# [3 + 4] Annulation of α,β-Unsaturated Acylsilanes with Enolates of α,β-Unsaturated Methyl Ketones: Scope and Mechanism

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**Abstract:** Reactions of the *E* and *Z* isomers of (β-(trimethylsilyl)acryloyl)(*tert*-butyl)dimethylsilanes with lithium enolate of α,β-unsaturated methyl ketones at −80 to −30 °C afford cis-5,6- and trans-5,6-disubstituted 3-cyclohepetenones, respectively. The same [3 + 4] annulation is observed in the reaction of (β-(tri-*n*-butylstannyl)acryloyl)silanes. The annulation products are readily transformed into 4-cycloheptene-1,3-dione by treatment with NBS or mCPBA. The observed stereospecificity in the annulation is explained by the reaction pathway that involves an anionic oxy-Cope rearrangement of 1,2-divinylcyclopropanediol intermediate generated via Brook rearrangement of the 1,2-adduct of a lithium enolate. Isolation of vinylcyclopropanol derivative from the reaction of (β-(tri-*n*-butylstannyl)acryloyl)silanes with lithium enolate of 2′-bromoacetophenone and its transformation into cycloheptenone derivative with LDA provide strong support for the proposed mechanism. Further support is obtained from the reactions of 1,2-divinylcyclopropyl acetates with 2 equiv of MeLi affording cycloheptenones stereospecifically. Also, β-alkyl-substituted acryloylsilanes and cycloalkenylcarbonylsilanes are found to participate in the [3 + 4] annulation.

## Introduction

The development of methodologies that allow for efficient construction of seven-membered ring systems has become a subject of great interest and intense effort for the synthetic chemist, because the ring systems are present in a large number of natural products and theoretically interesting molecules.[1] Although considerable efforts have been invested in the synthesis of six-membered carbocycles, relatively fewer annulative methods exist for the stereoselective synthesis of seven-membered carbocycles.[2,3] One of the most efficient and general methods for the preparation of functionalized cycloheptanes would be [3 + 4] annulations,[2c] in which a three-carbon unit directly couples with a four-carbon unit, forming two carbon−carbon bonds in one operation. We recently reported a new approach to highly functionalized cyclopentenol **4** using a [3 + 2] annulation involving the combination of (β-(phenylthio)-acryloyl)silane **1** as the three-carbon unit and lithium enolate of alkyl methyl ketone as the two-carbon unit,[4] which relies on the formation of delocalized allylic anion **3** via the 1,2-anionic rearrangement of silicon (Brook rearrangement)[5] in the 1,2-adduct **2** followed by internal carbonyl attack by the anion (Scheme 1).

We envisaged that the use of the lithium enolate diene **6** would provide a new [3 + 4] annulation via the tandem Brook/Michael sequence (Scheme 2; **7** → **8** → **9**). In this paper we describe in full detail the [3 + 4] annulation communicated earlier in a preliminary form.[6]

## Results and Discussion

**Preparation of β-Heteroatom-Substituted Acryloylsilanes.** Acryloylsilanes **1**, **11**, and **12** were prepared via allenylsilane **10** employing Reich's procedure,[7] except for the last hydrolysis steps in which trifluoroacetic acid for β-trimethyl derivatives

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(3) (a) Lee, J.; Kim, H.; Cha, J. K. *J. Am. Chem. Soc.* **1995**, *117*, 9919−9920 and references therein. (b) Barluenga, J.; Aznar, F.; Martín, A.; Vázquez, J. T. *J. Am. Chem. Soc.* **1995**, *117*, 9419−9426 and references therein. (c) Trost, B. M.; Yamazaki, S. *Chem. Lett.* **1994**, 2245−2248 and references therein. (d) Hudlicky, T.; Fleming, A.; Radesca, L. *J. Am. Chem. Soc*. **1989**, *111*, 6691−6707 and references therein. (e) Wulff, W. D.; Yang, D. C.; Murray, C. K. *J. Am. Chem. Soc.* **1989**, *110*, 2653−2655. (f) Molander, G. A.; Eastwood, P. R. *J. Org. Chem.* **1996**, *61*, 1910−1911 and references therein. (g) Harmata, M.; Elomari, S.; Barnes, C. L. *J. Am. Chem. Soc.* **1996**, *118*, 2860−2871.

(4) Takeda, K.; Fujisawa, M.; Makino, T.; Yoshii, E.; Yamaguchi, K. *J. Am. Chem. Soc.* **1993**, *115*, 9351−9352.

(5) (a) Brook, A. G.; Bassindale, A. R. In *Rearrangements in Ground and Excited States*; de Mayo, P., Ed.; Academic Press: New York, 1980; pp 149−221. (b) Brook, A. G. *Acc. Chem. Res.* **1974**, *7*, 77−84.

(6) (a) Takeda, K.; Takeda, M.; Nakajima, A.; Yoshii, E. *J. Am. Chem. Soc.* **1995**, *117*, 6400−6401. (b) Takeda, K.; Nakajima, A.; Yoshii, E. *Synlett* **1996**, 753−754.

(7) (a) Reich, H. J.; Kelly, M. J.; Olson, R. E.; Holtan, R. C. *Tetrahedron* **1983**, *39*, 949−960. For reviews on acylsilanes, see: (a) Qi, H.; Curran, D. P. In *Comprehensive Organic Functional Group Transformations*; Katritzky, A. R., Meth-Cohn, O., Rees, C. W., Moody, C. J., Eds.; Pergamon: Oxford, 1995; pp 409−431. (b) Cirillo, P. F.; Panek, J. S. *Org. Prep. Proc. Int.* **1992**, *24*, 553−582. (c) Bulman Page, P. C.; Klair, S. S.; Rosenthal, S. *Chem. Soc. Rev.* **1990**, *19*, 147−195. (d) Ricci, A.; Degl'Innocenti, A. *Synthesis* **1989**, 647−660.

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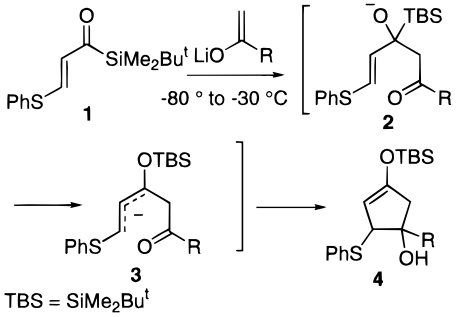
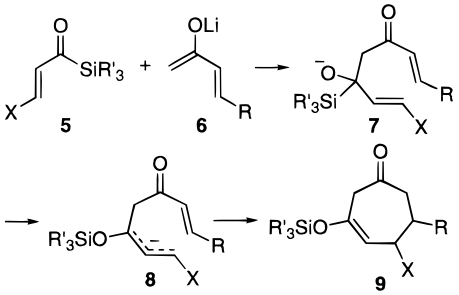
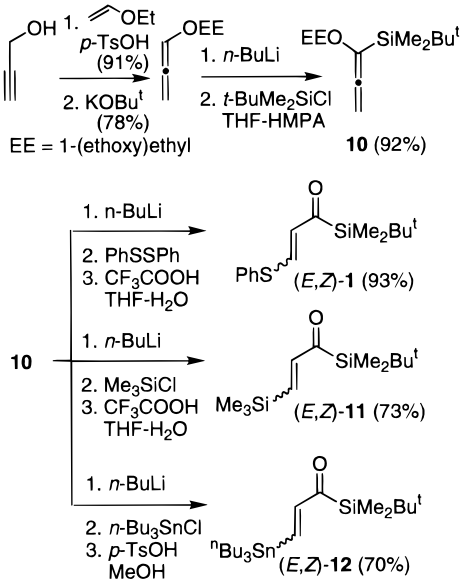
**Scheme 1**




