

The β -effect of silicon in the orthogonal geometry ¹

Joseph B. Lambert ^{*}, Xiaoyang Liu

Department of Chemistry, Northwestern University, Evanston, IL 60208, USA

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Abstract

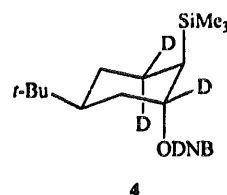
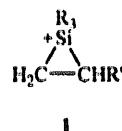
The inductive contribution to the β -effect of silicon has been investigated through the preparation of 1-(trimethylsilyl)bicyclo[2.2.2]octan-2-ol (**5-OH**) and its sulfonate derivatives. The dihedral relationship in **5** between the trimethylsilyl group and the bond to the leaving group approaches orthogonality, preventing any contribution to the β -effect from either hyperconjugation or bridging. Any residual effect of silicon should come from induction. The rate of the tosylate, compared with that of the silicon-free model bicyclo[2.2.2]oct-2-yl tosylate (**7-OTs**), was found to be 1.2–1.3 in 80–97% aqueous trifluoroethanol at 20–35°C. This negligible β -effect compares with values of about 10^5 at the synperiplanar geometry, 10^4 at clinal geometries, and 10^{12} at the antiperiplanar geometry. The complete dihedral dependence resembles the cosine-squared curve expected for a hyperconjugative mechanism rather than for bridging, with little contribution from induction.

Keywords: β -effect; Dihedral dependence; Hyperconjugation; Induction; Orthogonal geometry; Silicon; 1-(Trimethylsilyl)cyclohexa-1,3-diene

1. Introduction

β -Substituents M in the fragment M–C–C–X enhance the nucleofugal activity of X either by direct displacement, to form a bridged intermediate such as **1** (M = Me, Si) (the non-vertical mechanism), or by hyperconjugative stabilization of a carbocationic intermediate **2** \leftrightarrow **3** (the vertical mechanism). When M contains electropositive elements such as silicon, charge induction additionally can stabilize these positively charged intermediates. Evidence in the condensed phase has favored the vertical mechanism. Davis and Jacobs [1] found that the second silicon in 1,3-bis(trimethylsilyl)-2-propanol had about the same β -effect as the single silicon in 1-(trimethylsilyl)-2-propanol. Only a single silicon can be involved in non-vertical displacement to form the bridged intermediate **1**, but a hyperconjugative overlap from two C–Si bonds can occur readily when the C–X bond to the nucleofuge bisects the Si–C–Si angle. We found [2] that the α secondary H/D kinetic isotope effect for **4** is 1.17 in 97% trifluoroethanol at 25°C. This is a typical value for a transition state with carboca-

tonic character as in **2**, but not for a displacement transition state such as that leading to **1**. Computational studies by Jorgensen and coworkers [3,4] found considerable stabilization by silicon for both the bridged (**1**)



^{*} Corresponding author.

¹ Dedicated to Professor Robert Corriu in recognition of his outstanding contributions to organosilicon chemistry.

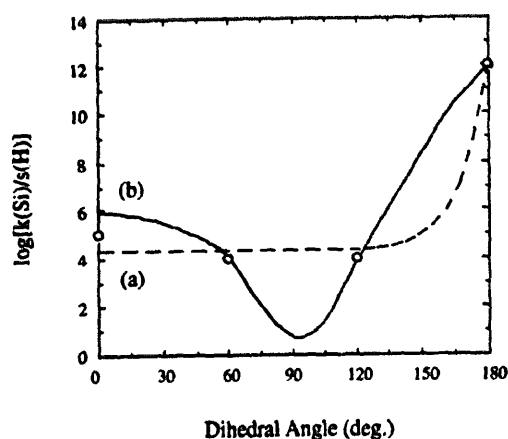


Fig. 1. The dihedral angle dependence of the β -effect of silicon based on rate accelerations measured for 0, 60, 120, and 180°. The dashed line is the expectation for non-vertical participation, the solid line for vertical participation.

and the hyperconjugated unbridged (2) structures, with the latter favored by about 4 kcal mol⁻¹ in the case of H₃SiCH₂CH⁺CH₃.

Fleming [5] has pointed out some of the difficulties in trying to distinguish between the bridged 1 and unbridged 2 structures. He pointed out that bridging by silicon and its congeners ought to be represented by dotted lines, since the two bonds to Si in 1 are composed of only two electrons in total (in contrast to bridging from lone pair-bearing β -substituents such as amines and halogens). Although he concluded that the open structure (2 \leftrightarrow 3) is probably favored, he pointed out limitations to the isotope effect experiments.

The modes of stabilization may also be distinguished by their different dependences on the dihedral angle defined by the Si=C and C=X bonds in the Si=C-C-X fragment [6]. The bridged intermediate 1 can be achieved only by displacement of X by Si in an antiperiplanar (backside) Si=C-C-X geometry, i.e. a dihedral angle of about 180°. Thus any contribution from this mechanism should drop off rapidly as the dihedral angle moves away from 180°. The hyperconjugative mechanism should exhibit a cosine-squared dependence on dihedral angle (resembling the Karplus curve), with maxima at 0 and 180°C and a minimum at 90° [7]. Any inductive contributions should be angular independent, and hence be present equally for all dihedral angles.

