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Systematic Repression of β-Silyl Carbocation Stabilization

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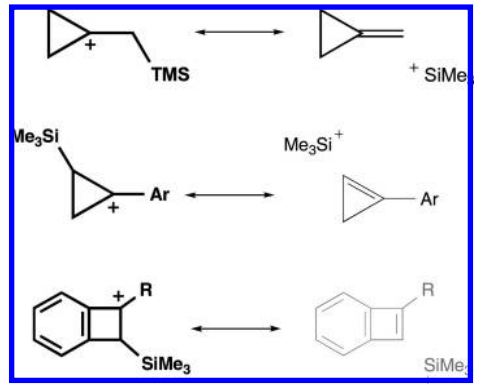

Solvolysis of 1-(trimethylsilylmethyl)cyclopropyl mesylate in CD_3CO_2D gives ring-opened products as well as methylenecyclopropane. The rate enhancement due to the β-trimethylsilyl group is a factor of about 10^6. The large stabilizing effect of a β-silyl group (which can cause rate enhancements of up to 10^{12}) on the intermediate cation has been repressed. B3LYP/6-31G* computational studies indicate a carbocation stabilization energy of 16.6 kcal/mol. Rates of solvolyses of 1-phenyl-2-trimethylsilylcyclopropyl chlorides are enhanced by a factor of 10^3-10^4. The intermediate cyclopropyl cation undergoes substantial ring opening since β-silyl stabilization is not large (calculated stabilization energy of 12 kcal/mol). Solvolysis rates of 2-trimethylsilylbenzocyclobutyl derivatives are not significantly enhanced by the β-trimethylsilyl group. β-Silyl stabilization of benzocyclobutenyl carbocations generated in solution has been effectively eliminated due to antiaromatic considerations (calculated stabilization energy of 3.7 kcal/mol when R = Ph). While computational studies parallel solvolytic rate studies, they overestimate the extent of β-trimethylsilyl stabilization of solvolytically generated carbocations.

Introduction

Features that stabilize and destabilize reactive intermediates have fascinated chemists over the years. We have been heavily involved in the study of carbocation reactive intermediates that are both stabilized and destabilized by electronic factors. Carbocations **1**, where the group E is formally electron-withdrawing, represent so-called "destabilized carbocations",[1] while cyclopropyl cations **2** represent a class of carbocations that are destabilized due to bond angle effects.[2] Both of these types of carbocations have been studied in much detail. On the other side of the general stability spectrum lie carbocations of general structure **3**, where stabilization by adjacent silicon is quite dramatic.[3,4] This phenomenon has also been extensively

(1) (a) Bégué, J.-P.; Charpentier-Morize, M. *Acc. Chem. Res.* **1980**, *13*, 207. (b) Gassman, P. G.; Tidwell, T. T. *Acc. Chem. Res.* **1983**, *16*, 279. (c) Creary, X. *Acc. Chem. Res.* **1985**, *18*, 3. (d) Allen, A. D.; Tidwell, T. T. In *Advances in Carbocation Chemistry*; Creary, X., Ed.; JAI Press Inc.: Greenwich, CT, 1989, p 1. (e) Creary, X. *Advances in Carbocation Chemistry*; Creary, X., Ed.; JAI Press Inc.: Greenwich, CT, 1989, p 45. (f) Charpentier-Morize, M.; Bonnet-Delpon, D. In *Advances in Carbocation Chemistry*; Creary, X., Ed.; JAI Press Inc.: Greenwich, CT, 1989, p 219. (g) Takeuchi, K.; Yoshida, M. *J. Org. Chem.* **1989**, *54*, 3772. (h) Creary, X. *Chem. Rev.* **1991**, *91*, 1625.

(2) (a) Roberts, J. D.; Chambers, V. C. *J. Am. Chem. Soc.* **1951**, *73*, 5034. (b) Foote, C. S. *J. Am. Chem. Soc.* **1964**, *86*, 1853. (c) Schleyer, P. v. R. *J. Am. Chem. Soc.* **1964**, *86*, 1854. (d) Schleyer, P. v. R. *J. Am. Chem. Soc,* **1964**, *86*, 1856. (e) Woodward, R. B.; Hoffman, R. *J. Am. Chem. Soc.* **1965**, *87*, 395. (f) Schleyer, P. v. R.; Su, T. M.; Saunders, M.; Rosenfeld, J. C. *J. Am. Chem. Soc.* **1969**, *91*, 5174. (g) Schleyer, P. v. R.; Sliwinski, W. F.; Van Dine, G. W.; Schoellkopf, U.; Paust, J.; Fellenberger, K. *J. Am. Chem. Soc.* **1972**, *94*, 125. (h) DePuy, C. H.; Schnack, L. G.; Hausser, J. W.; Wiedemann, W. *J. Am. Chem. Soc.* **1965**, *87*, 4006. (i) Creary, X. *J. Org. Chem.* **1976**, *41*, 3740. (j) DePuy, C. H.; Schnack, L. G.; Hausser, J. W. *J. Am. Chem. Soc.* **1966**, *88*, 3343. (k) Brown, H. C.; Rao, C. G.; Ravindranathan, M. *J. Am. Chem. Soc.* **1977**, *99*, 7663.

(3) For reviews and early studies, see: (a) Colvin, E. W. *Silicon in Organic Synthesis*; Butterworths: London, 1981. (b) White, J. M. *Aust. J. Chem.* **1995**, *48*, 1227.

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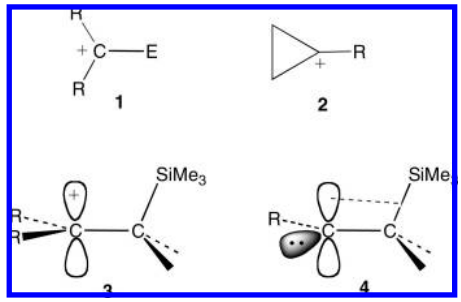
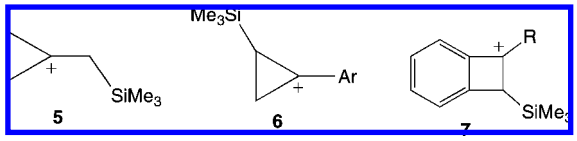
studied quantitatively by Lambert.[5] Stabilization of carbocations by β-silyl groups is due to a favorable interaction between the cation vacant p-orbital with the adjacent C−Si σ-bond. A recent X-ray crystallographic and computational study on a cyclopropylcarbinyl type of β-silyl cation supports this stabilization mechanism.[6] Stabilization of aryl cations by β-silyl groups has also recently been reported.[7] A similar type of stabilization occurs in carbenes **4** and this interaction leads to facile silyl migration to the carbenic center of β-silyl carbenes **4**.[8]



It was our desire to combine these two contrasting themes. What kind of reactivity will a β-silylcyclopropyl carbocation have? Is the carbocation-stabilizing ability of a β-silyl group enhanced due to the extraordinary stabilization demands of cyclopropyl cations? Is this β-silyl effect powerful enough to stabilize cyclopropyl cations enough to prevent ring opening? Or is the β-silyl effect repressed due to hyperconjugation problems in small rings? To what extent will these cations undergo desilylation, the usual fate of β-silyl carbocations? We now report on the chemistry of carbocations **5** and **6**. It was hoped that potential cations **5** and **6** would give further insight into both cyclopropyl and β-trimethylsilyl carbocations. Finally, the benzocyclobutenyl carbocations **7** were also investigated. This system represents one in which the large demand for β-trimethylsilyl stabilization is potentially repressed due to antiaromatic considerations.



Results and Discussion

Solvolytic Generation of Carbocation 5. Synthesis of the mesylate **9** (a precursor to carbocation **5**) from the alcohol **8** was straightforward (Scheme 1). The mesylate **9** reacted readily in CD_3CO_2D at room temperature to give methylenecyclopropane **10** (30%), the ring-opened acetate **11** (26%), and the ring-opened mesylate **12** (44%). These products are consistent with the involvement of cation **5** in the acetolysis of **9**. Loss of the trimethylsilyl group from **5** would generate **10**, while competing ring opening to allylic cation **13** and solvent capture gives **11**. Internal return is often seen in cationic rearrangements, and mesylate **12** is derived from this process. This mesylate **12** is unreactive under the acetolysis conditions.

Kinetic studies provide evidence for the role of the trimethylsilyl group in the solvolysis of **9**. Rate data for **9** in CD_3CO_2D and previously studied substrates are summarized in Table 1. Note that in terms of solvolysis rates, tosylate and mesylate

SCHEME 1. Synthesis and Solvolysis of 1-(Trimethylsilylmethyl)cyclopropyl Mesylate

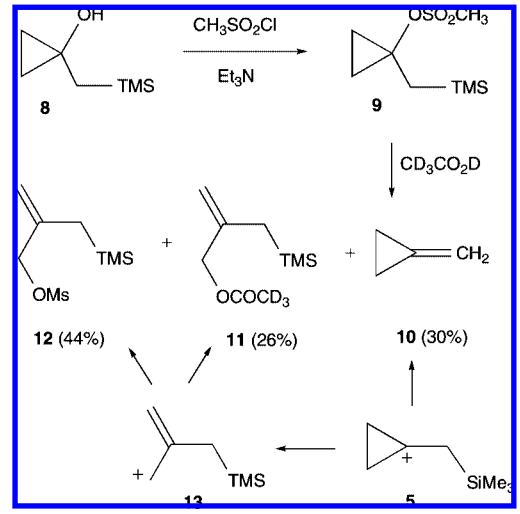
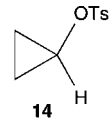
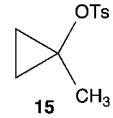
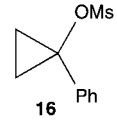
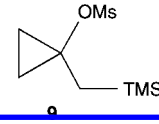


TABLE 1. Solvolysis Rates for Substrates in CD_3CO_2D

Compound	T (°C)	$k(s^{-1})$	k_{rel}
 **14**	25.0	5.71×10^{-13} [a]	1
 **15**	25.0	6.16×10^{-10} [a]	10^3
 **16**	59.8 40.0 25.0	8.38×10^{-5} 6.78×10^{-6} 8.11×10^{-7} [b]	10^6
 **9**	25.0	4.75×10^{-4}	10^9

[a] Solvent is nondeuterated. [b] Extrapolated from data at higher temperatures.