**Scheme 2**




**Scheme 3**

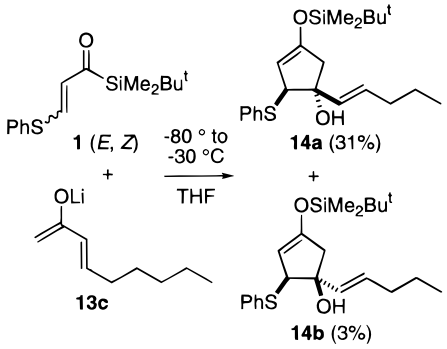



and *p*-TsOH in MeOH for $\beta$-tri-*n*-butylstannyl derivatives were used in place of sulfuric acid in aqueous THF (Scheme 3). Use of trifluoroacetic acid for the hydrolysis of the $\beta$-stannyl derivative resulted in the predominant formation of (*Z*)-**12** and extensive protodestannylation. All *E* and *Z* derivatives could be separated by silica gel column chromatography.

**[3 + 4] Annulation Using ($\beta$-(Trimethylsilyl)- and ($\beta$-(Tri-*n*-butylstannyl)acryloyl)silanes 11 and 12.** We first attempted the reaction of ($\beta$-(phenylthio)acryloyl)silane **1** with lithium enolate **13c** under the same conditions as employed for the [3 + 2] annulation,[4] but it did not afford the desired [3 + 4] annulation products, but rather the [3 + 2] annulation products **14a** and **14b** in 31% and 3% yields, respectively (Scheme 4).

In the [3 + 2] annulation,[4] the products and product distributions greatly depend on the $\beta$-substituent of the acryloylsilane. Consequently, we examined the annulation using $\beta$-trimethylsilyl derivatives **11**. When lithium enolate **13a** (generated with LDA) was added to (*E*)-($\beta$-trimethylsilyl)-acryloyl)silane (*E*)-**11** in THF at −80 °C and then the solution (0.02 M) was allowed to warm to −30 °C, *cis*-6-propyl-5-(trimethylsilyl)-3-cycloheptenone **15a** was obtained in 73% yield (Table 1, entry 1). This annulation was successfully applied to enolates of both alkenyl and cycloalkenyl methyl ketones (Table 1). It should be noted that only the 5,6-cis isomer was obtained in all cases except for **15d**. The relative stereochemistries for **15a**−**c** were assigned on the basis of $J_{5,6}$ (3.8−4.5 Hz) and NOESY experiments. The stereostructure of **15f** was determined by X-ray analysis, and the all-cis structure of **15e** was derived from a NOESY experiment.

**Scheme 4**




It is particularly noteworthy that aromatic double bonds can also participate in the annulation (Scheme 5). Thus, although the reaction with acetophenone enolate resulted in recovery of the starting materials, reaction with the lithium enolate of 2′-bromoacetophenone **16** provided benzocycloheptenone **17** in 30% yield. Interestingly, in the case of heteroaromatics, even on substrates lacking a leaving group, lithium enolates of 3-acetyl-*N*-methylpyrrole **18** and 3-acetylthiophene **19**, the reaction proceeded albeit in poor yields, affording seven-membered ring fused heterocycles **20** and **21** after the spontaneous aromatization.

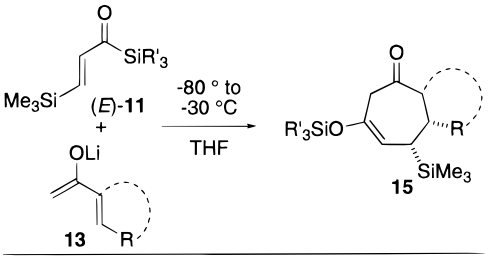
In sharp contrast to the cases of (*E*)-**11**, the reaction of (*Z*)-**11** proceeded considerably more slowly and produced 5,6-trans derivatives **22** as the only isomer in lower yields, together with substantial recovery of the starting materials (Scheme 6). Moreover, no reaction was observed with 2′-bromoacetophenone enolate **16**. The assignment of the 5,6-trans stereochemistry of **22** is based on the $J_{5,6}$ (6.4−7.9 Hz) and NOESY experiments. We will later discuss a possible mechanism that can explain the stereospecificity.

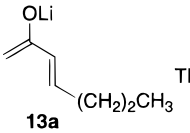
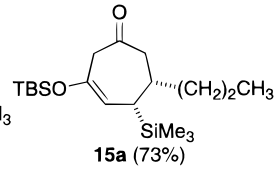
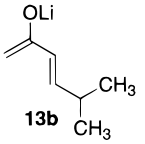
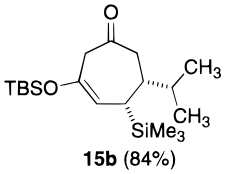
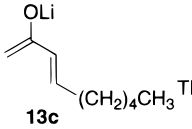
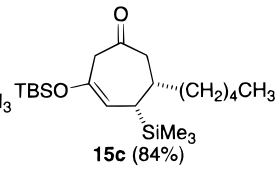
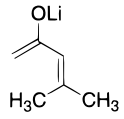
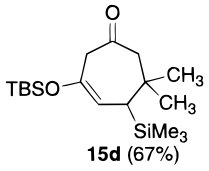
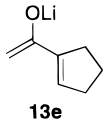
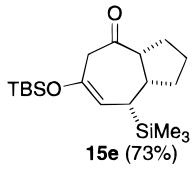
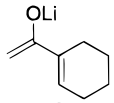
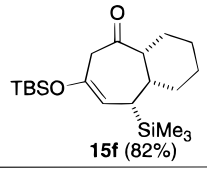
The same stereospecificity was observed in the reaction of $\beta$-tributylstannyl derivatives (*E*)- and (*Z*)-**12**. Thus, when (*E*)-**12** was subjected to the same reaction conditions as (*E*)-**11**, the cycloheptenones **23** with 5,6-cis stereochemistry were obtained in comparable yields (Scheme 7). On the other hand, reaction of (*Z*)-**12** was slow even in comparison with (*Z*)-**11** and required higher concentration and temperatures (0.1 M, −30 to 0 °C), affording 5,6-trans derivatives **24** in lower yields probably because of the increased steric bulk of the tributylstannyl group (Scheme 8).

**Synthetic Elaboration of the Annulation Products 15 and 23.** The annulation products **15** and **23** can be readily transformed into synthetically valuable systems. One useful transformation involves the conversion of the siloxycycloheptenones **15** to enediones **25**. Treatment of **15** in THF with NBS[8] followed by tetra-*n*-butylammonium fluoride (TBAF) afforded enediones **25** in good to excellent yields (Scheme 9).

(8) Reuss, R. H.; Hassner, A. *J. Org. Chem.* **1974**, *39*, 1785−1787.