We have previously examined systems with approximate dihedral angles of 0, 60, 120, and 180° and found relative rates (k_{Si}/k_H : the rate k_{Si} of the silicon system compared with that, k_H , of the structurally analogous system with hydrogen replacing silicon) of about 10⁵, 10⁴, 10⁴, and 10¹² respectively [7,8]. Dihedral angles were fixed by the use of cyclohexyl and norbornyl systems. As seen from Fig. 1, these data may be fitted by either a bridged (dashed line) or an unbridged (solid line) mechanism. The bridged (non-vertical) interpreta-

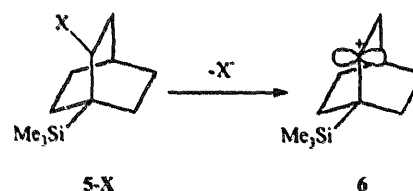
tion requires that the inductive effect contribute a factor of about 10⁴ for all dihedral angles, and then at 180° internal displacement raise the factor to 10¹². This is a very large contribution from induction, particularly in the light of the calculations [3,4], but the model cannot be eliminated on the basis of experiment. The unbridged (vertical) interpretation [8] requires that the rate for the synperiplanar geometry be diminished by factors other than hyperconjugation. We adopted this model and attributed the small synperiplanar value, compared with the antiperiplanar value, to inherent differences in *syn* and *anti* overlap and to steric inhibition of the $\sigma\pi$ overlap by the leaving group in the *syn* case [8]. The distorted cosine-squared curve must drop to close to zero in the middle in this vertical model, implying a negligible inductive effect.

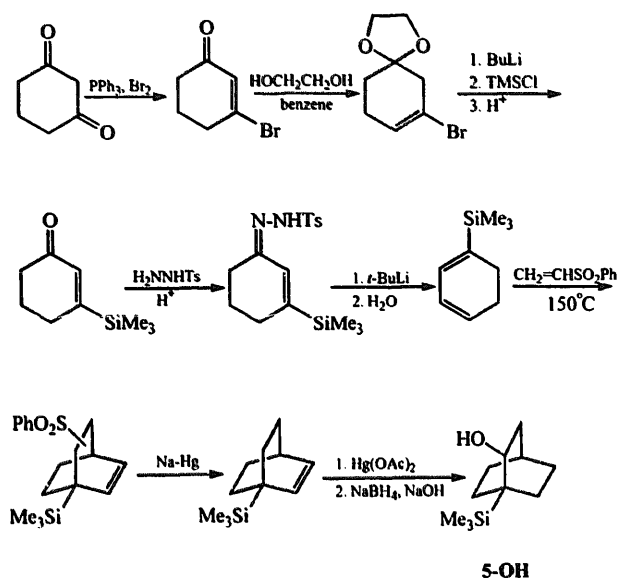
It is clear from Fig. 1 that the critical geometry to distinguish between the two mechanisms is at 90°, the orthogonal relationship between the Si-C and C-X bonds. The flat response between 0° and about 150° for the bridged mechanism requires that the 90° system exhibit an acceleration of about 10⁴ from induction. The cosine-squared response for the hyperconjugative mechanism requires a minimum between the 60 and 120° values that is significantly less than 10⁴ and possibly as low as zero, as obtained computationally [3,4].

Consequently, we have prepared a system that approaches orthogonality and report the results herein. Loss of the nucleofuge X from 1-(trimethylsilyl)bicyclo[2.2.2]oct-2-yl (5-X) begins with a nearly orthogonal relationship between Si-C and C-X, and would eventually reach a fully orthogonal carbocation 6. In this ion neither bridging nor hyperconjugation is possible and any stabilization must derive from induction alone.

2. Results

1-(Trimethylsilyl)bicyclo[2.2.2]octan-2-ol (5-OH) was synthesized by the procedure outlined in Scheme 1. The key intermediate was the novel diene 1-(trimethylsilyl)cyclohexa-1,3-diene. The precursor 3-(trimethylsilyl)cyclohex-2-en-1-one is a known material, having been prepared from 3-(trimethylsilyl)cyclohex-1-ene [9] and from cyclohexan-1,3-dione [10]. We tried both

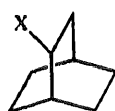




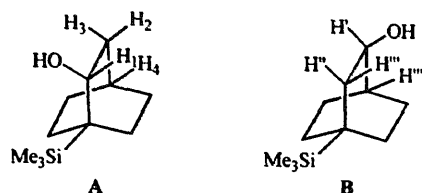
Scheme 1.

methods and selected that of Shih and Swenton [10] because of the expense of the Wilkinson catalyst and low yields in the first method. The enone was successfully converted to the diene by the Shapiro reaction [11]. The standard use of methyl lithium in this reaction, however, resulted in loss of the trimethylsilyl group, but use of *tert*-butyllithium was successful. To construct the second ring, we used phenyl vinyl sulfone as the dienophile in the Diels–Alder reaction. Despite the presence of the electron-donating trimethylsilyl group on the diene, the reaction proceeded more slowly than the reaction of phenyl vinyl sulfone with the parent 1,3-cyclohexadiene [12], requiring 150°C for 3–4 days rather than 125°C for 17 h, possibly because of a steric effect of the trimethylsilyl group. Reductive desulfonation of the bicyclooctene was accomplished most efficiently with an excess of 6% sodium amalgam [13]. Finally, hydration of the double bond by mercuration/demercuration yielded the desired product, 5-OH [14].

