Chemistry of *O*-Silylated Ketene Acetals: An Efficient Synthesis of Carbapenem and 1β-Methylcarbapenem Intermediates

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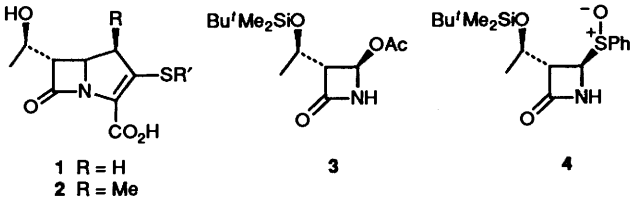
3-(1-*tert*-Butyldimethylsiloxyethyl)-4-phenylsulfinylazetidin-2-one reacted smoothly with various types of *O*-silylated ketene acetals and silylated enol ethers in the presence of a catalytic amount of zinc iodide to give the corresponding *trans*-4-substituted azetidin-2-ones in good yields. The latter compounds are key intermediates for the synthesis of carbapenems and 1β-methylcarbapenems.

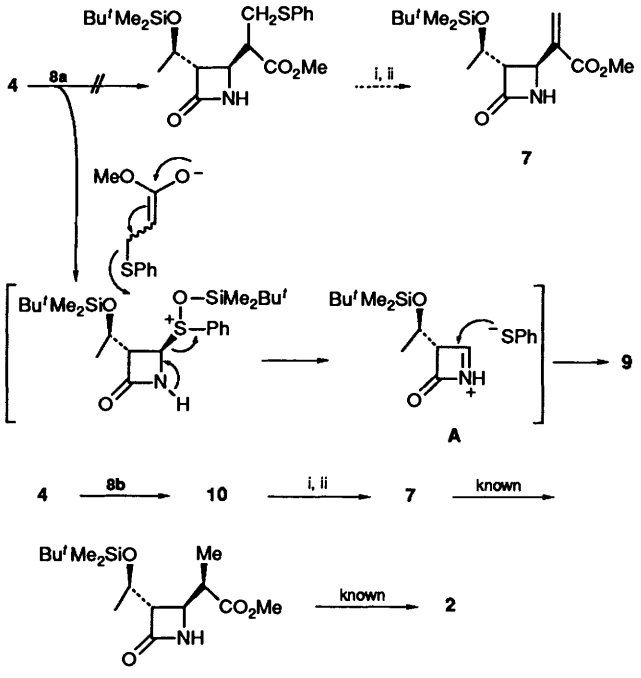
Since the discovery of the highly active carbapenem **1** [R′ = $(CH_2)_2NH_2$, thienamycin] and 1β-methylcarbapenem **2**, a variety of stereoselective syntheses of these compounds and their analogues have been reported.[1] Among them, the most popular route to these antibiotics have relied on the aldol-type reaction of the (+)-4-acetoxyazetidin-2-one **3** with properly designed metal enolates.†[2] Recently, we have reported a novel efficient synthesis of racemic[3] and optically active **1**[4] from racemic and optically active *trans*-3-(1-*tert*-butyldimethylsiloxyethyl)-4-phenylsulfinylazetidin-2-ones **4** obtained using our silicon-induced Pummerer-type reaction.[5,6] In this paper, we wish to report the generality of the reaction of **4** with various types of silyl ketene acetals **5a–e**[7] and silyl enol ethers **5f–h** and an application of this method to a synthesis of a key useful intermediate[8] for **2**.



A typical experimental procedure is as follows for the reaction of **4** with *O*-*tert*-butyldimethylsilyl-*O*-methyl ketene acetal **5a**. A solution of **4**, **5a** and a catalytic amount of zinc iodide in dry acetonitrile was stirred at 0 °C for 1 h followed by usual work-up to give (3*S*,4*R*)-3-[(1*R*)-1-*tert*-butyldimethylsiloxyethyl]-4-methoxycarbonylmethyl-*N*-*tert*-butyldimethylsilylazetidin-2-one **6a** (entry 1, Table 1). Similarly, **4** reacted with various types of silyl ketene acetals **5b–e** and silyl enol ethers **5f–h** in the presence of a catalytic amount of zinc iodide in acetonitrile at room temperature to give high yields of the corresponding C-4 substituted *trans*-azetidin-2-ones **6b-h**, stereoselectively (entries 2–8, Table 1). The selective formation of *trans*-azetidin-2-ones **6a–h** is reasonably explained by assuming the intermediacy of acyliminium salt **A**. These azetidin-2-ones are useful intermediates for the synthesis of carbapenem antibiotics and their analogues. The reaction conditions and the ratios of α- and β-isomers on C-1 (carbapenem numbering) of the products are listed in Table 1.

