Registry No. Maleic acid, 110-16-7; fumaric acid, 110-17-8; diethyl maleate, 141-05-9; diethyl fumarate, 623-91-6; maleic anhydride, 108-31-6; succinic-d_2 acid, 91314-17-9; *cis*-succinic-d_2 anhydride, 80655-74-9; Pd, 7440-05-3; Pt, 7440-06-4.

Supplementary Material Available: Tables containing raw and corrected data for reduction of maleic and fumaric acids and derivatives over a variety of different experimental conditions are available (7 pages). Ordering information is given on any current masthead page.

Trimethylsilyl-Substituted Optically Active β-Lactams

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Introduction of funtionalized units at the C-3 position of β-lactams has become an increasingly interesting and worked over reaction. As part of a program devoted to the synthesis of β-lactams which would provide access to a variety of functionalized carbon units at the C-3 position by exchange of a feasible substituent, we turned our attention to the synthesis of β-lactams silylated at the C-3 carbon atom.

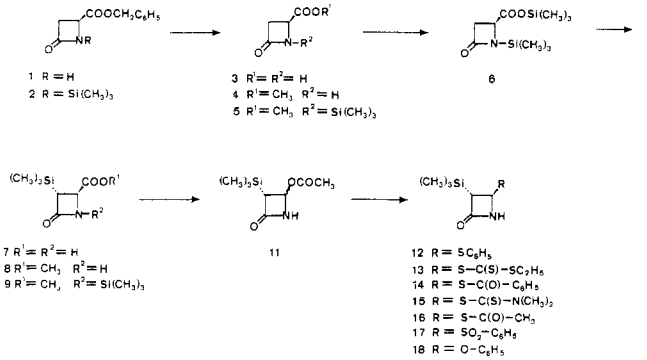
The evolution of the synthetic strategy employed for the approach was based on the following considerations: (1) the desire to develop a chiral stereocontrolled synthesis with regard to the C-3–C-4 substituents, (2) elaboration of a suitable C-4-substituted azetidinone derivative from the readily available azetidinone carboxylic acid benzyl ester which has already the correct absolute configuration at C-4, and (3) formation of a C-3–silicon bond with the hope of allowing preparation of analogues involving facile replacement of the trimethylsilyl unit.[1] Consequently, the general synthetic approach was outlined as depicted in Scheme I.

The synthesis of the benzyl ester **1** was executed essentially analogous to the report of Salzmann et al.[2] in which the chirality at C-4 was derived from L-aspartic acid. The debenzylation of **1** with hydrogen in the presence of palladium-on-carbon furnished the crystalline carboxylic acid.[2a-c] Racemization does not occur under those conditions.[2]

N-Silylation of β-lactam derivatives with chlorotrimethylsilane has been performed previously in the presence of base,[3] and furthermore a C-3 trimethylsilyl derivative has been found a useful precursor for the synthesis of 3-alkylidenazetidinones.[1] Application of hexamethyldisilazane (HMDS) in the presence of 2–5 mol % of saccharin as a catalyst[4] in refluxing chloroform caused clean formation (84–88%) of the *N*,*O*-bis(trimethylsilyl) derivative of the β-lactam carboxylic acid **6**.

The yield of **6** dropped to 48% without saccharin even after a reaction time of 4 h. The product was separated from excess of HMDS by distillation. Its extreme sensitivity toward moisture made working under an atmosphere of argon mandatory. The analytical and spectral data supported structure **6**.

Scheme I



Similarly, catalyzed N-silylation of the benzyl (**1**) and the methyl ester (**4**) respectively provided the corresponding N-silylated products **2** and **5** in yields of 78% and 86%. A lower yield (44%) of **2** was obtained starting from **1** and by using chlorotrimethylsilane in the presence of triethylamine. Here again, the superior effect of saccharin as catalyst was noted: no formation of product was observed after 2 h without saccharin, and a yield of only 57% was realized in the presence of catalytic amounts of ammonium sulfate.[4] Small samples of **2** could be sublimed, while the product from larger runs was more conveniently purified by short-path distillation yielding white crystals.

Quite in contrast to the air sensitivity of **6**, the compounds **2** and **5** respectively proved surprisingly stable on exposure to air and may be stored without special protection for several weeks. The good solubility of **2** in ligroin and subsequent workup permit ready separation from any hydrolyzed product while **5** was purified by distillation.

