The Application of Intramolecular Radical Cyclizations of Acylsilanes in the Regiospecific Formation of Cyclic Silyl Enol Ethers

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Acylsilanes with terminal α-stannyl bromide or xanthate functionalities are prepared. α-Stannyl radicals generated from these acylsilanes undergo intramolecular cyclizations to give cyclic silyl enol ethers regiospecifically. The radical processes involve radical cyclization, Brook rearrangement, and β-fragmentation in sequence. A tributylstannyl group serves as the radical leaving group. The newly formed α-bond and π-bond are located at the same two carbon atoms. This approach is limited to the formation of five-membered rings. In another route, α-bromo-α-styrylsulfonylacetylenes are synthesized. The radical cyclizations of these α-sulfonylacetylenes also give cyclic silyl enol ethers. The phenylsulfonyl moiety is the radical leaving group in this system. Furthermore, the newly formed α-bond and π-bond are located at adjacent positions sharing a single carbon atom. The latter approach is effective for both five- and six-membered ring formation.

Introduction

Intramolecular cyclizations of radicals with carbonyl groups are known to be reversible processes.1 To drive these reactions toward the cyclization side, there are two general strategies. One is to trap the cyclized alkoxy radical with dibutyltin hydride,2 general strategies. One is to trap the cyclized alkoxy radical by triethylborane.5 This may be attributed to the trapping of the cyclized alkoxy radical by triethylborane.5b The latter approach is effective for both five- and six-membered ring formation.


3 is generated after the radical-Brook rearrangement of \( \beta \)-silyl alkoxy radical 2. By introducing additional structural features, one may utilize the newly generated carbon radical in useful ways. One possibility involves a preexisting radical leaving group X at the \( \beta \)-position of the carbon radical as in radical 4. A \( \beta \)-scission will occur to generate a silyl enol ether in a regiospecific fashion. In principle, there are two possible approaches to obtain radical 4. Route a starts from the generation of radical 6 with the radical leaving group attached at the carbon carrying the initial radical. In this direction, we found that the tributylstannyl group served well as the desired radical leaving group.16 An alternative approach (route b) is to put the radical leaving group at the \( \alpha \)-position of the carbonyl group. We found that this route can be realized by the use of phenylsulfonyl group.17 In this paper, we describe our full investigation of the use of phenylsulfonyl group for the preparation of \( \beta \)-silyl alkoxy radicals and the resulting silyl enol ethers.

Silyl enol ethers are important synthetic intermediates. There are two widely used methodologies for their synthesis.18 One is to generate silyl enol ethers from ketones and aldehydes. Another is to prepare them from enones. The latter approach may be the better choice when regiochemically pure silyl enol ethers are required. Both methodologies are performed under basic conditions. Alternatively, silyl enol ethers can be prepared from acylsilanes.18,19 In this regard, a useful method involves the coupling of an acylsilane with a carbanion bearing a leaving group (eq 1) was developed by Reich et al.19 The initial adduct undergoes a Brook rearrangement, and the resulting silyloxy substituted carbanion fragments to give the silyl enol ether regiospecifically. The leaving group can also be placed at the \( \alpha \)-position of the acylsilane as shown in eq 2.19 Conceptually, the two routes described in Scheme 1 belong to a neutral radical version of Reich's polar acylsilane chemistry.

**Results and Discussion**

**Intramolecular Cyclizations of \( \alpha \)-Stannyl Bromide with Acylsilanes.** To explore the route a approach (Scheme 1), we selected a tributylstannyl group as the radical leaving group. There are two reasons for this selection. First, the tributylstannyl group when situated at the \( \beta \)-position of a radical as exemplified in the well-known radical chemistry of allyltributylstannane readily undergoes \( \beta \)-scission.20 In addition, the tributyltin radical generated through \( \beta \)-scission can be recycled in the radical chain reactions. Second, \( \alpha \)-stannyl bromides are a known class of compounds that can be synthesized through established methods.21

As shown in Scheme 2, alkylation of 2-silyldithianes \( \text{(2)} \)2 with the unprotected 4-chlorobutanol in the presence of excess LDA gave alcohols \( \text{(9)} \) in excellent yields. Alcohols \( \text{(9)} \) were oxidized with PCC in dichloromethane to give aldehydes \( \text{(10)} \) in mild yields. Aldehydes \( \text{(10)} \) were coupled with tributyltin lithium, and the resulting \( \alpha \)-stannyl alcohols were converted to bromides \( \text{(11)} \) with carbon tetrabromide and triphenylphosphine.22 As a result of the presence of nucleophilic sulfur atoms in bromides \( \text{(11)} \), these compounds are not stable. Therefore, it is better to hydrolyze these bromides immediately with cemic