**Table 1.** [3 + 4] Annulation of (*E*)-**11** With Ketone Enolates



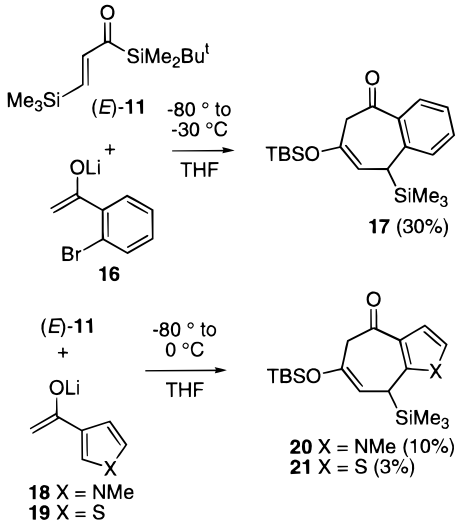

| entry | ketone enolate | product |
|---|---|---|
| 1 |  **13a** |  **15a** (73%) |
| 2 |  **13b** |  **15b** (84%) |
| 3 |  **13c** |  **15c** (84%) |
| 4 |  **13d** |  **15d** (67%) |
| 5 |  **13e** |  **15e** (73%) |
| 6 |  **13f** |  **15f** (82%) |

In the case of tri-*n*-butystannyl derivatives **23**, more facile transformation into the enedione **25** was realized by treatment of **23** with *m*-chloroperbenzoic acid (mCPBA)[9] in $CH_2Cl_2$ at 0 °C (Scheme 10). The formation of vinylstannane derivative **26** in the cases of **23d** and **23f** can be interpreted as the result of a less favorable *anti*-periplanar relationship between the stannyl group and the epoxy group owing to the nonbonding interactions involving the stannyl group.

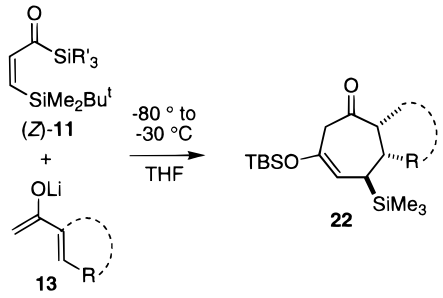
The attempted Fleming oxidative desilylation[10] of 5-dimethylphenylsilyl derivative **28**, derived from **27** which was prepared from (β-(dimethylphenylsilyl)acryloyl)silane, resulted in the formation of a mixture of 5-hydroxy derivative **29** and hemiketal **30** in low yield (Scheme 11).

(9) Still, W. C. *J. Am. Chem. Soc.* **1977**, *99*, 4186−4187.
(10) Fleming, I.; Henning, R.; Parker, D. C.; Plaut, H. E.; Sanderson, P. E. J. *J. Chem. Soc., Perkin Trans. 1* **1995**, 317−337.

**Scheme 5**

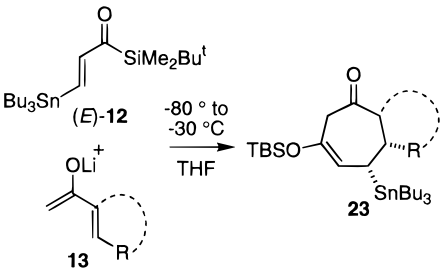



**Scheme 6**




| entry | ketone enolate | yield (%) | |
|---|---|---|---|
| | | **22** | recovered (*Z*)-**11** |
| 1 | **13a** | 31 | 56 |
| 2 | **13b** | 29 | 55 |
| 3 | **13c** | 11 | 59 |
| 4 | **13d** | 18 | 31 |
| 5 | **13e** | 24 | 51 |
| 6 | **13f** | 32 | 48 |
| 7 | **16** | 0 | 48 |

**Scheme 7**

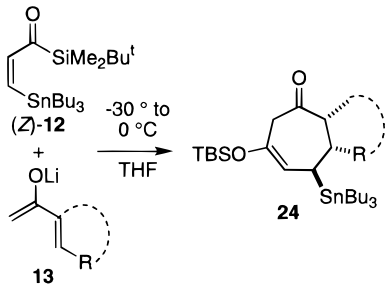



| ketone enolate | yield (%) |
|---|---|
| **13b** | 72 |
| **13c** | 72 |
| **13d** | 69 |
| **13e** | 42 |
| **13f** | 63 |
| **16** | 26 [a] |

*a* Only 5-protodestannylated compound was obtained.

**Reaction Mechanism of the [3 + 4] Annulation.** The observed stereospecificity and the participation of the aromatic double bond in the [3 + 4] annulation are incompatible with a pathway involving intramolecular Michael addition of delocalized allylic anion (**8** → **32**). A reasonable mechanism to explain

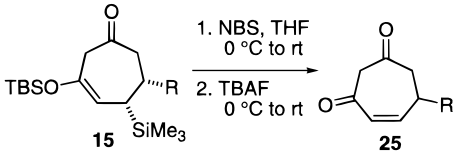
**Scheme 8**




| ketone enolate | yield (%) | |
|---|---|---|
| | **24** | recovered (*Z*)-**12** |
| **13b** | 14 | 60 |
| **13c** | 18 | 26 |
| **13e** | 15[a] | 52 |
| **13f`** | 11 | 62 |

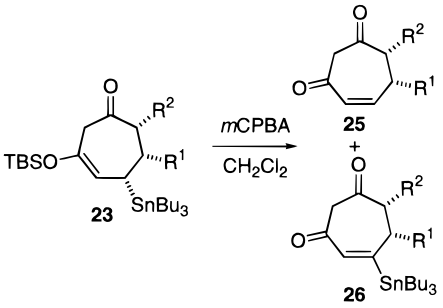
*a* Both 5,6,7-cis isomer and its C-7 epimer were obtained in a ratio of 1:2.

**Scheme 9**




**25b** R = $CHMe_2$ 89%
**25c** R = $(CH_2)_4Me$ 97%
**25d** R = Me, Me 75%

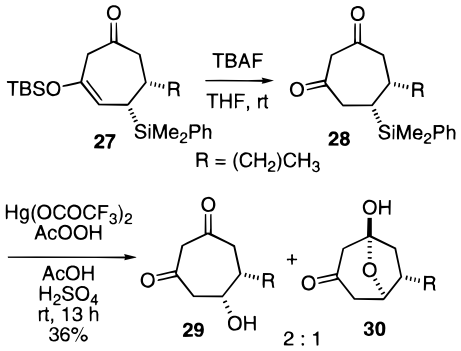
**Scheme 10**



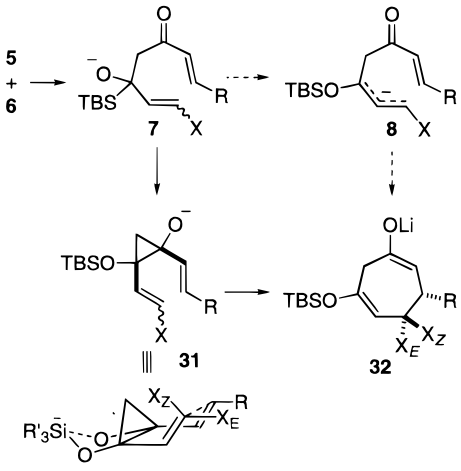

| | $R^1$ | $R^2$ | **25** | **26** |
|---|---|---|---|---|
| b | $CHMe_2$ | H | 84% | - |
| c | $(CH_2)_4Me$ | H | 89% | - |
| d | Me, Me | H | 76% | 11% |
| e | - $(CH_2)_3$ - | | 89% | - |
| f | - $(CH_2)_4$ - | | 57% | 10% |

these observations seems to be a pathway involving a concerted anionic oxy-Cope rearrangement of the *cis*-1,2-divinylcyclopropanediolate intermediate **31** (**31** → **32**)[11] which was stereoselectively derived from the 1,2-adduct **7** by the Brook rearrangement, followed by internal trapping of the generated carbanion by the ketone carbonyl (Scheme 12). The observed stereospecificity can be rationalized by a concerted pathway of the Cope rearrangement via a boatlike transition state, and the high reactivity can be interpreted as a result of the rate acceleration of the rearrangement by the oxyanion.[12,13] The stereoselective formation of the *cis*-1,2-divinyl derivative **31** can be explained by invoking the internally O−Si coordinated structure.[14]