Treatment of **6** with 1 equiv of lithium diisopropylamide in tetrahydrofuran at −75 °C generated the azetidinone enolate of **6** in situ, which underwent a 1,4-silyl shift from the carboxylic acid oxygen to the C-3 carbon atom, providing the carboxylic acid **7** in 78% yield. The trimethylsilyl group attached to nitrogen presumably was lost during the hydrolytic workup. Inspection of the NMR spectrum of the crude acid indicated that it consisted of at least 98% of the trans stereoisomer on the basis of the coupling constant[5] $J_{3,4}$ = 2.5 Hz in the ^{1}H NMR spectrum. Recrystallization from methanol yielded samples of the pure trans acid **7**.

The somewhat surprising silyl shift yielding exclusively *trans*-**7** requires some further explanation. None of the N-silylated β-lactam carboxylic acid esters (**2**, **5**) showed any indication of a migration of the trimethylsilyl group from the nitrogen to C-3. This was taken, at least in the case of the methyl ester **5**, as indicative that preference is given to a 1,4-silyl shift from oxygen to the C-3 carbon atom rather than a 1,3-shift from nitrogen to C-3. Anionic 1,4-silyl shifts are commonly observed when a silylated compound is treated with strong base. Several cases of 1,4-silyl group shifts from carbon to oxygen have been reported,[6] and the reverse migration has also been noted.[7,8] The details of the mechanism by which **7** is formed remain still open to question, but it may be presumed that **7** could arise from a 1,4-silyl shift from oxygen to the C-3 carbon

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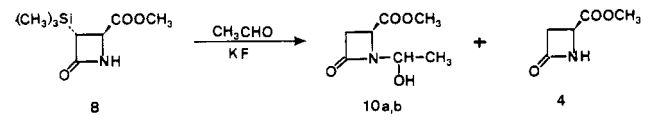
Scheme II



atom to provide first *cis*-7, which would subsequently undergo a facile epimerization to the stable *trans*-7. It seems reasonable to assume that this epimerization might be catalyzed by the excess of base in the reaction mixture. Various examples of direct epimerizations at the C-6 atom of penicillins and the C-7 atom of cephalosporins, respectively, are known and have been effected by base.[9]

Treatment of 7 with an excess of diazomethane furnished the methyl ester 8, the silylation of which with HMDS gave the N-silylated methyl ester 9.

The lability of the trimethylsilyl group in 8 became first apparent when it was treated with an excess of acetaldehyde in the presence of potassium fluoride in acetonitrile as solvent (Scheme II). The analytical data for the products obtained and their NMR spectra indicated that reaction had occurred with elimination of the trimethylsilyl groups and substitution of the β-lactam nitrogen by the α-hydroxyethyl group, yielding a mixture of **10a,b** and small amounts of **4**.

Oxidative decarboxylation of the acid 7 with lead tetraacetate in dimethylformamide–acetic acid proceeded smoothly (74%) to introduce the acetoxy group at C-4. The product consisted of a mixture (**11a,b**) of approximately 55% trans ($J_{3,4}$ = 1.5 Hz) and 45% cis azetidinone ($J_{3,4}$ = 4,5 Hz). Repeated experiments on a somewhat larger scale (0.02–0.07 mol) provided yields ranging from 65–70%.

Although a rather fast reaction of lead tetraacetate with the trimethylsilyl group may have been anticipated in the light of present knowledge,[10] the reagent attacked preferably the carboxyl group of 7. However extended reaction times caused formation of desilylated product, as one might have expected from extensive desilylation observed in the synthesis of a trifluoromethyl-substituted β-lactam[11] and also in ipso-desilylation reactions using lead tetraacetate.[12a,b]

The literature is replete with examples of substitutions of the acetoxy group at C-4 by RO, RS, or RSO_2 substituents and with investigations as to the retention of their stereochemistry. Several examples of substitutions of the acetoxy group of 11 by anions of sulfur or oxygen derivatives (12–18) are compiled in Scheme 1. The synthesis of 13–17 were performed best in aqueous acetone as solvent at 25 °C, while 12 and 18 respectively were synthesized in methanol by using freshly prepared sodium salts of the reagents.

Generally, high yields (based on the mixture of epimers) were realized with the exception of 16, and reactions occurred exclusively at the sterically less hindered face of the β-lactam ring to afford only the trans compounds, as could be inferred from the coupling constants $J_{3,4}$ in the ^{1}H NMR spectra, which are between 1,5 and 2,8 Hz.

