carboxy groups which forces the dipeptide into the cis conformation. A general scheme indicating the relative rates of racemization of amino acids in DKPs and in the various ionic forms and positions of peptides has been presented. At the neutral pHs of natural systems our results indicate that amino acids in DKPs will be more rapidly racemized than those at the N-terminal, internal, or C-terminal positions of peptides. Amino acids at the C-terminal position racemize much more slowly than N-terminal or internally bound amino acids at neutral pH. A review of the literature has shown that these relative rates are not reflected by analysis of enantiomeric ratios in the various components of a peptide system due to the rapid rates of interconversion between DKPs and dipeptides. However, an interpretation of these ratios in terms of the factors expected to affect these interconversions has revealed trends fully consistant with our scheme.

High rates of DKP formation in aqueous solution at neutral pH have important implications for the biogeochemical cycles of amino acids and proteins. Our results, as well as those of Steinberg,[3] Steinberg and Bada,[4] and Kriausakul and Mitterer[33] imply that DKP formation from peptides occurs rapidly enough to constitute a major pathway for degradation of proteins in natural waters, sediments, and fossils. It is possible that DKPs may constitute a temporary sink for degrading peptides in biogeochemical systems.

Acknowledgment. We thank the donors of the Petroleum Research Fund, administered by the American Chemical Society, for partial support of this research.

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Supplementary Material Available: Tables of the data used in calculating the rate constants in Table I (2 pages). Ordering information is given on any current masthead page.

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(32) Kopple, K. D.; Ohnishi, M. *J. Am. Chem. Soc.* **1969**, *91*, 962–970.

(33) Kriausakul, N.; Mitterer, R. M. *Geochim. Cosmochim. Acta* **1983**, *47*, 963–966.

Rates of Hydrogen Atom Abstraction from Benzyltrimethylsilanes by Bromine and *tert*-Butoxy Radical. The Question of the Stability of the α-(Trimethylsilyl)benzyl Radical

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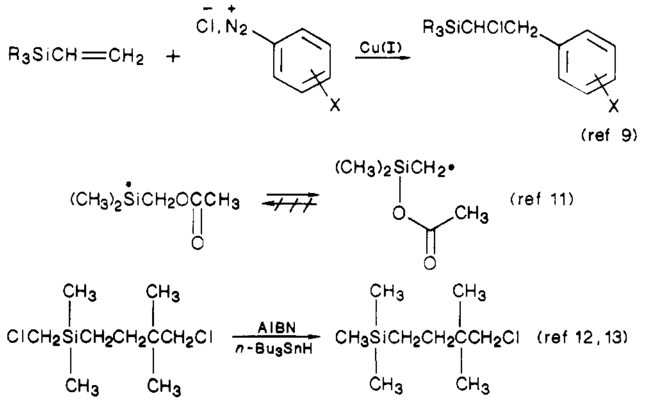
The benzylic position of benzocyclobutene derivatives shows enhanced reactivity in free-radical bromination reactions when a benzylic hydrogen is replaced by a trimethylsilyl group. However, the rates of free-radical brominations (*N*-bromosuccinimide/AIBN) of the respective benzyltrimethylsilanes are accelerated by a factor of only $\simeq 7$ relative to the respective toluene. Furthermore, the ρ value (−1.33) is not significantly different from that reported ($\rho = -1.38, -1.42$) for the reaction of *N*-bromosuccinimide with substituted toluenes. The absolute rate constants for benzylic hydrogen abstraction from benzyltrimethylsilanes by *tert*-butoxy radical are $\simeq 5 \times 10^6$ L/mol·s as measured by laser flash spectroscopy. On a per hydrogen basis, these values are a factor of about 10 times faster than the rates measured for *tert*-butoxy radical abstraction from the α-position of tetraethylsilane, $\simeq 3 \times 10^5$ L/mol·s, and a factor of 5–15 times faster than those of the reactions with the analogous toluenes. Although substitution of a methylene hydrogen with a trimethylsilyl group is often synthetically beneficial for effecting free-radical reactions at this center, there is only a small increase in the ease of formation of radicals generated α to a trimethylsilyl group as compared to an alkyl group.

Introduction

Scheme I. Selected Reactions Involving α-Silyl Radical Intermediates



Trisubstituted silyl groups are often synthetically advantageous because they facilitate certain transformations and are then readily replaced, most commonly by a hydrogen[1] atom or hydroxyl[2] group. Extensive use has been made of silicon-derived reagents in cationic and anionic processes since a β-trialkylsilyl group is known to stabilize a positively charged center and an α-trisubstituted silyl group stabilizes anionic centers.[3] Recently, the effect of α-trimethylsilyl groups on radical centers has been of interest, and several reports suggest that radical stabilization in such systems is small or negligible.[4–6c,7] Thus, the C–H bond strength of tetramethylsilane is only 0.5 kcal/mol weaker than that of neopentane,[4] and ESR measurements

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(1) For a general discussion, see: Colvin, E. W. *Silicon in Organic Synthesis*; Robert E. Krieger: Malabar, FL, 1985.