**Scheme 11**




**Scheme 12**




To obtain support for the proposed mechanism, we decided to trap the cyclopropanolate intermediate **31** by low-temperature quenching of the reaction of the $\beta$-tributylstannyl derivative (*E*)-**12** with 2′-bromoacetophenone enolate **16** which appeared to be the slowest [3 + 4] annulation examined so far. While treatment of (*E*)-**12** with **16** at −80 °C for 60 min afforded **34**, the addition/Brook rearrangement product, together with recovery of the starting ketone, upon warming to −45 °C, cyclopropanol **33** was isolated in 24% yield, in addition to cycloheptenone **23g** and **34** (Scheme 13). The cyclopropanol structure of **33** was ascertained by $^1H$ and $^{13}C$ NMR in which the H-3 proton and C-3 carbon appeared at 1.21 and 1.75 ppm (each doublet, $J = 7.5$ Hz, H-3) and at 23.5 ppm, respectively. The 1,2-cis stereochemistry of **33** was indicated by the presence of cross-peaks between H-1″ and H-6′ in NOESY experiments.

The yield of **33** decreased, and that of **23g** increased with rising temperature, suggesting that the alkoxide of cyclopropanol **33** is the precursor to **23g**. In fact, treatment of **33** with LDA in THF at −30 °C for 10 min afforded **23g** in 18% yield along with **34** and **35**. These observations provide strong support for the proposed mechanism, but this is a rather specific case because an aromatic double bond is involved in the reaction, and no stereochemical information on the anionic oxy-Cope rearrangement is available. Although the stereocontrolled process of the Cope rearrangement of divinylcyclopropanes is

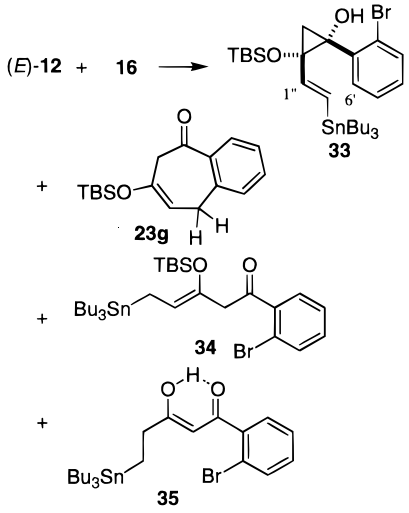
(11) For reviews on rearrangement of divinylcyclopropanes, see ref 2b. See also: (a) Piers, E. In *Comprehensive Organic Synthesis*; Trost, B. M., Fleming, I., Eds.; Pergamon: Oxford, 1991; Vol. 5, pp 971−998. (b) Hill, R. K. *Ibid.;* Vol. 5, pp 785−826.

(12) (a) Wilson, S. R. *Org. React*. **1993**, *43*, 93−250. For related charge accelerated rearrangements, see: (b) Bronson, J. J.; Danheiser, R. L. In *Comprehensive Organic Synthesis*; Trost, B. M., Fleming, I., Eds.; Pergamon: Oxford, 1991; Vol. 5, pp 999−1036.

(13) For thermal Cope rearrangement of *cis*-1-aryl-2-vinylcyclopropanes, see: Marvell, E. N.; Lin, C. *J. Am. Chem. Soc*. **1978**, *100*, 877−883. See also ref 11b.

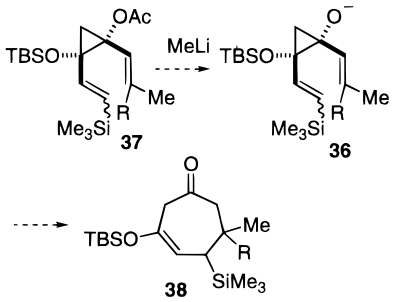
(14) Takeda, K.; Nakatani, J.; Nakamura, H.; Sako, K.; Yoshii, E.; Yamaguchi, K. *Synlett* **1993**, 841−843.

**Scheme 13**




| conditions | yield (%) | | | | recovery of ketone |
|---|---|---|---|---|---|
| | **33** | **23g** | **34** | **35** | |
| -80 °C, 60 min | 0 | 0 | 31 | 0 | 69 |
| -80 °C to -45 °C 40 min | 24 | 5 | 16 | 0 | 32 |
| -80 °C to -40 °C 60 min | 17 | 7 | 33 | 7 | 9 |
| -80 °C to -30 °C 60 min | 8 | 26 | 31 | 3 | 8 |

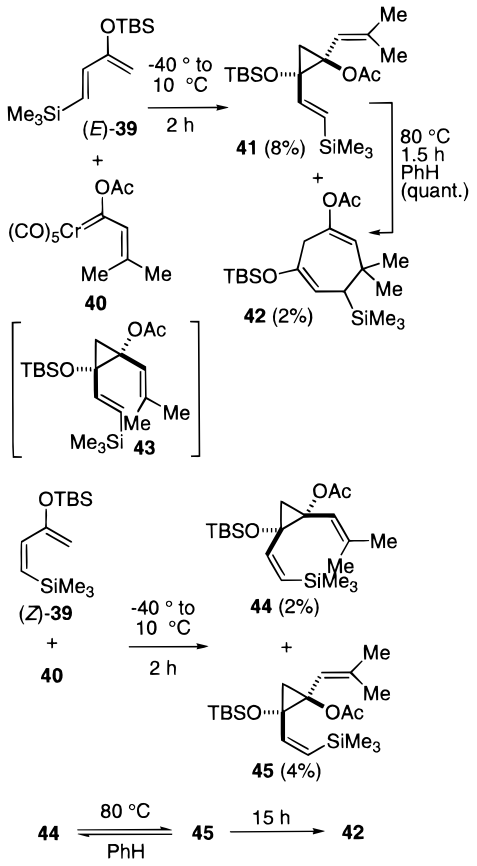
**Scheme 14**




well-known and the fact that the anionic reaction is qualitatively faster than the neutral counterpart is fully expected from other anion-accelerated rearrangements,[12] anionic oxy-Cope rearrangement has never been previously reported for any divinylcyclopropanes. Therefore, to gain further support for the mechanism, we decided to synthesize independently 1,2-divinylcyclopropanolates **36** and explore the reactivity and stereochemical aspect of their anionic oxy-Cope rearrangement. First, to gain insight into the reactivity, we investigated the rearrangement of 1-(2-methylpropenyl)-2-(2-(trimethylsilyl)-ethenyl)cyclopropanolates **36** (R = Me), derived from the reaction of the corresponding cyclopropyl acetates **37** with 2 equiv of MeLi, to cycloheptenone **38**, creating no stereogenic center (Scheme 14).