Desilylation was encountered on extended reaction times, especially noteworthy in the process of preparation of 16 and 18, respectively.

Altogether, substitution of the acetoxy group at C-4 of silylated β-lactams is feasible without altering the stereochemistry and without excessive desilylation.

Experimental Section

Melting points were obtained in open capillary tubes and are uncorrected. Samples for the infrared spectra were prepared either in potassium bromide disks or in carbon disulfide solutions. Optical rotations were determined in chloroform solutions using a cell length of 100 mm (*c* 1). ^{1}H NMR spectra were measured at 400.1 MHz on a Bruker WM 400 spectrometer in the Fourier transform mode. Chemical shifts were referenced to internal tetramethylsilane (δ 0). Some of the derivates in this study were prepared by known procedures.

(4*S*)-Benzyl 2-Oxoazetidine-4-carboxylate (1). This was prepared by a known procedure[2] and isolated as white crystals: mp 140 °C, $[\alpha]^{20}_D$ −41.8° ($CHCl_3$) [lit.[2] mp 141–143 °C, $[\alpha]^{20}_D$ −43° ($CHCl_3$)].

(4*S*)-*N*-(Trimethylsilyl)-2-oxoazetidine-4-carboxylic Acid Benzyl Ester (2). A solution of benzyl 2-oxoazetidine-4-carboxylate (1) (20.5 g, 0.1 mol), hexamethyldisilazane (32 g, 0.2 mol), and saccharin (2 g) in 1,2-dimethoxyethane (300 mL) was heated to reflux for 2 h. Removal of the solvent by rotary evaporation followed by applying high vacuum afforded white crystals. They were dissolved in boiling petroleum ether (500 mL), and the solution was filtered from the undissolved residue. Evaporation of the solvent furnished 22 g (78%) of large crystals, which were subject to a short-path distillation at 128 °C (1.5×10^{-4} mm) affording 21.5 g of a colorless oil, which solidified to white waxy crystals: mp 38–40 °C, $[\alpha]^{20}_D$ −64.9° ($CHCl_3$); IR (KBr) 2960, 1752, 1290, 1195, 852 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 7.37 (m, 5 H), 5.19 (AB, 2 H), 4.07 (dd, *J* = 6, 3 Hz, 1 H), 3.33 (dd, 1 H), 3.08 (dd, 1 H), 0.22 (s, 9 H). Anal. Calcd for $C_{14}H_{19}NO_3Si$: C, 60.62; H, 6.91; N, 5.05; Si, 10.13. Found: C, 60.39; H, 6.64; N, 5.16; Si, 9.68.

(4*S*)-2-Oxoazetidine-4-carboxylic Acid (3). A solution of (4*S*)-benzyl 2-oxoazetidine-4-carboxylate (1) (20.5 g, 0.1 mol) in anhydrous tetrahydrofuran (2.1 L) was hydrogenated over 10% palladium-on-carbon (2.1 g) at 25 °C until the hydrogen uptake (calcd 2240 mL, found 2403 mL) ceased after 45 min. The catalyst was filtered from the solution and the solvent distilled under reduced pressure at a bath temperature of 25–30 °C to afford 11.8 g (103%) of white crystals: mp 105–107 °C, $[\alpha]^{20}_D$ −80.0° (H_2O) [lit.[13] mp 102–104 °C, $[\alpha]^{25}_D$ −82.8° (c 3, H_2O)]; IR (KBr) 3340, 2958, 2922, 1745, 1720, 1215, 1195, 1165 cm^{-1}; ^{1}H NMR (Me_2SO-d_6) δ 8.29 (br, 1 H), 4.02 (dd, 1 H), 3.19 (ddd, 1 H), 2.83 (ddd, 1 H).

Methyl (4*S*)-2-Oxoazetidine-4-carboxylate (4). To a suspension of (4*S*)-2-oxoazetidine-4-carboxylic acid (3) (11.5 g, 0.1 mol) in anhydrous ether (250 mL) was added an ethereal solution of diazomethane until crystals had dissolved and the light yellow color persisted. Excess diazomethane was decomposed with a few drops of acetic acid. Removal of the solvent by rotary evaporation followed by distillation at 102–104 °C (0.05 mm) afforded 8.8 g (68.2%) of distillate, which solidified on standing: mp 47–49 °C, $[\alpha]^{20}_D$ −44.3° ($CHCl_3$); IR (KBr) 3225, 1745, 1224 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 6.22 (br, 1 H), 4.20 (dd, 1 H), 3.80 (s, 3 H), 3.34 (ddd, 1 H), 3.09 (ddd, 1 H). Anal. Calcd for $C_5H_7NO_3$: C, 46.51; H, 5.47; N, 10.85. Found: C, 46.83; H, 5.61; N, 10.68.

