

for the *p*-nitrobenzoates and the smallest for the bromides. The $k(\text{Me})/k(\text{Me}_3\text{Si})$ of 3010 measured for 3, $\text{X} = \text{Br}$, translates into an energy difference of 4.8 kcal/mol between Me_3C^+ and $(\text{Me}_3\text{Si})\text{Me}_2\text{C}^+$, in very good agreement with the computational predictions^{4a} (taking into account the residual difference of 1.9 kcal/mol between the two bromides).

Another dramatic manifestation of these ground-state geminal effects is found in the Br/OPNB rate ratios. While $k(\text{Br})/k(\text{OPNB})$ for 3a is 7.6×10^5 ,¹² it is only 44.8 for 3b. The latter value is, to the best of our knowledge, the lowest known $k(\text{Br})/k(\text{OPNB})$ rate ratio in a k_c process.^{1,13}

In conclusion, geminal interactions even for nonpolar substituent groups such as alkyl and silyl groups must be included in the interpretation of solvolysis rates,¹⁴ as well as for other reactions in which a C-X bond is broken in a rate-determining step (e.g., radical and anionic processes). Geminal effects are significant for benzoates and sulfonates but are relatively small for Br and I. The latter should therefore be preferred for comparing solvolysis rates. Finally, this study reinforces our previous conclusion^{4a} that substitution of a Me by a Me_3Si group destabilizes tertiary carbenium ions¹⁵ by ca. 6 kcal/mol.

Acknowledgment. This work was supported by the Wolf Fund for the Promotion of the Sciences and the Arts, administered by the Israel Academy of Sciences and Humanities and partially by the Fund for the Promotion of Research at the Technion.

(11) In agreement, the ionization energy of the oxygen lone pair in α -silicon-substituted ethers is lower by ca. 1 eV relative to those of alkyl-substituted ethers. See: Matsunaga, S.; Isoe, S.; Yoshida, J.; Maekawa, T.; Murata, T. *J. Am. Chem. Soc.* 1990, 112, 1962.

(12) This value is close to other reported $k(\text{Br})/k(\text{OPNB})$ rate ratios, e.g., 5×10^5 for Ph_2CHX . See: Goering, H. L.; Hopf, H. *J. Am. Chem. Soc.* 1971, 93, 1224.

(13) For examples of the common situation, where the relative nucleofugalities of leaving groups in solvolysis reactions are nearly independent of the substrate, see: Bentley, T. W.; Roberts, K. *J. Org. Chem.* 1985, 50, 5852; 1985, 50, 4821.

(14) Richard, J. P.; Amyes, T. L.; Rice, D. *J. Am. Chem. Soc.*, following paper in this issue. The authors reach similar conclusions regarding the rates of solvolysis of MeOCH_2X , $\text{X} = \text{F}, \text{Cl}, \text{OCH}_3$. Note that in this case polar geminal groups are involved.

(15) For recent support, see: Soderquist, J. A.; Hassner, A. *Tetrahedron Lett.* 1988, 1899. See also ref 10.

Effects of Electronic Geminal Interactions on the Solvolytic Reactivity of Methoxymethyl Derivatives

John P. Richard,* Tina L. Amyes, and Douglas J. Rice

Department of Chemistry, University of Kentucky
Lexington, Kentucky 40506-0055

Received December 7, 1992

We report that compounds with strong stabilizing geminal interactions, methoxymethyl fluoride and methoxymethyl methyl ether, are strongly stabilized toward hydrolysis in comparison with methoxymethyl chloride, a compound with a much weaker stabilizing geminal interaction.