Reaction of (*E*)-**39**[15] with in situ generated **40**[16] at −40 to +10 °C for 2 h afforded *trans*-divinylcyclopropyl acetate **41** and cycloheptadiene **42**, while (*Z*)-**39** produced both *cis*- and *trans*-cyclopropyl acetates **44** and **45** under the same conditions (Scheme 15). Cycloheptadiene **42** can arise from the thermal

**Scheme 15**




Cope rearrangement of *cis*-1,2-divinycyclopropyl acetate **43** below room temperature, because conversion of the trans derivative **41** into **42** via trans-to-cis isomerization required heating at 80 °C for 1.5 h.[17] On the other hand, separate heating of **44** and **45** in benzene resulted in equilibration between them, and complete transformation into **42** required refluxing in the solvent for 15 h.

Because the desired *cis*-1,2-divinyl derivatives could not be obtained in the case of the *E* derivative, the reaction with MeLi was performed using the trans derivatives **41** and **44**, in anticipation of fast trans-to-cis isomerization, and cis-derivative **45**. When **41** was treated with MeLi (2.2 equiv) at −80 °C for 5 min and then quenched with acetic acid (2.2 equiv), cycloheptenone **15d** was obtained in 71% yield (Scheme 16). This observation suggests that the anionic oxy-Cope rearrangement from **47** to **15d** is a rapid process even at −80 °C because the overall transformation involving the acetyl cleavage, ring-opening/reclosure sequence and the anionic oxy-Cope rearrangement (**41** → **46** → **47** → **15d**) was almost completed within 5 min at −80 °C.

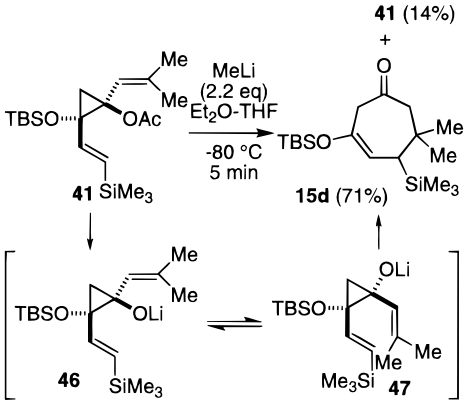
On the other hand, reactions of the *Z* derivatives **45** and **44** proceeded more slowly and afforded cyclopentenol **48** as a major product in addition to the Cope product **15d** (Scheme 17). The cyclopentenol **48** can be formed via competing oxyanion

(15) Takeda, K.; Sakurama, K.; Yoshii, E. *Tetrahedron Lett.* **1997**, *38*, 3257−3260.

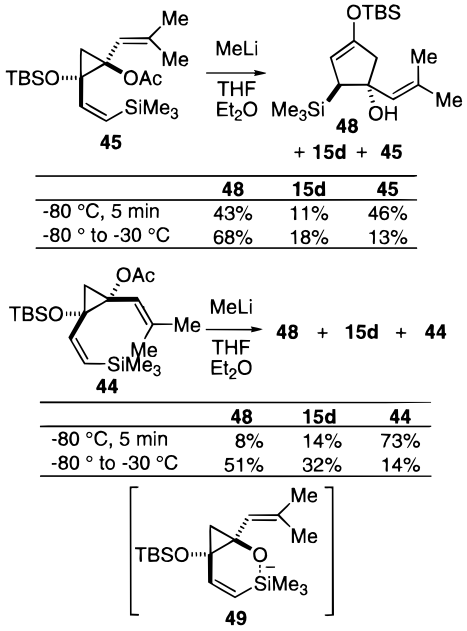
(16) This compound was prepared according to Wulff's procedure. Murray, C. K.; Yang, D. C.; Wulff, W. D. *J. Am. Chem. Soc.* **1990**, *112*, 5660−5662.

(17) Similar results have been reported for the reaction of Danishefsky's diene and cyclohexenylmethoxychromium carbene complex by Wulff and co-workers. Wulff, W. D.; Bauta, W. E.; Kaesler, R. W.; Lankford, P. J.; Miller, R. A.; Murray, C. K.; Yang, D. C. *J. Am. Chem. Soc.* **1990**, *112*, 3642−3659. The relatively facile cis-to-trans isomerization of **41** involving ring-opening/reclosure and the fast thermal Cope rearrangement of the cis derivative of **41** may be interpreted in terms of the push−pull effect by the siloxy and acetoxy groups.

**Scheme 16**




**Scheme 17**




| | 48 | 15d | 45 |
|---|---|---|---|
| -80 °C, 5 min | 43% | 11% | 46% |
| -80 ° to -30 °C | 68% | 18% | 13% |



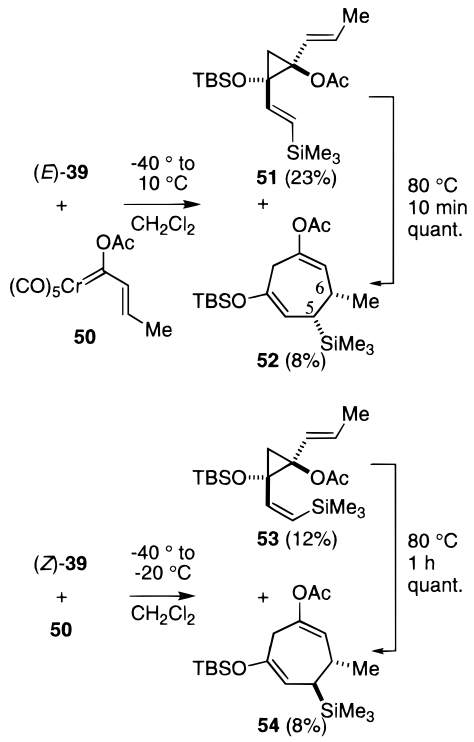

| | 48 | 15d | 44 |
|---|---|---|---|
| -80 °C, 5 min | 8% | 14% | 73% |
| -80 ° to -30 °C | 51% | 32% | 14% |




accelerated vinylcyclopropane−cyclopentene rearrangement.[15,18] The relative slowness of the anionic oxy-Cope rearrangement can be attributed to the steric repulsion between the (*Z*)-trimethylsilyl group and the hydrogen atom on the cyclopropane ring in the transition state from **44** leading to **15d**, which is well documented for the thermal Cope rearrangement of *cis*-1,2-divinylcyclopropanes.[11] The more predominant formation of **48** from **45** than from **44** at lower temperature can be explained by assuming that the 1,3-sigmatropic shift of internally Si−O coordinated bicycle **49**, generated from **45**, to **48** is much faster than the trans-to-cis isomerization required for the Cope rearrangement, presumably because of its fixed conformation suitable for the overlap of the orbitals required for the rearrangement.[15]

Having obtained results indicating very rapid process of the anionic oxy-Cope rearrangement of 1,2-divinylcyclopropanolates, we next proceeded to prepare propenyl derivative **36** (R = H) to examine the stereochemical course of the anionic oxy-Cope rearrangement. Not unexpectedly, the requisite cis-derivatives were not obtained from both reactions of (*E*)- and (*Z*)-**39** with **50**,[16] and trans-derivatives **51** and **53** formed

**Scheme 18**



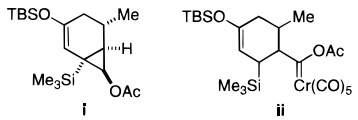

together with thermal Cope products **52** and **54**[19] (Scheme 18). The thermal Cope rearrangement of **51** into **52** was faster than those of **41**, **44**, **45**, and **53**.