The 1-D ^1H and ^{13}C spectra were entirely in accord with the desired structure but did not entirely eliminate the alternative regioisomer from mercuration. The major question was thus distinguishing structures A and B. The easily identifiable proton α to the hydroxyl group (H_1) at δ 3.91 was a broad doublet with only two cross-peaks in the COSY spectrum, as expected for



7-X



A but not for B, which should have had three cross peaks (H' with each of H'' , H''' , and H''''). The proton with the larger (*syn*) coupling (9.4 Hz) then was identified as H_2 and the one with the smaller (*ant*iclin) coupling (4.0 Hz) as H_3 . Consequently, the double doublet at δ 1.88 was assigned to H_2 , with a *geminal* coupling of 11.6 Hz to H_3 , a *syn* coupling of 9.4 Hz to H_1 , and a skew *vicinal* coupling of 2.6 Hz to H_4 , and with three COSY cross-peaks, to H_1 , H_3 , and H_4 . The double doublet at δ 1.20 was assigned to H_3 , with the same *geminal* coupling of 11.6 Hz to H_2 , the *ant*iclin coupling of 4.0 Hz to H_1 , and the skew *vicinal* coupling of 2.6 Hz to H_1 , and with three COSY cross-peaks, to H_1 , H_2 , and H_4 . The bridgehead proton H_4 was found at δ 1.30, with two COSY cross-peaks to H_2 and H_4 . Thus the couplings and 2-D cross-peaks eliminate alternative B.

A silicon-free model compound, bicyclo[2.2.2]octan-2-ol, 7-OH, was prepared by mercuration/demercuration of bicyclo[2.2.2]octene.

For solvolysis studies, the tosylates 5-OTs and 7-OTs were prepared by reaction of the alcohols with tosyl chloride in the presence of pyridine [15]. In addition, because of solubility difficulties with 5-OTs, the mesylate 5-OMs was also prepared. The rate constants for solvolysis in aqueous trifluoroethanol (TFE) and ethanol (EtOH) are given in Table 1. From the temperature dependence of the rates, activation parameters were calculated at 25°C for 5-OTs to be $E_a = 21.4 \pm 0.4$ kcal mol $^{-1}$, $\Delta H^\ddagger = 20.8 \pm 0.4$ kcal mol $^{-1}$, $\Delta S^\ddagger = -3.94 \pm 0.06$ cal deg $^{-1}$ mol $^{-1}$, and $\Delta G^\ddagger = 21.9 \pm 0.04$ kcal mol $^{-1}$ and for 7-OTs to be $E_a = 19.1 \pm 0.8$ kcal mol $^{-1}$, $\Delta H^\ddagger = 18.5 \pm 0.8$ kcal mol $^{-1}$, $\Delta S^\ddagger = -11.9 \pm 0.2$ cal deg $^{-1}$ mol $^{-1}$, and $\Delta G^\ddagger = 22.1 \pm 0.8$ kcal mol $^{-1}$. In both cases the Arrhenius plots exhibited correlation coefficients of 0.999.

Product studies were carried out in 97% TFE at 35.0°C. Solvolysis of 5-OTs gave 1-(trimethylsilyl)bicyclo[2.2.2]octene (8%), 1-(trimethylsilyl)-2-(trifluoroethoxy)bicyclo[2.2.2]octane (59%), 1-(trimethylsilyl)-3-(trifluoroethoxy)bicyclo[2.2.2]octane (33%), and traces of 1-(trimethylsilyl)bicyclo[2.2.2]octan-1-ol. Solvolysis of 5-OMs gave respectively 5%, 15%, 15%, and 36% of the same products, as well as 30% of 1-(trimethylsilyl)bicyclo[2.2.2]octan-3-ol. Solvolysis of 7-OTs gave 56% of bicyclo[2.2.2]octanol and 42% of 2-(trifluoroethoxy)bicyclo[2.2.2]octane.