There is extensive evidence from thermochemical measurements,¹ ab initio calculations,² and experiment³ that geminal interactions between electronegative substituents across a methylene group are stabilizing by up to 17.4 kcal/mol for formaldehyde hydrate.² These stabilizing geminal interactions are responsible for the anomeric effect.⁴ It is evident from first

Table I. Rate Constants for the Hydrolysis of 4-Methoxybenzyl Derivatives and Methoxymethyl Derivatives^a

X	MeOCH_2X	4-MeOC ₆ H ₄ CH ₂ X
MeO/H ⁺ ^b	$1.3 \times 10^{-5} \text{ M}^{-1} \text{ s}^{-1 \text{ c}}$	$3.7 \times 10^{-5} \text{ M}^{-1} \text{ s}^{-1 \text{ d}}$
F ^e	$1.6 \times 10^{-3} \text{ s}^{-1 \text{ f,g}}$	$8.0 \times 10^{-3} \text{ s}^{-1 \text{ f,h}}$
Cl ^e	$5 \times 10^4 \text{ s}^{-1 \text{ i}}$	$4 \text{ s}^{-1 \text{ j}}$
$k_{\text{Cl}}/k_{\text{F}}$	3.1×10^7	5.0×10^2
$k_{\text{Cl}}/k_{\text{MeOH}}$	$3.8 \times 10^9 \text{ M}$	$1.1 \times 10^5 \text{ M}$

^aIn aqueous solution at 25 °C. ^bSecond-order rate constants for specific-acid-catalyzed cleavage of the methyl ethers. ^cReference 7. A statistical correction was made by dividing the reported rate constants by 2. ^dAt $I = 0.30$ (KCl), this work. Pseudo-first-order rate constants, k_{obsd} , in the presence of 0.10, 0.20, and 0.30 M HCl were determined by following the disappearance of the substrate by HPLC. The second-order rate constant was obtained from the slope of a plot of k_{obsd} against $[\text{H}^+]$. ^eThe first-order rate constant for the hydrolysis reaction. ^fFor a reaction in the presence of 0.10 M NaOH and 0.10 M NaClO₄. ^gReference 9. ^hThis work. Determined spectrophotometrically by following the disappearance of the substrate at 240 nm. ⁱEstimated by extrapolation of a plot of $\log k$ for solvolysis of MeOCH_2Cl in acetone/water mixtures at 25 °C (ref 8) against Y to $Y = 3.49$ for 100% water.¹⁷ ^jEstimated by extrapolation of $\log k$ for solvolysis of 4-MeOC₆H₄CH₂Cl in 70% and 80% acetone in water at 25 °C (ref 12) using $m = 1.08$ (Graczyk, D. G.; Taylor, J. W.; Turnquist, C. R. *J. Am. Chem. Soc.* 1978, 100, 7333-7339) and $Y = 3.49$ for 100% water.¹⁷

principles that the presence of geminal interactions must be manifested in the rate constants for reactions in which they are lost.^{5,6} However, this fact has not gained wide recognition because of the absence of quantitative evaluations of the effect of ground-state geminal interactions on the reactivity of classical substrates for nucleophilic substitution reactions such as 4-methoxybenzyl and methoxymethyl derivatives.

Table I compares rate constants obtained from the literature for the acid-catalyzed hydrolysis of methoxymethyl methyl ether⁷ and the uncatalyzed hydrolysis reactions of methoxymethyl chloride⁸ and fluoride⁹ with rate constants for the hydrolysis of the corresponding 4-methoxybenzyl derivatives that were determined in this work.¹⁰



$\text{X} = \text{Cl}, \text{F}, \text{MeO}/\text{H}^+$

The data in Table I show that there are large differences between the relative nucleofugalities of leaving groups at methoxymethyl derivatives and at the corresponding 4-methoxybenzyl derivatives. The difference in the reactivities of a chloride ion and a fluoride ion as leaving groups is 60 000-fold larger for the reactions of MeOCH_2X , for which $k_{\text{Cl}}/k_{\text{F}} = 3.1 \times 10^7$, than for the reactions of 4-MeOC₆H₄CH₂X, for which $k_{\text{Cl}}/k_{\text{F}} = 500$. That is, fluoride ion is a much worse leaving group compared with chloride ion when it is attached to a MeOCH_2 - moiety than when it is attached to a 4-MeOC₆H₄CH₂- moiety. Assuming that geminal interactions in 4-MeOC₆H₄CH₂X are negligible, then the 60 000-fold larger value of $k_{\text{Cl}}/k_{\text{F}}$ for the reaction of MeOCH_2X can be explained by a ≥ 6.4 kcal/mol larger geminal ground-state stabilization of MeOCH_2F than of MeOCH_2Cl and

(5) Harcourt, M. P.; More O'Ferrall, R. A. *J. Chem. Soc., Chem. Commun.* 1987, 823-824.