Finally, our attention was focused on the synthesis of the 1β-methylcarbapenem **2**. We examined the synthesis of the significant key intermediate **7**[8] for **2** by the reaction of **4** with two types of sulfur substituted silyl ketene acetals **8a**, **b** followed by oxidative thermal elimination of sulfinic acid as exemplified in Scheme 1. The first approach using **8a** gave the unexpected 4-phenylthioazetidin-2-one **9** selectively (entry 9), the formation of which is explained by nucleophilic attack of the phenylthio anion generated by 1,4-fragmentation reaction of **8a** onto the acyliminium salt **A**. On the other hand, the second approach using **8b** gave the expected 4-substituted azetidin-2-one **10** in 95% yield (entry 10), which was readily converted to the desired *exo*-methylene compound **7** (68% yield) by *m*-chloroperbenzoic acid (*m*-CPBA) oxidation and subsequent thermal treatment in refluxing toluene for 1 h. The stereoselective hydrogenation of these types of compounds leading to **2** is well documented and has been accomplished with extremely high stereoselectivity.[8,9]

Using the present method, four contiguous asymmetric centres in **2** were constructed in a short, efficient and extremely stereocontrolled way.



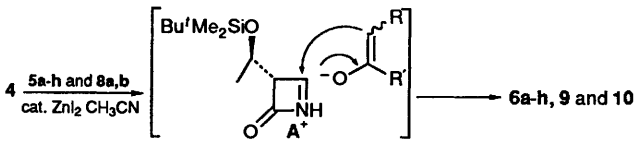
Scheme 1 *Reagent and conditions:* i, *m*-CPBA; ii, heat

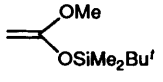
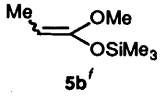
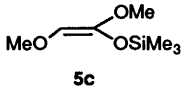
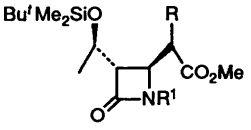
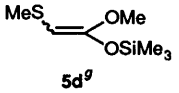
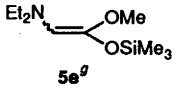
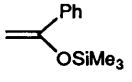
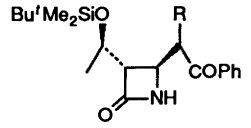
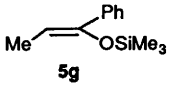
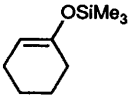
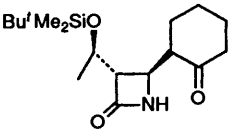
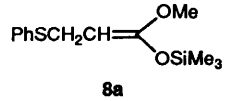
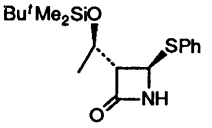
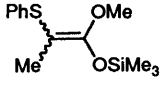
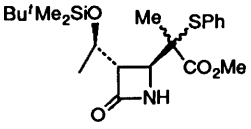
Experimental

All m.p.s and b.p.s are uncorrected. ^1H NMR spectra were recorded on a Hitachi R-22 (90 MHz), Hitachi R-250 (250 MHz), JEOL JNM-EX 270 (270 MHz) or JEOL JNM-GX 500 (500 MHz) spectrometers with $CDCl_3$ as a solvent (tetra-

† The azetidin-2-one **3** is available from Kanegafuchi Chemical Industry Co. Ltd., Osaka, Japan.

Table 1



Entry	Starting material	Reaction conditions[a]	Product[b]		Yield[c] (%)	Ratio[d] α:β
1	 **5a**	0 °C, 1 h		**6a**[e]; R = H, R^1 = $SiMe_2Bu^t$	73	
2	 **5b**[f]	r.t., 1 h		**6b**; R = Me, R^1 = H	96	85:15
3	 **5c**	r.t., 1 h		**6c**; R = OMe, R^1 = H	86	80:20
4	 **5d**[g]	r.t., 1 h		**6d**; R = SMe, R^1 = H	82	80:20
5	 **5e**[g]	r.t., 1 d		**6e**; R = NEt_2, R^1 = H	30	77:23
6	 **5f**	r.t., 1 d		**6f**; R = H	89	
7	 **5g**	r.t., 1 d		**6g**; R = Me	75	77:23 (or 39:61)
8	 **5h**	r.t., 1 d	 **6h**		90	61:39
9	 **8a** (PhSSiMe$_3$ + CH_2=$CHCO_2$Me)	r.t., 1 h	 **9**		79	
10	 **8b**[g]	r.t., 1 h	 **10**		95	50:50

