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[10] ^{1}H NMR (750 MHz, CD_3OD, 50 °C): $\delta = 0.93$ (1H, ddd, $J = 12$, 4.5, 1.5 Hz; C(8)H), 1.21 (1H, qd, $J = 14$, 4 Hz; C(9)H), 1.36 – 1.40 (1H, m; C(14)H), 1.42 – 1.63 (8H, m; C(14)H′, C(15)H_2, C(16)H, C(22)H, C(23)H_2, and C(9)H′), 1.67 (1H, dd, $J = 9$, 2.5 Hz; C(6)H), 1.69 – 1.76 (4H, m; C(20)H_2, C(19)H, and C(22)H′), 1.99 (1H, br d, $J = 13$ Hz; C(24)H), 2.08 (1H, d, $J = 11.5$ Hz; C(12)H), 2.09 – 2.12 (1H, m; C(27)H), 2.20 (1H, ddd, $J = 12.5$, 5.5, 1.5 Hz; C(13)H), 2.20 – 2.28 (2H, m; C(5)H and C(24)H′), 2.30 – 2.42 (7H, m; C(28)H_2, C(27)H′, C(19)H′, C(16)H′, C(21)H, and C(12)H′), 2.69 – 2.71 (1H, m; C(10)H), 2.78 (1H, br t, $J = 13$ Hz, C(10)H′), 2.87 (1H, dd, $J = 9$, 2 Hz; C(6)H′), 2.95 (1H, td, $J = 12.5$, 5 Hz; C(13)H′), 3.03 – 3.06 (1H, m; C(21)H′), 3.11 (1H, s; C(2)H), 5.25 (1H, pseudot, $J = 10.5$ Hz; C(25)H), 5.38 (1H, pseudot, $J = 10$ Hz, C(26)H), 5.60 – 5.66 (2H, m; C(17)H and C(18)H), 5.86 (1H, d, $J = 6$ Hz; C(4)H); diastereotopic protons are assigned as X and X′, where the ′ indicates the lower field proton; ^{13}C NMR (188.7 MHz, CD_3OD) $\delta = 21.32$ (C22), 21.68 (C19), 23.80 (C16), 26.10 (C24), 26.53 (C27), 27.12 (C9), 27.50 (C14, C15 and C23), 37.81 (C28), 38.99 (C5), 42.10 (C20), 44.62 (C8), 48.77 (C10), 50.94 (C12), 54.48 (C6), 55.15 (C13), 57.04 (C21), 65.04 (C2), 124.52 (C4), 131.27 (C18), 132.59 (C25), 132.60 (C17), 133.33 (C26), 142.94 (C3); only signals which can be clearly observed above the noise or which can be traced back through HMQC experiments are reported; *m*/*z* (APCI) 381 (MH^+, 100%); HRMS found: 381.3270; calcd for $C_{26}H_{41}N_2$ (MH^+): 381.3270.

[11] The reaction of **7** in buffer was monitored by ^{1}H NMR spectroscopy. By the time the reaction was quenched with $NaBH_4$, all the signals arising from **7** had virtually disappeared. Therefore, the majority of **13** was not derived from the reduction of **7**.

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A New Route to Heterosilsesquioxane Frameworks**

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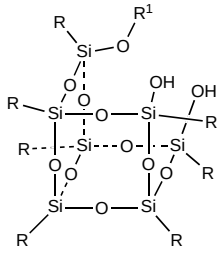
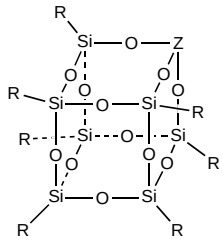
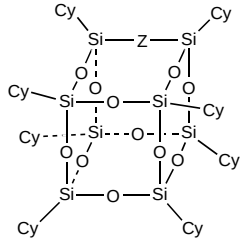
Incompletely condensed silsesquioxanes such as **1** and **2**[1, 2] are versatile precursors to a diverse range of Si/O and Si/O/M frameworks, and a wide variety of heterosilsesquioxanes can be prepared by reactions that transform Si – OH groups into new siloxane (i.e., Si-O-Si) or heterosiloxane (i.e., Si-O-M) linkages.[3–11] In virtually all cases, the resulting products are formally derived from the substitution of heteroatoms for Si atoms in a silsesquioxane framework (e.g., **3**). In this paper we report a new method for preparing discrete heterosilsesquioxane frameworks. This method introduces heteroatoms and heteroatom-containing groups by nucleophilic substitution reactions at framework Si atoms and affords products derived from the formal replacement of a framework oxygen atom in **4** by a heteroatom or other divalent bridging group (e.g., **5**).