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*(Footnotes are not included in the natural text representation)*
Regiospecific Formation of Cyclic Silyl Enol Ethers


β-silyl alkoxy radicals 21. Radicals 21 were converted to α-silyloxy radicals 22 through a radical-Brook rearrangement. As a result of the presence of a β-stannyl group, radicals 22 underwent facile β-scission to give silyl enol ethers 18 with concomitant formation of tributylin radical. Since tributylin radical was regenerated in the reaction, a catalytic amount of tributylin hydride (0.15 equiv) was sufficient. The cyclization of acyl-tert-butyldimethylsilyl 12c gave low yield (36%) of hydrazone 19 indicating a sluggish cyclization of 12c. This may be due to the presence of a bulky tert-butyldimethylsilyl (TBDMS) group on the carbonyl carbon of the α-stannyl radical 20c. The steric interaction between the TBDMS and tributylstannyl groups presumably decreased the rate of cyclization significantly. The cyclization of the homologous acylsilane 17 did not occur when a catalytic amount of tributylin hydride (0.15 equiv) was used. When 1.2 equiv of tributylin hydride was used, we only isolated 83% of straight reduction product 23 (Scheme 3). Previously, we found that 1,6-radical cyclizations of acylsilanes are sensitive toward steric effect.10 Presumably, with a bulky α-stibutylstannyl radical the cyclization of acylsilane 17 becomes very slow.

To demonstrate the regiospecific nature of this silyl enol ether preparation method, we studied the radical cyclization of acylsilane 29 (Scheme 4). We started from the alkylation of dithiane 8b with bromide 24. The resulting acetal 25 (82% yield) was hydrolyzed in aqueous acetic acid to give aldehyde 26 in 74% yield. Originally we tried to prepare bromide 28 according to the methodology described in Scheme 2. However, because of the instability of bromide 28, we obtained this bromide in very low yield. We then decided to prepare the xanthate 27 because the xanthate moiety may tolerate the presence of the two sulfur atoms in the same molecule.27 Indeed, when aldehyde 26 was treated with tributylin lithium followed by trapping the alkoxy intermediate with carbon disulfide and methyl iodide in sequence, we

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were able to synthesize xanthate 27 in quantitative yield. Hydrolysis of the dithiane moiety in xanthate 27 was carried out with iodobenzenedia(striﬂuoroacetate)28 in wet acetonitrile to afford acylsilane 29 (70%). This new route turned out to be a much better way to provide suitable substrates to generate α-stannyl radicals. Treatment of acylsilane 29 with a catalytic amount of tributyltin hydride and AIBN in reﬂuxing benzene led to the formation of silyl enol ether 30. Simply concentrating the reaction mixture and redesolving the residue in dichloromethane, followed by the addition of phenylselenenyl bromide at ∼78 °C, gave the selenide 31 in 77% yield as a mixture of cis/trans isomers.29 In this way, we demonstrated that silyl enol ether 30 was formed in a regiospeciﬁc way. In principle, silyl enol ethers such as 30 can be prepared from 3-substituted cyclopentanones through deprotonation. However, it is diﬃcult to control the regiochemistry of the enolate. Although the use of a bulky base may give the regioisomer such as 30,29 the other isomer cannot be eliminated completely. Our method provides a useful approach in addition to other methods.10,12

Radical Cyclizations of α-Sulfonylacylsilanes.

Although the α-stannyl radical cyclization of acylsilanes is successful for ﬁve-membered ring formation, this strategy cannot be applied to six-membered ring formation. The route b approach shown in Scheme 1 may provide an alternative way to accomplish the same goal. In the route b approach, the radical leaving group X is designed at the α-position of the carbonyl. The initial radical 7 does not carry a large substituent at the carbon bearing the radical. Therefore, it will not introduce bad steric interaction between the initial radical and the acylsilane moiety during cyclization as in the case of α-stannyl radical cyclizations.