[a] The reactions were carried out on 0.1–1 mmol scale of **4** and 3–5 equiv. of **5** or **8** in the presence of a catalytic amount (0.1 equiv.) of ZnI_2; r.t. = room temperature. [b] All new compounds were characterised by microanalyses and IR and ^{1}H NMR spectral data and known compounds were identified by comparison with authentic samples. The stereochemistry of **6b–e** was assigned by the reported method[10] by reduction of ester group followed by acetonide formation. [c] Isolated yields (by column chromatography on silica gel) are given. [d] The ratios were determined by 500 MHz ^{1}H NMR spectroscopy. [e] *N-tert*-Butyldimethylsilylated compound **6a** was obtained, although *N*-trimethylsilylated compounds were readily converted to N-H compounds **6b–h**, **9** and **10** by usual work-up. [f] An 85 : 15 mixture of *E* and *Z* isomers was used. [g] A mixture of *O*-silylated ketene acetals (*E* and *Z* isomers) containing a small amount of *C*-silylated ester was used in the reaction without separation.

methylsilane was used internal standard unless otherwise noted. *J* values are given in Hz. IR absorption spectra were recorded in $CHCl_3$ on a JASCO HPIR-102 spectrophotometer. Low- and high-resolution mass spectra (MS) were obtained with a JEOL JMSD-300 instrument, with a direct inlet system at 70 eV. For column chromatography, Merck silica gel (70–230 mesh ASTM) was used. For preparative TLC, Merck TLC plates pre-coated with silica gel $60F_{254}$ (0.5 mm) were used.

Silyl ketene acetals **5a–c** *and silyl enol ethers* **5f–h**. The silky ketene acetals **5a–c** and silyl enol ethers **5f–h** were prepared by the reported method.[7]

General Procedure for the Synthesis of Silyl Ketene Acetals **5d, e** *and* **8b**.—An ester (10 mmol) was added to a solution of lithium diisopropylamide [prepared from diisopropylamine (12 mmol) and butyllithium (12 mmol) in hexane] in dry tetrahydrofuran (THF) at −78 °C. After 30 min, trimethylsilyl chloride (TMSCl, 20 mmol) was added slowly, and the temperature of the reaction mixture was allowed to warm to room temperature over 30 min. After being stirred for 1 h, the mixture was then concentrated under reduced pressure. Pentane was added, and the precipitated LiCl removed by filtration through a Celite pad. The filtrate was concentrated under reduced pressure. The residual oil was distilled to give the silyl ketene acetal as a mixture of stereoisomers (*E* and *Z* forms) and the α-silyl ester.

1-*Methoxy*-2-*methylthio*-1-(*trimethylsiloxy*)*ethylene* **5d**. The title compound (3.25 g, 68%) was obtained from methyl methylthioacetate (3.0 g, 0.025 mol) and TMSCl (4.8 cm^3, 0.038 mol) in dry THF as a colourless oil; b.p. 80–83 °C/11 mmHg; $\nu_{max}(CHCl_3)/cm^{-1}$ 1615 and 1580; δ_H 0.12, 0.25, 0.33 (total 9 H, each s, $SiMe_3$), 2.00, 2.13 (total 3 H, each s, SMe), 3.51, 3.57 and 4.14 (total 4 H, each s, OMe, CH=) (Found: C, 43.75; H, 8.5%; M^+, 192.0617. $C_7H_{16}O_2SSi$ requires C, 43.75; H, 8.33%; *M*, 192.0638).

2-*Diethylamino*-1-*methoxy*-1-(*trimethylsiloxy*)*ethylene* **5e**. The title compound (2.40 g, 71%) was obtained from methyl diethylaminoacetate (3.0 g, 0.021 mol) and TMSCl (5.9 cm^3, 0.047 mol) in dry THF as a colourless oil; b.p. 70 °C/4 mmHg; $\nu_{max}(CHCl_3)/cm^{-1}$ 1730 and 1685; δ_H 0.046, 0.13, 0.21, 0.23 (total 9 H, each s, $SiMe_3$), 0.99, 1.01, 1.04 (total 6 H, each t, *J* 7.5, CH_2Me × 2), 2.52, 2.57, 2.63 (total 4 H, each q, *J* 7.5, $MeCH_2$ × 2), 3.30, 3.50, 3.57, 3.70, 3.88 and 3.99 (total 4 H, each s, OMe, CH=) (Found: C, 54.95; H, 10.55; N, 6.45%; M^+, 217.1502. $C_{10}H_{23}NO_2Si$ requires C, 55.24; H, 10.68; N, 6.49%; M, 217.1497).