(4) (a) Ushakav, S. N.; Itenberg, A. M. *Zh. Obshch. Khim.* **1937**, *7*, 2495. (b) Sommer, L. H.; Dorfman, E.; Goldberg, G. M.; Whitmore, F. C. *J. Am. Chem. Soc.* **1946**, *68*, 488. (c) Sommer, L. H.; Bailey, D. L.; Whitmore, F. C. *J. Am. Chem. Soc.* **1948**, *70*, 2869. (d) Sommer, L. H.; Baughman, G. A. *J. Am. Chem. Soc.* **1961**, *83*, 3346. (e) Davis, D. D.; Jacocks, H. M., III. *J. Organomet. Chem.* **1981**, *206*, 33.

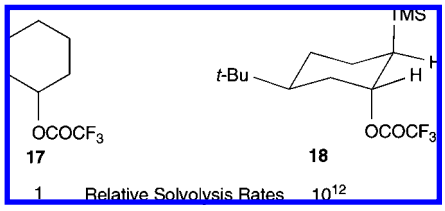
(5) (a) Lambert, J. B.; Wang, G.-t.; Finzel, R. B.; Teramura, D. H. *J. Am. Chem. Soc.* **1987**, *109*, 7838. (b) Lambert, J. B.; Chelius, E. C. *J. Am. Chem. Soc.* **1990**, *112*, 8120. (c) Lambert, J. B. *Tetrahedron* **1990**, *46*, 2677. (d) Lambert, J. B.; Liu, X. *J. Organomet. Chem.* **1996**, *521*, 203. (e) Lambert, J. B.; Zhao, Y.; Emblidge, R. W.; Salvador, L. A.; Liu, X.; So, J. H.; Chelius, E. C. *Acc. Chem. Res.* **1999**, *32*, 183.

(6) Klaer, A.; Saak, W.; Haase, D.; Müller, T. *J. Am. Chem. Soc.* **2008**, *130*, 14956.

(7) (a) Dichiarante, V.; Salvaneschi, A.; Protti, S.; Dondi, D.; Fagnoni, M.; Albini, A. *J. Am. Chem. Soc.* **2007**, *129*, 15919. (b) Himeshima, Y.; Kobayashi, H.; Sonada, T. *J. Am. Chem. Soc.* **1985**, *107*, 5286.

(8) (a) Creary, X.; Wang, Y.-X. *Tetrahedron Lett.* **1989**, *19*, 2493. (b) Creary, X.; Wang, Y.-X. *J. Org. Chem.* **1994**, *59*, 1604. (c) Creary, X.; Butchko, M. A. *J. Org. Chem.* **2001**, *66*, 1115. (d) Creary, X.; Butchko, M. A. *J. Org. Chem.* **2002**, *67*, 112.

leaving groups are comparable.[9] The mesylate **9** is the most reactive substrate in Table 1. It is 10^3 more reactive than the phenyl analogue **16** and 10^6 more reactive than the "desilylated analogue" **15**. How does this 10^6 rate enhancement relative to **15** compare with other cases of β-silyl rate enhancements?[10] A classic example is Lambert's β-trimethylsilylcyclohexyl trifluoroacetate **18**, where the rate enhancement relative to the "desilylated" cyclohexyl trifluoroacetate **17** is a factor of 10^{12}.[5b] In view of this enormous rate-enhancing ability of a β-trimethylsilyl group in **18**, the rate enhancement of 10^6 in **9** appears to have been "repressed" significantly relative to this maximum value.



Computational Studies on Cation 5. Molecular orbital calculations can also be used to gain insight into the structure of carbocation intermediates. Figure 1 shows the B3LYP/6-31G*-calculated structure of cation **5**, which is an energy minimum, as well as the corresponding neutral molecule **19**. The indicated carbon−carbon bond has contracted from 1.522 to 1.368 Å in the cation. This implies some double-bond character in **5** and, thus, a stabilizing effect by the trimethylsilyl group. Furthermore, the calculated structure of 5 shows a tilting of the trimethylsilyl group toward the cationic center, which is also indicative of significant β-silyl stabilization.

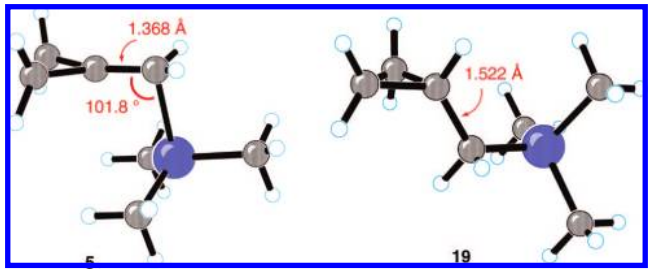
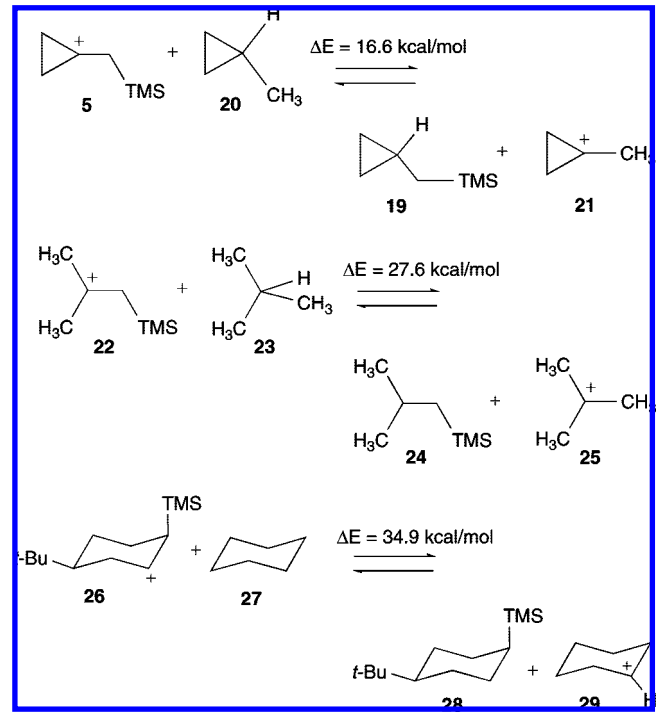


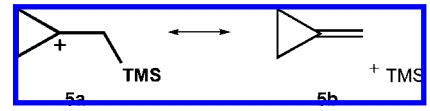
FIGURE 1. B3LYP/6-31G*-calculated structures of cation **5** and (trimethylsilylmethyl)cyclopropane, **19**.

How does the stabilization of carbocation **5** compare to calculated measures of β-silyl stabilization? There have been previous ab initio calculations of β-SiH_3 stabilization of other carbocations,[10] as well as estimations of β-silyl stabilization based on gas-phase studies.[11] The isodesmic calculations (B3LYP/6-31G*) shown in Scheme 2 represent an attempt to quantify the stabilizing effect of the β-trimethylsilyl group in **5**. Comparison of the energy of **5** with that of the 1-methylcyclopropyl cation **21** is complicated by the fact that **21** is not an energy minimum at the B3LYP/6-31G* level but opens without barrier to the corresponding allylic cation. For the purpose of this calculation, cation **21** was therefore constrained by fixing the internal carbocation bond angle to prevent ring opening. The resulting calculation suggests that the β-silyl cation **5** is stabilized by 16.6 kcal/mol relative to the desilylated analogue **21**. Silyl stabilization of the acyclic cation **22** is quantified by the second isodesmic calculation in Scheme 2. This cation **22** is stabilized by 27.6 kcal/mol relative to **25**. The β-silyl stabilization of cyclopropyl cation **5**, at least computationally, is 11 kcal/mol less than stabilization of the acyclic analogue **22**. The third isodesmic calculation in Scheme 2 suggests that the β-silyl cation **26** involved in the Lambert rate study[5b] is stabilized by 34.9 kcal/mol relative to the cyclohexyl cation **29**. By any computational measure, stabilization of cation **5** by the β-silyl group does not approach that of model systems.

SCHEME 2. Isodesmic Calculations Evaluating β-Trimethylsilyl Cation Stabilization



These computational studies are in line with our kinetic studies that suggest that there is significant stabilization of cation **5** by the β-silyl group. However, this stabilization is substantially smaller than one might expect given the large demands of cyclopropyl cations. This repression of β-silyl stabilization in **5** is a manifestation of repressed overlap between the carbon−silicon bond and the vacant p-orbital of the carbocation. This can be rationalized using a valence bond approach. The high strain in methylenecyclopropane (40 kcal/mol)[13] makes contributions of form **5b** less important than in analogous acyclic forms. In qualitative terms, **5b** is less prominent, i.e., less "bold" than **5a**.



Solvolytic Generation of Carbocation 6. Attention was next focused on systems where the trimethylsilyl group was directly

(9) Robertson, R. E. *Prog. Phys. Org. Chem.* **1967**, *4*, 213.
(10) Enhancement due to trimethylsilyl assistance in **9** may in fact be larger than a factor of 10^6. This is because the model system **15** is itself rate-enhanced[2i] due to the k_Δ process by which it solvolyzes.
(11) (a) Wierschke, S. G.; Chandrasekhar, J.; Jorgensen, W. L. *J. Am. Chem. Soc.* **1985**, *107*, 1496. (b) Ibrahim, M. R.; Jorgensen, W. L. *J. Am. Chem. Soc.* **1989**, *111*, 819.
(12) (a) Hajdasz, D.; Squires, R. *J. Chem. Soc., Chem. Commun.* **1988**, 1212. (b) Li, X.; Stone, J. A. *J. Am. Chem. Soc.* **1989**, *111*, 5586.
(13) Johnson, W. T. G.; Borden, W. T. *J. Am. Chem. Soc.* **1997**, *119*, 5930.