The selection of the radical leaving group X is crucial for the success of this strategy. We found that the selenide 3334,35 (Scheme 5), prepared from acylsilane 32, reacted with 2 equiv of tributyltin hydride and gave only straight reduction product 34 in 62% yield. We believe that this result indicates that tributyltin hydride has selectively removed the iodo group to generate the terminal radical 35. If the phenylselenenyl group were removed ﬁrst, this would give iodide 38. We knew that the iodide 38 will further react with tributyltin hydride to give cyclized product 39.25 Since we did not observe the formation of silyl ether 39, it indicates that the iodo group has been removed ﬁrst. Although the terminal radical 35 was formed, a 1.5-hydrogen atom transfer presumably occurred to give α-carbonyl radical 36. Acylmethylidiphenylsilane without an α-phenylselenenyl group undergoes 1,6-radical cyclization quite eﬃciently with little problem associated with the 1,5-hydrogen transfer process.33 The presence of the phenylselenenyl group probably enhanced the α-radical formation by weakening the α-C–H bond.34 Hydrogen abstraction of radical 36 from the hydride gave α-phenylselenenylacylsilane 37 which was further reduced to give acylsilane 34.

With the above understanding in mind, we picked a phenylsulfonyl group as the radical leaving group. There are several reasons for this choice. First, the phenylsulfonyl group has been shown to be a good leaving group for 1,6-reduction. Second, the phenylsulfonyl group is quite ubiquitous in organic chemistry and is easy to introduce and remove. Third, the phenylsulfonyl group is more electron-withdrawing than the silyl group, which may facilitate the radical cyclization. For example, Scheme 5 shows that the use of a phenylsulfonyl radical leads to the formation of a phenylsulfonylacylsilane 38, which is further reduced to give acylsilane 34. Finally, the phenylsulfonyl group is easily removed with tributyltin hydride, which is an useful radical source for the synthesis of acylsilanes.

[a] Reagents and conditions: (i) 8b, BuLi, THF, 0 °C; (ii) AcOH, H2O; (iii) Bu3SnH, LDA, THF, –78 °C; Cs2CO3, –78 °C; Me3SiCl, –78 °C; (iv) (CF3COO)2IPh, CH3CN, H2O; (v) Bu3SnH (0.15 equiv), AIBN (0.05 equiv), PhH, 80 °C; (vi) PhSeBr, CH2Cl2, –78 °C.
Reactions appear to have a short radical chain length, with 1H NMR, we were not able to observe the presence in 85% yield. Radical cyclization of sulfone 

The electron-withdrawing sulfonyl group will be destabilized. We hope that this feature will inhibit the undesired 1,5-hydrogen atom transfer process mentioned above. Moreover, we hope that the presence of an electron-withdrawing group at the α-position will enhance the positive character of the carbonyl carbon. Alkyl-substituted radicals are generally considered as nucleophilic radicals. Therefore, the cyclization rate may enhance the positive character of the carbonyl carbon.

We found that the α-phenylthioacilsilane 40 (Scheme 6) could be prepared in 88% yield from the reaction of bromaocilsilane 32 with N-phenylthiucoscinimide in acetonitrile catalyzed by p-toluenesulfonic acid (0.05 equiv). Oxidation of sulfide 40 was performed using m-chloroperbenzoic acid (MCPBA) to afford sulfone 41 in 85% yield. Radical cyclization of sulfone 41 employing tributyltin hydride was expected to give silyl enol ether 42. However, by examining the crude cyclization mixture with 1H NMR, we were not able to observe the presence of 42. Gas chromatographic analysis of the crude cyclization mixture showed the presence of cyclohexanone. Addition of a methanol solution of 2,4-dinitrophenyldrazine (2,4-DNP) and sulfuric acid to the reaction mixture resulted in the isolation of the 2,4-dinitrophenyldrazone 43 in 81% yield. These results indicate that silyl enol ether 42 was initially formed. However, as a result of the presence of phenylsulfonic acid (44) as the byproduct, silyl enol ether 42 likely reacted further with sulfonic acid 44 to produce cyclohexanone as the final product.

To stop the cyclization reaction at the silyl enol ether stage, one needs to remove the nuisance acid 44 in situ. When we used 6 equiv of freshly ground sodium bicarbonate powder in the cyclization condition, silyl enol ether 42 was isolated in 41% yield through silica gel column chromatography. Further increment of sodium bicarbonate powder to 10 equiv resulted in 88% isolation yield of silyl enol ether 42. Because we did not isolate any reduction product or cyclization product such as 39 (Scheme 5), we believe that the bromide in sulfone 41 was removed selectively by tributyltin radical in the presence of the β-ketosulfonyl group.