1-*Methoxy*-2-*methyl*-2-*phenylthio*-1-(*trimethylsiloxy*)*ethylene* **8b**. The title compound (3.02 g, 75%) was obtained from methyl 1-methyl-1-phenylthioacetate (3.0 g, 0.015 mol) and TMSCl (2.9 cm^3, 0.023 mol) in dry THF as a colourless oil; b.p. 105 °C/0.25 mmHg; $\nu_{max}(CHCl_3)/cm^{-1}$ 1640 and 1580; δ_H 0.25, 0.31 (total 9 H, each s, $SiMe_3$), 1.84 (1.2 H, s, Me), 1.87 (1.8 H, s, Me), 3.63 (1.8 H, s, OMe), 3.64 (1.2 H, s, OMe) and 7.05–7.35 (5 H, m, Ph) (Found: C, 58.0; H, 7.4%; M^+, 268.0965. $C_{13}H_{20}O_2SSi$ requires C, 58.16; H, 7.51%; *M*, 268.0954).

General Procedure for the Reaction of 4-*Phenylsulfinylazetidin*-2-*one* **4** *with Silyl Ketene Acetals* **5a–e** *and* **8b** *or Silyl Enol Ethers* **5f–h**.—To a stirred solution of 4-phenylsulfinylazetidin-2-one **4** (0.10 mmol) and silyl ketene acetal or silyl enol ether **5a–h**, **8b** (0.2–0.5 mmol) in dry CH_3CN (2 cm^3) was added ZnI_2 (0.01 mmol). After the mixture had been stirred for the period indicated in Table 1, it was quenched with saturated aqueous $NaHCO_3$ (20 cm^3) and diluted with CH_2Cl_2 (50 cm^3). The mixture was partitioned between CH_2Cl_2 and water. The aqueous layer was separated and extracted with CH_2Cl_2 (100 cm^3). The combined organic layer was washed with brine, dried (Na_2SO_4) and concentrated under reduced pressure. The residue was purified by prepartive TLC on silica gel to give the 4-substituted azetidin-2-one.

(3S,4R)-3-[(1R)-1-tert-*Butyldimethylsiloxyethyl*]-N-tert-*butyldimethylsilyl*-4-*methoxycarbonylmethyl*-2-*one* **6a**. The title compound (43.0 mg, 73%) was obtained from **4** (50.0 mg, 0.14 mmol), **5a** (106 mg, 0.565 mmol) and ZnI_2 (4.5 mg, 0.0141 mmol) in dry CH_3CN as a colourless oil; $\nu_{max}(CHCl_3)/cm^{-1}$ 1720; δ_H 0.0373, 0.0593, 0.196, 0.216 (total 12 H, each s, $SiMe_2$ × 2), 0.865, 0.934 (total 18 H, each s, $SiBu^t$ × 2), 1.121 (3 H, d, *J* 6.2, >CCH*Me*), 2.521 (1 H, dd, *J* 8.8, 14.3, C*H*HCO_2), 2.786 (1 H, dd, *J* 4.6, 14.3, CH*H*CO_2), 2.977 (1 H, dd, *J* 2.7, 4.2, 3-H), 3.669 (3 H, s, OMe), 3.962 (1 H, ddd, *J* 2.7, 4.6, 8.8, 4-H) and 4.171 (1 H, qd, *J* 6.2, 4.2, >C*H*Me) (Found: M^+, 415.2577. $C_{20}H_{41}NO_4Si_2$ requires *M*, 415.2574).