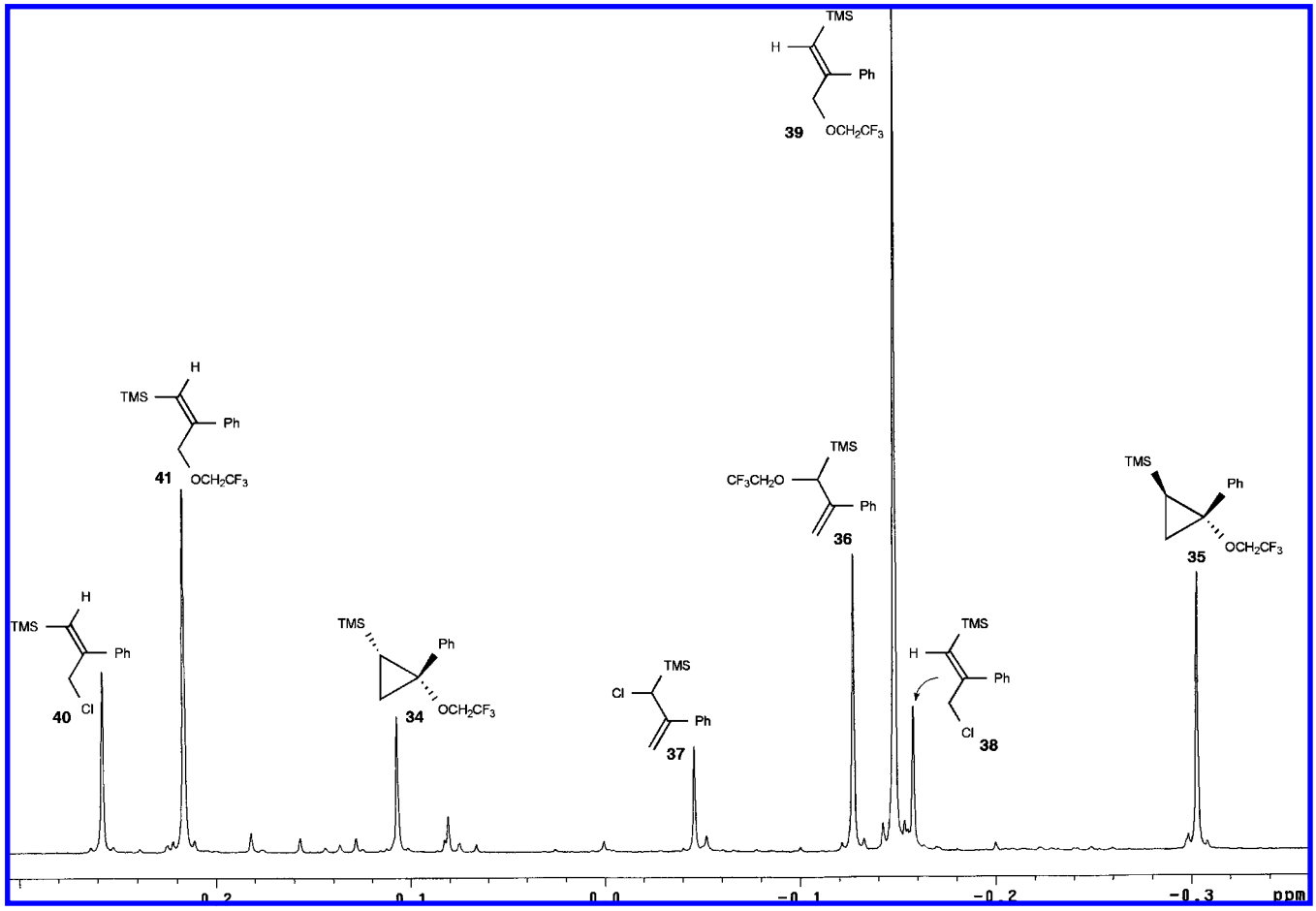
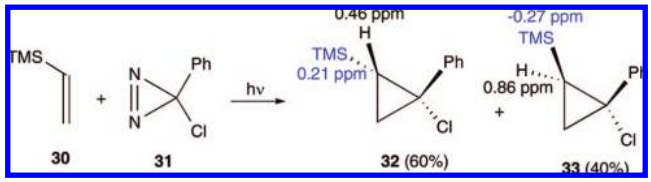


FIGURE 2. ^{1}H NMR spectrum (upfield region) of products from reaction of **32** and **33** in CF_3CH_2OH.

SCHEME 3. Synthesis of Chlorides 32 and 33

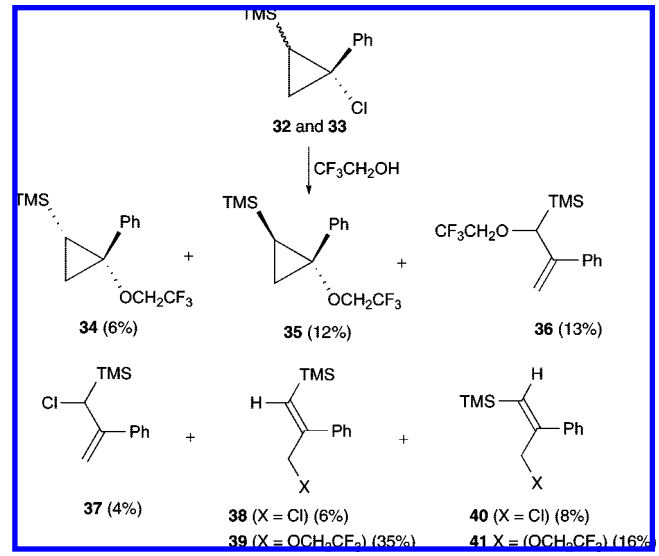


attached to the cyclopropyl ring. Chlorides **32** and **33** were prepared as an inseparable mixture by photolysis of a solution of phenylchlorodiazarine **31**[14] in vinyltrimethylsilane **30** (Scheme 3). Stereochemical assignments were based on NMR shifts of the trimethylsilyl groups and the corresponding α-protons of **32** and **33**. The trimethylsilyl group of **33** is in the shielding region of the *cis*-phenyl ring and therefore has a distinct upfield shift (−0.24 ppm). For similar reasons, the *cis*-hydrogen in **32** (0.46 ppm) is further upfield than the corresponding *trans*-hydrogen in **33** (0.86 ppm). These observed chemical shifts correspond well with calculated chemical shifts based on the B3LYP/6-31G* structures of **32** and **33**.

The mixture of chlorides **32** and **33** was solvolyzed in CF_3CH_2OH containing 2,6-lutidine as a buffering base. Under these conditions, a complex mixture of products was formed as evidenced by the trimethylsilyl region of the ^{1}H NMR spectrum of the products (Figure 2). Despite the challenge presented by this mixture, the eight different products were all

(14) (a) Graham, W. H. *J. Am. Chem. Soc.* **1965**, *87*, 4396. (b) Padwa, A.; Pulwer, M. J.; Blacklock, T. J. *Org. Synth., Coll. Vol. VII* **1990**, 203.

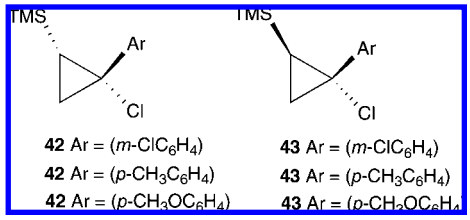
SCHEME 4. Solvolysis Products from 32 and 32 in CF_3CH_2OH



identified using a variety of techniques that included independent syntheses, and comparison of calculated ^{1}H NMR chemical shifts to differentiate isomers. Structures are shown in Scheme 4 and trimethylsilyl signals are all appropriately labeled in Figure 2. This mixture of rearranged and unrearranged products is completely consistent with the intermediacy of a cyclopropyl

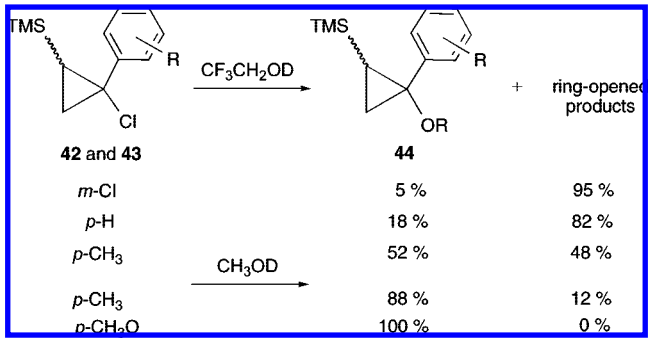
cationic intermediate which partitions between solvent capture and ring-opening processes.

Kinetic Studies on 32, 33, and Aryl Analogues. In order to further probe the nature of the cationic intermediate produced on solvolysis of **32** and **33**, the aryl-substituted cyclopropyl chlorides **42** and **43** were synthesized using the same general method involving arylchlorodiazirine photolyses in vinyltrimethylsilane. As before, inseparable mixtures of **42** and **43** were formed.



Solvolytic studies were carried out in either CF_3CH_2OD or CH_3OD for the very reactive *p*-CH_3- and *p*-CH_3O-containing substrates. Mixtures of ring-retained trifluoroethyl ethers **44** and ring-opened allylic products analogous to those formed in Scheme 4 were produced, and these are summarized in Scheme 5. As the substituent became more electron donating, more of the products derived from solvent capture of the closed cyclopropyl carbocation were formed. In the case of *p*-OCH_3 substitution, only ring-closed products **44** were formed. It is important to note that none of these solvolyses gave products where the trimethylsilyl group was lost.

SCHEME 5. Solvolysis Products from 42 and 43 in CF_3CH_2OD and CH_3OD



Rates of reaction of **32** and **33**, as well as substituted analogues **42** and **43**, were determined by monitoring the disappearance of the ^1H NMR signal corresponding to the trimethylsilyl groups of the starting chlorides. There were no problems encountered by using isomeric mixtures for kinetic studies since signals corresponding to **32** and **33** are cleanly separated from each other as well as from product signals. Rate data are summarized in Table 2. For comparison purposes, rate data for 1-chlorophenylcyclopropane, **45**, the desilylated analogue of **32** and **33**, are also given. Solvolyses of **42** (*p*-OCH_3) and **43** (*p*-OCH_3) in CF_3CH_2OD were too fast to monitor accurately by ^1H NMR. Therefore, these reactions were monitored in CH_3OD. The rate of solvolysis of **42** (*p*-CH_3) was measured in both solvents and was determined to be 2860 times faster in CF_3CH_2OD. Using this CF_3CH_2OD/CH_3OD solvent rate ratio, rates of **43** (*p*-CH_3), **42** (*p*-OCH_3), and **43** (*p*-OCH_3) in CF_3CH_2OD were calculated.