(2) Tamao, K.; Ishida, N.; Kunada, M. *J. Org. Chem.* **1983**, *48*, 2121. Fleming, I.; Henning, R. *J. Chem. Soc., Chem. Commun.* **1984**, 29. Tamao, K.; Kumada, M.; Maeda, K. *Tetrahedron Lett.* **1984**, *25*, 321. Tamao, K.; Tanaka, T.; Takashi, N.; Sumiya, R.; Arai, H.; Ito, Y. *Tetrahedron Lett.* **1986**, *27*, 3377.

(3) Reference 1, Chapter 2.

0022-3263/88/1953-2764$01.50/0

suggest that there may be stronger interactions ($\simeq$5 kcal/mol) in β-substituted trialkylsilyl radicals than in their α-substituted counterparts.[5]

Although the above reports suggest that an α-trimethylsilyl group has only a small effect on the stabilization of a radical center, the chemical consequences (Scheme I) of this moiety in free-radical reactions can be quite pronounced.[6] Thus, radical addition reactions that proceed well with dienes, but not with simple olefins, are successful with vinylsilanes.[9] The 1,2-chlorine and phenyl migrations that occur readily in carbon radicals are not observed with analogous α-silyl radicals;[10] however, an acetoxy migration[11] resulting in formation of an α-silyl radical has been reported. Tri-*n*-butylstannane reductions of α-chlorosilanes proceed at a much faster rate than do reductions of primary alkyl chlorides;[12,13] this observation led to the suggestion that α-silyl radicals possess enhanced stability.[12] Finally, a kinetic study reported that both α- and β-positions of triethylsilane were activated toward hydrogen abstraction by a *tert*-butoxy radical.[14]

Our interest in α-trimethylsilyl radicals derived from the synthetic benefit of substitution of a trimethylsilyl group for a hydrogen on the free-radical bromination of the benzocyclobutanone ketals below.[15] Thus, all attempts to brominate the benzylic position of the ketals **1a,b** under free-radical conditions led to complex mixtures of products. In contrast, the corresponding trimethylsilyl-substituted systems, **2a,b**, gave excellent yields of the corresponding α-bromosilanes, which were subsequently converted into the desired benzocyclobutenedione monoketals.[15] Since an understanding of these results could provide useful information for introduction of a functionality α to silicon in other systems via the α-halosilane, the origin of this striking effect of trimethylsilyl substitution on *N*-bromosuccinimide bromination has been studied. In addition, the absolute rates for hydrogen abstraction from benzyltrimethylsilanes by *tert*-butoxy radical are reported.

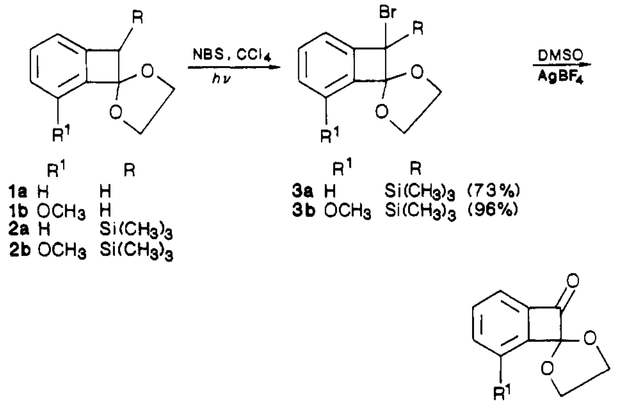

Table I. Rates of NBS Bromination of Benzyltrimethylsilanes vs Toluenes at 80 °C

substit	$k_{\text{benzyltrimethylane}}/k_{\text{toluene}}$ (per H)	k_{rel}(benzyltrimethylsilane)
p-OCH_3	6.7	12.9
p-*t*-Bu	6.4	2.1
p-H	6.1	1.0
p-CO_2CH_3	6.0	0.18
p-NO_2	6.8	0.12