3. Discussion

Examination of the effect of solvent nucleophilicity and ionizing power provides information about the molecularity of the reactions studied. Raber, Harris, and coworkers [16] have developed a method for determining molecularity for pseudo first order solvolysis reactions. They recognized that varying the water levels in aqueous TFE changes nucleophilicity but not ionizing power, whereas varying the water levels in aqueous EtOH changes ionizing power but not nucleophilicity. Measurement of rates in both solvents as a function of water concentration can distinguish between the two properties. By plotting the rates against those of a substrate known to react by a carbocation mechanism (k_c), they observed two classes of result. A substrate also reacting unimolecularly was found to give a linear plot. The TFE points clustered in the upper right, reflecting little response to solvent nucleophilicity on either axis, and the EtOH points were well distributed along the line, reflecting x and y dependence on ionizing power. When the substrate, however, reacted bimolecularly with solvent (k_s , whether reaction with C for substitution, H for elimination, or elsewhere in the molecule), the two solvents produced two distinct non-parallel lines reflecting their different responses to nucleophilicity. For example, cyclohexyl tosylate exhibited two lines and illustrates a k_s substrate [16], whereas the 2-(trimethylsilyl)cyclohex-1-yl tosylates exhibited one line and illustrate a k_c substrate [6].

The Raber–Harris plot for bicyclo[2.2.2]oct-2-yl tosylate (7-OTs) is given in Fig. 2. Although the plot is

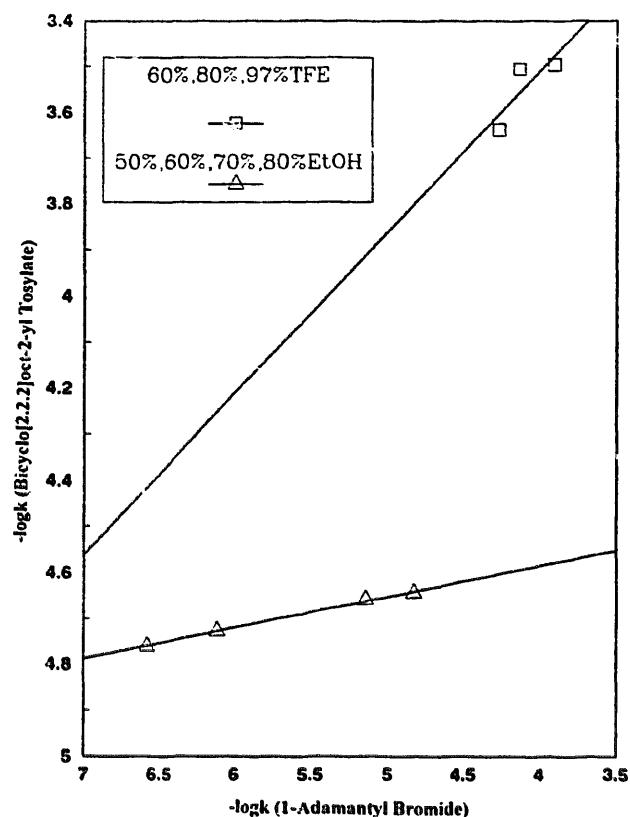


Fig. 2. Raber–Harris plot for bicyclo[2.2.2]oct-2-yl tosylate (7-OTs).

clearly non-linear, it does not fall neatly into the k_s category. Normally the TFE points for a k_s substrate show a steep slope and occur at slower rates than the EtOH points, reflecting sensitivity to nucleophilicity. The clustered TFE points in fact resemble k_c behavior. The EtOH points, however, show normal k_s behavior, with a low slope that indicates little sensitivity of the substrate to ionizing power. Such intermediate behavior suggests a change in mechanism between the two solvents: k_c in TFE and k_s in EtOH.

The Raber–Harris plot (Fig. 3) for 1-(trimethylsilyl)bicyclo[2.2.2]oct-2-yl mesylate (5-OMs) shows typical k_c behavior in both solvents: a single line, a high slope for the EtOH points, and the TFE points clustered in the upper right corner. We could not construct a Raber–Harris plot for 5-OTs because of its insolubility in EtOH, but we do not expect appreciably different behavior from the two leaving groups. The product studies for both substrates are consistent with carbocation mechanisms in 97% TFE.

The β -effect of silicon was first recognized by the presence of rate enhancements [5]. The rate ratio k_{Si}/k_H is the standard measure of the β -effect. For the present structures, this ratio is $k(5-OTs)/k(7-OTs)$. The data in Table 1 indicate that this ratio is 1.31 at 35.0°C and 1.19 at 20.0°C in the most ionizing solvent (97% TFE). In 80% TFE, the ratio is 1.24 at 20.0°C. Thus, in the absence of hyperconjugative (vertical) and internal par-

Table 1

Rate constants ^a for solvolysis in aqueous 2,2,2-trifluoroethanol ^b and ethanol ^c

System	Solvent	Temperature (°C)	k (s ⁻¹)	r
5-OMs	97% TFE	30.0	6.54×10^{-4}	0.999
	80% TFE	30.0	8.86×10^{-4}	0.999
	60% TFE	30.0	1.27×10^{-3}	0.996
	80% EtOH	30.0	6.93×10^{-5}	0.999
	90% EtOH	30.0	2.35×10^{-5}	0.999
5-OTs	97% TFE	35.0	1.64×10^{-3}	0.999
		30.0	9.56×10^{-4}	0.999
		20.0	2.76×10^{-4}	0.999
	80% TFE	20.0	3.89×10^{-4}	0.999
7-OTs	97% TFE	35.0	1.25×10^{-3}	0.999
		20.0	2.31×10^{-4}	0.999
		10.0	8.07×10^{-4}	0.998
	80% TFE	20.0	3.13×10^{-4}	0.999
	60% TFE	20.0	3.19×10^{-4}	0.994
	50% EtOH	20.0	2.27×10^{-5}	0.999
	60% EtOH	20.0	2.21×10^{-5}	0.998
	70% EtOH	20.0	1.89×10^{-5}	0.998
80% EtOH	20.0	1.74×10^{-5}	1.000	

^a Average of two or more runs. ^b Per cent by weight. ^c Per cent by volume.