(3*S*,4*R*)-*N*-(Trimethylsilyl)-2-oxoazetidine-4-carboxylic Acid Methyl Ester (5). A solution of (4*S*)-methyl 2-oxoazetidine-4-carboxylate (4) (5.16 g, 0.004 mol), hexamethyldisilazane (12.9 g, 0.08 mol), and saccharin (0.37 g) in dimethoxyethane (60 mL) was heated to reflux for 2.5 h. Solvent was removed by rotary evaporation and subsequent distillation at 68–70 °C (0.1 mm) afforded 7.2 g (89%) of an oil: $[\alpha]^{20}_D$ −78.1° ($CHCl_3$); IR (neat) 2994, 1760, 1295, 860 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 4.05 (dd, 1 H), 3.79 (s, 3 H), 3.34 (dd, 1 H), 3.08 (dd, 1 H), 0.28 (s, 9 H). Anal. Calcd for $C_8H_{15}NO_3Si$: C, 47.74; H, 7.51; N, 6.96; Si, 13.96. Found: C, 48.01; H, 7.69; N, 7.02; Si, 13.78.

(3*S*,4*R*)-*N*-(Trimethylsilyl)-2-oxoazetidine-4-carboxylic Acid Trimethylsilyl Ester (6). To a suspension of 3 (23 g, 0.1 mol) and saccharin (1 g) in chloroform (200 mL) was added hexamethyldisilazane (64.6 g, 0.4 mol) and the mixture refluxed

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for 100 min. The excess of HMDS was removed under reduced pressure and the residue distilled at 74–76 °C (0.08 mm) to afford **6** as colorless liquid (46.5 g, 89%): $[\alpha]^{20}_D$ –69.5° ($CHCl_3$); IR (CS_2) 2960, 1745, 1730, 1285, 1260, 1215, 845 cm^{-1}; ^1H NMR ($CDCl_3$) δ 4.00 (dd, 1 H), 3.33 (dd, 1 H), 3.03 (dd, 1 H), 0.33 (s, 9 H), 0.28 (s, 9 H). Anal. Calcd for $C_{10}H_{21}NO_3Si_2$: C, 46.29; H, 8.16; N, 5.40; Si, 21.65. Found: C, 46.70; H, 8.02; N, 5.62; Si, 21.74.

(3*S*,4*R*)-3-(Trimethylsilyl)-2-oxoazetidine-4-carboxylic Acid (7). To diisopropylamine (8.5 mL, 0.06 mol) in dry tetrahydrofuran (150 mL) at –15 °C under a nitrogen atmosphere was added a 1.6 M solution of *n*-butyllithium in hexane (37.5 mL, 0.06 mol) dropwise over 35 min, stirring continued for 20 min, and then the mixture cooled to –75 °C. This solution was added dropwise to a stirred solution of **6** (13 g, 0.05 mol) in tetrahydrofuran (350 mL) cooled to –75 °C, within 2 h, and stirred for an additional 30 min. Then the temperature was allowed to reach 0 °C and formic acid (10.82 g, 0.3 mol, 85%) added, followed by dichloromethane (400 mL) and stirring for 1 h at 25 °C. After addition of water (150 mL) the organic phase was separated and dried with Na_2SO_4. Concentration in a rotary evaporator yielded 6.8 g (72.7%) of crystals, which consisted of 98% *trans*-**7**— according to the NMR spectrum. Recrystallization of 1 g of **7** from 6 mL of ethyl acetate gave 0.55 g of pure **7** as white crystals: mp 148–149 °C, $[\alpha]^{20}_D$ –40.1° ($CHCl_3$); IR (KBr) 3320, 1755, 1690, 1255, 1215, 850 cm^{-1}; ^1H NMR (Me_2SO-d_6) δ 8.09 (br, 1 H), 3.80 (d, J = 2.5 Hz, 1 H), 2.76 (dd, 1 H), 0.09 (s, 9 H). Anal. Calcd for $C_7H_{13}NO_3Si$: C, 44.90; H, 7.00; N, 7.48; Si, 15.00. Found: C, 44.86; H, 7.16; N, 7.51; Si, 15.04.