Relative Rates for Bromination of Benzyltrimethylsilanes

The relative rates of free-radical bromination of substituted toluenes with both *N*-bromosuccinimide (NBS) and bromine are well-established[16] and facilitated the present study. The substituted benzyltrimethylsilane and the analogously substituted toluene were brominated in carbon tetrachloride at 80 °C. The reaction mixture was then analyzed by integrating the methylene signals for the substituted benzyl bromides (4.5 ppm) and benzyltrimethylsilyl bromides (4.3 ppm) in the ^{1}H NMR spectrum, with acenaphthene as internal standard. The relative rates for the bromination of the benzyltrimethylsilanes vs toluenes were then determined via eq 1[16a] in which B is the

$$\frac{k_{\text{benzyltrimethylsilane}}}{k_{\text{toluene}}} = \frac{\log\,[(B - X_{\text{B}})/B]}{\log\,[(T - X_{\text{T}})/T]} \qquad (1)$$

initial amount of benzyltrimethylsilane, X_{B} is the amount of brominated benzyltrimethylsilane, T is the initial amount of toluene, and X_{T} is the amount of brominated toluene. The results of the competitive studies are presented in Table I. In general, the substituted benzyltrimethylsilanes were 6–7 times more reactive than the analogously substituted toluenes at 80 °C. With use of the literature values[16] for the relative rates of bromination of the substituted toluenes, the relative rates of bromination of the substituted benzyltrimethylsilanes were calculated (k_{rel} in Table I), and the Hammett plot using σ^+ led to a ρ value of -1.33 (correlation coefficient = 0.994).

The modest rate accelerations noted in the free-radical bromination of benzyltrimethylsilanes vs toluenes did not reflect the synthetic benefit of this substitution observed in the reactions of **2a,b**. An intramolecular comparison of the reactivity of the benzylic hydrogens in benzocyclo-

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(4) Walsh, R. *Acc. Chem. Res.* **1981**, *14*, 246.

(5) Kawamura, T.; Kochi, J. K. *J. Am. Chem. Soc.* **1972**, *94*, 648. Mackey, J. H.; Wood, D. E. *Mol. Phys.* **1970**, *18*, 783.

(6) (a) For other reactions in which radicals α to a silicon atom may be involved, see: Shih, C.; Fritzen, E. L.; Swenton, J. S. *J. Org. Chem.* **1980**, *45*, 4462. (b) Chenard, B. L.; Slapak, C.; Anderson, D. K.; Swenton, J. S. *J. Chem. Soc., Chem. Commun.* **1981**, 179. (c) Paquette, L. A.; Wells, G. J.; Horn, K. A.; Yan, T-H. *Tetrahedron Lett.* **1982**, *23*, 263. (d) Hart, D. J.; Tsai, Y-M. *J. Am. Chem. Soc.* **1984**, *106*, 8209. (e) Paquette, L. A.; Uchida, T.; Gallucci, J. C. *J. Am. Chem. Soc.* **1984**, *106*, 335. (f) Zweifel, G.; On, H. P. *Synthesis*, **1980**, 803. (g) Zweifel, G.; Lewis, W. *J. Org. Chem.* **1978**, *43*, 2739. (h) On, H. P.; Lewis, W.; Zweifel, G. *Synthesis* **1981**, 999. (i) Miller, R. B.; Al-Hassan, M. I. *J. Org. Chem.* **1983**, *48*, 4113. (j) Bjorking, F.; Norin, T.; Unelius, C. R. *J. Org. Chem.* **1987**, *52*, 292. (k) Koyayshi, Y.; Okamoto, S.; Shimazaki, T. *Tetrahedron Lett.* **1987**, *28*, 3959. (l) Wilt, J. W. *Tetrahedron* **1985**, *41*, 3979.

(7) The free-radical chlorination of trichloroethylsilane affords a 1:2.5 mixture of the α- and β-chlorination products.[8a,b] However, this is not evidence that α-silyl radicals lack stabilization.[8c] This result undoubtedly arises instead from a polar effect on the abstraction step.[8c]

(8) (a) Sommer, E. D.; Goldberg, G. M.; Whitmore, F. C. *J. Am. Chem. Soc.* **1946**, *68*, 488. (b) See also: Benkesser, R. A.; Nagai, Y.; Noe, J. L.; Cunico, R. F.; Gund, P. H. *J. Am. Chem. Soc.* **1964**, *86*, 2446. (c) Walling, C. *Free Radicals in Solution*; Wiley: New York, 1957; p 362 and associated discussion.

(9) Benkeser, R. A.; Bennett, E. W.; Hickner, R. A. *J. Am. Chem. Soc.* **1957**, *79*, 6253.

(10) Wilt, J. W. *Reactive Intermediates*; Abramovitch, R. A., Ed.; Plenum: New York, 1983; Vol. 3, pp 159–174. Wilt, J. W. *Free Radicals*; Kochi, J. E., Ed.; Wiley: New York, 1973; Vol 1, pp 261–267.