(3S,4S)-3-[(1R)-1-tert-*Butyldimethylsiloxyethyl*]-4-(1-*methoxycarbonylethyl*)*azetidin*-2-*one* **6b**. The title compound (85.1 mg, 96%, 1α : 1β = 77:23) was obtained from **4** (100 mg, 0.282 mmol), **5b** (272 mg, 1.70 mmol) and ZnI_2 (9.00 mg, 0.0281 mmol) in dry CH_3CN as a colourless powder, m.p. 128–133 °C (hexane–CH_2Cl_2); $\nu_{max}(CHCl_3)/cm^{-1}$ 3400, 1760 and 1725; δ_H 0.0603, 0.0604, (total 6 H, each s, $SiMe_2$), 0.859 (2.07 H, s, $SiBu^t$), 0.867 (6.93 H, each s, $SiBu^t$), 1.135 (0.69 H, d, *J* 6.2, >CH*Me*), 1.227 (0.69 H, d, *J* 7.0, *Me*$CHCO_2$), 1.229 (4.62 H, d, *J* 7.0, *Me*CHC<, *Me*$CHCO_2$), 2.533 (0.23 H, dq, *J* 9.8, 7.0, $CHCO_2$), 2.689 (0.23 H, dq, *J* 6.0, 7.0, $CHCO_2$), 2.761 (0.77 H, ddd, *J* 1.2, 2.0, 5.2, 4-H), 2.971 (0.23 H, ddd, *J* 0.8, 2.4, 4.2, 4-H), 3.680 (0.77 H, dd, *J* 2.0, 9.8, 3-H), 3.863 (0.23 H, dd, *J* 2.2, 6.0, 3-H), 3.688 (0.69 H, s, OMe), 3.708 (2.31 H, s, OMe), 4.167 (0.77 H, dq, *J* 7.0, 5.2, >C*H*Me), 4.183 (0.23 H, dq, *J* 6.2, 4.2, >C*H*Me), 6.008 (0.23 H, br s, NH) and 6.107 (0.77 H, br s, NH) (Found: M^+ − Bu^t, 258.1171. $C_{11}H_{20}NO_4Si$ requires *m/z*, 258.1161).

(3S,4S)-3-[(1R)-1-tert-*Butyldimethylsiloxyethyl*]-4-(1-*methoxy*-1-*methoxycarbonylmethyl*)*azetidin*-2-*one* **6c**. The title compound (41.6 mg, 86%, 1α:1β = 80:20) was obtained from **4** (50.0 mg, 0.141 mmol), **5c** (71.4 mg, 0.419 mmol) and ZnI_2 (4.50 mg, 0.0141 mmol) in dry CH_3CN as colourless needles, m.p. 111–113 °C (CH_2Cl_2–hexane); $\nu_{max}(CHCl_3)/cm^{-1}$ 3420 and 1755; δ_H 0.0589 (1.2 H, s, $SiMe_2$), 0.0638 (4.8 H, s, $SiMe_2$), 0.8596 (1.8 H, s, $SiBu^t$), 0.8656 (7.2 H, s, $SiBu^t$), 1.1011 (0.6 H, t, *J* 6.1, *Me*CH<), 1.1426 (2.4 H, d, *J* 6.1, *Me*CH<), 3.125 (0.2 H, m, 3-H), 3.167 (0.8 H, m, 3-H), 3.4319, 3.7845 (each 0.6 H, each s, each OMe), 3.462, 3.801 (each 2.4 H, each s, each OMe), 3.866 (0.8 H, d, *J* 5.5, >C*H*OMe), 3.883 (0.2 H, dd, *J* 2.3, 7.5, 4-H), 3.585 (0.8 H, dd, *J* 2.4, 5.5, 4-H), 4.231 (1 H, dq, *J* 3.0, 6.1, >C*H*Me), 5.782 (0.8 H, br s, NH) and 5.938 (0.2 H, br s, NH). Other signals cannot be assigned (Found: C, 54.3; H, 8.75; N, 4.2%. $C_{15}H_{29}NO_5Si$ requires C, 54.35; H, 8.82; N, 4.23%).

(3S,4S)-3-[(1R)-1-tert-*Butyldimethylsiloxyethyl*]-4-(1-*methoxycarbonyl*-1-*methylthiomethyl*)*azetidin*-2-*one* **6d**. The title compound (81.0 mg, 82%, 1α:1β = 80:20) was obtained from **4** (100 mg, 0.282 mmol), **5d** (163 mg, 0.848 mmol) and ZnI_2 (9.00 mg, 0.0282 mmol) in dry CH_3CN as colourless needles, m.p. 109–111 °C (CH_2Cl_2–hexane); ν_{max}(KBr)/cm^{-1} 1767 and 1736; δ_H 0.063, 0.073 (6 H, s, $SiMe_2$), 0.863 (1.8 H, s, $SiBu^t$), 0.871 (7.2 H, s, $SiBu^t$), 1.152 (0.6 H, t, *J* 6.0, *Me*CH<), 1.263 (2.4 H, d, *J* 6.8, *Me*CH<), 2.182 (2.4 H, s, SMe), 2.207 (0.6 H, s, SMe), 2.924 (0.8 H, dd, *J* 2.0, 2.3, 3-H), 3.055 (0.2 H, m, 3-H), 3.236 (0.8 H, d, *J* 10, >C*H*SMe), 3.298 (0.2 H, d, *J* 7.5, >C*H*SMe), 3.764 (2.4 H, s, OMe), 3.786 (0.6 H, s, OMe), 4.015 (0.8 H, dd, *J* 2.3, 10.0, 4-H), 4.265 (0.8 H, dq, *J* 2.0, 6.8, >C*H*Me), 5.969 (0.8 H, br s, NH) and 6.12 (0.2 H, br s, NH). Other signals could not be assigned (Found: C, 52.05; H, 8.3; N, 3.95; S, 9.1. $C_{15}H_{29}NO_4SSi$ requires C, 51.84; H, 8.41; N, 4.03; S, 9.22%).