(3*S*,4*R*)-3-(Trimethylsilyl)-2-oxoazetidine-4-carboxylic Acid Methyl Ester (8). To a suspension of **7** (1.9 g, 0.01 mol) in ether (40 mL) was added a slight excess of an ethereal solution of diazomethane. Evaporation and distillation of the oily residue at 95–97 °C (0.02 mm) afforded **8** as a colorless oil (0.85 g, 42%), which solidified, yielding white crystals: mp 46–48 °C, $[\alpha]^{20}_D$ –37.2° ($CHCl_3$); IR (CS_2) 3390, 1780, 1758, 1260, 845 cm^{-1}; ^1H NMR ($CDCl_3$) δ 5.99 (br, 1 H), 3.92 (d, J = 2.5 Hz, 1 H), 3.78 (s, 3 H), 2.90 (dd, 1 H), 0.19 (s, 9 H). Anal. Calcd for $C_8H_{15}NO_3Si$: C, 47.74; H, 7.51; N, 6.96; Si, 13.96. Found: C, 47.67; H, 7.54; N, 6.92; Si, 13.69.

(3*S*,4*R*)-3,*N*-Bis(trimethylsilyl)-2-oxoazetidine-4-carboxylic Acid Methyl Ester (9). A solution of **8** (1.05 g, 0.005 mol), saccharin (0.046 g), and hexamethyldisilazane (1.61 g, 0.01 mol) in 1,2-dimethoxyethane (12 mL) was refluxed for 2 h. Volatile compounds were removed by rotary evaporation at reduced pressure, and subsequent vacuum distillation at 73 °C (0.04 mm) afforded 1.0 g (73%) of an oil: $[\alpha]^{20}_D$ –74.2° ($CHCl_3$); IR (neat) 2998, 1760, 1258, 850 cm^{-1}; ^1H NMR ($CDCl_3$) δ 3.72 (d, J = 2.5 Hz, 1 H), 3.70 (s, 3 H), 2.84 (d, 1 H), 0.20 (s, 9 H), 0.10 (s, 9 H). Anal. Calcd for $C_{11}H_{23}NO_3Si_2$: C, 48.31; H, 8.48; N, 5.12; Si, 20.54. Found: C, 48.45; H, 8.53; N, 5.16; Si, 20.44.

(4*S*)-*N*-(α-Hydroxyethyl)-2-oxoazetidine-4-carboxylic Acid Methyl Ester (10a,b). Diastereomeric Mixture. To a solution of **8** (0.9 g, 0.0024 mol) and acetaldehyde (1 g, 0.02 mol) in acetonitrile (10 mL) was added potassium fluoride and the mixture stirred for 3 h. The suspension was filtered and the filtrate concentrated in a rotary evaporator to yield an oil (0.6 g), the composition of which was determined by NMR as two diastereomeric compounds **10a,b** and the desilylated methyl ester **4** in approximately equal ratios. The crude oil was chromatographed in a manner identical with that reported for **10**, yielding the diastereomeric mixture of **10a,b**: IR (KBr) 3350, 1770, 1745, 1440, 1220 cm^{-1}; ^1H NMR ($CDCl_3$) δ 5.33 and 5.26 (2 q, 1 H), 4.31 and 4.26 (2 dd, 1 H), 3.81 and 3.80 (2 s, 3 H), 3.30 and 3.29 (2 dd, 1 H), 2.98 and 2.94 (2 dd, 1 H), 1.35 and 1.34 (2 d, 3 H). Anal. Calcd for $C_7H_{11}NO_4$: C, 48.55; H, 6.40; N, 8.09. Found: C, 48.70; H, 6.28; N, 8.05.