TABLE 2. Solvolysis Rates for Substrates in CF_3CH_2OD and CH_3OD

	in CF_3CH_2OD		in CH_3OD	
compd	T (°C)	k (s^{-1})	T (°C)	k (s^{-1})
42 (*m*-Cl)	80.0	6.85×10^{-5}		
	60.0	1.11×10^{-5}		
	25.0	2.61×10^{-7}[a]		
32 (*p*-H)	25.0	1.70×10^{-5}		
			80.0	1.60×10^{-4}
42 (*p*-CH_3)	25.0	7.38×10^{-4}	50.0	6.26×10^{-6}
			25.0	2.58×10^{-7}[a]
42 (*p*-OCH_3)	25.0	2.25×10^{-1}[b]	25.0	7.86×10^{-5}
	60.0	9.81×10^{-5}		
43 (*m*-Cl)	40.0	1.17×10^{-5}		
	25.0	1.97×10^{-4}[a]		
33 (*p*-H)	25.0	1.40×10^{-4}		
43 (*p*-CH_3)	25.0	4.12×10^{-3}[b]	25.0	1.44×10^{-6}
43 (*p*-OCH_3)	25.0	1.20×10^{0}[b]	25.0	4.18×10^{-4}
1-chlorophenylcyclopropane	95.0	2.47×10^{-5}		
	75.0	4.25×10^{-6}		
	25.0	1.87×10^{-8}[a]		

[a] Extrapolated from data at higher temperatures. [b] Calculated using a CF_3CH_2OD/CH_3OD rate ratio of 2860.

The rate data in Table 2 as well as the product studies in Schemes 4 and 5 are in line with the involvement of cyclopropyl cations **6** as discrete intermediates that can capture solvent or undergo competing ring-opening processes. Comparison of rates of solvolyses of **32** and **33** with that of 1-chlorophenylcyclopropane gives trimethylsilyl rate-enhancing effects of about 10^3 and 10^4, respectively. These values are even smaller than the trimethylsilyl rate-enhancing effect of 10^6 in cation **5** and does not come close to the 10^{12} value observed in cation **26**. The slightly higher reactivity of **32** and **42** relative to the isomeric substrates **33** and **43** might be a ground-state effect, where there is relief of steric interactions between the *cis*-aryl and trimethylsilyl groups of **33** and **43** as the ionization process occurs. Alternatively, the faster rates of **33** and **43** could be an angular effect, where there is better transition-state interaction of the developing cation with the C−Si σ-bond when the trimethylsilyl group is trans to the leaving group. This angular effect on trimethylsilyl stabilization has been discussed in detail by Lambert.[4]

From the kinetic data in Table 2, Hammett plots were constructed, and these are shown in Figure 3. The large negative ρ^+ values of −4.9 and −5.1 verify that carbocations of type **6** are involved in the rate-determining step of these solvolyses. Of interest is a comparison of these ρ^+ values with those of analogous desilylated systems. Previous Hammett studies on tosylates **46** and dinitrobenzoates **47** by DePuy[2j] and Brown[2k] gave ρ^+ values of −5.15 and −5.19, respectively. These ρ^+ values are very similar to those observed for chlorides **42** and **43**. This similarity indicates that both carbocation **6** and the unsilylated arylcyclopropyl analogues rely on stabilization by the aryl group to a similar extent. Furthermore, this suggests that the trimethylsilyl group in **6** does little to offset the demand for aryl group stabilization.

Computational Studies on Cation 6. The structure of cation **6** (Ar = Ph) was also calculated at the B3LYP/6-31G* level.

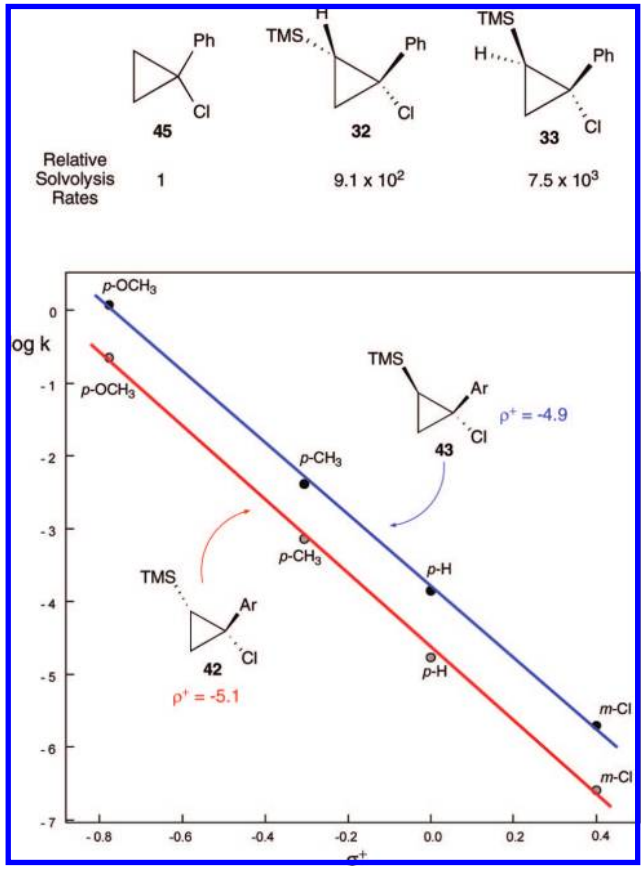


FIGURE 3. Hammett plots for solvolyses of **42** and **43** in CF_3CH_2OD.

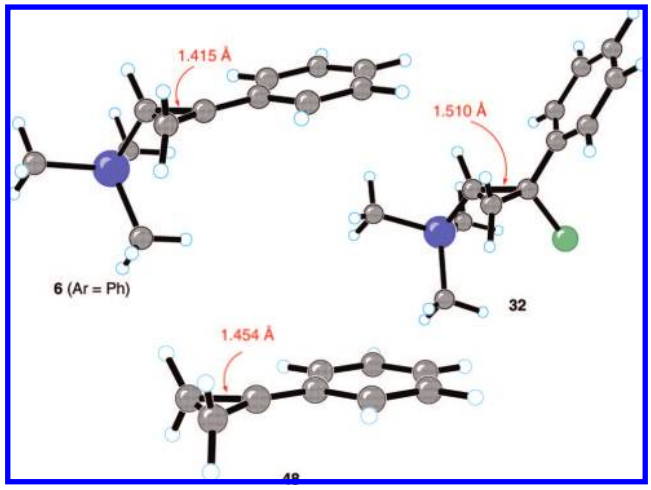
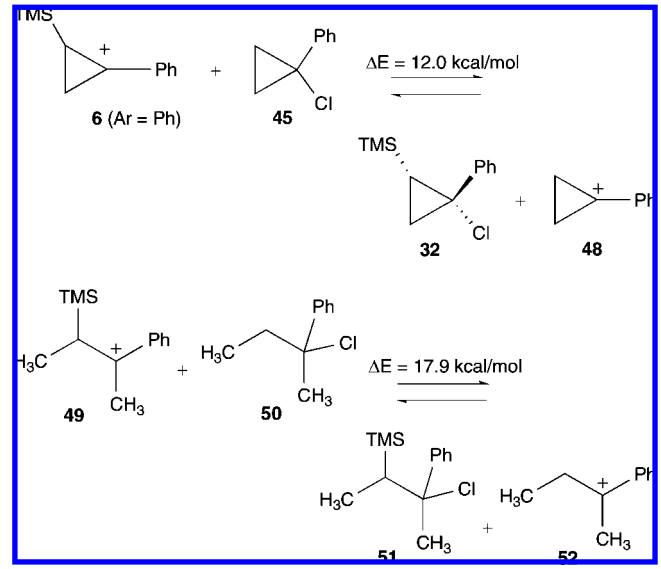


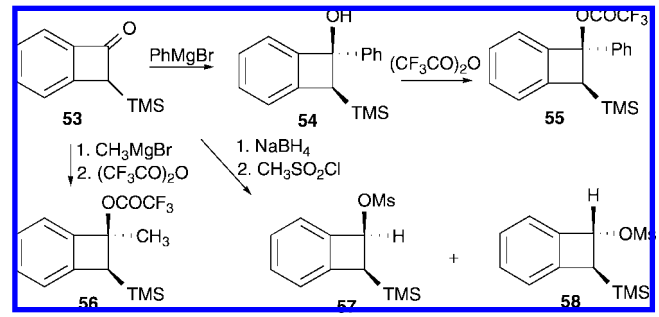
FIGURE 4. B3LYP/6-31G* structures of cation **6** (Ar = Ph), cation **48**, and chloride **32**.

As in cation **5**, the carbocation **6** (Ar = Ph) shows a contraction of the cyclopropane carbon−carbon bond (1.415 Å) relative to that in the chloride **32** (1.510 Å). The cyclopropane bond in **6** (Ar = Ph) is also shorter than the analogous bond in the phenylcyclopropyl cation **48** (1.454 Å) (Figure 4). These contractions point to some stabilizing effect by the trimethylsilyl group in **6** (Ar = Ph). In the cation **5**, a contraction of about 0.15 Å between the neutral and cation was observed. In the present case, however, the contraction is about 0.10 Å. This suggests a smaller stabilizing interaction of the trimethylsilyl group in **6** (Ar = Ph).

SCHEME 6. Isodesmic Calculations Evaluating β-Trimethylsilyl Cation Stabilization



SCHEME 7. Synthesis of Precursors to Cation 7



In order to quantify the stabilization provided by the trimethylsilyl group in cation **6** (Ar = Ph), isodesmic calculations (B3LYP/6-31G*) were again carried out (Scheme 6). The stabilization amounts to 12 kcal/mol relative to the 1-phenylcyclopropyl cation **48**. In the unconstrained system **49**, the β-trimethylsilyl group provides 17.9 kcal/mol of stabilization to this benzylic carbocation. This computational study again agrees with conclusions based on kinetic studies. While there is clearly some stabilization by the β-trimethylsilyl group in cation **6** (Ar = Ph), it is less than in cation **5** or in models cations such as **22**, **26**, or **49**.