1, R^1 = H
2, R^1 = $SiMe_3$



3, Z = heteroatom and any ligands



4, Z = O; Cy = *c*-C_6H_{11}
5, Z = heteroatom or other bridging group

The key to our approach is ditriflate **6**, which can be prepared in high yield by the reaction of $Cy_8Si_8O_{12}$ (**4**) with triflic acid (TfOH) in noncoordinating solvents such as CH_2Cl_2 or C_6H_6.[12] The triflate groups from **6** are rapidly displaced by many nucleophiles with complete stereochemical inversion at both Si centers. With difunctional nucleophiles (e.g., H_2O), there are two possible products: difunctional derivatives resulting from two sequential bimolecular displacement reactions (e.g., **7**) or "edge-capped" products resulting from intramolecular cyclization of the monosubstituted (e.g., **4**).[12] Cyclization is usually favored when reactions are performed in dilute solutions with stoichiometric quantities of reagents.

The reaction of **6** with aniline produces **8** and/or **9** in high yield. When the reaction is performed in toluene/Et_3N with an excess of aniline (> 4 equiv), **8** is obtained in > 95% NMR yield. The structure of **8**, which was assigned on the basis of

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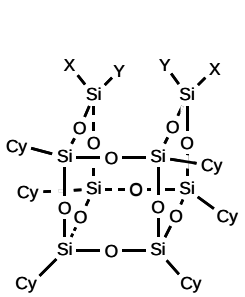
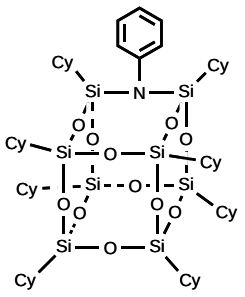


6, X = OTf, Y = Cy
7, X = Cy, Y = OH
8, X = Cy, Y = NHPh



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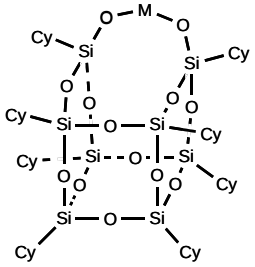

10, M = SO_2
11, M = B*n*Bu
12, M = CrO_2

compelling multinuclear NMR data, a mass spectrum, and combustion analysis, was confirmed by a single-crystal X-ray diffraction study.[13] As illustrated in Figure 1, the placement