Reaction of **51** with MeLi (2.2 equiv) afforded *cis*-6-methyl-5-(trimethylsilyl)cycloheptenone **55** as a single diastereomer and the ring-opening product **56** (Scheme 19). The ratio of **55** to **56** increased with an increase in temperature and reaction time, suggesting that **56** can be formed from *trans*-divinylcyclopropanolate during the hydrolytic workup because the ring closure of **56** to **55** seems unlikely.[20] The same reaction with **53** resulted in the formation of 5,6-trans derivative **57** and **56** in addition to the cyclopentenol **58**. The results indicated that the anionic oxy-Cope rearrangement of the 1,2-divinylcyclopropanolates is stereospecific. In these cases, the rate-determining step seems to be the trans-to-cis isomerization and not the Cope rearrangement, because even in the more congested system such as **41**, the overall transformation was completed within 5 min.

The results obtained with **44**, **45**, **51**, and **53** have shown that the anionic oxy-Cope rearrangement of *cis*-1,2-divinylcyclopropanolates proceeds very rapidly at lower temperatures and stereospecifically, providing additional support for the proposed pathway involving the anionic oxy-Cope rearrangement of 1,2-divinylcyclopropanolate. Moreover, the intermediacy of the cyclopropanolate **31** can reasonably account for the unsuccessful [3 + 4] annulation in the case of (*β*-(phenylthio)acryloyl)silane

(18) For an oxyanion-accelerated vinylcyclopropane rearrangement, see: (a) Danheiser, R. L.; Martinez-Davila, C.; Morin, J. M., Jr. *J. Org. Chem.* **1980**, *45*, 1340−1341. (b) Danheiser, R. L.; Martinez-Davila, C.; Auchus, R. J.; Kadonaga, J. T. *J. Am. Chem. Soc.* **1981**, *103*, 2443−2446. See also ref 12b.

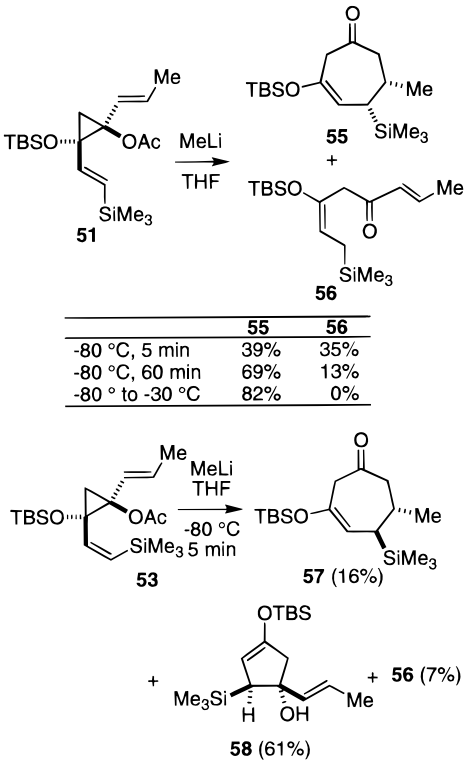
(19) The major side product of the reaction was bicyclo[4.1.0]heptene **i** (X-ray) which was an intramolecular C−H insertion product of Diels−Alder adduct **ii**.




See: Takeda, K.; Okamoto, Y.; Nakajima, A.; Yoshii, E.; Koizumi, T. *Synlett* **1997**, 1181−1183.

(20) We believe that the slower trans-to-cis isomerization of **51** relative to more congested **41** would be due to the lower ground-state energy of the *trans*-1,2-divinylcyclopropanolate from **51** than that of **41**.

**Scheme 19**

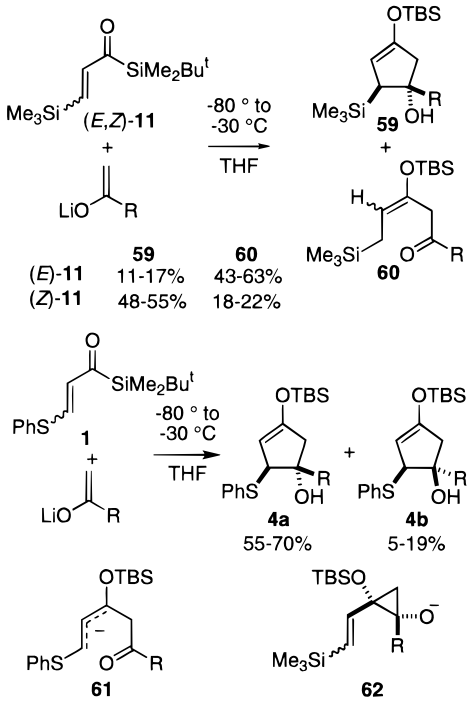



**1** on the basis of our earlier studies on [3 + 2] annulation using **1**. Thus, we have found that the reaction of β-substituted acryloylsilanes with ketone enolates greatly depends on the β-substituent.[4] The β-trimethylsilyl derivative **11** affords a single cyclopentenol **59** and uncyclized enol silyl ethers **60** in different ratios depending on the vinylsilane geometry, in contrast to the observation with β-phenylthio derivative **1** in which isomeric cyclopentenols **4a** and **4b** are obtained in almost the same ratio irrespective of the acylsilane geometry (Scheme 20). We propose a reaction course either by way of delocalized allylic carbanion intermediate **61** or by way of cyclopropanolate intermediate **62** depending on the α-carbanion-stabilizing ability of the β-substituent, the former for the more anion-stabilizing phenylthio derivative, and the latter for the less anion-stabilizing trimethylsilyl group.[21] Consequently, the failure of the [3 + 4] annulation in the reaction of **1** can be attributed to the formation of delocalized allylic carbanion which does not lead to cycloheptenone.

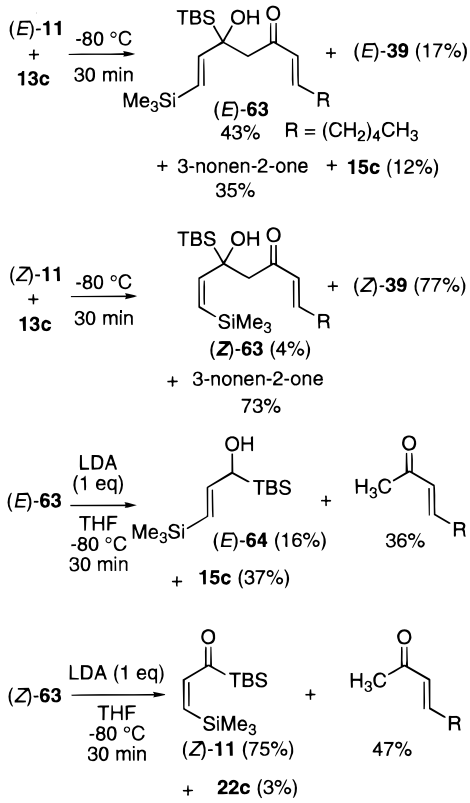
The relatively slow reaction of (*Z*)-**11** and (*Z*)-**12** in comparison with their *E* counterparts, at first glance, seems to be due to unfavorable steric interaction between the heteroatom substituents and ring hydrogen atom in the transition state leading to 5,6-trans derivatives as previously mentioned. This, however, is incompatible with the fact that a large amount of the starting acylsilanes was recovered, because the required retro-Aldol/Brook sequence (**31** → **7** → **5**, **6**, Scheme 12) seems unlikely. Moreover, the fact that, in the reaction of *cis*-1,2-divinylcyclopropyl acetate **44** with MeLi, acryloylsilane **11** could not be detected rules out the possibility of the reverse process. To obtain information about the relative reactivity of the (*E*)- and (*Z*)-acryloylsilanes toward ketone enolates, we conducted the low-temperature quenching of the reaction of the acryloylsilanes with the enolate **13c** (Scheme 21). The reaction

(21) We will report the mechanistic details of the [3 + 2] annulation including the comparison of α-carbanion-stabilizing ability between the phenylthio and trimethylsilyl groups elsewhere.