(11) Wilt, J. W.; Keller, S. M. *J. Am. Chem. Soc.* **1983**, *105*, 1395.

(12) Wilt, J. W.; Aznavoorian, P. M. *J. Org. Chem.* **1978**, *43*, 1285.

(13) Wilt, J. W.; Belmonte, F. G.; Zieske, P. A. *J. Am. Chem. Soc.* **1983**, *105*, 5665.

(14) Jackson, R. A.; Ingold, K. U.; Griller, D.; Nazran, A. S. *J. Am. Chem. Soc.* **1985**, *107*, 208.

(15) (a) Presented at the 19th Central Regional Meeting of the American Chemical Society, June 24–26, 1987, Columbus, OH, paper 275. (b) Swenton, J. S.; Anderson, D. K.; Jackson, D. K.; Narasimhan, L. *J. Org. Chem.* **1981**, *46*, 4825.

(16) (a) Walling, C.; Rieger, A. L.; Tanner, D. D. *J. Am. Chem. Soc.* **1963**, *85*, 3129. (b) Walling, C.; Rieger, A. L. *J. Am. Chem. Soc.* **1963**, *85*, 3134. (c) Pearson, R. E.; Martin, J. C. *J. Am. Chem. Soc.* **1963**, *85*, 3142. (d) Russell, G. A.; Desmond, K. M. *J. Am. Chem. Soc.* **1963**, *85*, 3139. (e) Russell, G. A.; DeBoer, C. *J. Am. Chem. Soc.* **1963**, *85*, 3136.

Scheme II. Kinetic Scheme for Laser Flash Photolysis

$$t\text{-Bu-O-O-}t\text{-Bu} \xrightarrow{h\nu} 2t\text{-Bu-O}\bullet$$

$$t\text{-Bu-O}\bullet + \text{R—H} \xrightarrow{k_1} \text{R}\bullet + t\text{-BuOH}$$

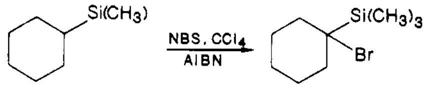
$$t\text{-Bu-O}\bullet + \text{Ph}_2\text{CHOH} \xrightarrow{k_2} \text{Ph}_2\text{C(OH)}\bullet + t\text{-BuOH}$$

butenes could be obtained by studying the NBS bromination of **4**. This reaction, effected under standard NBS

4 **5**(95%)

free-radical conditions, gave a 95% yield of **5** as determined by GLC and ^{1}H NMR spectroscopy, the remaining 5% being starting material. This experiment indicates that the hydrogen α to the trimethylsilyl group is at least 50 times more reactive than the methylene hydrogen.

Finally, the NBS bromination of (trimethylsilyl)cyclohexane was studied. Again, despite the hydrogen α to the trimethylsilyl group being statistically disfavored by a factor of 10 to 1, the bromosilane **7** was formed in 69% yield. Unreacted starting material, **6**, was also detected (11%) in addition to numerous minor products (presumably bromination of the methylene positions). Thus, the selectivity imparted to NBS brominations in the benzocyclobutenes was also manifested in simple alkyl systems.



6 **7**(69%)

Absolute Rate Constants for *tert*-Butoxy Radical Abstraction from Benzylsilanes

At the time this work was initiated, there were no reports of absolute rate constants for reactions generating carbon radical centers α to a trimethylsilyl group in benzyltrimethylsilanes. It would have been most desirable to measure the rate constants for hydrogen abstraction by bromine radical from benzyltrimethylsilanes for comparison with the relative rate studies presented above. However, a method for conveniently measuring these rates is not available. Thus, for expediency we have measured the rates of hydrogen abstraction from benzyltrimethylsilanes by *tert*-butoxy radical, recognizing that the lower selectivity of *tert*-butoxy vs bromine radical abstractions would dampen the stabilizing effect of the α-trimethylsilyl group on a radical center.

The laser flash photolysis technique has been described in detail[17] and has been used to measure the rate constants for a number of radical reactions. The procedure involves the flash photolysis (337 nm, N_2 laser) of di-*tert*-butyl peroxide in benzene containing benzhydrol (diphenylmethanol). This gives rise to benzhydrol radical Ph_2COH, which has an absorption at 525 nm. The addition of a reactive substrate increases the rate of pseudo-first-order decay of *tert*-butoxy radical and decreases the overall quantum yield of benzhydrol radical (Scheme II). The rates of abstraction can then be determined by a plot of observed rates of formation of benzhydrol radical vs the concentration of RH or by a Stern–Volmer plot.[18] The former method is usually more reliable.[17]

Table II. Rates of Reaction of *tert*-Butoxy Radical with Substituted Toluenes Determined by Laser Flash Photolysis

entry	substituted toluene	rate constant (10^{-6} L/mol/s)[a]
1	p-OCH$_3$	2.0 ± 0.6
2	p-t-Bu	1.0 ± 0.3
3	p-H	0.95 ± 0.3
4	(toluene-d_8)	0.94 ± 0.3
5	p-CO$_2$CH$_3$	0.65 ± 0.2
6	p-CN	0.50 ± 0.2

[a] ±1 standard deviation; these data were obtained by Stern–Volmer analysis.