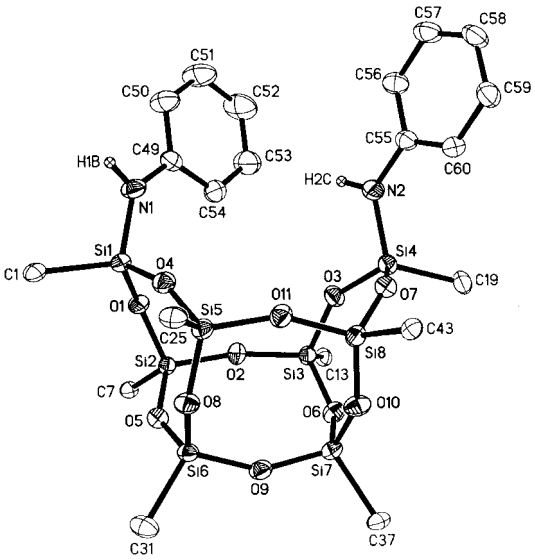

Figure 1. ORTEP plot of **8**. For clarity, thermal ellipsoids are plotted at 50% probability level and only C attached to Si are shown. Selected bond lengths [Å] and angles [°]: Si1 – N1 1.714(3), Si1 – O4 1.629(2), Si1 – O1 1.625(2), Si4 – N2 1.708(3), Si4 – O3 1.625(2), Si4 – O7 1.630 (2), other Si – O 1.609 – 1.630; N1-Si1-O4 110.76(13), N1-Si1-O1 109.06(13), O1-Si1-O4 109.47(12), O1-Si1-O4 109.47(12), N2-Si4-O3 105.01(13), N2-Si4-O7 110.73(13), O3-Si4-O7 109.04(12).

of two C_6H_5NH groups in nominally "endo" positions induces conformational changes within the Si/O framework of **8** that lead to a more open structure. All of the bond lengths and interbond angles are normal, but torsional rotation about the Si – O bonds involving Si1 and Si4 increases the Si1 – Si4 distance to approximately 5.8 Å. This is almost twice the Si – Si separation typically observed for Si-O-Si linkages in polyhedral silsesquioxanes ($\sim$3.1 Å).[14]

When the reaction of **6** with aniline is performed with only a slight excess of aniline (1.1 equiv), the product obtained in high yield is **9**, which was assigned on the basis of multinuclear NMR data, a mass spectrum, and combustion analysis. To the best of our knowledge, **9** is the first polyhedral heterosilsesquioxane to contain nitrogen within the framework. As a solid, **9** is relatively air stable, and its thermal stability appears to rival **4**. However, solutions of **9** react slowly with water to afford a number of products derived from the hydrolysis of Si – N bonds.

Ditriflate **6** also reacts rapidly with $(n\text{Bu})_4\text{NHSO}_4$ to produce **10** in high yield. The reaction can be accomplished with 1.1 equiv of the HSO_4^- salt in the presence of Et_3N or by reacting **6** with slightly more than two equivalents of $(n\text{Bu})_4\text{NHSO}_4$. In the latter reaction, the second equivalent of HSO_4^- appears to act as a base for deprotonation and cyclization of the monosubstituted intermediate rather than a second nucleophile. This reaction is surprising at first because it produces strongly acidic H_2SO_4 in a noncoordinating solvent, but it is undoubtedly preferable to the formation of two bisulfate groups containing a strongly electron-withdrawing silsesquioxane framework. Compound **10** reacts quickly with traces of water to produce disilanol **7** and sulfuric acid.

The structure of **10** was assigned on the basis of multinuclear NMR data and the fact that only one equivalent of HSO_4^- is required for the reaction; this assignment was confirmed by a single-crystal X-ray diffraction study.[13] As illustrated in Figure 2, the formal substitution of a large SO_4

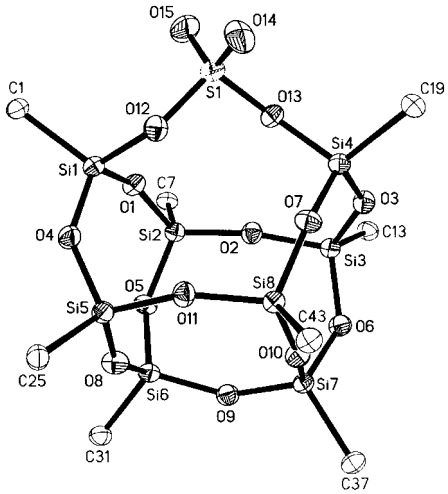

Figure 2. ORTEP plot of **10**. For clarity, thermal ellipsoids are plotted at 50% probability level and only C attached to Si are shown. Selected bond lengths [Å] and angles [°]: S1 – O14 1.417(2), S1 – O15 1.418(2), S1 – O12 1.549(2), S1 – O13 1.548(2), Si1 – O12 1.693(2), Si4 – O13 1.686 (2), other Si – O 1.610 – 1.629; O14-S1-O15 120.21(14), O14-S1-O12 107.18(11), O14-S1-O13 109.17(11), O15-S1-O12 109.34(11), O15-S1-O13 107.28(11), O12-S1-O13 102.19(10), S1-O12-Si1 129.63, S1-O13-Si4 131.87(11).

group for a single bridging siloxane oxygen requires many conformational changes. None of these changes are energetically costly because the bending potential of Si-O-Si is very broad and shallow,[15] but the cumulative effect of these changes is a highly distorted structure for **10**.

