6082–6095.