Table III. Rates of Reaction of *tert*-Butoxy Radical with Substituted Benzylsilanes Determined by Laser Flash Photolysis

entry	substituted benzylsilane	rate constant (10^{-6} L/mol/s) I[a,c]	II[b,c]
1	p-OCH$_3$	6.7 ± 1.8	6.7 ± 1.2
2	p-OCH$_3$ (methylene-d_2)	5.1 ± 1.5	
3	p-t-Bu	3.0 ± 0.9	5.2 ± 1.3
4	p-H	2.3 ± 0.8	4.3 ± 1.4
5	p-CO$_2$CH$_3$	4.6 ± 1.4	3.6 ± 1.0
6	p-CO$_2$CH$_3$ (methylene-d_2)	4.5 ± 1.2	
7	m-CN	1.6 ± 0.8	
8	p-CN	5.3 ± 1.1	5.9 ± 1.2

[a] Stern–Volmer method.[18] [b] Formation of benzhydrol radical method.[18] [c] ±1 standard deviation.

First, the rate of reaction of *tert*-butoxy radical with toluene was studied to insure that the method and technique were correct. Irradiating 24% solutions of di-*tert*-butyl peroxide in benzene containing 0.05 M benzhydrol with either an excimer (Xe\HCl\He fill gas, 308 mm) or nitrogen laser gave satisfactory signals for analysis. The rate constant for *tert*-butoxy radical abstracting hydrogen from toluene was found to be 1.3 × 10^5 L/mol·s by plotting observed rates vs concentration and 9.54 × 10^5 L/mol·s by using the Stern–Volmer method. The literature value for the rate of reaction between toluene and *tert*-butoxy radical as measured by essentially the same method is 2.3 × 10^5 mol·s.[17b] The two methods of analysis yield values within a factor of $\simeq$2 and $\simeq$4, respectively, of the literature value. Although the agreement with the literature value was poorer than desired, the values obtained from these measurements should be internally consistent. The validity of the experimental method was further supported by the rates for *tert*-butoxy radical hydrogen abstraction from substituted toluenes given in Table II. The ρ value of -0.39 obtained from a plot of ln k vs σ^+ compared favorably with the value of -0.35 obtained for this reaction using relative rate data.[19]

Table III lists the rate constants for reaction of *tert*-butoxy radical with six benzyltrimethylsilanes. Two sets of values are reported since the rates obtained first via the Stern–Volmer method[18] were somewhat surprising (the p-CN-substituted system was about as reactive as the p-OCH$_3$ compound). A second independent set of determinations using the rates for formation of benzhydrol radical[18] gave essentially the same values. Since it would not be valid statistically to report only the second set of determinations, both sets of rate constants are recorded in Table III. Unfortunately, the insensitivity of the rate constants to substituents coupled with the experimental error in the measurements did not allow the calculation

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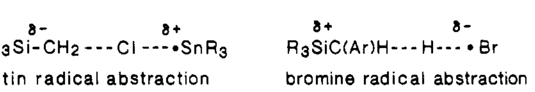
[17] (a) Scaiano, J. C. *J. Am. Chem. Soc.* **1980**, *102*, 7747. (b) Paul, H.; Small, R. D.; Scaiano, J. C. *J. Am. Chem. Soc.* **1978**, *100*, 4520.

[18] A more detailed discussion of the application of these methods is given in the Experimental Section.

[19] Sakurai, H.; Hosomi, A. *J. Am. Chem. Soc.* **1967**, *89*, 458.

Scheme III. Comparison of the Polar Nature of the Transition States for Trialkyltin and Bromine Radical Abstraction



$$R_3\overset{\delta-}{Si}\text{-}CH_2\text{---}\overset{\delta+}{Cl}\text{---}\bullet SnR_3 \qquad R_3Si\overset{\delta+}{C}(Ar)H\text{---}H\text{---}\overset{\delta-}{\bullet Br}$$

of a ρ value for the reaction.[20] The low selectivity of the *tert*-butoxy radical abstraction process is also consistent with the very small isotope effect observed when the benzyltrimethylsilanes are deuteriated at the methylene group.