It is likely that many structurally similar heterosilsesquioxanes and metallasilsesquioxanes can be prepared by reactions of **6** with reagents capable of delivering divalent O-M-O

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groups. We have only begun to explore these possibilities, but our preliminary work with nBuB(OH)$_2$ and K_2CrO_4/[18]crown-6 is very encouraging. In the case of nBuB(OH)$_2$, the addition of freshly purified nBuB(OH)$_2$ to a solution of **6** in C_6H_6/Et_3N produces **11** and variable amounts of **4**. We suspect that **4** is formed by the reaction of **6** with water rather than a direct reaction of **6** with the boronic acid because nBuB(OH)$_2$ is extremely difficult to dry without effecting its cyclotrimerization[16] and because the reaction of **6** with traces of water is known to produce **4**.[12] In the case of K_2CrO_4/[18]crown-6, extensive decomposition of the chromium reagent is observed during the reaction, but multinuclear NMR spectra clearly indicate that **12** is produced in approximately 20% yield. Authentic **12** can be prepared in high yield by the reaction of **7** with CrO_3/$MgSO_4$ in CCl_4.[17]

In summary, we have developed a new and potentially general method for synthesizing discrete heterosilsesquioxane frameworks. This method, which introduces heteroatoms by nucleophilic substitution on framework Si atoms rather than electrophilic substitution on framework O atoms, provides access to a wide range of new compounds, including polyhedral clusters that are formally derived from replacement of a framework oxygen atom in **4** by a heteroatom or other divalent bridging group.

Experimental Section

8: A solution of aniline (98 mg, 1.1 mmol) in benzene (1 mL) was added dropwise to a solution of **6** (308 mg, 0.23 mmol) and triethylamine (45 mg, 0.45 mmol) in benzene (2 mL). After stirring the resulting emulsion for 1 h at 25 °C, the benzene layer was decanted from the ammonium triflate. The oily ammonium triflate was rinsed twice with benzene (0.5 mL). The combined benzene fractions were evaporated to dryness under reduced pressure to afford **8** as a microcrystalline white solid (201 mg, 71%). The product obtained in this manner is spectroscopically pure (^{1}H, ^{13}C, ^{29}Si NMR); colorless crystals were obtained by recrystallization from hexanes. ^{1}H NMR (500 MHz, $CDCl_3$, 25 °C): $\delta = 7.20$ (t, $J = 7.7$ Hz, 4H), 6.79 (t, $J = 7.8$ Hz, 2H), 6.68 (d, $J = 7.3$ Hz, 4H), 3.73 (br s, 2H), 1.86 (br m, 40H), 1.34 (br m, 40H), 1.00 (br m, 2H), 0.89 (br m, 6H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, 25 °C): $\delta = 145.68$, 128.82, 118.16, 117.41, 27.635, 27.508, 26.937, 26.902, 26.867, 26.826, 26.632, 26.546 (CH_2), 24.75, 24.14, 23.06 (1:2:1 for CH); ^{29}Si{^{1}H} NMR (99 MHz, $CDCl_3$, 25 °C): $\delta = -51.91$, -67.41, -69.77 (1:1:2); elemental analysis calcd for $C_{60}H_{100}N_2O_{11}Si_8$ (found): C 57.65 (57.81), H 8.06 (7.87), N 2.24 (2.63); m.p. 164.7 °C (by differential scanning calorimetry).