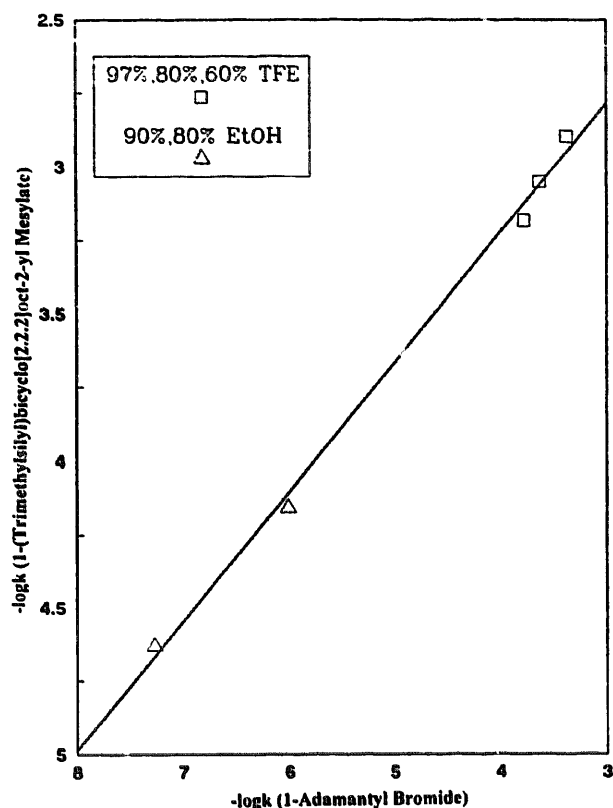


Fig. 3. Raber-Harris plot for 1-(trimethylsilyl)bicyclo[2.2.2]oct-2-yl mesylate (5-OMs).

tipication (non-vertical) interactions, there is essentially no β -effect of silicon. These observations indicate that the inductive effect of Me_3Si is essentially nil in TFE.

The dihedral angle dependence of the β -effect of silicon now may be completed (Fig. 4). It resembles a cosine-squared curve with a highly flattened synperiplanar left side, for reasons discussed previously [8]. This curve gives further evidence that the β -effect of silicon

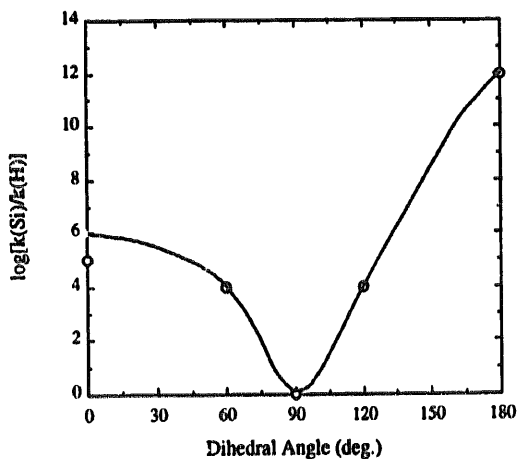


Fig. 4. The dihedral angle dependence of the β -effect of silicon including data for 90° .

is caused by hyperconjugative interactions across the full range of dihedral angles, although the curve alone does not exclude an additional rate-enhancing non-vertical effect exclusively at 180° . The observation of a carbocation-like kinetic isotope effect of 1.17, however, indicates that hyperconjugation is the primary mechanism at this geometry as well.

4. Experimental section

NMR spectra were recorded on a Gemini 300 and a Varian XLA-400 spectrometer. Mass spectra were obtained on a VG Analytical 70-SE spectrometer. Diethyl ether and tetrahydrofuran (THF) were dried over sodium. Pyridine, methanol, and chlorotrimethylsilane were dried over CaH_2 . The solvent ethanol for kinetics was distilled from magnesium ethoxide as described by Lund and Bjerrum [17]. The solvent 2,2,2-trifluoroethanol for kinetics was distilled from aqueous K_2CO_3 , dried over P_2O_5 , and fractionally distilled.