**Scheme 20**

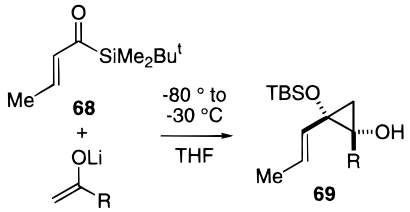



**Scheme 21**



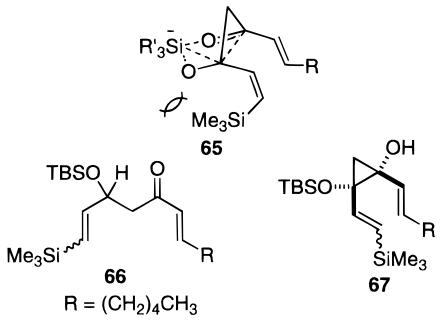

of (*Z*)-**11** with **13c** at −80 °C for 30 min resulted in the recovery of the starting acylsilane (*Z*)-**11** in 77% yield along with the formation of a trace amount of 1,2-adduct (*Z*)-**63**, in contrast to the reaction of (*E*)-**11** under the same conditions in which the 1,2-adduct (*E*)-**63** (43%), the annulation product **15c** (12%), and (*E*)-**11** (17%) were isolated. Treatment of the isolated 1,2-adduct (*E*)-**63** with LDA (1 equiv) afforded the cycloheptenone **15c** (37%), 3-nonen-2-one, and (*E*)-**64**, the reduction product of (*E*)-**11** with LDA. On the other hand, under the same

**Scheme 22**




conditions, (*Z*)-**63** produced (*Z*)-**11** (75%), 3-nonen-2-one, and cycloheptenone **22c**.

These results suggest that the lower reactivity of (*Z*)-acryloylsilanes is attributed in part to the slow formation of the 1,2-adduct due to an unfavorable equilibrium toward the starting materials. Although the origin of this unfavorable equilibrium in the *Z* isomer remains unclear at this time, we assume that it may be ascribed to the relatively severe steric repulsions in the *Z* 1,2-adduct and in the transition state **65** leading to the divinylcyclopropanolate via the Brook rearrangement/cyclopropanation. The assumption that the Brook rearrangement/cyclopropanation sequence is a concerted process is based on the fact that the attempted isolation of Brook rearrangement product **66** and cyclopropanol derivative **67** was unsuccessful and the anionic oxy-Cope rearrangement is very rapid even at −80 °C as previously mentioned.




The precise mechanism of the [3 + 4] annulation is still unclear. Nonetheless, the available data are consistent with the proposed mechanism that involves the anionic oxy-Cope rearrangement of the *cis*-1,2-divinylcyclopropanolate.

**[3 + 4] Annulation of *β*-Alkyl-Substituted Acryloylsilanes with the Lithium Enolates of Alkenyl Methyl Ketones.** The previously discussed mechanistic consideration suggests that a requirement for the successful [3 + 4] annulation would be the formation of *cis*-1,2-divinylcyclopropanolates. In fact, very recently we have found that the reaction of *trans*-1-(3-methyl-(1*E*)-butenyl)-2-(1-propenyl)cyclopropyl acetate with MeLi (2.2 equiv) produced the cycloheptenone derivative.[22] Also, we have previously reported that the reaction of crotonoylsilane **68** with the lithium enolate of methyl ketones produced *cis*-2-vinyl-1,2-cyclopropanediol derivative **69**[14] (Scheme 22).

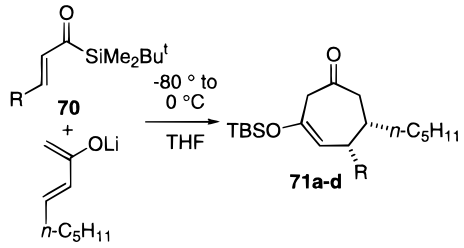
This led us to examine the [3 + 4] annulation using *β*-alkyl-substituted acryloylsilanes which would allow stereoselective introduction of an alkyl group at the 5-position of cycloheptenones and constitute a general and stereoselective approach to the highly functionalized seven-membered carbocycles.

When the lithium enolate of 3-nonen-2-one **13c** was added to a THF solution of 4-methyl-2-pentenoylsilane **70a** (R = *i*-Pr)[23] at −80 °C and then the solution was warmed to 0 °C,

(22) Takeda, K,; Okamoto, Y.; Koizumi, T. Unpublished results. Also, see ref 19.

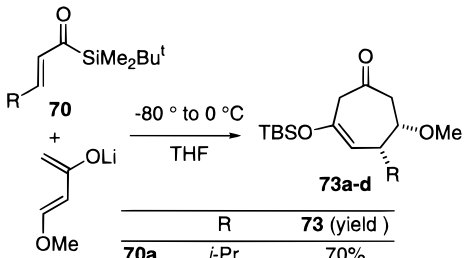
(23) Nowick, J. S.; Danheiser, R. L. *J. Org. Chem.* **1989**, *54*, 2798−2802.

**Scheme 23**




| | R | **71** (yield ) |
|---|---|---|
| **70a** | *i*-Pr | 75% |
| **70b** | *n*-Pr | 69% |
| **70c** | *t*-Bu | 65% |
| **70d** | cyclohexyl | 77% |

**Scheme 24**




| | R | **73** (yield ) |
|---|---|---|
| **70a** | *i*-Pr | 70% |
| **70b** | *n*-Pr | 44% |
| **70c** | *t*-Bu | 65% |
| **70d** | cyclohexyl | 57% |

*cis*-5-isopropyl-6-pentyl-3-cycloheptenone **71a** was obtained as a single diastereomer in 75% yield.[24] The same results were obtained in the reaction of other *β*-alkyl-substituted acryloylsilanes **70b**−**d**, with stereochemistry determined on the basis of NOESY experiments (Scheme 23).

The use of the lithium enolate of 4-methoxy-3-buten-2-one **72** as the C4 unit allowed the introduction of an oxygen function at the 6-position to give 6-methoxy derivatives **73a**−**d** (Scheme 24).