(3S,4S)-3-[(1R)-1-tert-*Butyldimethylsiloxyethyl*]-4-(1-*diethylamino*-1-*methoxycarbonylmethyl*)*azetidin*-2-*one* **6e**. The title compound (31.2 mg, 30%, 1α:1β = 77:23) was obtained

from **4** (100 mg, 0.282 mmol), **5e** (185 mg, 0.852 mmol) and ZnI_2 (9.00 mg, 0.0282 mmol) in dry CH_3CN as colourless crystals, m.p. 71–73 °C (hexane); $\nu_{max}(CHCl_3)/cm^{-1}$ 3420, 1760 and 1720; δ_H 0.063 (6 H, s, $SiMe_2$), 0.871 (9 H, s, SiBu^t), 1.006 (1.38 H, t, *J* 7.3, Me_2CH_2 × 2), 1.035 (4.62 H, t, *J* 6.8, Me_2CH_2 × 2), 1.139 (0.69 H, d, *J* 6.8, *Me*CH<), 1.196 (2.31 H, d, *J* 6, *Me*CH<), 2.4–2.7 (4 H, m, CH_2Me × 2), 2.802 (0.77 H, dd, *J* 1.8, 2.0, 3-H), 2.97 (0.23 H, m, 3-H), 3.272 (0.77 H, d, *J* 9.8, >C*H*NEt_2), 3.33 (0.23 H, d, *J* 7.9, >C*H*NEt_2), 3.693 (0.69 H, s, OMe), 3.720 (2.31 H, s, OMe), 3.928 (0.77 H, dd, *J* 2.5, 9.0, 4-H), 4.274 (0.77 H, dq, 1.8, 6, >C*H*Me), 5.79 (0.77 H, br s, NH) and 6.00 (0.23 H, br s, NH) (Found: M^+, 372.2452. $C_{18}H_{36}N_2O_4SI$ requires *M*, 372.2444).

(3S,4R)-3-[(1R)-1-tert-*Butyldimethylsiloxyethyl*]-4-*benzoylmethylazetidin-2-one* **6f**. The title compound (43.9 mg, 89%) was obtained from **4** (50.0 mg, 0.141 mmol), **5f** (70.0 mg, 0.421 mmol) and ZnI_2 (4.50 mg, 0.0141 mmol) in dry CH_3CN as pale yellow crystals, m.p. 93–95 °C (hexane–CH_2Cl_2); $\nu_{max}(CHCl_3)/cm^{-1}$ 3420, 1760 and 1680; δ_H 0.0749, 0.0813 (total 6 H, each s, $SiMe_2$), 0.874 (9 H, s, SiBu^t), 1.252 (3 H, d, *J* 6.2, *Me*CHC<), 2.887 (1 H, ddd, *J* 0.6, 2.4, 5.4, 3-H), 3.167 (1 H, dd, *J* 10.2, 17.6, C*H*HCO), 3.472 (1 H, dd, *J* 3.0, 17.6, CH*H*CO), 4.127 (1 H, ddd, *J* 2.4, 3.0, 10.2, 4-H), 4.226 (1 H, qd, *J* 6.2, 5.4, >C*H*Me), 6.13 (1 H, br s, NH) and 7.4–8.0 (5 H, m, Ar) (Found: C, 65.8; H, 8.35; N, 3.9. $C_{19}H_{29}NO_3Si$ requires C, 65.67; H, 8.41; N, 4.03%).