***cis*- and *trans*-3-(Trimethylsilyl)-2-oxoazetidin-4-yl Acetate (11).** To a solution of **8** (1.87 g, 0.01 mol) in a mixture of dimethylformamide (40 mL) and acetic acid (7.5 mL) was added lead tetracetate (5.2 g, 85%, 0.01 mol) in one portion. The yellow suspension was heated to 54 °C, whereupon the evolution of carbon dioxide commenced. When the gas evolution had ceased after 30 min, the solvents were distilled off under reduced pressure (0.2 mm). Water (80 mL) was added to the residue and the solution extracted successively with ether (4 × 100 mL). The organic phase was washed with aqueous $NaHCO_3$ (25 mL) and saturated aqueous sodium chloride and dried (Na_2SO_4). Removal of the solvent gave 1.57 g (78%) of a yellow oil, which was purified by chromatography (silica, 5:2 chloroform/ethyl acetate as the eluent) to afford 1.38 g of **10** as a viscous oil: IR (CS_2) 3390, 1785, 1750, 1256, 1235, 845 cm^{-1}; ^1H NMR ($CDCl_3$) [**11a**] δ 6.35 (br, 1 H), 5.64 (d, J = 1.5 Hz, 1 H), 2.81 (dd, 1 H), 2.00 (s, 3 H), 0.18 (s, 9 H), [**11b**] 6.40 (br, 1 H), 5.90 (d, J = 4.5 Hz, 1 H), 2.98 (dd, 1 H), 2.01 (s, 3 H), 0.21 (s, 9 H). Anal. Calcd for $C_8H_{15}NO_3Si$: C, 47.74; H, 7.51; N, 6.96; Si, 13.96. Found: C, 47.91; H, 7.54; N, 7.03; Si, 13.81.

(3*S*,4*R*)-3-(Trimethylsilyl)-4-(phenylthio)-2-azetidinone (12). A solution of sodium thiophenolate was prepared by addition of thiophenol (0.55 g, 0.05 mol) to a solution of sodium methylate (0.27 g, 0.05 mol) in methanol (40 mL). Then **11** (1.0 g, 0.005 mol) was added and stirred at 25 °C for 3 h. Solvent was removed by rotary evaporation at reduced pressure, and water (30 mL) was added to the residue. The oily suspension was extracted successively with chloroform (3 × 20 mL), washed with brine, and dried (Na_2SO_4). Evaporation yielded a yellow oil (1.1 g), which was purified in a manner identical with that for the above example to yield 0.61 g (48.6%) of **12** as white crystals: mp 58–60 °C, $[\alpha]^{20}_D$ +857.4° ($CHCl_3$); IR (KBr) 3230, 1750, 1712, 1250, 850 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.47–7.36 (m, 5 H), 6.08 (br, 1 H), 4.76 (d, J = 2.2 Hz, 1 H), 2.73 (dd, 1 H), 0.14 (s, 9 H). Anal. Calcd for $C_{12}H_{17}NOSSi$: C, 57.46; H, 6.82; N, 5.57; S, 12.75; Si, 11.17. Found: C, 57.46; H, 6.74; N, 5.54; S, 12.78; Si, 11.27. From higher fractions were obtained 0.2 g of 4-(phenylthio)azetidinone which was identified by comparison with an authentic sample.[14]

(3*S*,4*R*)-3-(Trimethylsilyl)-4-[((ethylthio)thiocarbonyl)-thio]-2-azetidinone (13): prepared from **11** and ethyl trithiocarbonate sodium salt; yield 75%; yellow crystals, mp 99–101 °C, $[\alpha]^{20}_D$ +312.2° ($CHCl_3$); IR (KBr) 3160, 1760, 1722, 1085, 850 cm^{-1}; ^1H NMR ($CDCl_3$) δ 6.53 (br, 1 H), 5.38 (d, J = 2.5 Hz, 1 H), 3.37 (m, 2 H), 2.81 (dd, 1 H), 1.37 (t, 3 H), 0.20 (s, 9 H). Anal. Calcd for $C_9H_{17}NOS_3Si$: C, 38.67; H, 6.13; N, 5.01; S, 34.41; Si, 10.05. Found: C, 38.88; H, 6.11; N, 4.94; S, 34.50; Si, 10.21.

(3*S*,4*R*)-3-(Trimethylsilyl)-4-(benzoylthio)-2-azetidinone (14): prepared from **11** and thiobenzoic acid sodium salt; yield 84%; white crystals, mp 124–126 °C (cyclohexane), $[\alpha]^{20}_D$ +175.5° ($CHCl_3$); IR (KBr) 3280, 1755, 1658, 1210, 1110, 912, 853 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.92–7.48 (m, 5 H), 6.34 (br, 1 H), 5.22 (d, J = 2.5 Hz, 1 H), 2.91 (dd, 1 H), 0.22 (s, 9 H). Anal. Calcd for $C_{13}H_{17}NO_2SSi$: C, 55.88; H, 6.13; N, 5.01; S, 11.47; Si, 10.05. Found: C, 55.78; H, 6.15; N, 5.05; S, 11.54; Si, 10.01.