4.1. 3-Bromocyclohex-2-en-1-one [10]

A three-necked flask equipped with two pressure-equalized dropping funnels and a stirring bar was charged with 37.40 g (0.142 mol) of triphenylphosphine in 400 ml of C_6H_6 . To this cooled solution (ca. 5°C) was added 23 g (0.142 mol) of Br_2 in 25 ml of C_6H_6 over a period of 1 h followed by the dropwise addition of 14.40 g (0.142 mol) of triethylamine. To this cooled solution was added 10.30 g (0.089 mol) of 1,3-cyclohexanedione (97%) in 125 ml of CHCl_3 over 1 h. The resulting reaction mixture was stirred at room temperature until the starting ketone was consumed. The mixture was filtered through Celite. The filtrate was washed with H_2O (50 ml) and brine (50 ml), and dried over Na_2SO_4 . Removal of the solvent by rotary evaporation gave a red-brown viscous liquid that was distilled under vacuum to give 13.20 g (85%) of the product as a colorless liquid (b.p. $75\text{--}80^\circ\text{C}$ (1 mmHg)), which showed spectroscopic properties in agreement with those reported [18].

4.2. Ketalization of 3-bromocyclohex-2-en-1-one [10]

A solution of 5.00 g (0.03 mol) of the bromo ketone, 3.54 g of ethylene glycol, and 100 mg of *p*-toluenesulfonic acid monohydrate in 400 ml of C_6H_6 was refluxed for 4 h for azeotropic removal of H_2O . The reaction mixture was washed with 5% NaHCO_3 (50 ml) and brine (25 ml), and dried over Na_2SO_4 . The solution was concentrated by rotary evaporation, and the residue was chromatographed on Activity II neutral alumina (10% ether/hexane as eluant) to give 3.20 g (52%) of the ketal as a colorless liquid: $^1\text{H NMR}$ (CDCl_3) δ 1.74

(t, 2H), 2.25 (m, 2H), 2.65 (d, 2H), 3.99 (s, 4H), 6.06 (m, 1H); ^{13}C NMR (CDCl_3) δ 25.4, 30.3, 45.3, 60.0, 64.5, 103.2, 127.6.

4.3. 3-(Trimethylsilyl)cyclohex-2-en-1-one [10]

To a solution of 0.73 g (3.3 mmol) of the ketal in 45 ml of anhydrous THF cooled to -78°C was added dropwise 3.12 ml (6.6 mmol) of 2.5 M butyllithium. The resulting solution was stirred at -78°C for 0.5 h (the color changed from clear pink to brown and finally to a cloudy pale yellow suspension). Then 1 ml of chlorotrimethylsilane (5 mmol, Aldrich) was added. The reaction mixture was stirred at -78°C for 1 h, then at room temperature for several hours until GC showed that the starting material had entirely disappeared. The reaction mixture was poured into 15 ml of 5% HCl, the solution was extracted by ether, and the organic layer was washed with H_2O , 5% NaHCO_3 , and brine. The solvent was removed, and the crude, slightly yellow liquid was chromatographed through a silica gel column (8–10% ether/petroleum ether as eluant) to give 0.40 g (60%) of the desired silyl ketone: ^1H NMR (CDCl_3) δ 0.12 (s, 9H), 1.97 (m, 2H), 2.36 (m, 4H), 6.21 (m, 1H); MS (EI) m/z 168 (61%) (M^+), 153 (64), 140 (32), 125 (45), 97 (11), 73 (100), 45 (17); and 0.11 g (17%) of the isomer 3-(trimethylsilyl)cyclohex-3-en-1-one.

4.4. 3-(Trimethylsilyl)cyclohex-2-en-1-one tosylhydrazone

A three-necked, round-bottomed flask equipped with a reflux condenser, an addition funnel, and a stirring bar was charged with 2.67 g (0.014 mol) of *p*-toluenesulfonylhydrazide, 36 ml of CH_3OH , and three drops of 1% HCl/ CH_3OH . The flask was cooled to 0°C , and 2.01 g (0.012 mol) of the silyl ketone in 48 ml of CH_3OH was added in a dropwise fashion. The mixture was allowed to warm slowly to room temperature over several hours until GC showed that there was no more starting ketone. Removal of the solvent gave 0.60 g (90%) of a slightly yellow solid: ^1H NMR (CDCl_3) δ 1.72 (m, 2H), 2.15 (t, 2H), 2.25 (t, 2H), 2.40 (s, 3H), 5.65 (m, 1H), 6.37 (s, 1H), 7.35 (d, 2H), 7.80 (d, 2H).

4.5. 1-(Trimethylsilyl)cyclohexa-1,3-diene

To a round-bottomed flask fitted with a condenser and a stirring bar was added 4.27 g (0.0133 mol) of the tosylhydrazone in 130 ml of anhydrous ether. The flask was cooled to -78°C , and 31 ml (0.0532 mol) of 1.7 M $^t\text{BuLi}$ was added slowly to the cooled flask over 1 h. The color of the solution changed from slightly yellow to deep red. The reaction mixture was warmed slowly to room temperature and stirred for several hours until TLC showed that the hydrazone had been consumed.