(6) (a) Kirmse, W.; Goer, B. *J. Am. Chem. Soc.* 1990, 112, 4556-4557. (b) Wu, Y.-D.; Kirmse, W.; Houk, K. N. *J. Am. Chem. Soc.* 1990, 112, 4557-2559. (c) Apeloig, Y.; Karni, M. *J. Chem. Soc., Perkin Trans. 2* 1988, 625-636. (d) Kirmse, W.; Wonner, A.; Allen, A. D.; Tidwell, T. T. *J. Am. Chem. Soc.* 1992, 114, 8828-8835.

(7) Salomaa, P. *Suomen Kemis. B* 1960, 33, 11-16.

(8) Jones, T. C.; Thornton, E. R. *J. Am. Chem. Soc.* 1967, 89, 4863-4867.

(9) Kokesh, F. C.; Hine, J. *J. Org. Chem.* 1976, 41, 1976-1979.

(10) 4-Methoxybenzyl fluoride was synthesized by a literature procedure.¹¹ 4-Methoxybenzyl methyl ether was prepared by reaction of 4-methoxybenzyl chloride with sodium methoxide in methanol at room temperature for 22 h.

(1) Hine, J. *Structural Effects on Equilibria in Organic Chemistry*; Wiley-Interscience: New York, 1975, pp 8-10.

(2) (a) Schleyer, P. v. R.; Jemmis, E. D.; Spitznagel, G. W. *J. Am. Chem. Soc.* 1985, 107, 6393-6394. (b) Reed, A. E.; Schleyer, P. v. R. *J. Am. Chem. Soc.* 1987, 109, 7362-7373.

(3) More O'Ferrall, R. A.; Murray, B. A. *J. Chem. Soc., Chem. Commun.* 1988, 1098-1099.

(4) Lemieux, R. U.; Koto, S. *Tetrahedron* 1974, 30, 1933-1944. Kirby, A. J. *The Anomeric Effect and Related Stereoelectronic Effects in Organic Chemistry*; Pergamon: Oxford, 1983.

a large fractional loss of this interaction on moving to the carbocation-like transition state for the hydrolysis reactions.^{8,9,12} The difference in the geminal stabilization energy of HOCH₂F compared with HOCH₂Cl obtained from ab initio calculations, 10.4 kcal/mol,^{2a} is significantly larger than the 6.4 kcal/mol geminal stabilization of MeOCH₂F toward hydrolysis. This difference may reflect only a partial loss of stabilizing geminal interactions at the transition state for the hydrolysis reaction and/or a failure of the assumption that geminal interactions in 4-MeOC₆H₄CH₂X are negligible.

Data for the acid-catalyzed hydrolysis reactions of MeOCH₂OMe and 4-MeOC₆H₄CH₂OMe yield similar conclusions. The 35 000-fold difference between the rate constant ratios $k_{Cl}/k_{MeOH} = 3.8 \times 10^9$ M for the reaction of MeOCH₂X and $k_{Cl}/k_{MeOH} = 1.1 \times 10^5$ M for the reaction of 4-MeOC₆H₄CH₂X is consistent with a ≥ 6.1 kcal/mol larger geminal ground-state stabilization of MeOCH₂OMe than of MeOCH₂Cl.¹³ By comparison, the difference in the geminal stabilization energies of HOCH₂OMe and HOCH₂Cl obtained from ab initio calculations is 11.6 kcal/mol.^{2a}