The relative rate data, the Hammett ρ^+ values, the lack of desilylated products, and the computational data all point to a greatly repressed interaction of the trimethylsilyl group with the cationic center in **6**. A valence bond rationalization is again of value. Contribution of forms such as **6b** impart cyclopropene character to the cation. Keeping in mind that the strain energy of cyclopropene is 50 kcal/mol,[13] forms such as **6b** have decreased importance. In other words, stabilization of cation **6** by the β-trimethylsilyl group is beginning to fade away (as is structure **6b**).

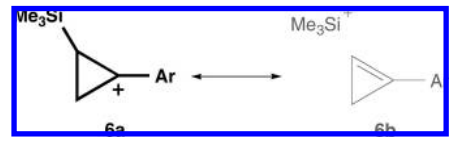
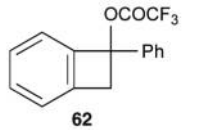
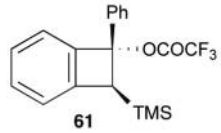
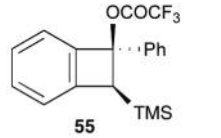
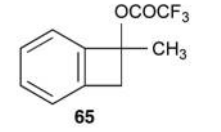
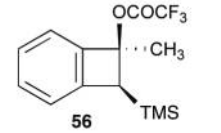
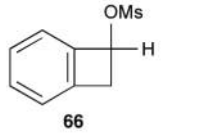
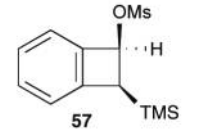
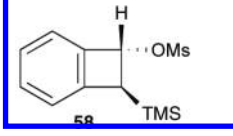


TABLE 3. Solvolysis Rates for Substrates in CD_3CO_2D

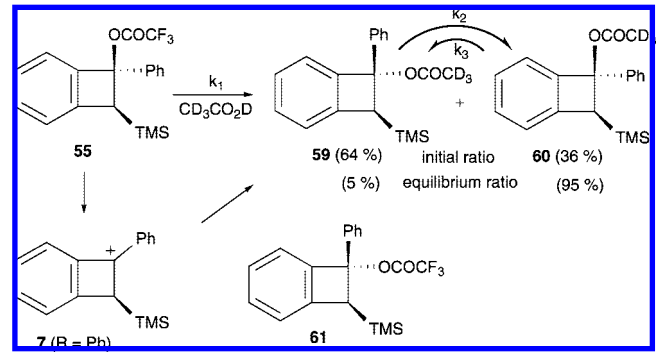
Compound	T (°C)	k(s^{-1})	k_{rel}
 **62**	25.0	1.10×10^{-2}	1.0
 **61**	25.0	4.71×10^{-2} [a]	4.3
 **55**	25.0	2.45×10^{-3}	0.22
 **65**	65.0 45.0 25.0	7.38×10^{-5} 5.94×10^{-6} 3.42×10^{-7} [b]	1.0
 **56**	60.0 40.0 25.0	8.39×10^{-5} 6.14×10^{-6} 6.88×10^{-7} [b]	2.0
 **66**	65.0 45.0 25.0	6.70×10^{-5} 5.73×10^{-6} 3.54×10^{-7} [b]	1.0
 **57**	25.0	9.73×10^{-7}	2.7
 **58**	25.0	2.33×10^{-6}	6.6

[a] Calculated value from K_{eq}. [b] Calculated from data at higher temperatures.

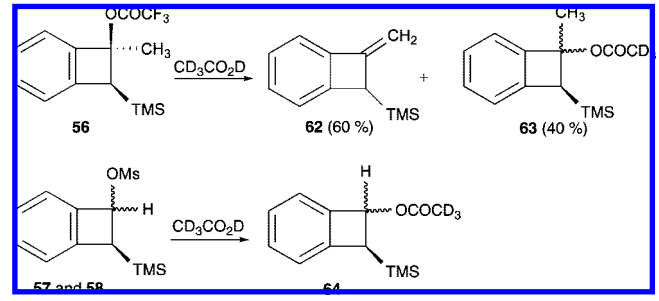
Solvolytic Generation of Carbocation 7. The next carbocations to be investigated were the trimethylsilyl-substituted benzocyclobutenyl cations **7**. Precursors to these systems were prepared from the ketone **53** by standard methods (Scheme 7). The tertiary alcohols formed by addition of PhMgBr and CH_3MgBr to **53** were converted to trifluoroacetate derivatives **55** and **56** for solvolytic study, while the secondary alcohols formed from $NaBH_4$ reduction of **53** were converted to mesylates **57** and **58**.

The trifluoroacetate **55** was solvolyzed in CD_3CO_2D, where reaction readily occurred at room temperature. Kinetic data for **55** and related substrates are given in Table 3. As shown in Scheme 8, acetates **59** and **60** were produced from **55** in a 64:36 ratio. There was no desilylation as usually occurs when

SCHEME 8. Solvolysis Products from 55 in CD_3CO_2D



SCHEME 9. Solvolysis Products from 56, 58, and 59 in CD_3CO_2D



β-silyl cations are generated under solvolytic conditions. The 64:36 product ratio does not remain constant after **55** has completely disappeared. Instead, **59** and **60** continue to react, eventually equilibrating to produce 5:95 ratio of products. This presumably occurs via reionization of acetates **59** and **60** to the cationic intermediate **7** (R = Ph) and eventual equilibration favoring the more stable acetate **60**. This information allows an approximation of the acetolysis rate of trifluoroacetate **61**, which is not available from ketone **53**. From the equilibrium constant $K_{eq} = k_2/k_3 = 19$, acetate **59** ionizes 19 times faster than acetate **60**. Assuming trifluoroacetate ionization rates parallel acetate ionization rates, **61** should be 19 times more reactive than **55**.

Rates of **55** and **61** are the same order of magnitude as that of the desilylated model compound **62**. The solvolysis rate of **55** is actually slower than that of the model **62**. As before, the slightly faster rate of **61** may be an angular effect due to the trimethylsilyl group being trans to the leaving group or it may be a ground-state effect involving relief of strain between the *syn*-phenyl and -trimethylsilyl groups as the ionization proceeds. By any measure, trimethylsilyl rate enhancements in solvolyses of **55** and **61** are negligible.

The tertiary trifluoroacetate **56** reacted in CD_3CO_2D to form the elimination product **62** (60%) along with the acetates **63** (40%; mixture of stereoisomers). The secondary mesylates **57** and **58** both gave mixtures of the acetates **64** (Scheme 9). Comparison of rates of **56**, **57**, and **58** with those of desilylated analogues **65** and **66** showed only minor rate differences. Rate enhancements due to trimethylsilyl stabilization or cationic intermediates again appear to be minimal.

Computational Studies on Cation 7. As before, computational studies were used to shed further light on the β-silyl effect on benzocyclobutenyl cations **7**. The isodesmic calculations (B3LYP/6-31G*) in Scheme 10 show a decreasing amount of trimethylsilyl stabilization as the R group in **7** changes from H

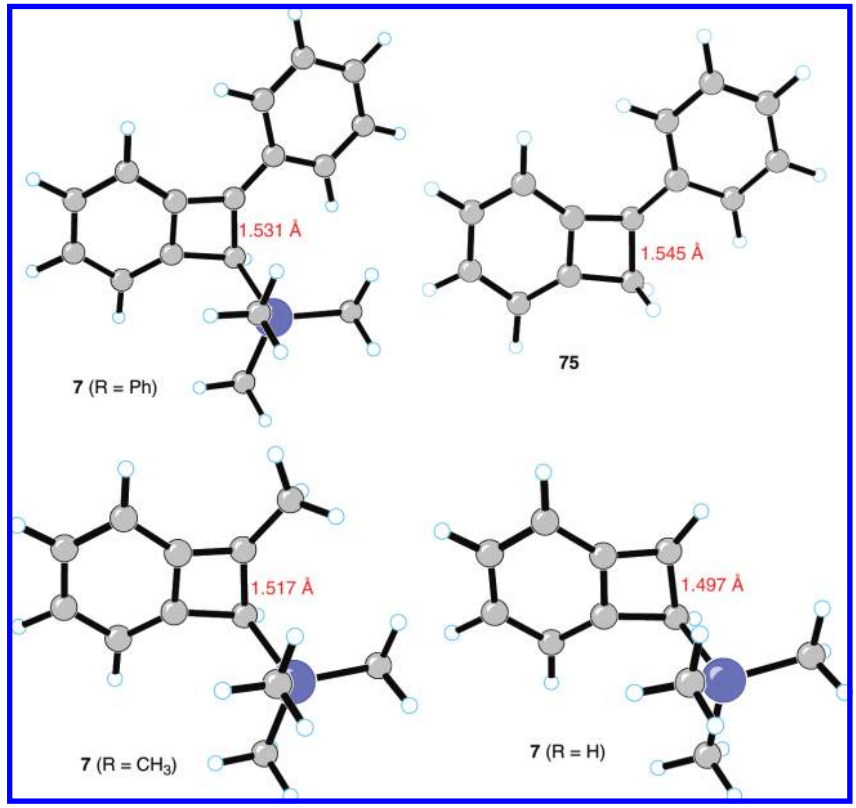
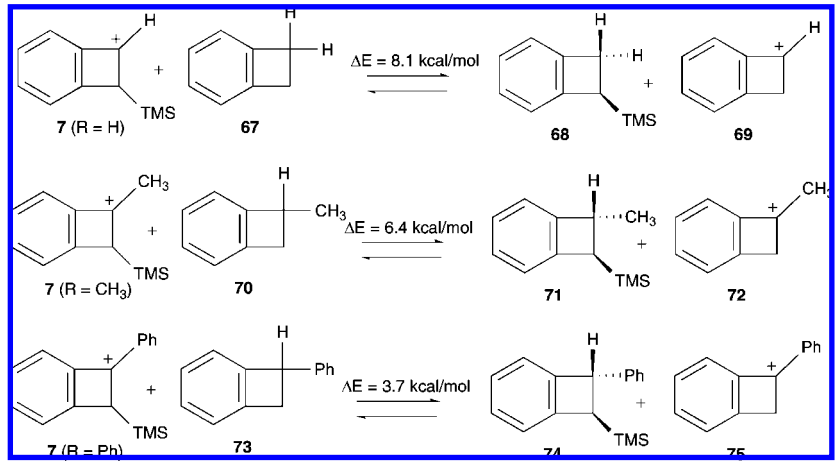


FIGURE 5. B3LYP/6-31G* structures of cation **7** (R = Ph), **7** (R = CH_3), **7** (R = H), and cation **75**.