The flask was cooled in an ice bath, and 20 ml of H_2O was added to quench the reaction. The aqueous layer was extracted with ether. The combined organic layer was washed with brine and dried (MgSO_4). Distillation gave 1.00 g (50%) of a colorless liquid: ^1H NMR (CDCl_3) δ 0.08 (s, 9H), 2.11 (m, 4H), 5.95 (m, 1H), 6.17 (d, $J = 4.8$ Hz, 1H); ^{13}C NMR (CDCl_3) δ 2.3, 22.1, 23.9, 124.6, 127.6, 131.6, 139.6; MS (EI) m/z 152 (22%) (M^+), 137 (21), 78 (30), 73 (100), 59 (38). Anal. Found: C, 70.59; H, 10.45. $\text{C}_9\text{H}_{16}\text{Si}$ Calc.: C, 70.99; H, 10.59%.

4.6. (Phenylsulfonyl)-1-(trimethylsilyl)bicyclo[2.2.2]oct-2-ene

To a Pyrex test tube were added 0.50 g (2.97 mmol) of phenyl vinyl sulfone, 0.14 g (0.95 mol) of the diene, several crystals of hydroquinone, and 2 ml of benzene. The tube was sealed under vacuum and heated to $145\text{--}150^\circ\text{C}$ in an oil bath for 3–4 days. The reaction mixture was chromatographed directly on silica gel (10% acetone/hexane as eluant) to give 0.24 g of the sulfone (80%, slightly yellow solid) as a mixture of two isomers. Location of the sulfone group is not certain. A fraction containing one pure isomer was used for characterization: ^1H NMR (CDCl_3) δ 0.0 (s, 9H), 1.0–1.2 (m, 6H), 2.9 (m, 1H), 3.3 (t, $J = 8$ Hz, 1H), 6.2 (d, $J = 8.0$ Hz, 1H), 6.2 (dd, $J = 6$ and 8 Hz, 1H), 7.55 (t, 2H), 7.62 (d, 1H), 7.85 (d, 2H).

4.7. 1-(Trimethylsilyl)bicyclo[2.2.2]oct-2-ene

To a mixture of 0.62 g of 6% sodium amalgam (1.6 mmol of Na) and 0.15 g of Na_2HPO_4 in 1 ml of anhydrous CH_3OH , 0.05 g (0.156 mol) of the sulfone in 1 ml of anhydrous THF was added. The reaction mixture was stirred at room temperature for 25 h. The contents of the flask was decanted into a separatory funnel. The flask was rinsed with pentane (2×2 ml), and the combined organic portions were washed with H_2O (4×2 ml) and brine (2 ml), and then dried over MgSO_4 . After careful distillation, 0.03 g (96%) of a colorless liquid was obtained: ^1H NMR (CDCl_3) δ 0.0 (s, 9H), 1.2 (m, 4H), 2.5 (m, 1H), 6.1 (d, $J = 8$ Hz, 1H), 6.4 (dd, $J = 7.3$ and 8 Hz, 1H); ^{13}C NMR (CDCl_3) δ -4.3, 14.2, 26.5, 27.1, 29.7, 134.8, 136.6; MS (EI) m/z 180 (M^+), 165, 152, 137, 106, 78, 73 (100), 59, 45. Anal. Found: C, 72.21; H, 10.91. $\text{C}_{11}\text{H}_{20}\text{Si}$ Calc.: C, 73.25; H, 11.18%.

4.8. 1-(Trimethylsilyl)bicyclo[2.2.2]octan-2-ol (5-OH)

To a 5 ml flask containing a magnetic stirrer and 0.06 g (0.2 mmol) of $\text{Hg}(\text{OAc})_2$ in 0.2 ml of H_2O and 6 ml of THF, was added 0.04 g (0.2 mmol) of the bicyclic alkene slowly. The reaction mixture was stirred at room

temperature for 30 h until the yellow color of $\text{Hg}(\text{OAc})_2$ in THF had disappeared. Then 0.2 ml of 3 M NaOH solution was added slowly, followed by the addition of 0.2 ml of 0.5 M NaBH_4 in 3 M NaOH. Reduction of the mercurial was almost instantaneous. The reaction mixture was stirred for 1 h more, and the mercury was allowed to settle. The solution was decanted and the precipitate rinsed with ether. The aqueous solution was extracted with 2×2 ml of ether. The combined organics were dried (MgSO_4), and the solvent was removed by rotary evaporation. Chromatography (silica gel, 1/10 ether/petroleum ether as eluant) gave 0.03 g (61%) of 5-OH as a white solid: $^1\text{H NMR}$ (CDCl_3) δ -0.1 (s, 9H), 1.2–1.6 (m, 9F), 1.8–1.9 (m, 2H), 3.91 (m, 1H); $^{13}\text{C NMR}$ (CDCl_3) δ -4.8, 17.4, 18.5, 24.3, 24.5, 25.5, 31.8, 37.3, 69.6; MS (EI) m/z 198 (15%) (M^+), 108 (26), 93 (63), 79 (35), 73 (100), 45 (12).