Discussion

There is indisputable evidence that some reactions which generate α-trialkylsilyl radicals are kinetically accelerated relative to an analogous all-carbon system. An especially striking case is the reduction of α-chlorosilanes by tin hydrides in which rate factors of 20–100 have been observed relative to all-carbon systems. The silane reduction studies have been explained by proposing a polar transition state for the radical abstraction step wherein the buildup of negative charge adjacent to the silicon atom is delocalized by pπ–dπ bonding as is depicted in Scheme III.[13] This rationale was strongly supported by Hammett studies on the silane reductions of aryldimethyl(chloromethyl)silanes.[13] The results reported herein indicate that there is only a small rate enhancement and correspondingly only limited stabilization arising from interaction of an adjacent radical center with a trialkylsilyl moiety in benzyltrimethylsilanes, a conclusion suggested by bond dissociation energies reported earlier.[4] The NBS reactions of benzyltrimethylsilanes are accelerated by a factor of only about 7 relative to the respective toluene. In fact, ethylbenzene is reported to be 8–14 times more reactive than toluene in the NBS reaction;[16] thus, the trimethylsilyl group is functioning kinetically as an alkyl substituent. The transition state for the NBS reaction would not benefit from any polar effect since a partial positive charge would be generated α to the silyl group; thus, no dramatic rate acceleration should result.

The ρ value of −1.33 observed for NBS reaction of benzyltrimethylsilanes is not significantly different from that reported for toluenes (ρ −1.38, −1.41).[16] The replacement of one hydrogen of toluene with a trimethylsilyl group accelerates the NBS reaction by about the same amount as the replacement of a hydrogen with a methyl group. Thus, the ρ value for the benzyltrimethylsilane reaction might have been expected to be close to that for the free-radical bromination of ethylbenzene (ρ −0.69[22a]). Perhaps an even better model would be the free-radical bromination of neopentylbenzene (ρ −0.74[22b]). Our findings that the trimethylsilyl group increases the rate of benzylic hydrogen abstraction by bromine and does not decrease the sensitivity of the reaction to substituent effects (comparable ρ's for toluene and benzyltrimethylsilanes) appear to violate the reactivity–selectivity principle (RSP). The RSP assumes that the differences in the rates of two reactions are a result of differential activation enthalpies and that the activation entropy is constant. However, studies of the temperature dependence of the ρ value for hydrogen abstraction by bromine reveal an isokinetic temperature well below that of this study.[21] This means that substituent effects in toluene hydrogen transfer reactions involving bromine radical are strongly influenced by entropic effects. Under these conditions the RSP is not applicable.

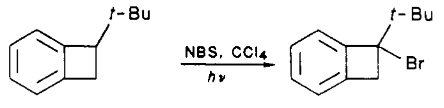
Scheme IV. Comparison of the Selectivities of *tert*-Butoxy Radical Abstraction

$$(CH_3CH_2)_3C\overset{4.2}{-\,-}CH_2\overset{1.0}{-\,-}CH_3 \qquad (CH_3CH_2)_3Si\overset{22.0}{-\,-}CH_2\overset{5.5}{-\,-}CH_3$$

In contrast, the absolute rate constants of $\simeq 5 \times 10^6$ L/mol·s measured for the reaction of *tert*-butoxy radical and benzyltrimethylsilanes follow the reactivity–selectivity principle. On a per hydrogen basis these values are about a factor of 10 times faster than the rates measured for *tert*-butoxy radical abstraction from the α-position of tetraethylsilane, $\simeq 3 \times 10^5$ L/mol·s,[10] and a factor of 5–15 times faster than the reactions with the analogous toluenes. Comparison of the benzylsilanes and the toluenes reveals a normal reactivity–selectivity relationship, with the more reactive benzylsilanes being much less sensitive to substituent effects. Although kinetic studies of the reaction of *tert*-butoxy radical with silanes have been interpreted as showing anchiomeric assistance by an α-trialkylsilyl group, the effects are modest as seen by comparing the relative reactivities as shown in Scheme IV.[14]

One must bear in mind that all of the butoxy radical abstractions are quite exothermic ($\Delta H \leq -15$ kcal/mol, assuming a C–H BDE of toluene of 88 and OH BDE of *tert*-butyl alcohol of 103). Thus, the transition states will be early and will reflect only a part of any stabilization due to the α-trimethylsilyl substituent. An early asymmetric transition state also explains the low kinetic isotope effects observed in the reaction of *tert*-butoxy radical and the deuteriated benzyltrimethylsilanes. The previously studied[14] reactions of *tert*-butoxy radical with the tetraethylsilane–tetraethylmethane pair must be less exothermic than with the benzyltrimethylsilane–toluene pair. The later, more symmetric transition state in the former series should therefore display somewhat greater selectivity differences than the latter series of compounds. The higher selectivities observed in the NBS brominations (Table I) are a result of the small exothermicity ($\Delta H \simeq 0$, HBr BDE $\simeq 85$); thus, the transition states in the NBS reaction have more radical character at the benzylic position and correspondingly more selectivity.