(3*S*,4*R*)-3-(Trimethylsilyl)-2-oxoazetidin-4-yl *N*,*N*-Dimethyldithiocarbamate (15): prepared from **11** and *N*,*N*-dimethyldithiocarbamate sodium salt dihydrate in water; yield 97%; white crystals, mp 148 °C (methanol), $[\alpha]^{20}_D$ +297° ($CHCl_3$); IR (KBr) 3227, 1748, 1255, 1100, 853 cm^{-1}; ^1H NMR ($CDCl_3$) δ 6.79 (br, 1 H), 5.21 (d, J = 2.8 Hz, 1 H), 3.52 (s, 3 H), 3.34 (s, 3 H), 2.81 (dd, 1 H), 0.20 (s, 9 H). Anal. Calcd for $C_9H_{18}N_2OS_2Si$: C, 41.24; H, 6.83; N, 10.68; S, 24.40; Si, 10.78. Found: C, 41.42; H, 6.93; N, 10.58; S, 24.48; Si, 11.08.

(3*S*,4*R*)-3-(Trimethylsilyl)-4-(acetylthio)-2-azetidinone (16). To a solution of thioacetic acid sodium salt (prepared by addition of thioacetic acid (0.456 g, 0.006 mol) to sodium methylate (0.32 g, 0.006 mol) in methanol (10 mL) was added a solution of **11** (1.05 g, 0.005 mol) in methanol (5 mL) and the mixture stirred for 6 h. Removal of the solvent under reduced pressure gave a semicrystalline residue, which was suspended in water (25 mL) and extracted with ether (4 × 20 mL). The combined ethereal extracts were washed with brine and dried (Na_2SO_4). Evaporation of the residue left a yellow oil (0.7 g), which was purified in a manner analogous with that described for **11**, yielding 0.33 g (30%) of **15** as an oil: $[\alpha]^{20}_D$ +150° ($CHCl_3$); IR (CS_2) 3380, 1775, 1695, 1253, 1130, 846 cm^{-1}; ^1H NMR ($CDCl_3$) δ 6.24 (br, 1 H), 5.05 (d, J = 2.5 Hz, 1 H), 2.78 (dd, 1 H), 2.37 (s, 3 H), 0.18 (s, 9 H). Anal. Calcd for $C_9H_{18}NO_2SSi$: C, 44.21; H, 6.96; N, 6.44; S, 14.75; Si, 12.92. Found: C, 44.01; H, 7.02, N, 6.52; Si, 14.68; Si, 12.93.

(3*S*,4*R*)-3-(Trimethylsilyl)-4-(phenylsulfonyl)-2-azetidinone (17): prepared from **11** and benzenesulfinic acid sodium salt in water; yield 49%; white crystals, mp 138–141 °C (benzene), $[\alpha]^{20}_D$ –17.5° ($CHCl_3$); IR (KBr) 3150, 1750, 1705, 1150, 1090, 855

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cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.94–7.62 (m, 5 H), 6.13 (br, 1 H), 4.42 (d, J = 2.2 Hz, 1 H), 3.04 (dd, 1 H), 0.11 (s, 9 H). Anal. Calcd for $C_{12}H_{17}NO_3SSi$: C, 50.86; H, 6.05; N, 4.95; Si, 11.31; Si, 9.91. Found: C, 50.82; H, 5.97; N, 5.20; Si, 11.27; Si, 10.06.

(3*S*,4*R*)-3-(Trimethylsilyl)-4-phenoxy-2-azetidinone (18) was prepared from 11 and sodium phenolate in water. The semicrystalline product was purified in a manner identical with that described for 11 to afford 51% of 18: white crystals, mp 99–100 °C (cyclohexane), $[\alpha]^{20}_D$ +62.0° ($CHCl_3$); IR (KBr) 3200, 1758, 1723, 1603, 1596, 1501, 1230, 1158, 1050, 850 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.33–6.88 (m, 5 H), 6.41 (br, 1 H), 5.46 (d, J = 1.5 Hz, 1 H), 2.96 (d, 1 H), 0.20 (s, 9 H). Anal. Calcd for $C_{12}H_{17}NO_2Si$: C, 61.24; H, 7.28; N, 5.95; Si, 11.94. Found: C, 61.28; H, 7.41; N, 6.02; Si, 12.15.