(3S,4R)-4-(1-*Benzoylethyl*)-3-[(1R)-1-tert-*butyldimethylsiloxyethyl*]*azetidin-2-one* **6g**. The title compound (38.5 mg, 75%, 1α:1β = 77:23) was obtained from **4** (50.0 mg, 0.141 mmol), **5g** (70.0 mg, 0.414 mmol) and ZnI_2 (4.50 mg, 0.0141 mmol) in dry CH_3CN as a colourless powder, m.p. 102–105 °C (hexane–CH_2Cl_2); $\nu_{max}(CHCl_3)/cm^{-1}$ 3420, 1755 and 1675; δ_H 0.027, 0.046 (total 1.38 H, each s, $SiMe_2$), 0.071, 0.083 (total 4.62 H, each s, $SiMe_3$), 0.842 (2.07 H, s, SiBu^t), 0.871 (6.93 H, s, SiBu^t), 1.14 (1.38 H, d, *J* 6.5, Me × 2), 1.27 (4.62 H, d, *J* 6.5, Me × 2), 2.85 (0.77 H, dd, *J* 1.5, 6.5, 3-H), 2.89 (0.23 H, dd, *J* 2.0, 6.5, 3-H), 3.49 (0.77 H, qd, *J* 6.5, 10.0, C*H*COPh), 3.71 (0.23 H, qd, *J* 6.5, 5.0, C*H*COPh), 3.98 (0.23 H, dd, *J* 2.0, 5.0, 4-H), 3.99 (0.77 H, dd, *J* 1.5, 10.0, 4-H), 4.17 [0.23 H, quint, >C*H*(OSi)], 4.20 [0.77 H, quint, >C*H*(OSi)], 5.95 (0.77 H, br s, NH), 6.14 (0.23 H, br s, NH), 7.47 and 7.90 (total 5 H, m, Ar) (Found: C, 66.3; H, 8.65; N, 3.75. $C_{20}H_{31}NO_3Si$ requires C, 66.44; H, 8.64; N, 3.87%).

(3S,4R)-3-[(1R)-1-tert-*Butyldimethylsiloxyethyl*]-4-(2-*oxocyclohexylazetidin-2-one* **6h**. The title compound (43.0 mg, 93%, mixture of diastereoisomers, 39:61) was obtained from **4** (50.0 mg, 0.141 mmol), **5h** (144 mg, 0.848 mmol) and ZnI_2 (4.50 mg, 0.0141 mmol) in dry CH_3CN as a yellow oil; $\nu_{max}(CHCl_3)/cm^{-1}$ 3425, 1750 and 1710; δ_H 0.050, 0.061 (total 6 H, each s, $SiMe_2$), 0.857, 0.866 (total 9 H, each s, SiBu^t), 1.210 (1.83 H, d, *J* 6.0, *Me*CH<), 1.225 (1.17 H, d, *J* 6.0, *Me*CH<), 1.24–2.54 (total 9 H, m, cyclohexyl), 2.682 (0.61 H, dd, *J* 1.8, 6.0, 3-H), 2.863 (0.39 H, dd, *J* 2.4, 6.0, 3-H), 3.600 (0.61 H, dd, *J* 1.8, 9.8, 4-H), 4.077 (0.39 H, dd, *J* 2.4, 3.4, 4-H), 4.148 (0.61 H, quint, *J* 6.0, >C*H*Me), 4.184 (0.39 H, quint, *J* 6.0, >C*H*Me), 5.821 (0.39 H, br s, NH) and 6.134 (0.61 H, br s, NH) (Found: M^+, 325.2059. $C_{17}H_{31}NO_3Si$ requires *M*, 325.2070).

(3S,4S)-3-[(1R)-1-tert-*Butyldimethylsiloxyethyl*)-4-(1-*methoxycarbonyl*-1-*phenylthioethyl*)*azetidin-2-one* **10**. The title compound (117 mg, 95%, mixture of diastereoisomers, 1:1) was obtained from **4** (150 mg, 0.425 mmol), **8b** (342 mg, 1.28 mmol) and ZnI_2 (13.5 mg, 0.0425 mmol) in dry CH_3CN as colourless crystals; m.p. 89.5–90.5 °C (light petroleum); $\nu_{max}(CHCl_3)/cm^{-1}$ 3400, 1755 and 1720; δ_H 0.050, 0.058, 0.085 (total 6 H, each s, $SiMe_2$), 0.86, 0.88 (total 9 H, each s, SiBu^t), 1.20 (1.5 H, d, *J* 6.1, *Me*CH<), 1.32 (1.5 H, d, *J* 6.7, *Me*CH<), 1.40, 1.47 (total 3 H, each s, MeS), 3.07 (0.5 H, dd, *J* 1.8, 2.4, 3-H), 3.19 (0.5 H, t, *J* 1.8, 3-H), 3.63, 3.70 (total 3 H, each s, MeO), 4.04 (0.5 H, d, *J* 2.4, 4-H), 4.24 (0.5 H, d, *J* 1.8, 4-H), 4.25 (1 H, m, >C*H*Me), 5.80, 6.01 (total 1 H, each br s, NH) and 7.29–7.56 (total 5 H, m, Ph) (Found: C, 59.4; H, 8.0; N, 3.2; S, 7.78%; M^+, 423.1907. $C_{21}H_{33}NO_4SSi$ requires C, 59.54; H, 7.85; N, 3.41; S, 7.57%; *M*, 423.1899).