There is another way that one can eliminate the formation of sulfinic acid 44. As shown in Scheme 7, acylsilane 32 was treated with allyltin tributyltin (1.2 equiv) in the presence of catalytic amount of tributyltin hydride (0.1 equiv) and AIBN (0.1 equiv) to yield silyl enol ether 42 (79%) and allyl phenyl sulfone 38 (81%). This process involves the formation of radical 45 first. Cyclization of 45 followed by radical-Brook rearrangement of the resulting alkoxy radical gave α-silyloxy radical 46. β-Elimination of phenylsulfinyl radical produced silyl enol ether 42. The phenylsulfinyl radical was trapped by allyltin tributyltin and converted to allyl phenyl sulfone. Tributyltin radical was formed at the same time and reacted further with acylsilane 32 to continue a new cycle. Without the formation of phenylsulfinic acid (44), silyl enol ether 42 was obtained successfully.

This methodology can be employed in five-membered ring formation. As shown in Scheme 8, α-sulfonylacilsilanes 49 and 53 were prepared in high yields from acylsilanes 47 and 51 respectively, according to the methods described above. Radical cyclization of acylsilane 49 with tributyltin hydride (1.2 equiv) in the presence of large excess of sodium bicarbonate powder (15 equiv) resulted in the formation of silyl enol ether 50. This silyl enol ether appeared to be quite sensitive toward silica.

References:

A tetrabromide and triphenylphosphine followed by hyborohydride in ethanol gave alcohol.

On the other hand, reduction of aldehyde was performed using methods described above.

Reduction of acylsilane through -Sulfonylacylsilane and oxidation was prepared from 2-methylcyclopentanone.

Demonstration of Regiospecific Synthesis of Isomeric Silyl Enol Ethers through a Common Starting Material. With the development of two methods of silyl enol ether synthesis from radical cyclizations of acylsilanes, one can begin with a single starting material and control the regiochemistry of silyl enol ether formation by proper choice of the method. As shown in Scheme 9, alkylation of dithiane gave acetal in 83% yield. Hydrolysis of the acetal afforded aldehyde (72%). Conversion of aldehyde to xanthate was formed from radical cyclization is a single isomer corresponding to the kinetic isomer obtained from 2-methylcyclopentanone.

In comparison, -sulfonfylacylsilane was treated with 1.2 equiv of tributyltin hydride along with catalytic amount of AIBN (0.1 equiv) and excess sodium bicarbonate, fine powder (15 equiv) in refluxing benzene. The crude reaction mixture was analyzed by gas chromatography using tetradecane as internal standard, and the yield of silyl enol ether was determined as 85%. NMR analysis showed that a single isomer was formed. An authentic sample of a mixture of silyl enol ethers and silyl enol ether and yielded 3-methylcyclopentanone. Silyl enol ether actually formed in 99% yield. Gas chromatographic analysis also showed that silyl enol ether and yielded 3-methylcyclopentanone. Silyl enol ether 30 was formed from 2-methylcyclopentanone.

Reagents and conditions: (i) BuLi, THF, 0 °C; (ii) AcOH, H2O; (iii) Bu3SnH, LDA, THF, −78 °C; CF3SO2, −78 °C; Mel, −78 °C; (iv) (CF3COO)2IPh, CH3CN, H2O; (v) NaHCO3, EtOH/CH2Cl2, 0 °C; (vi) Br2, PPh3, CH2Cl2, 0 °C; (vii) red HgO, BF3 ï€ descriptor (0.1 equiv), AIBN (0.05 equiv), PhH, 80 °C; (viii) N-phenylthiosuccinimide, TsOH, CH3CN, rt; (ix) MCPBA (2.2 equiv), NaHCO3, CH2Cl2, 0 °C; (x) Bu3SnH (0.15 equiv), AIBN, NaHCO3 powder (15 equiv), PhH, 80 °C; (xi) Bu3SnH (1.2 equiv), AIBN (0.1 equiv), NaHCO3 powder (15 equiv), PhH, 80 °C.

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of sodium bicarbonate was used, phenylsulfonic acid (44) can be removed more efficiently. Therefore, isomerization of silyl enol ether 30 was not observed.

Conclusions

In this study, we have successfully developed two routes in the synthesis of regiospecific cyclic silyl enol ethers employing intramolecular radical cyclizations of acylsilanes. Both approaches involve β-fragmentation of the cyclized α-silyloxy radical intermediates. The cyclizations of acylsilanes carrying terminal α-tributylstannyl bromide or xanthate functionalities adopt the tributylstannyl group as the radical leaving group. The latter approach works well for both five- and six-membered ring formation. Although the latter approach works for five-membered ring formation, the two radical approaches are complementary regarding the regiochemistry of cyclic silyl enol ether formation. Within the same route, tuning the position of the substituents on the acylsilane backbone will also lead to the formation of the desired regiosomer.