Effect of A-Strain on a Diastereoselective Synthesis of 6-Hydroxy-4a-aryldecahydroisoquinolines. Revised Structures of *N*-Acyliminium Ion-Polyene Cyclization Products

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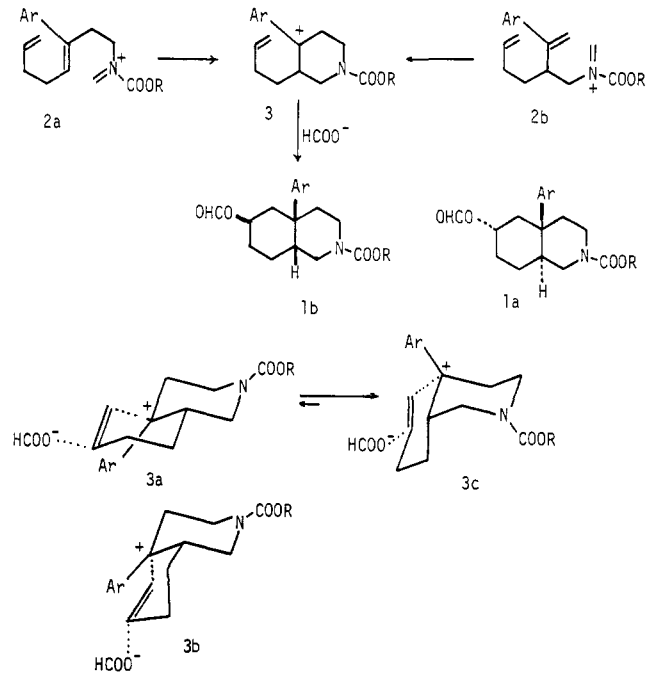
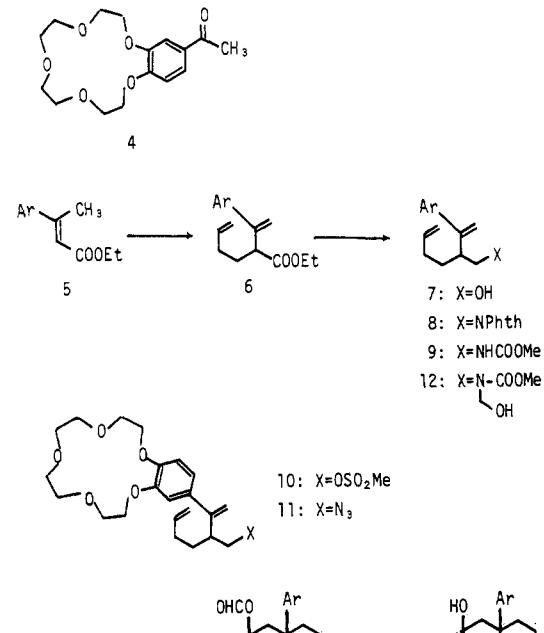
Biomimetic polyene cyclizations have been applied to the synthesis of multicyclic compounds with excellent stereocontrol.[1,2] Allyl alcohols, epoxides, acetals, or sulfonates have been used as suitable cationic initiators for successful polyene cyclizations. The use of *N*-acyliminium ions as cationic initiating center for olefin cyclizations has been well established.[3] The development of *N*-acyliminium ion–polyene cyclizations had led to a versatile route to N-polycyclic compounds in remarkably stereocontrolled manner.[4] Of special interest to us from pharmacological point of view is the development of a facile procedure for a synthesis of 6-hydroxy-4a-aryldecahydroisoquinolines.[5] Previously, we reported an efficient diastereoselective synthesis of 6-oxygenated 4a-aryldecahydroisoquinolines[6,7] by cyclization of **2a** and **2b**.

Scheme I



Scheme II



a: Ar=4-(OCH_3)-C_6H_4- ; b: Ar=3,4-$(OCH_3)_2$-C_6H_3-;
c: Ar=3,4-crowned(15-crown-5)-C_6H_3-

In the previous papers,[6,7] the relative configuration of the cyclization products was assigned to **1a**. The cyclizations were found to proceed via the common benzyl cationic intermediates **3**. We now wish to report that the relative configuration previously assigned by us to these products needs to be revised to **1b**, i.e., 4a,6-cis, 4a,8a-cis as the result of our successful conversion of **1b** (Ar = C_6H_5) to *cis*-4a-phenyl-2-methyldecahydroisoquinoline by an unambigous method.[8] Cis-ring fusion of **1b** can be accounted for by the effect of A-strain[9] on the monocyclization intermedi-

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