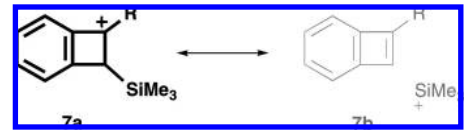
SCHEME 10. Isodesmic Calculations Evaluating β-Trimethylsilyl Cation Stabilization



to CH_3 to Ph. The cation **7** (R = Ph) is stabilized by only 3.7 kcal/mol relative to the desilylated analogue **75**. This represents the smallest calculated value for β-silyl stabilization in our studies.

The calculated structures of cations **7** are also revealing (Figure 5). The bond contraction in **7** (R = Ph), relative to the desilylated cation **75**, is only 0.014 Å and is indicative of minimal trimethylsilyl stabilization. There is a systematic bond contraction in **7** as the R group becomes less cation stabilizing. The implication is that silyl stabilization increases in importance in the series **7** (R = Ph), **7** (R = CH_3), and **7** (R = H).

The kinetic studies in Table 3 indicate essentially no significant rate enhancements when cations **7** are solvolytically generated. The β-trimethylsilyl stabilizing effect has therefore been essentially eliminated when cations **7** are generated in solution. This is attributed to the antiaromatic character of **7** that would necessarily come along with β-silyl stabilization. Contribution of benzocyclobutadienyl forms[15] such as **7b** has essentially faded away (just as structure **7b** has faded).



Computational studies, on the other hand, indicate a small β-silyl stabilizing effect on cations **7**. It is important to realize, however, that all of these calculations describe gas-phase properties and that these do not always correspond precisely to solution-phase chemistry. Stabilization of transition states in solvolysis reactions is not expected to be as large as in fully formed gas-phase cations. In the gas phase, however, where

demands for carbocation stabilization are greater, a minimal amount of β-trimethylsilyl stabilization of **7** is still apparent.

Conclusions

Although the β-silyl effect is one of the largest neighboring group effects in carbocation chemistry, it is greatly attenuated when incorporated into cyclopropyl cations. Rate enhancements are reduced to a factor of about 10^6 in the solvolysis of 1-(trimethylsilylmethyl)cyclopropyl mesylate and further reduced to only a factor of 10^3-10^4 in the solvolyses of 1-phenyl-2-trimethylsilylcyclopropyl chlorides. Despite the extraordinary stabilization demands of cyclopropyl cations, these rate enhancements are substantially repressed relative to maximum enhancements previously observed in the literature. In addition, the β-silyl effect can be effectively quashed upon incorporation of a β-trimethylsilyl group into benzocyclobutyl cations. β-Silyl stabilization in these cations would lead to antiaromatic character, and hence, rate enhancements observed in solvolysis reactions involving these cations are minimal.

Experimental Section

Preparation of 1-(Trimethylsilylmethyl)cyclopropanol), 8. The general cyclopropanol synthesis procedure of DePuy[16] was employed. Trimethylsilylmethylmagnesium chloride (30 mL of a 1.0 M solution in ether) was cooled to 0 °C, and a solution of 3.206 g of 1,3-dichloroacetone in 18 mL of ether was added dropwise. The reaction was allowed to warm to room temperature and then recooled to 0 °C. Solutions of 723 mg of $FeCl_3$ in 25 mL of ether and ethylmagnesium bromide (prepared from 5.0 g of magnesium and 18.7 g of ethyl bromide in 60 mL of ether) were simultaneously added dropwise to the reaction mixture. After the mixture was allowed to stand at room temperature for 16 h, the reaction was recooled to 0 °C and an aqueous solution of ammonium chloride was added. The organic layer was then separated, washed with water and saturated salt solution, and dried over a mixture of Na_2SO_4 and $MgSO_4$. After filtration, the solvent was removed using a rotary evaporator. The crude product was distilled to give 1.65 g of a mixture of alcohol **8**[17] (83% of the mixture) and 2-butanone (17% of the mixture): bp 63−65 °C (15 mm); ^{1}H NMR of **8** ($CDCl_3$) δ 1.66 (br s, 1 H), 0.98 (s, 2 H), 0.74 (m, 2 H), 0.41 (m, 2 H), 0.09 (s, 9 H); ^{13}C NMR of **8** ($CDCl_3$) δ 54.4, 27.4, 15.3, −0.3.

Preparation of 1-(Trimethylsilylmethyl)cyclopropyl Mesylate, 9, and 1-Phenylcyclopropyl Mesylate, 16. A solution of 287 mg (2.0 mmol) of the alcohol **8** obtained above (containing 17% 2-butanone) and 368 mg (3.2 mmol) of mesyl chloride in 2.5 mL of CH_2Cl_2 was cooled to −10 °C, and a solution of 393 mg of triethylamine in 1.5 mL of CH_2Cl_2 was added dropwise. The reaction was allowed to warm to 20 °C for 7 min and then recooled to −5 °C. Cold water (2 mL) was then added along with 5 mL of ether. A fast aqueous workup ensued with ether extraction. The organic layer was separated and washed with ice-cold aliquots of water, dilute HCl solution, water, aqueous $NaHCO_3$ solution, and saturated NaCl solution. The ether extract was then dried over a mixture of Na_2SO_4 and $MgSO_4$ and filtered, and solvent was removed using a rotary evaporator to yield mesylate **9**. Mesylate **9** is highly reactive and was stored in ether solution at −20 °C prior to use: ^{1}H NMR of **9** ($CDCl_3$) δ 2.96 (s, 3 H), 1.31 (m, 4 H), 0.66 (m, 2 H), 0.11 (s, 9 H); ^{13}C NMR of **9** ($CDCl_3$) δ 65.8, 40.1, 25.5, 13.4, −0.3.

Mesylate **16**[18] was prepared from 1-phenylcyclopropanol[16] using an analogous procedure: ^{1}H NMR of **16** ($CDCl_3$) δ 7.57 (d, J = 6.9, 2 H), 7.40 (t, J = 7.2, 2 H), 7.36 (t, J = 7.3, 1 H) 2.54 (s, 3 H), 1.66 (m, 2 H), 1.21 (m, 2 H); ^{13}C NMR of **16** ($CDCl_3$) δ 137.4, 129.3, 129.1, 128.9, 67.6, 39.9, 13.5.

Preparation of 1-Phenyl-2-trimethylsilylcyclopropyl Chlorides 32 and 33. General Procedure for Preparation of 42 and 43. Approximately 100 mg of the appropriate arylchlorodiazirine[14] was dissolved in approximately 2.5 mL of vinyltrimethylsilane, and the solution was sealed in a Pyrex tube. The tube was irradiated for approximately 2 h using a 450 W Hanovia lamp. Excess vinyltrimethylsilane was removed using a rotary evaporator, and the crude products were filtered through 0.5 g of silica gel and eluted with hexanes. The solvent was removed using a rotary evaporator to yield an inseparable mixture of the corresponding chlorides **42** and **43**. Chlorides **42** and **43** were typically formed in approximately a 60:40 ratio. The following procedure is representative.

Irradiation of 80 mg of phenylchlorodiazarine **31**[14] dissolved in 2.6 mL of vinyltrimethylsilane for 2.25 h yielded 91 mg (77% yield) of chlorides **32** and **33** in a 60:40 ratio: ^{1}H NMR of **32** (C_6D_6) δ 7.36 (m, 2 H), 7.08 (m, 2 H), 7.02 (m, 1 H), 1.27 (d of d, J = 4.9, 11.7 Hz 1 H), 1.24 (d of d, J = 4.9, 9.5 Hz, 1H) 0.25 (d of d, J = 9.5, 11.8 Hz, 1 H), 0.20 (s, 9 H); ^{13}C NMR of **32** (C_6D_6) δ 144.8, 129.0, 128.1, 128.1, 51.0, 20.7, 17.7, −0.4. ^{1}H NMR of **33** (C_6D_6) δ 7.39 (m, 2 H), 7.02 (m, 2 H), 6.96 (m, 1 H), 1.45 (d of d, J = 5.1, 12.0 Hz, 1 H), 1.13 (d of d, J = 5.1, 9.1 Hz, 1 H), 0.83 (d of d, J = 9.1, 12.0 Hz, 1 H), −0.34 (s, 9 H); ^{13}C NMR of **33** (C_6D_6) δ 141.7, 130.0, 128.8, 128.6, 48.9, 19.7, 17.5, −1.6; exact mass (EI) calcd for $C_{12}H_{17}ClSi$ (M^+) 224.0788, found 224.0811.

Preparation of 2-(Trimethylsilyl)benzocyclobutanone, 53. Following the general procedure developed by Suzuki and Tsujiyama,[19] *o*-iodophenyl triflate (2.925 g) was dissolved in 30 mL of tetrahydrofuran, and 2.444 g of trimethylsilylketene diethylacetal[20] was added. The solution was cooled to −78 °C, and 5.2 mL of 1.6 M *n*-butyllithium in hexanes was added dropwise. After being stirred for 1 h, the solution was warmed to −50 °C over 30 min. Water (15 mL) was added, and the solution was then warmed to room temperature. An aqueous workup ensued with ether extraction. The ether extract was washed with water and saturated salt solution and dried over a mixture of Na_2CO_3 and $MgSO_4$. After filtration, the solvent was removed using a rotary evaporator. The residue was distilled, and after a lower boiling forerun, 884 mg of distillate was collected at 56−62 °C (0.25 mm). This distillate contained 1,1-diethoxy-2-(trimethylsilyl)benzocyclobutanone, 2-iodo-*n*-butylbenzene, and biphenylene in a 1.0:0.81:0.49 ratio, along with smaller amounts of other impurities. The distillate was dissolved in 10 mL of tetrahydrofuran and a solution of 160 mg of sulfuric acid in 6 mL of water was added. After stirring vigorously for 2 h at room temperature, $NaHCO_3$ was added followed 15 mL of ether and NaCl until the aqueous phase was saturated. The organic phase was separated and dried over a mixture of Na_2SO_4 and $MgSO_4$. After filtration, the solvent was removed using a rotary evaporator and the residue was chromatographed on 10.5 g of silica gel. The column was eluted with increasing amounts of ether in hexanes. Ketone **53**[21] (206 mg, 13% yield) eluted with 4% ether in hexanes: ^{1}H NMR of **53** ($CDCl_3$) δ 7.44 (t of d, J = 7, 1 Hz, 1 H), 7.33 (m, 1 H), 7.29 (t, J = 7 Hz, 1 H), 7.26 (t of t, J = 7, 1 Hz, 1 H), 3.87 (br s, 1 H), 0.08 (s, 9 H); ^{13}C NMR of **53** ($CDCl_3$) δ 191.3, 153.5, 146.7, 134.9, 127.2, 122.1, 120.2, 59.4, −2.7.