This study extended the synthetic utility of acylsilanes. Although there are many methods for the preparation of silyl enol ethers, most of them employ strongly basic conditions. Our radical approach works under neutral conditions and may offer some advantages when base-sensitive functionalities are present. However, the efficiency of our method depends on how easily the acylsilanes can be synthesized, and it is successful only for five- and six-membered cyclic silyl enol ethers.

Experimental Section

Melting points are uncorrected. 1H NMR spectra were recorded at 200 or 300 MHz. 13C NMR spectra were recorded at 50 or 75 MHz. Tetramethylysilane (δ = 0 ppm) or CHCl3 (δ = 7.24 ppm) were used as internal standards, and CDCl3 was used as the solvent. Benzene and THF were distilled from sodium/benzophenone ketyl under N2. Diisopropylamine and acetonitrile were dried with CaH2 and distilled. The benzene used for cyclization reactions was deoxygenated by passing a gentle stream of argon through it for 0.5 h before use. All reactions were performed under a blanket of N2 or Ar. Lobar LiChroprep Si 60 (40–63 μm) prepacked columns purchased from Merck were used for medium-pressure liquid chromatography (MPLC). Gas chromatography was performed on a Shimadzu GC-8A apparatus with TCD using a 3.3 mm x 2 m column of 10% SE-30 on Chromosorb W (AW-DMCS), 80–100 mesh, and hydrogen as carrier gas. Aldehydes 10 were prepared from the corresponding 2-silyl-1,3-dithianes 8 according to the general procedure described before.

General Procedure for the Preparation of Acylsilanes

12. 2-Methyl-2-silyloxy-3-(phenylsulfonyl)pentane (11c).

To a solution of 0.34 mL (2.4 mmol) of diisopropylamine in 2 mL of dry THF cooled at 0 °C under argon was added over 10 min a solution of 1.5 N butyllithium in hexane (1.6 mL, 2.4 mmol). The resulting solution was stirred at the same temperature for another 10 min. The resulting solution was added dropwise over 10 min a solution of 2.5 mL of CHCl3 (contains 1.03 mmol of bromide or xanthate functionalities) to the resulting mixture. The resulting reaction mixture was added dropwise over 10 min a solution of 839 mg (3.2 mmol) of triphenylphosphine in 2.5 mL of dichloromethane. The reaction mixture was stirred at the same temperature for another 10 min, diluted with ether, and filtered. The filtrate was partitioned between ether and water. The organic layer was washed with brine, dried (MgSO4), and concentrated in vacuo. The resulting residue and 1.06 g (3.2 mmol) of carbon tetrabromide were dissolved in 5 mL of dichloromethane and then cooled in an ice/water bath. To this solution was added dropwise over 20 min a solution of 839 mg (3.2 mmol) of triphenylphosphine in 2.5 mL of dichloromethane. The resulting mixture was stirred at room temperature for 1 h and then cooled in an ice/water bath. To this solution was added dropwise over 20 min a solution of 377 mg (55%) of tributyltin hydride in hexane/ethyl acetate, 98/2 as a pale yellow liquid. 1H NMR (CDCl3, 300 MHz) δ 0.78 (s, 3 H), 0.83–0.95 (two overlapped t, J = 7.0 Hz, at 0.89 and 0.93, 15 H), 1.29 (sextet, J = 7 Hz, 6 H), 1.41 to 2.28 ppm (two overlapped t, J = 7.0 Hz, 15 H), 2.42 (dt, J = 13.5, 4 Hz, 2 H), 2.98 (ddt, J = 13.5, 11, 4 Hz, 2 H), 3.48 (dd, J = 9.5, 5.5 Hz, 1 H), 7.28–7.42 (m, 6 H), 7.42–7.61 (m, 6 H), 7.61–7.84 (m, 4 H); 13C NMR (CDCl3, 75 MHz) δ −3.9, 9.9 (J C-Sn = 315 Hz), 13.6, 24.0, 27.3 (J C-Sn = 60 Hz), 27.6, 28.9 (J C-Sn = 20 Hz), 37.2, 38.0, 39.0, 127.5, 129.6, 134.2, 135.9.