9: A solution of aniline (11.9 mg, 0.128 mmol) in benzene (0.5 mL) was added dropwise to a solution of **6** (159.0 mg, 0.117 mmol) and triethylamine (34.1 mg, 0.337 mmol) in benzene (2 mL). Workup as described above for **8** and precipitation from $CHCl_3$/CH_3CN affords **9** as an analytically pure white powder (115 mg, 85%). ^{1}H NMR (500 MHz, $CDCl_3$, 25 °C): $\delta = 7.13$ (m, 4H), 7.05 (m, 1H), 1.69–1.58 (br s, 35H), 1.47–1.39 (br m, 10H), 1.20–1.12 (br s, 35H), 0.95–0.82 (br s, 10H), 0.70–0.65 (br s, 6H), 0.22 (m, 2H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, 25 °C): $\delta = 142.66$, 130.94, 128.56, 125.20 (s for C's aromatic), 27.60, 27.55, 26.92, 26.87, 26.75, 26.71, 26.68, 26.55 (CH_2), 23.48, 23.21, 23.11 (s for CH, 2:1:1); ^{29}Si{^{1}H} NMR (99 MHz, $CDCl_3$, 25 °C): $\delta = -55.52$, -67.81, -68.26 (1:2:1); MS (70 eV, 200 °C, relative intensity): m/z: 1156 ([M+H]$^+$, 35%), 1072 ([M − Cy]$^+$, 100%); elemental analysis calcd for $C_{54}H_{93}NO_{11}Si_8$ (found): C 56.06 (55.43), H 8.10 (8.12), N 1.21 (1.41); m.p. 358.7 °C (by differential scanning calorimetry).

10: A solution of **6** (295.4 mg, 0.217 mmol) in benzene (3 mL) was added to a solution Bu_4NHSO_4 (162.3 mg, 0.478 mmol) in benzene (3 mL) and stirred for 1 h. The colorless benzene solution was decanted and evaporated to dryness (25 °C, 0.01 Torr) to afford a white solid, which was washed with CH_3CN and dried in vacuo to afford spectroscopically pure **10** (196 mg, 90%). Analytically pure, colorless crystals were obtained by crystallization from benzene/CH_3CN. ^{1}H NMR (500 MHz, $CDCl_3$, 25 °C): $\delta = 1.74$ (br s, 40H), 1.23 (br s, 40H), 1.02 (br m, 2H), 0.80 (br m, 6H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, 25 °C): $\delta = 27.32$, 27.30, 27.04, 26.73, 26.70, 26.41, 25.61 (CH_2), 23.20, 22.87, 22.84 (2:1:1 for CH); ^{29}Si{^{1}H} NMR (99 MHz, $CDCl_3$, 25 °C): $\delta = -67.38$, -67.76, -69.34 (1:1:2); MS (70 eV, 200 °C, relative intensity): m/z: 1077.7 ([M − Cy]$^+$, 100); elemental analyis calcd for $C_{48}H_{88}O_{15}SSi_8$ (found): C 49.62 (49.45), H 7.63 (7.67).

11: A solution of nBuB(OH)$_2$ (27.9 mg, 0.274 mmol) in benzene (0.5 mL) was added to a solution of **6** (152.6 mg, 0.112 mmol) and Et_3N (60.8 mg, 0.601 mmol) in benzene (3 mL) and stirred for 0.5 h at 25 °C. Evaporation of the solvent, extraction with benzene (10 mL), concentration to ≈1 mL and addition of CH_3CN (10 mL) afforded 127 mg of a white powder containing **11** and **4** in a ratio of 81:19. Attempts to separate **11** and **4** by extraction or fractional crystallization were unsuccessful. For **11**: ^{1}H NMR (500 MHz, $CDCl_3$, 25 °C): $\delta = 1.74$ (br s, 40H), 1.36 (m, 2H), 1.23 (44H), 0.88 (t, 3H), 0.74 (br s, 8H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, 25 °C): $\delta =$ 27.57, 27.55, 27.51, 26.91, 26.76, 26.56, 25.23, 17.36, 16.63 (s for CH_2), 24.00, 23.66, 23.12 (s for CH, 1:2:1), 14.07 (CH_3); ^{29}Si{^{1}H} NMR (99 MHz, $CDCl_3$, 25 °C): $\delta = -67.39$, -69.58, -69.94 (1:2:1); MS (70 eV, 200 °C, relative intensity): m/z: 1107 ([M − Bu]$^+$, 20%), 1081 ([M − Cy]$^+$, 100%).