The high selectivity noted for the trimethylsilyl-substituted benzocyclobutenes **2a,b** and **4** and (trimethylsilyl)cyclohexane (**6**) requires an explanation. However, here, too, a rationale for the data need not involve enhanced stability associated with the radical center α to a trimethylsilyl group. The NBS bromination of **8** affords **9** in 70% yield,[23] indicating that the tertiary benzylic hydrogen is substantially more reactive than the methylene hydrogens in the benzocyclobutene series. Thus, the reactivity differences between secondary methylene hydrogens and tertiary hyrogens in benzocyclobutenes appear to be more dramatic. It has been suggested from the results of free-radical chlorination studies of cyclobutanes that the release of strain in the free-radical-forming step of the reaction enhances reactivity at the tertiary hydro-



8 9(70%)

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[20] The temperature dependence of the rho value noted for free-radical bromination of toluenes[21] could also play a role in the low ρ value noted here since the laser flash experiments were done at 25 °C.

[21] Wright, J. G.; Gilliom, R. D. *J. Am. Chem. Soc.* **1986**, *108*, 2340 and references cited therein.

[22] (a) Huang, R. L.; Lee, K. H. *J. Chem. Soc. C* **1966**, 936. (b) Totherow, W. D.; Gleicher, G. J. *J. Am. Chem. Soc.* **1969**, *91*, 1967.

[23] Avram, M.; Constantinescu, D.; Dinulescu, I. G.; Nenitzescu, C. D. *Tetrahedron Lett.* **1969**, 5215.

gen.[24] Perhaps this effect is also operating in the benzocyclobutene series. Since the products from bromination of the methylene positions of (trimethylsilyl)cyclohexane (**6**) were not characterized, the exact selectivity in the **6** → **7** reaction could not be established. However, the selectivity is only slightly greater than that which would arise in the comparison of secondary methylene hydrogens vs a tertiary hydrogen.

Conclusion

The trimethylsilyl group directs free-radical bromination α to the trimethylsilyl group relative to secondary positions in benzocyclobutenes and cyclohexane. Thus, substitution of a methylene hydrogen with a trimethylsilyl group improves the reactivity and selectivity of free-radical bromination at that position in the molecule. Presumably, this effect would also be transferred to other ring systems. Although the chemistry of this type of α-bromosilane unit has not been extensively studied, it does undergo facile metal–halogen exchange,[7b] it has been converted to a carbonyl group,[13] and other useful conversions can be envisioned. The synthetic benefit arising from a substitution of hydrogen on the radical center by a trisubstituted silyl group can be substantial. This is especially advantageous since the silyl moiety can be readily converted to other functionalities. However, the kinetic studies reported herein suggest that there is only a small increase in stability associated with radicals generated α to trimethylsilyl groups as compared to an alkyl group. Thus, the trimethylsilyl group serves superbly as a removable alkyl group in an organic synthetic scheme.

Experimental Section[25]

Preparation of Silanes and Bromosilanes. Literature methods were employed for the preparation of (*p*-methoxybenzyl)trimethylsilane[26] and (*p*-nitrobenzyl)trimethylsilane.[27] The preparation of the remaining silanes, the brominated silanes, and the deuteriated silanes were by standard methods; details regarding their preparation and spectroscopic data are given in the supplementary material.

Procedure for Relative Rates of NBS Reaction of Benzyltrimethylsilanes. The procedure was essentially that of Pearson and Martin.[16c] The substituted benzyltrimethylsilane, toluene, NBS, and AIBN in dry CCl_4 were placed in a sealed tube, three freeze–thaw cycles were conducted, and the sealed tube was heated at 80 °C (ca. 1 h). The tube was then cooled and opened, and a known amount of acenaphthene was added. Analysis was performed on an aliquot by ^1H NMR spectroscopy at 80 MHz. A typical procedure involved the following amounts of compound: 71.74 mg of benzylsilane, 44.97 mg of the respective toluene, 50 μL of a 0.4545 M acenaphthene solution, and 70 μL of 6.12 M AIBN in CCl_4.