Bromide 11b was not stable at room temperature and should be hydrolyzed as soon as possible. To a mixture of 771 mg (1.04 mmol) of 11b, 71 mg (0.85 mmol) of sodium bicarbonate, and 48 mg of Celite in dichloromethane/acetonitrile (3 mL/2 mL) cooled at −15 °C (dry ice/dry ice tetrachloride bath) was added dropwise over 10 min a solution of 1.72 g (31 mmol) CAN in aqueous acetonitrile (acetonitrile/water = 15 mL/1 mL). The resulting mixture was stirred at the same temperature for another 10 min, diluted with ether, and filtered. The filtrate was partitioned between ether and water. The organic layer was washed with brine, dried (MgSO4), and concentrated in vacuo. The residue was chromatographed on silica gel eluted with hexane/ethyl acetate, 95/5 to give 377 mg (55%) of 11b as a pale yellow oil: IR (neat) 1634 cm−1; 1H NMR (CDCl3, 300 MHz) δ 0.74 (s, 3 H), 0.78–1.10 (m, 15 H), 1.28 (sextet, J = 7 Hz, 6 H), 1.37–1.67 (m, 6 H), 1.67–1.95 (m, 4 H), 2.65 (br t, J = 7 Hz, 2 H), 3.49 (dd, J = 8.5, 6 Hz, 1 H), 7.27–7.48 (m, 6 H), 7.50–7.62 (m, 4 H), 7.60–7.70 (m, 4 H); 13C NMR (CDCl3, 75 MHz) δ −5.3, 9.9 (J C-Sn = 315 Hz), 13.6, 22.6, 27.3 (J C-Sn = 60 Hz), 28.9 (J C-Sn = 20 Hz), 37.0, 39.1, 48.5, 128.1, 130.1, 132.7, 135.0, 243.8.


General Procedure for Intramolecular Radical Cyclizations of α-Stannyl Bromides

Cyclization of 12b. To a refluxing solution of 325 mg (0.50 mmol) of 12b in 2.5 mL of benzene was added via syringe pump over 1 h a solution of 19 μL (0.060 mmol) of tributyltin hydride and 4.0 mg (0.024 mmol) of AlIBN in 2.5 mL of benzene. The resulting solution was heated for 1 h and then cooled to room temperature. To the resulting reaction mixture was added a solution of 197 mg (1.0 mmol) of 4-dinitrophenylhydrazine in 5 mL of methanol followed by 0.25 mL of 98% sulfuric acid. The resulting mixture was stirred overnight, poured into a saturated sodium bicarbonate solution, and then extracted with ether. The combined organic phases were washed with brine, dried (MgSO4), and concentrated in vacuo.

gel (eluted with hexane/ethyl acetate, 9/1) to give 110 mg (84%) of cyclopentanone 2,4-dinitrophenylhydrazone (19) as an orange solid: mp 148–150 °C (lit. 146–148 °C).

2-(4-Bromo-3-methylpropyl)-1,3-dioxolane (24). Ozonide gas was bubbled into a solution of 3.87 g (23.7 mmol) of 5-bromo-4-methyl-1-pentene44 in 20 mL of methanol cooled at −78 °C until the solution turned into pale blue. To the reaction mixture was added 20 mL of dimethyl sulfide, and the resulting solution was stirred at room temperature for 3 days. The resulting reaction mixture was partitioned between ether and water. The organic layer was washed with brine, dried (MgSO₄), and concentrated in vacuo. To the resulting residue was added 1.44 mL of ethylene glycol, 380 mg (2.0 mmol) of p-toluenesulfonic acid, and 30 mL of benzene. The resulting mixture was heated under reflux for 24 h, and water was removed via a Dean–Stark apparatus. The reaction mixture was partitioned between ether and water. The organic layer was washed with brine, dried (MgSO₄), and concentrated in vacuo. The residue was distilled to give 3.87 g (78%) of 24 as a colorless liquid: bp 72–73 °C/1.5 mmHg; 1H NMR (CDCl₃, 200 MHz) δ 1.08 (d, J = 6.6 Hz, 3 H), 1.51–1.70 (m, 1 H), 1.71–1.80 (m, 1 H), 1.95–2.16 (m, 1 H), 3.32–3.58 (m, 2 H), 3.72–4.01 (m, 4 H), 4.89 (s, t; J = 5 Hz, 1 H). Anal. Calcd for C₄H₉BrO₂: C, 40.21; H, 6.27. Found: C, 39.89; H, 6.10.