Preparation of 1-Phenyl-*cis*-2-(Trimethylsilyl)benzocyclobutanol, 54. A solution of 29 mg of ketone **53** in 1.5 mL of ether was added dropwise to 0.3 mL of 1 M phenylmagnesium bromide in ether at 0 °C. After 10 min, the solution was warmed to room

(15) For a discussion of antiaromaticity in benzocyclobutadiene and related compounds, see: (a) Cava, M. P.; Napier, D. R. *J. Am. Chem. Soc.* **1957**, *79*, 1701. (b) Nenitzescu, C. D.; Avram, M. *Chem. Ber.* **1957**, *90*, 2541. (c) Pettit, R.; Merk, W. *J. Am. Chem. Soc.* **1967**, *80*, 4788. (d) Schleyer, P. v. R.; Maerker, C.; Dransfeld, A.; Jiao, H.; Hommes, N. J. R. v. E. *J. Am. Chem. Soc.* **1996**, *118*, 6317. (e) Nagorski, R. W.; DeAtley, A. D.; Broadus, K. M. *J. Am. Chem. Soc.* **2001**, *123*, 8428. (f) Fu, N.; Allen, A. D.; Kobayashi, S.; Sequeira, P. A.; Shang, M.; Tidwell, T. T.; Mishima, M. *J. Am. Chem. Soc.* **2007**, *129*, 6210.

(16) DePuy, C. H.; Dappen, G. M.; Eilers, K. L.; Klein, R. A. *J. Org. Chem.* **1964**, *29*, 2813.

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temperature for 1.5 h. The solution was then warmed to 35 °C for 15 min and then cooled to 0 °C. Aqueous NH_4Br solution was added. The ether phase was then separated, washed with saturated salt solution, and dried over a mixture of Na_2SO_4 and $MgSO_4$. After filtration, the solvent was removed using a rotary evaporator. The residue was chromatographed on 2.6 g of silica gel. The column was eluted with increasing amounts of ether in pentane. Alcohol **54**[22] (36 mg, 88% yield) eluted with 2% ether in pentane: ^{1}H NMR of **54** ($CDCl_3$) δ 7.44 (m, 2 H), 7.32 (m, 3 H), 7.26 (m, 3 H), 7.10 (d of q, J = 1.0, 7.2 Hz, 1 H) 3.30 (t, J = 0.9, 1 H), 2.39 (s, 1 H) 0.15 (s, 9 H); ^{13}C NMR of **54** ($CDCl_3$) δ 148.0, 145.6, 145.5, 129.8, 128.6, 127.5, 126.4, 125.7, 122.5, 121.5, 83.7, 53.3, −1.4; exact mass (FAB) calcd for $C_{17}H_{21}OSi$ 269.1362, found 269.1347 (M + 1).

General Procedure for the Preparation of Trifluoroacetates. A solution of the appropriate alcohol in ether along with 2 equiv of 2,6-lutidine was cooled to 0 °C, and 1.5 equiv of trifluoroacetic anhydride was added dropwise. After 15 min at 0 °C, cold water was added, and a cold aqueous workup ensued with ether extraction. In the case of trifluoroacetate **55**, the solution was warmed to room temperature for 1 h before the aqueous workup. The ether layer was rapidly washed with cold aliquots of water, dilute HCl solution, water, aqueous $NaHCO_3$ solution, and saturated salt solution and dried over a mixture of Na_2SO_4 and $MgSO_4$. Solvent removal using a rotary evaporator gave the corresponding trifluoroacetates in ∼95% yield. This general procedure was used for the preparation of trifluoroacetates **55**, **56**, **57**, **62**, and **65** from the corresponding alcohols. These trifluoroacetate esters are prone to decomposition on standing as neat liquids and were therefore stored at −20 °C in ether solution.

1-Phenyl-*cis*-2-(Trimethylsilyl)benzocyclobutyl trifluoroacetate, 55: mp 84−86 °C; ^{1}H NMR of 55 ($CDCl_3$) δ 7.59 (d of d of t, J = 7, 1, 0.3 Hz, 2 H), 7.35 (m, 7 H), 7.34 (d of q, J = 7, 1 Hz, 2 H), 3.30 (t, J = 1 Hz, 1 H), 0.18 (s, 9 H); ^{13}C NMR of 55 ($CDCl_3$) δ 156.5 (q, J = 42 Hz), 145.1, 141.4, 139.9, 131.4, 128.7, 128.6, 127.0, 126.3, 126.0, 122.3, 114.6 (q, J = 287 Hz), 90.2, 52.2, −1.9; exact mass (FAB) calcd for $C_{19}H_{19}F_3O_2Si$ 364.1106, found 364.1103.

1-Phenylbenzocyclobutyl Trifluoroacetate, 62. This substrate was prepared from 1-phenylbenzocyclobutanol:[23] ^{1}H NMR of **62** ($CDCl_3$) δ 7.62 (d of t, J = 7.4, 1 Hz, 1 H), 7.45 (m, 3 H), 7.36 (m, 4 H), 7.25 (d of quin, J = 7, 1 Hz, 1 H), 3.99 (d of d, J = 14, 0.4 Hz, 1 H), 3.64 (d, J = 14 Hz, 1 H); ^{13}C NMR of **62** ($CDCl_3$) δ 156.7 (q, J = 42 Hz), 142.8, 141.9, 138.5, 131.5, 128.9, 128.7, 128.4, 126.8, 125.9, 124.2, 114.6 (q, J = 286 Hz), 89.0, 47.0; exact mass (FAB) calcd for $C_{16}H_{11}F_3O_2$ 292.0711, found 292.0728.

1-Methyl-*cis*-2-(Trimethylsilyl)benzocyclobutyl Trifluoroacetate, 56. Methylmagnesium iodide (0.6 mL of 1.0 M in ether) was added to 1 mL of ether, and the solution was cooled to −10 °C in an ice/acetone bath. A solution of 56 mg of the ketone **53** in 2 mL of ether was added dropwise. The solution was warmed to room temperature and then recooled to −10 °C. Aqueous NH_4Br solution was then added dropwise to the stirred solution, and the ether phase was then separated and washed with saturated NaCl solution. The ether extract was dried over $MgSO_4$ and filtered, and the solvent was removed using a rotary evaporator to give 57 mg (95% yield) of 1-methyl-*cis*-2-(trimethylsilyl)benzocyclobutanol: ^{1}H NMR of 1-methyl-*cis*-2-(trimethylsilyl)benzocyclobutanol ($CDCl_3$) δ 7.23 (m, 1 H), 7.16−7.11 (m, 2 H), 7.03 (d of q, J = 7.2, 1.0 Hz, 1 H), 3.03 (br s, 1 H), 2.00 (s, 1 H), 1.69 (s, 3 H), 0.08 (s, 9 H); ^{13}C NMR of 1-methyl-*cis*-2-(trimethylsilyl)benzocyclobutanol ($CDCl_3$) δ 150.0, 144.5, 129.2, 125.8, 122.2, 119.9, 80.3, 50.9, 27.9, −1.7.

Trifluoroacetate **56** was prepared from 1-methyl-*cis*-2-(trimethylsilyl)benzocyclobutanol by the general procedure described above: ^{1}H NMR of **56** ($CDCl_3$) δ 7.39 (d of t, J = 7, 1 Hz, 1 H), 7.30 (t of d, J = 7.5, 1 Hz, 1 H), 7.18 (t of t, J = 7.5, 1 Hz, 1 H), 7.04 (d of q, J = 7, 1 Hz, 1 H), 3.10 (t, J = 1 Hz, 1 H), 1.92 (s, 3 H), 0.08 (s, 9 H); ^{13}C NMR of **56** ($CDCl_3$) δ 156.7 (q, J = 42 Hz), 144.20, 144.17, 130.6, 126.5, 124.3, 121.7, 114.5 (q, J = 287 Hz), 89.3, 49.8, 23.6, −2.2; exact mass (FAB) calcd for $C_{14}H_{17}F_3O_2Si$ 302.0950, found 302.0958.

1-Methylbenzocyclobutyl Trifluoroacetate, 65. This substrate was prepared from 1-methylbenzocyclobutanol.[23] ^{1}H NMR of **65** ($CDCl_3$) δ 7.39 (d of t, J = 7, 1 Hz, 1 H), 7.36 (t of d, J = 7, 1 Hz, 1 H), 7.28 (t of q, J = 7, 1 Hz, 1 H), 7.19 (d of quin, J = 7, 1 Hz, 1 H), 3.63 (d, J = 14 Hz, 1 H), 3.42 (d, J = 14 Hz, 1 H), 1.91 (d, J = 0.3 Hz, 3 H); ^{13}C NMR of **65** ($CDCl_3$) δ 156.8 (q, J = 42 Hz), 145.2, 140.8, 130.8, 127.9, 123.74, 123.70, 114.4 (q, J = 286 Hz), 86.9, 45.2, 22.1; exact mass (FAB) calcd for $C_{11}H_{10}F_3O_2$ 231.0633, found 231.0636 (M + 1).