12 was prepared as a bright orange solid in 55% yield (87 mg) from **7** (148 mg, 0.135 mmol), CrO_3 (133 mg, 1.330 mmol), and $MgSO_4$ (371 mg) in CCl_4 (4 mL) according to the procedure described in ref. [17]. ^{1}H NMR (500 MHz, $CDCl_3$, 25 °C): $\delta = 1.75$ (br m, 40H), 1.24 (br m, 40H), 0.87 (br m, 2H), 0.78 (br m, 6H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, 25 °C): $\delta = 27.54$, 27.49, 27.46, 27.40, 26.83, 26.69, 26.66, 26.54, 26.51 (s for CH_2), 23.76, 23.68, 23.02 (s for CH, 1:2:1); ^{29}Si{^{1}H} NMR (99 MHz, $CDCl_3$, 25 °C): $\delta = -62.19$, -67.14, -69.68 (1:1:2).

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Keywords: cage compounds · silicon

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[13] Crystal data for **8**: $M = 1250.14$, monoclinic, space group $P2_1/c$, $a =$ 1023.02(5), $b = 2610.18(13)$, $c = 2519.10(12)$ pm, $\beta = 97.538(1)°$, $V =$ 6.6685(6) nm^3, $Z = 4$, $\rho_{calcd} = 1.245$ Mg m^{-3}, $F(000) = 2696$, $\lambda =$ 71.073 pm, $T = 158$ K, $\mu(Mo_{K\alpha}) = 0.218$ mm^{-1}, crystal dimensions: $0.09 \times 0.23 \times 0.30$ mm, $2.26° \le 2\theta \le 56.6°$; of the 40533 collected reflections, 15573 are independent, and these were used for the refinement of 786 parameters; maximal residual electron density: 539 e nm^{-3}, $R1(F > 4\sigma(F)) = 0.068$ and $wR2 = 0.147$ (all data) with $R1 = \Sigma||F_o| - |F_c||/\Sigma|F_o|$ and $wR2 = (\Sigma w(F_o^2 - F_c^2)^2/\Sigma w(F_o^2)^2)^{0.5}$. Crystal data for **10**: $M = 1161.96$, monoclinic, space group $P2_1/n$, $a =$ 1558.20(7), $b = 1847.80(9)$, $c = 2093.07(10)$ pm, $\beta = 100.106(1)°$, $V =$ 5.9330(5) nm^3, $Z = 4$, $\rho_{calcd} = 1.301$ Mg m^{-3}, $F(000) = 2496$, $\lambda =$ 71.073 pm, $T = 158$ K, $\mu(Mo_{K\alpha}) = 0.277$ mm^{-1}, crystal dimensions: $0.13 \times 0.21 \times 0.22$ mm, $2.96° \le 2\theta \le 56.6°$; of the 37062 collected

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reflections, 14141 are independent, and these were used for the refinement of 650 parameters; maximal residual electron density: 402 e nm^{-3}, $R1(F>4\sigma(F))=0.054$ and $wR2=0.113$ (all data) with $R1=\Sigma||F_o|-|F_c||/\Sigma|F_o|$ and $wR2=(\Sigma w(F_o^2-F_c^2)^2/\Sigma w(F_o^2)^2)^{0.5}$. Data were collected on a Siemens CCD platform diffractometer. The SMART program package was used for data collection. Raw frame data was processed by using SAINT and SADABS to yield the reflection data file. All subsequent calculations were performed using the SHELXTL program. The structure was solved by direct methods and refined on F^2 by full-matrix least-squares techniques. The analytical scattering factors for neutral atoms were used throughout the analysis and hydrogen atoms were included by using a riding model. Crystallographic data (excluding structure factors) for the structures reported in this paper have been deposited with the Cambridge Crystallographic Data Center as supplementary publication no. CCDC-101403. Copies of the data can be obtained free of charge on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK (fax: (+44) 1223-336-033; e-mail: deposit@ccdc.cam.ac.uk).