1,2-(2-Methyl-3-(2,5-dioxacyclopentyl)propyl)-2-(methyl-dithiocarbonate (27). To a solution of 0.16 mL (1.1 mmol) diisocyanate (27) was added 94 mL (1.5 mmol) of methyl iodide, and the reaction mixture was warmed to room temperature. The resulting mixture was stirred at room temperature for 1 h and partitioned between ether and water. The organic layer was washed with brine, dried (MgSO₄), and concentrated in vacuo. The residue was chromatographed over silica gel (eluted with hexane/ethyl acetate, 9/1) to give 716 mg (100%) of 27 as a yellow oil. This material is a 1:1 mixture of two diastereomers: 1H NMR (CDCl₃, 400 MHz) δ 0.65–1.00 (m, 21 H), 1.10–2.50 (m, 21 H), 2.49 (s, 1.5 H, S-Me of one isomer), 2.54 (s, 1.5 H, S-Me of another isomer), 2.75–3.04 (m, 2 H), 5.69–5.89 (m, 1 H), 7.26–7.44 (m, 4 H), 7.73–7.90 (m, 4 H). Anal. Calcd for C₃₆H₅₈O₄S₄SiSn: C, 55.30; H, 7.48. Found: C, 54.89; H, 7.49.

General Procedure for the Hydrolysis of Dithiane Xanthates. O-(1-Tritylbistannyl-3-methyl-5-methylidiphenylsilyl)-5-oxo pentyl Dithioacetate (30). To a mixture of 781 mg (1.0 mmol) of 27 and 126 mg (1.5 mmol) of sodium bicarbonate in 4.5 mL of THF, 4.5 mL of acetonitrile, and 1 mL of water was added over 5 min a solution of 602 mg (1.4 mmol) of iodobenzenebis(trifluoroacetate) in 2 mL of acetonitrile. The resulting mixture was stirred at room temperature for 15 min and then partitioned between ether and water. The organic layer was washed with brine, dried (MgSO₄), and concentrated in vacuo. The residue was chromatographed over silica gel (eluted with hexane/ethyl acetate, 9/1) to give 483 mg (70%) of 29 as a yellow oil. This material is a 1:1 mixture of two isomers: IR (CH₂Cl₂) 1633 cm⁻¹; 1H NMR (CDCl₃, 200 MHz) δ 0.70–1.10 (m, 21 H, 1.23–1.70 (m, 13 H), 2.02–2.28 (m, 2 H), 2.34–2.83 (m overlapped with two s at 2.53 and 2.55, 5 H), 5.82–5.89 (m, 0.5 H, OCH of one isomer), 5.89–5.95 (m, 0.5 H, OCH of another isomer), 7.27–7.48 (m, 6 H), 7.50–7.68 (m, 4 H). Anal. Calcd for C₃₆H₅₈O₄SeSn: C, 57.31; H, 7.58. Found: C, 57.39; H, 7.58.

Radical Cyclization of 29 and Direct Conversion to Selenide. 4-Methyl-2-(phenylelenyl)cyclopentanone (31). According to the general cyclization procedure of α-stannyl bromides, 483 mg (0.70 mmol) of 29 was cyclized with tributyltin hydride (29 mL, 0.11 mmol) and AlBN (6 mg, 0.037 mmol) in benzene. At the end of the cyclization, the solvent was removed in vacuo, and the residue was taken up into 2 mL of dichloromethane. The solution was cooled in a dry ice/acetone bath followed by the addition of a solution of 164 mg (0.70 mmol) of phenylenesilene bromide in 2 mL of dichloromethane. The resulting mixture was stirred at room temperature for 10 min. The resulting solution was stirred at the same temperature for 1 h and then partitioned between ether and water. The organic layer was washed with brine, dried (MgSO₄), and concentrated in vacuo. To the residue was added 3 mL of acetone, and the resulting mixture was chromatographed over silica gel (eluted with hexane/ethyl acetate, 9/1) to give 483 mg (70%) of 29 as a pale yellow oil. This material is a 9:1 mixture of two isomers: IR (CH₂Cl₂) 1725 cm⁻¹; 1H NMR (CDCl₃, 200 MHz) δ 1.08 (d, J = 6.5 Hz, 3 H), 1.23–1.70 (m, 13 H), 2.02–2.28 (m, 2 H), 2.34–2.83 (m overlapped with two s at 2.53 and 2.55, 5 H), 5.82–5.89 (m, 0.5 H, OCH of one isomer), 5.89–5.95 (m, 0.5 H, OCH of another isomer), 7.27–7.48 (m, 6 H), 7.50–7.68 (m, 4 H). Anal. Calcd for C₃₆H₅₈O₄SeSn: C, 57.31; H, 7.58. Found: C, 57.39; H, 7.58.
resulting mixture was partitioned between ether and water. The organic layer was washed with brine, dried (MgSO₄), and concentrated in vacuo. The residual oil was chromatographed with MPLC over a Florisil column (eluted with ethyl acetate, 95/5) to give 0.95 g (63%) of \( \text{cyclopentene (54)} \). The yield of 54 determined this way was 92% \( t_e = 16.06 \text{ min} \), column temperature = 210 °C, flow rate = 19 mL/min.