Procedure for Measurement of Absolute Rate Constants. Laser flash photolysis experiments were performed with either a Lumonics Model TE-861-4 excimer laser (Xe/HCl/He fill gases, 308 nm, maximum pulse energy 110 mJ, pulse duration 8–10 ns) or a Molectron Model UV22 nitrogen laser (337.1 nm, maximum pulse energy 6 mJ, pulse duration 5–10 ns) for sample excitation. A 1000-W Hanovia xenon arc lamp was used to monitor transient absorption. The solutions in supracil cells (1 cm × 1 cm × 5 cm) were deoxygenated by bubbling with high-purity nitrogen and placed between this lamp and an Oriel Model 240 monochrometer. Suitable Ealing glass filters were placed between the sample and monochrometer photomultiplier tube assembly to prevent laser irradiation impinging on the detector. The monitoring beam was focused on the slit of an Oriel monochrometer and detected with a IP 28 photomultiplier tube which was amplified and recorded with either a Biomation (Gould Co.) Model 8100 or a Tektronix 7912 transient digitizer. Digitized data were sent to a Tektronix plug-in model 7A26 dual trace amplifier in a Model 7623A storage oscilloscope for visual display and to an Apple II+ 48K computer equipped with a 16K RAM memory expansion card for processing and subsequent disk storage.

For the Stern–Volmer analysis, the pertinent equation is

$$\frac{OD_0}{OD_x} = \frac{k_1}{k_0 + k_2[Ar_2CHOH]}[Ar'CH_2X] + 1 \qquad (2)$$

in which OD_0 and OD_x are the maximum transient optical densities of benzhydrol radical with no added benzyltrimethylsilane and "x" concentration of benzyltrimethylsilane, respectively, and k_0 is the sum of all of the rates of first-order and pseudo-first-order rate constants of *tert*-butoxy which do not involve Ar_2CHOH or $Ar'CH_2X$. Generally, five to six concentrations of $Ar'CH_2X$ were used for generating plots of eq 2, which showed correlation coefficients in the 0.85–0.98 range with most values between 0.9 and 0.94. The difficulties in accurately measuring rate constants of this magnitude have been discussed.[14]

The measurement of the rate constants using the rate of formation of benzhydrol radical has been thoroughly discussed.[14,17a,b] The pertinent equation is

$$k_{exptl} = k_0 + k_1[ArCH_2X] + k_2[Ar_2CHOH]$$

The determinations of these rate constants were made with four to five different concentrations of benzyltrimethylsilanes, and correlation coefficients for the plots were generally better than 0.93. Individual values of k_{exptl} were obtained from

$$\ln\left(\frac{A_\infty}{A_\infty - A_t}\right) = k_{exptl}t \qquad (3)$$

in which A_∞ is the maximum transient absorption of the benzhydrol ketyl radical produced after laser photolysis and A_t is the transient absorption at time = t.

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Supplementary Material Available: Experimental details for preparation of the silanes and bromosilanes used in this work, a plot of the Hammett equation for the NBS bromination of the benzyltrimethylsilanes, and representative kinetic plots (14 pages). Ordering information is given on any current masthead page.

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(25) All melting points were determined in capillaries in a Thomas-Hoover Unimelt capillary melting point apparatus and are uncorrected. Reported boiling points are also uncorrected. Infrared spectra were determined on a Perkin-Elmer Model 283B spectrometer on KBr disks unless otherwise noted, reported in cm^{-1}, and calibrated with the polystyrene band at 1601.4 cm^{-1}. ^1H NMR spectra were determined at 80 MHz on an IBM NR-80 spectrometer using deuteriochloroform as solvent and residual chloroform as standard. Gas chromatography was conducted on a Varian 3700 instrument using a stainless steel column (6 ft × $^1/_4$ in.) prepacked from the Anspec Co. with 5% OV-101 on Chromosorb W-HP 80/100 mesh for preparative work and an aluminum column (11 ft × $^1/_8$ in.) packed with 5% OV-101 on Chromosorb G 120/140 mesh for most of the analytical work. Ultraviolet spectral data were recorded on a Beckman DU-7 instrument. The maxima are reported in nanometers with the extinction coefficients in parentheses. Mass spectral and exact mass measurements were obtained by Richard Weisenberger on a Kratos MS-30 mass spectrometer connected to a DS-55 data system. Gas chromatographs/mass spectra were obtained by David Chang by use of a Finnigan 4021 GC/MS instrument. *N*-Bromosuccinimide was used as purchased from Fisher. Alumina and silica gel were obtained from E. Merck Co. Tetrahydrofuran (THF) was purified by distillation from benzophenone ketyl directly into the reaction flask. Petroleum ether, bp 35–60 °C (PE), diethyl ether (Et_2O), ethyl acetate (EtOAc), benzene (C_6H_6), chloroform ($CHCl_3$), methylene chloride (CH_2Cl_2), and all other solvents used were dried and distilled before use. Compounds not explicitly referenced are commercially available.

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