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Highly Enantio- and Diastereoselective Synthesis of 2-Substituted 1-Bicyclo[3.1.0]hexanols**

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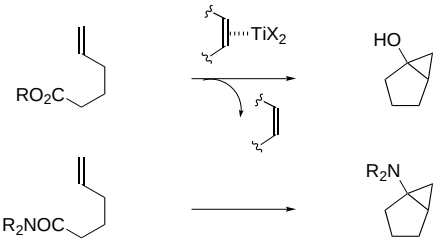
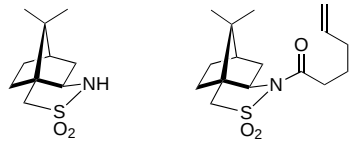
Bicyclic cyclopropanols and their derivatives, such as the trimethylsilyl ethers, have been utilized as useful intermediates in organic synthesis by the manipulation of their reactive cyclopropanol moiety.[1] However, the asymmetric preparation of these compounds has been quite limited so far,[2, 3] even though current developments in enantioselective synthesis should call for the use of optically active cyclopropanols as starting materials.

The reaction of unsaturated esters,[4] amides,[5] imides,[6] and related compounds[7] with an alkene–titanium complex[8] is a very convenient method to prepare bicyclic cyclopropanols[4] and cyclopropylamines[5] in one step [Eqs. (1) and (2); X = R′O, Cl, Br]. Extension of this transformation to an asymmetric version would clearly serve as a simple route to optically active cyclopropanols (or cyclopropylamines). To this end, the use of a chiral titanium complex was successful.[9] An alternative approach is to incorporate a chiral auxiliary in



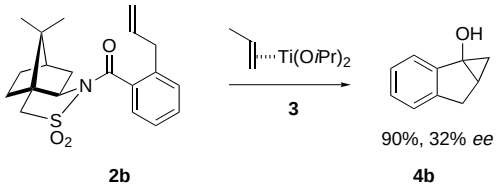
the substrate. Thus, an unsaturated carboxylic acid derivative having a chiral leaving group on its acyl group would afford the corresponding optically active bicyclic cyclopropanol; surprisingly, this method has not been reported yet. We chose Oppolzer's camphorsultam **1**[10] as the leaving group, because



1 **2a**

the known enantioselective α-alkylation of the *N*-acyl derivative **2a**[11] could be performed not only with activated halides (i.e., allyl or benzyl halides) but also with nonactivated counterparts (i.e., primary alkyl halides).[11] As we show here, this allowed the preparation of a variety of substituted bicyclic cyclopropanols.

The ability of acylsulfonamides to act as esters in reaction (1) to give cyclopropanols (rather than as amides in reaction (2) to yield cyclopropylamines) has not been demonstrated. This issue as well as the asymmetric induction in the nucleophilic addition to *N*-acylcamphorsultams[12] is addressed in the reaction of **2b** with [Ti(O*i*Pr)$_2$(η^2-propene)] (**3**) as shown in Equation (3).[4a] To our satisfaction, optically



2b **4b**

active cyclopropanol **4b** was obtained, while the possible byproduct, a *N*-cyclopropylsulfonamide, was not detected at all. Unfortunately, the enantiopurity of the product does not reach a satisfactory level.

Nonetheless, the α-branched acylsultams, readily prepared by diastereoselective alkylation of the *N*-acylcamphorsultam **2a** according to the literature method,[11] showed nearly complete stereocontrol in the cyclopropanol cyclization. Thus, treatment of **2c** with **3** afforded **4c** virtually as a single product and in high yield [Eq. (4)]. The diastereoselectivity was determined by ^{1}H NMR spectroscopy in comparison with an authentic mixture of the diastereoisomers, and the relative configuration shown for **4c** was established by NOE experi-

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