**Radical Cyclization of 53. 5-Methyl-1-(methylidiphenylsiloxy)cyclopentene (54).** Similar to the cyclization of 49, the cyclization of 53 was analyzed with gas chromatography using tetradecane as internal standard. The yield of 54 was determined as 92% \( t_e = 12.40 \text{ min} \) (column temperature = 220 °C, flow rate = 18 mL/min). Characteristic 1 H NMR signals of 54: (CDCl₃, 200 MHz) \( \delta = 0.70 \text{ (s, 3 H), 1.06 (d, } J = 7 \text{ Hz, 3 H), 2.50–2.62 (m, 1 H), 4.43 (br s, 1 H), 7.30–7.50 \text{ (m, 6 H), 7.56–7.70 \text{ (m, 4 H)}} \).

2-Methyl-5-[1-(methylidiphenylsilyl)-2,6-dithia[1.2.1]cyclohexyl]butanol (59). A mixture of 1.43 g (3.57 mmol) of 57 and 162 mg (4.28 mmol) of sodium borohydride in 6 mL of ethanol and 1 mL of dichloromethane was stirred in an ice-water bath for 2 h and then partitioned between ether and water. The organic layer was washed with brine, dried (MgSO₄), and concentrated in vacuo. The residue was chromatographed over silica gel (eluted with hexane/ethyl acetate, 82/2) to give 1.26 g (88%) of 59 as a pale yellow oil: \( \text{IR (neat) } 1641 \text{ cm}^{-1}; \text{ H NMR (CDCl₃, 300 MHz) } \delta = 0.72 \text{ (d, } J = 6.6 \text{ Hz, 3 H), 0.76 \text{ (s, 3 H), 1.10–1.28 \text{ (m, 1 H), 1.30–1.52 \text{ (m, 2 H), 2.34 \text{ (d, } J = 14 \text{ Hz, 2 H), 2.98 \text{ (br t, } J = 14 \text{ Hz, 2 H), 3.23–3.30 \text{ (m, 2 H), 7.25–7.48 \text{ (m, 6 H), 7.79 \text{ (d, } J = 6 \text{ Hz, 4 H)}; 13^C \text{ NMR (CDCl₃, 75 MHz) } \delta = 38.16, 16.23, 24.7, 30.3, 30.5, 36.0, 39.1, 67.7, 127.5, 129.7, 134.2, 135.8; HRMS calcd for } C_{25}H_{30}OS_{2}Si \text{ m/z 402.1507, found 402.1507.} \)

**General Procedure for the Oxidation of a-Phenylsulfanylcyclohexanes. 6-Bromo-1-(methylidiphenylsilyl)-2-phenylsulfonyl-1-hexanone (41).** To a reaction mixture of 118 mg \( \text{cyclopentene (50). According to the procedure for the cyclization of 41, 200 mg (0.399 mmol) of 49 reacted with 0.13 mL (0.48 mmol) of tributyltin hydride, 6.4 mg (0.039 mmol) of AIBN, and 0.053 g (5.98 mmol) of sodium borohydride. Purification of the product through silica gel column chromatography (eluted with hexane) gave 59 mg (52%) of 50 as a colorless liquid: \( \text{IR (neat) } 1670 \text{ cm}^{-1}; \text{ H NMR (CDCl₃, 300 MHz) } \delta = 0.76 \text{ (s, 3 H), 1.38–1.50 \text{ (m, 2 H), 1.55–1.65 \text{ (m, 2 H), 1.87–1.98 \text{ (m, 2 H), 1.98–2.05 \text{ (m, 2 H), 2.48–2.68 \text{ (m, 2 H), 7.30–7.42 \text{ (m, 2 H), 7.56–7.65 \text{ (m, 2 H)}}; 13^C \text{ NMR (CDCl₃, 75 MHz) } \delta = 36.8, 23.9, 42.9, 47.6, 56.6, 58.2, 125.7, 128.4, 128.9, 129.3, 130.4, 130.5, 131.6, 134.0, 134.4, 135.3, 135.4, 135.6, 137.0 \text{ (s, 13C NMR signal of 54, not shown); HRMS calcd for } C_{25}H_{30}OS_{2}Si \text{ m/z 402.1507, found 402.1507.} \)

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Supporting Information Available: Characterization data for compounds 9b, c, 10b, c, 11a, c, 12a, c, 14, 15, 17, 23, 48, 49, 52, 53, 56–58, 61, and 62 and copies of \(^1\)H and \(^{13}\)C NMR spectra of new compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

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