The 10⁴-fold greater reactivity of MeOCH₂Cl than of 4-MeOC₆H₄CH₂Cl toward hydrolysis (Table I) shows that MeOCH₂⁺ is at least 5.5 kcal/mol more stable than 4-MeOC₆H₄CH₂⁺ relative to the neutral chloride ion adducts. However, the relative rate constants for hydrolysis of MeOCH₂F and 4-MeOC₆H₄CH₂F or the corresponding methyl ethers show that 4-MeOC₆H₄CH₂⁺ is slightly more stable than MeOCH₂⁺ relative to the neutral fluoride or methoxide ion adducts. These data show that it is difficult to infer the relative stability of MeOCH₂⁺ and 4-MeOC₆H₄CH₂⁺ directly from the relative rate constants for solvolyses of neutral derivatives, because these depend upon the relative stabilities of the ground states and the carbocation-like transition states, both of which may differ. Similar difficulties have been encountered in the determination of the relative stabilities of α -cyano- and β -cyano-substituted carbocations^{6a,b} and of α -methyl- and α -silyl-substituted carbocations^{15,16} from relative rate constants for solvolysis reactions of neutral precursors.

We conclude that care must be exercised in the choice of a neutral ground state when evaluating substituent effects on carbocation stability. The use of leaving groups from the second and lower rows on the periodic table (e.g., I⁻, Cl⁻), which show relatively weak electronic geminal interactions,^{2a} is to be preferred over the use of oxygen leaving groups for the estimation of carbocation stabilities from the relative rate constants for solvolyses reactions. Electronic geminal interactions with hydrogen are particularly weak and are used as the 0 reference point in determination of geminal interactions between other groups. Therefore, substituent effects on carbocation stability are best

determined from experimental or computational data for the formation of carbocations from neutral alkanes.

Acknowledgment. This work was supported by grants from the National Institutes of Health (GM 39754) and the donors of the Petroleum Research Fund, administered by the American Chemical Society (23711-AC4).

Direct Observation of Reduced Bond Length Alternation in Donor/Acceptor Polyenes

Seth R. Marder,^{*,†,‡} Joseph W. Perry,^{*,†}
Bruce G. Tiemann,^{†,‡} Christopher B. Gorman,[†]
Sandra Gilmour,[†] Shawna L. Biddle,[†] and Grant Bourhill[†]

Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive, Pasadena, California 91109
Molecular Materials Resource Center
The Beckman Institute, 139-74
California Institute of Technology
Pasadena, California 91125

Received November 16, 1992

There has been tremendous interest in asymmetric cyanine and merocyanine compounds because of their applications as photographic sensitizers,^{1,2} membrane potential probes,^{3,4} and photochromic dyes for all-optical memory.⁵ On the basis of UV-visible spectroscopic data, Brooker suggested that merocyanine molecules could be described by a superposition of neutral and charge-separated canonical resonance forms and that, by changing the basicity of the endgroups and/or the solvent polarity, one could tune the molecular structure from neutral and polyene-like through polar and cyanine-like (with equal contributions from neutral and charge-separated resonance forms) to highly polar, charge-separated polyene-like.^{1,6-10} Since the neutral and charge-separated resonance structures have different equilibrium geometries, the degree of bond length alternation in merocyanines can be tuned from close to that found in a polyene [i.e., the difference between the average length of the carbon-carbon single and double bonds [$r(C-C) - r(C=C)$] equals 0.11 Å (for diphenyloctatetraene¹¹ and for octatetraene¹²)] to essentially none, as found in cyanines.^{13,14}

The degree of bond length alternation has been used as a structural parameter in interpreting electronic spectra of poly-

(11) Shimizu, M.; Nakahara, Y.; Yoshioka, H. *Tetrahedron Lett.* **1985**, 26, 4207-4210.