(3S,4R)-3-[(1R)-1-tert-*Butyldimethylsiloxyethyl*]-4-*phenylthioazetidin-2-one* **9**.—A solution of trimethylsilylthiophenol (129 mg, 0.710 mmol), methyl acrylate (61.1 mg, 0.710 mmol) and ZnI_2 (4.53 mg, 0.0142 mmol) in CH_3CN (1 cm^3) was stirred at room temperature for 1 h under nitrogen atmosphere.[11] A solution of **4** (50.0 mg, 0.142 mmol) in CH_3CN (1 cm^3) was added to the mixture. After 1 h, the solvent was removed under reduced pressure to give a yellow oil, which was purified by preparative TLC eluting with 20% AcOEt in hexane to give **9** (38.0 mg, 79%) as colourless crystals; m.p. 119–120 °C (light petroleum) (lit.,[5] no data); $\nu_{max}(CHCl_3)/cm^{-1}$ 3400 and 1765; δ_H 0.051, 0.066 (total 6 H, each s, $SiMe_2$), 0.87 (9 H, s, SiBu^t), 1.20 (3 H, d, *J* 6.4, *Me*CH<), 3.03 (1 H, ddd, *J* 0.7, 2.2, 3.5, 3-H), 4.22 (1 H, qd, *J* 6.4, 3.5, >C*H*Me), 5.07 (1 H, dd, *J* 0.4, 2.2, 4-H), 6.15 (1 H, br s, NH) and 7.34–7.50 (5 H, m, Ph); *m/z* 280 (M^+ − 57).

(3S,4S)-3-[(1R)-1-tert-*Butyldimethylsiloxyethyl*]-4-(1-*methoxycarbonylethylene*)*azetidin-2-one* **7**.—A solution of *m*-chloroperbenzoic acid (*m*-CPBA; 80% 46.4 mg, 0.216 mmol) in CH_2Cl_2 (5 cm^3) was added to a stirred solution of **10** (24.1 mg, 0.057 mmol) in CH_2Cl_2 (5 cm^3) at 0 °C. After 10 min, the mixture was partitioned between CH_2Cl_2 and water. The aqueous layer was separated and extracted with CH_2Cl_2. The combined organic layer was washed with brine, dried (Na_2SO_4) and concentrated under reduced pressure to give a crude sulfoxide [25.3 mg, m.p. 122–124 °C (hexane)] (Found: M^+, 439.1853. $C_{21}H_{33}NO_5SSi$ requires *M*, 439.1848). The crude sulfoxide was dissolved in toluene (10 cm^3) and refluxed for 1 h. The solvent was removed under reduced pressure to give an oil, which was purified by preparative TLC on silica gel to give **7** (10.8 mg 68%) as colourless crystals: m.p. 130.5–131.5 °C (hexane); $\nu_{max}(CHCl_3)/cm^{-1}$ 3400, 1760, 1720 and 1630; δ_H 0.071, 0.083 (total 6 H, each s, $SiMe_2$), 0.87 (9 H, s, SiBu^t), 1.26 (3 H, d, *J* 6.6, *Me*CH<), 3.07 (1 H, d, *J* 3.6, 3-H), 3.79 (3 H, s, OMe), 4.26 (1 H, dq, *J* 3.6, 6.6, >C*H*Me), 4.57 (1 H, br s, 4-H), 5.898 (1 H, s, C*H*H=), 5.903 (1 H, br s, NH), 6.35 (1 H, s, CH*H*=) (Found: C, 57.3; H, 8.7; N, 4.5; M^+, 313.1712. $C_{15}H_{27}NO_4Si$ requires C, 57.47; H, 8.68; N, 4.47%; *M*, 313.1709).

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Paper 2/01117D
Received 2*nd March* 1992
Accepted 13*th March* 1992