***cis*-2-(Trimethylsilyl)benzocyclobutyl Mesylate, 57.** A solution of 59 mg of ketone **53** in 2 mL of CH_3OH was cooled in an ice/salt bath at −10 °C, and 17.8 mg of $NaBH_4$ was added. The mixture was warmed to room temperature and then recooled to −10 °C. A solution of 40 mg of acetic acid in 0.5 mL of methanol was added dropwise with stirring, and then 3 mL of water was added. The mixture was then extracted with 6 mL of ether. Pentane (5 mL) was added to the ether extract, and the solution was then washed with water and saturated NaCl solution. The mixture was dried over Na_2SO_4, and the solvents were removed using a rotary evaporator to give 58 mg (97% yield) of *cis*-2-(trimethylsilyl)benzocyclobutanol and *trans*-2-(trimethylsilyl)benzocyclobutanol in a 94:6 ratio: ^{1}H NMR of *cis*-2-(trimethylsilyl)benzocyclobutanol ($CDCl_3$) δ 7.26 (t of m, J = 7.4 Hz, 1H), 7.19 (d of m, J = 7.1 Hz, 1 H), 7.17 (d of t, J = 7.4, 0.9 Hz, 1 H), 7.03 (d of m, J = 7.3 Hz, 1 H), 5.39 (d, J = 4.9 Hz, 1 H), 3.27 (t of d, J = 4.9, 0.9 Hz, 1 H), 2.05 (br, 1 H), 0.07 (s, 9 H); ^{13}C NMR of *cis*-2-(trimethylsilyl)benzocyclobutanol ($CDCl_3$) δ 146.7, 145.0, 129.3, 125.8, 121.8, 1231.7, 72.7, 44.3, −1.7.

A solution of 46 mg of the alcohols prepared above and 40 mg of CH_3SO_2Cl in 2 mL of methylene chloride was cooled to −10 °C as 50 mg of Et_3N in 0.5 mL of CH_2Cl_2 was added dropwise. The mixture was warmed to room temperature and taken up into 10 mL of ether. The mixture was then washed successively with cold water, cold dilute HCl solution, $NaHCO_3$ solution, and saturated NaCl solution. The organic phase was then dried over a mixture of Na_2SO_4 and $MgSO_4$. After filtration, the solvents were removed using a rotary evaporator to give 61 mg (94% yield) of mesylates **57** and **58** (94% of **57** and 6% of **58**): ^{1}H NMR of **57** ($CDCl_3$) δ 7.33 (t of t, J = 7.5, 0.8 Hz, 1 H), 7.29 (d of m, J = 7.5 Hz, 1 H), 7.21 (t of t, J = 7.5, 0.9 Hz, 1 H), 7.05 (d of m, J = 7.4 Hz, 1 H), 5.96 (d of m, J = 5.2 Hz, 1 H), 3.43 (d of t, J = 5.2, 0.9 Hz, 1 H), 3.09 (s, 3 H), 0.08 (s, 9 H); ^{13}C NMR of **57** ($CDCl_3$) δ 144.6, 141.6, 130.7, 126.5, 123.5, 121.5, 76.8, 42.3, 38.6, −2.1; exact mass (FAB) calcd for $C_{12}H_{18}O_3SSi$ 270.0746, found 270.0721.

Benzocyclobutyl Mesylate, 66. This substrate was prepared from benzocyclobutanol:[24] ^{1}H NMR of **66** ($CDCl_3$) δ 7.39 (t of d, J = 7.4, 1.4 Hz, 1 H), 7.34−7.28 (m, 2 H), 7.18 (d of m, J = 7.4 Hz, 1 H), 5.92 (d of d, J = 4.5, 1.9 Hz, 1 H), 3.73 (d of d, J = 14.5, 4.5 Hz, 1 H), 3.44 (d of m, J = 14.5 Hz, 1 H), 3.10 (s, 3 H); ^{13}C NMR of **66** ($CDCl_3$) δ 142.2, 142.1, 131.0, 128.0, 123.7, 123.5, 75.1, 39.6, 38.6; exact mass (FAB) calcd for $C_9H_{10}O_3S$ 198.0351, found 198.0365.

Solvolyses of Mesylates, Chlorides, and Trifluoroacetates. Kinetics Procedures. Rate constants reported in Tables 1−3 were

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all determined using 600 MHz ^{1}H NMR spectroscopy. A solution was prepared by dissolving approximately 5 mg of the appropriate substrate in 400 mg of CD_3CO_2D, CF_3CH_2OD, or CH_3OD containing approximately 1.5 equiv of 2,6-lutidine. The sample was sealed in an NMR tube. For runs at 25 °C, the tube was placed in the probe of an NMR set at 25.0 °C. At appropriate time intervals, the tube was analyzed by ^{1}H NMR, and relative areas due to starting mesylate, chloride, or trifluoroacetate were measured. In most instances, the 2,6-lutidine singlet at δ 2.74 was used as an internal standard. For runs at higher temperature, the tube was placed in a constant temperature bath at the appropriate temperature. At appropriate time intervals, the tube was then rapidly quenched in a water bath at 15 °C and rapidly analyzed by ^{1}H NMR at ambient temperature.

In the case of mesylates **9** and **16** in CD_3CO_2D, the rates of disappearance of the singlets due to the $ROSO_2CH_3$ group at δ 2.99 and 3.02, respectively, were monitored. For mesylates **57**, **58**, and **66** in CD_3CO_2D, the disappearance of singlets at δ 3.16, 3.13, and 3.14, respectively, was monitored.

For trifluoroacetate **55** in CD_3CO_2D, the rate of disappearance of the TMS singlet at δ 0.20 was monitored. For trifluoroacetate **56**, the TMS singlet at δ 0.09 was monitored. For trifluoroacetate **65**, the CH_3 singlet at δ 1.90 was monitored. The reaction of trifluoroacetate **62** (half-life = 63 s) was monitored by quenching CD_3CO_2D solutions of **62** in C_6D_6 before measuring the relative amount of unreacted **62** (doublet at δ 3.67).

For chlorides **32** and **33** in CF_3CH_2OD, the rates of disappearance of the TMS singlets at δ 0.21 and −0.27 respectively, were monitored. For chlorides **42** and **43** in CF_3CH_2OD and in CH_3OD, the TMS singlets at approximately δ 0.21 and −0.26 were also monitored.

Typical data illustrating reaction of **9** in CD_3CO_2D, **42** and **43** (Ar = *p*-$CH_3OC_6H_4$) in CH_3OD, and **55** in CD_3CO_2D are given as Supporting Information. First-order rate constants for disappearance of substrates were calculated by standard least-squares procedures. Correlation coefficients were all greater than 0.9997. The maximum standard deviation in duplicate runs was ±2%.

Solvolysis of Mesylate 9 in CD_3CO_2D. Product Study. A solution of the 3.3 mg of mesylate **9** and 2.6 mg of 2,6-lutidine in 350 mg of CD_3CO_2D was sealed in an NMR tube, and the tube was kept at 25 °C for 4 h. The mixture was then analyzed by 600 MHz ^{1}H NMR. The products (methylenecyclopropane **10**,[25] the protio analog of acetate **11**,[26] and mesylate **12**[27]) are known compounds. The relative amount of each product was determined by integration of the downfield region of the ^{1}H NMR spectrum and is shown as Supporting Information.

Solvolysis of Chlorides 32 and 33 in CF_3CH_2OH. Product Study. A solution of the 31 mg of chlorides **32** and **33** and 22 mg of 2,6-lutidine in 2.0 mL of CF_3CH_2OH was heated at 40 °C for 24 h. The solvent was removed using a rotary evaporator, the residue was taken up into ether, and the ether solution was washed with water and saturated NaCl solution and then dried over $MgSO_4$. After solvent removal using a rotary evaporator, the residue was analyzed by 600 MHz ^{1}H NMR. The upfield region of the spectrum is shown in Figure 2, and the downfield region is shown as Supporting Information. Products **34**−**36**, **38**, **39**, and **41** were identified by ^{1}H NMR spectral comparison with independently prepared samples. Products **37** and **40** were identified using ^{1}H NMR spectral data. Independent syntheses and spectral data for these compounds are given as Supporting Information.

Solvolysis of Trifluoroacetate 55 in CD_3CO_2D. Product Study. A solution of the 4.6 mg of trifluoroacetate **55** and 3.8 mg of 2,6-lutidine in 360 mg of CD_3CO_2D was placed in an NMR tube, and the tube was kept at 25 °C for 52 min. Analysis by 600 MHz ^{1}H NMR showed products **59** and **60** in a 64:36 ratio. The structure of **60** was verified by independent synthesis of the protio analogue by acetylation of alcohol **54** by reaction with acetic anhydride and dimethylamino pyridine in CH_2Cl_2.

The NMR tube was then placed in a water bath at 25.0 °C and periodically monitored by ^{1}H NMR over a period of 32 days. During this time, acetate **59** epimerized to **60**, and eventually an equilibrium position consisting of **59** and **60** in a 5:95 ratio was attained. The half-life for approach to equilibrium was 73 h. Corresponding spectra are shown as Supporting Information.

Computational Studies. Ab initio molecular orbital calculations were performed using the Gaussian 03 series of programs.[28] All structures, except the constrained system **21**, were characterized as minima via frequency calculations that showed no negative frequencies.

Supporting Information Available: Complete ref 28; the B3LYP/6-31G*-calculated structures, energies, and Cartesian coordinates of **5**, **6** (Ar = Ph), **7** (R = Ph), **7** (R = CH_3), **7** (R = H), **19**, **32**, **48**, and **75**; ^{1}H and ^{13}C NMR spectra of compounds **9**, **32** and **33**, **42** and **43** (Ar = *m*-ClC_6H_4), **42** and **43** (Ar = *p*-$CH_3C_6H_4$), **42** and **43** (Ar = *p*-$CH_3OC_6H_4$), **55**, **56**, **57** and **58**, **62**, **65**, and **66**, as well as evolving ^{1}H NMR spectra during reaction of **9** in CD_3CO_2D, **42** and **43** (Ar = $CH_3OC_6H_4$) in CH_3OD, and **55** in CD_3CO_2D; experimental procedures for independent syntheses of **34**, **35**, **37**−**39**, and **41**. This material is available free of charge via the Internet at http://pubs.acs.org.

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