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

(13) The difference in basicity for protonation of the leaving groups at MeOCH₂OMe and 4-MeOC₆H₄OMe should be close to the difference in acidities for deprotonation of MeOCH₂OH ($pK_a = 13.6$, Funderburk, L. H.; Aldwin, L.; Jencks, W. P. *J. Am. Chem. Soc.* **1978**, 100, 5444-5459) and 4-MeOC₆H₄OH ($pK_a = 15.6$).¹⁴ However, the difference in the stabilities of the two oxonium ions will be reflected to only a small extent in the rate constants k_H for the endothermic ionization reactions of these species, because 70-80% of the charge at oxygen has been lost at the "late" transition states for these reactions (Amyes, T. L.; Jencks, W. P. *J. Am. Chem. Soc.* **1989**, 111, 7888-7900).

(14) Estimated from $pK_a = 15.4$ for PhCH₂OH (Jencks, W. P.; Regenstein, J. In *Handbook of Biochemistry and Molecular Biology*, 3rd ed.; Fasman, G. D., Ed.; CRC Press: Cleveland, OH, 1976; Physical and Chemical Data, Vol. 1, pp 305-351) and the 0.2-unit effect of the 4-MeO substituent on the pK_a of trifluoroacetophenone hydrate (Stewart, R.; Van der Linden, R. *Can. J. Chem.* **1960**, 38, 399-406).

(15) Apeloig, Y.; Stanger, A. *J. Am. Chem. Soc.* **1985**, 107, 2806-2807.

(16) (a) Apeloig, Y.; Abu-Freih, A.; Biton, R.; Stanger, A. 11th IUPAC Conference on Physical Organic Chemistry, August 1992, Ithaca, NY. (b) Apeloig, Y.; Biton, R.; Abu-Freih, A. *J. Am. Chem. Soc.*, preceding paper in this issue.

(17) Fainberg, A. H.; Winstein, S. *J. Am. Chem. Soc.* **1956**, 78, 2770-2777.

[†] Jet Propulsion Laboratory.

[‡] Molecular Materials Resource Center, The Beckman Institute.

(1) Brooker, L. G. S. U.S. Patent 2,170,803, 1939.

(2) Carroll, B. H.; Brooker, L. G. S. U.S. Patent 2,430,558, 1947.

(3) Waggoner, A. *J. Membr. Biol.* **1976**, 27, 317-334.

(4) Dasheiff, R. M. *J. Clin. Neurophysiol.* **1988**, 5, 211-235.

(5) Pathenopoulos, D. A.; Rentzepis, P. M. *Science* **1989**, 245, 843-845.

(6) Brooker, L. G. S.; Sprague, R. H. *J. Am. Chem. Soc.* **1941**, 63, 3214-3215.

(7) Brooker, L. G. S.; Keyes, G. H.; Williams, W. W. *J. Am. Chem. Soc.* **1942**, 64, 199-210.

(8) Brooker, L. G. S.; Keyes, G. H.; Sprague, R. H.; VanDyke, R. H.; VanLare, E.; VanZandt, G.; White, F. L.; Cressman, H. W. J.; Dent, J. S. *G. J. Am. Chem. Soc.* **1951**, 73, 5332-5350.

(9) Brooker, L. G. S.; Keyes, G. H.; Sprague, R. H.; VanDyke, R. H.; VanLare, E.; VanZandt, G.; White, F. L. *J. Am. Chem. Soc.* **1951**, 73, 5326-5332.

(10) Brooker, L. G. S.; Craig, A. C.; Heseltine, D. W.; Jenkins, P. W.; Lincoln, L. L. *J. Am. Chem. Soc.* **1965**, 87, 2443-2450.

(11) Drenth, W.; Wiebenga, E. H. *Acta Crystallogr.* **1955**, 8, 755-760.

(12) Baughman, R. H.; Kohler, B. E.; Levy, I. J.; Spangler, C. *Synth. Met.* **1985**, 11, 37-52.

(13) Groth, P. *Acta Chem. Scand. B* **1987**, 41, 547-550.

(14) Chentli-Bechikha, F.; Declercq, J. P.; Germain, G.; Meerssche, M. *V. Cryst. Struct. Commun.* **1977**, 6, 421-424.