4.9. 1-(Trimethylsilyl)bicyclo[2.2.2]oct-2-yl tosylate (5-OTs)

A dried 10 ml round-bottomed flask containing 0.07 g (0.35 mmol) of 5-OH was flushed with N_2 , cooled to 0°C , and charged with 4 ml of dry pyridine and 0.15 g (0.79 mmol) of tosyl chloride. The mixture was swirled at 0°C until all the material had dissolved. The flask was then placed in the freezer for 4 months, until no additional pyridinium hydrochloride precipitated out. The mixture was poured into a mixture of ice and ether, and the resulting aqueous layer was extracted twice with cold ether. The combined organic layers were washed twice with cold water and dried (Na_2SO_4). Removal of the solvent gave a yellow solid that was recrystallized in pentane at 0°C to give a white solid: $^1\text{H NMR}$ (CDCl_3) δ 0.1 (s, 9H), 1.2–1.6 (m, 9H), 1.7–1.9 (m, 2H), 2.43 (s, 3H), 7.3 (d, 2H), 7.8 (d, 2H); $^{13}\text{C NMR}$ (CDCl_3) δ 1.0, 17.5, 18.5, 21.6, 23.7, 24.1, 25.0, 29.0, 34.5, 82.2, 127.6, 127.8, 128.7, 129.8, 134.5, 144.0. Anal. Found: C, 59.12; H, 7.90. $\text{C}_{18}\text{H}_{28}\text{O}_3\text{SSi}$ Calc.: C, 61.32; H, 8.00%.

4.10. 1-(Trimethylsilyl)bicyclo[2.2.2]oct-2-yl mesylate (5-OMs)

According to the procedure used for the synthesis of 5-OTs, 0.25 g (85%) of 5-OMs was prepared. The product was a slightly yellow semi-solid: $^1\text{H NMR}$ (CDCl_3) δ 0.1 (s, 9H), 1.3–2.0 (m, 11H), 3.0 (s, 3H), 4.89 (m, 1H).

4.11. Bicyclo[2.2.2]octan-2-ol (7-OH)

To a 50 ml round-bottomed flask, 1.48 g of mercury(II) acetate (4.6 mmol), 5 ml of H_2O , and 3 ml of anhydrous THF were added. Bicyclo[2.2.2]octene (0.50 g, 4.6 mmol, Aldrich) in 2 ml of THF was added

dropwise to the flask. The yellow color of $\text{Hg}(\text{OAc})_2$ disappeared in 5 min. The reaction flask was allowed to stir at room temperature for several hours. Then 5 ml of 3 M NaOH solution was added slowly, followed by 5 ml of 0.5 M NaBH_4 in 3 M NaOH. The reaction mixture was stirred for an additional 30 min until the black precipitate settled to the bottom of the flask. The solution was decanted into a separatory funnel and was saturated with NaCl. After the solvent was removed, 0.64 g of a gray solid was obtained. After sublimation, 0.46 g (79%) of a white solid was obtained: $^1\text{H NMR}$ (CDCl_3) δ 1.3–1.7 (m, 10H), 1.95 (m, 2H), 3.95 (m, 1H); $^{13}\text{C NMR}$ (CDCl_3) δ 18.5, 23.7, 24.4, 25.6, 31.6, 37.5, 69.6.

4.12. Bicyclo[2.2.2]oct-2-yl tosylate (7-OTs)

According to the procedure for the synthesis of 5-OTs, 0.34 g (84%) of tosylate was prepared from 7-OH: $^1\text{H NMR}$ (CDCl_3) δ 1.3–2.0 (m, 12H), 2.4 (s, 3H), 4.7 (m, 1H), 7.3 (d, 2H), 7.8 (d, 2H).

4.13. Kinetic methods

Rates in aqueous solvents were determined conductometrically with an Industrial Instruments Model RC 16B2 conductivity bridge. The conductivity cell (Industrial Instruments) had a black Pt electrode and a volume of approximately 35 ml. The conductivity measurements were performed on solutions with substrate concentrations of approximately 10^{-3} M. The conductance cell was stoppered and equilibrated in a constant temperature bath for at least 5 min. The solution was either cooled in a Techne RB-5 refrigerated bath or warmed in a Precision H8 heating bath. The temperature was measured to 0.1°C with factory certified (NBS standard) thermometers. The conductivity of the solutions was followed for one to three half-lives using a YSI Model 32 conductance meter. Linear first order rate plots were obtained for up to three half-lives.

4.14. Product studies

A 0.2–0.5 M solution of the substrate in the desired solvent (1–2 ml) was prepared in a Pyrex test tube. The tube was sealed and heated in a water bath. After 3–4 days the products were identified by MS or GC/MS. 1-(Trimethylsilyl)bicyclo[2.2.2]octene and 1-(trimethylsilyl)bicyclo[2.2.2]octan-2-ol were identified by comparison of the GC and MS data with the pure compounds. 1-(Trimethylsilyl)-2-(trifluoroethoxy)bicyclo[2.2.2]octane was identified by MS peaks at 280, 124, 108, 93, and 73. 1-(Trimethylsilyl)-3-(trifluoroethoxy)bicyclo[2.2.2]octane was identified by MS peaks at 280, 165, 108, 93, and 73.

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