This procedure was also successfully applied to the synthesis of bi- and tricyclic systems **76** and **77** using cycloalkenylcarbonylsilanes **74** and **75** which were prepared by the reaction of 1-cyclopentenecarboxaldehyde and 1-cyclohexenecarboxaldehyde with dimethyl(phenyl)silyl)lithium[25] followed by Swern oxidation (Scheme 25, Table 2). In these cases, better yields were obtained when the reaction was performed at 0 °C rather than −80 to 0 °C, and a nonaqueous workup by the addition of acetic acid (1 equiv) was used. The stereochemistry of the products was determined on the basis of NOESY experiments and the X-ray analysis of **77f**. The stereochemistry at C-1 in **76e**,**f** and **77e**,**f** is interpreted as the result of kinetic protonation from the less-hindered side of the cycloheptenone enolate.

In conclusion, we have demonstrated synthetically useful and mechanistically interesting [3 + 4] annulation methodology which permits a rapid and stereocontrolled construction of highly functionalized cycloheptenone derivatives that are often difficult to make in other ways.

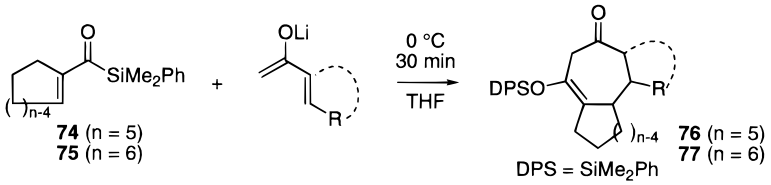
## Experimental Section

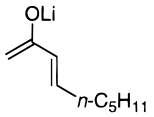
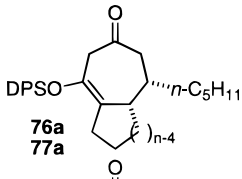
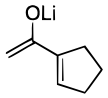
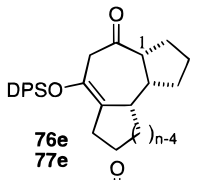
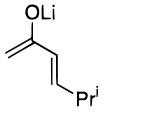
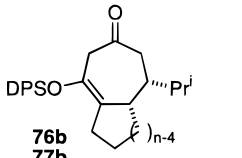
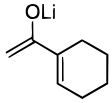
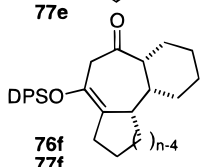
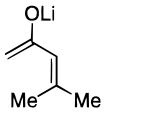
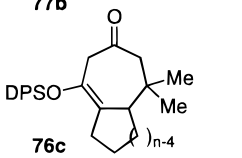
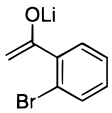
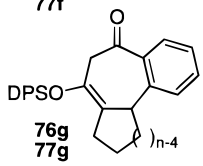
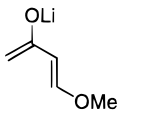
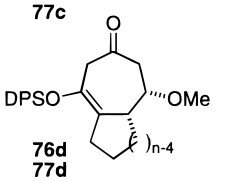
**General Procedures.** All NMR spectra were measured at 500 MHz ($^1$H) and 125 MHz ($^{13}$C) and in $CDCl_3$ with reference to $CHCl_3$ ($\delta$

(24) Reaction with crotonoylsilane **70** (R = Me) gave a poor yield of the cycloheptenone presumably because of decomposition caused by enolate-mediated deprotonation of the *β*-methyl group of **70**.

(25) Ager, D. J.; Fleming, I.; Patel, S. K. *J. Chem. Soc., Perkin Trans. 1* **1981**, 2520−2526.

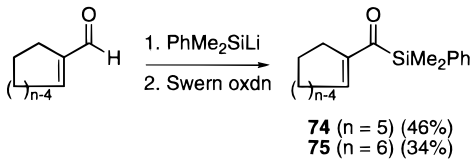
**Table 2**




| ketone enolate | n | product | yield | ketone enolate | n | product | yield |
|---|---|---|---|---|---|---|---|
|  | 5 |  **76a** **77a** | 82% |  | 5 |  **76e** **77e** | 51% |
| | 6 | | 82% | | 6 | | 65%[a] |
|  | 5 |  **76b** **77b** | 59% |  | 5 |  **76f** **77f** | 68% |
| | 6 | | 70% | | 6 | | 71% |
|  | 5 |  **76c** **77c** | 54% |  | 5 |  **76g** **77g** | 23% |
| | 6 | | 68% | | 6 | | 17% |
|  | 5 |  **76d** **77d** | 51% | | | | |
| | 6 | | 73% | | | | |

*a* The C-1 epimer was isolated in 12% yield.

**Scheme 25**




7.26) and the $CDCl_3$ triplet ($\delta$ 77.2) unless otherwise noted. Liquid chromatography under medium pressures (MPLC) was carried out by using prepacked columns (22 mm × 300 mm, 10 $\mu$m silica gel, or 22 mm × 150 mm, 5 $\mu$m silica gel). For routine chromatography, the following adsorbents were used: Fuji-Davison silica gel BW-200 (150−325 mesh) for column chromatography; Merck precoated silica gel 60 F-254 plates for analytical thin-layer chromatography. All moisture sensitive reactions were performed under a positive pressure of nitrogen. Anhydrous $MgSO_4$ was used for drying all organic solvent extracts in workup, and the removal of the solvents was performed with a rotary evaporator. Dry solvents and reagents were obtained by using standard procedures. Melting points were not corrected. Elemental combustion analysis was performed at the Microanalysis Laboratory of the Toyama Medical and Pharmaceutical University.

**General Procedure for the [3 + 4] Annulation Using 11 and 12: Reaction of (*E*)-11 with the Lithium Enolate of 3-Nonen-2-one (13c).** To a cooled (−80 °C) solution of lithium diisopropylamide (LDA), prepared from diisopropylamine (139 $\mu$L, 100 mg, 0.99 mmol) and *n*-BuLi (1.32 M in hexane, 0.75 mL, 0.99 mmol) in THF (1 mL), was added dropwise a solution of 3-nonen-2-one (149 $\mu$L, 126 mg, 0.90 mmol) in THF (1 mL). After being stirred at −80 °C for 30 min, the solution was added dropwise via a cannula to a cooled (−80 °C) solution of (*E*)-**11** (262 mg, 1.08 mmol) in THF (41 mL). The reaction mixture was allowed to warm to −30 °C over 1 h, and then quenched by saturated aqueous $NH_4Cl$ solution (30 mL). The mixture was extracted with $Et_2O$ (15 mL × 2), and the combined organic phases were washed with water (30 mL), dried, and concentrated. The residual oil was subjected to column chromatography (silica gel, 40 g; elution with 20:1 hexane−AcOEt) to give **15c (R = $(CH_2)_4CH_3$)** (289 mg, 84%): a colorless oil; $R_f$ = 0.48 (hexane:AcOEt = 15:1); IR (film) 1710, 1640, 1250 cm$^{-1}$; $^1$H NMR $\delta$ 0.01 (9H, s), 0.13 and 0.17 (each 3H, s), 0.93 (9H, s), 1.11−1.38 (8H, m), 0.88 (3H, t, $J$ = 6.4 Hz), 1.64 (1H, dd, $J$ = 8.1, 3.8 Hz), 2.29−2.37 (2H, m), 2.43 (1H, dd, $J$ = 11.8, 6.4 Hz), 2.59 (1H, dd, $J$ = 11.8, 9.8 Hz), 2.83 (1H, d, $J$ = 18.4 Hz), 3.46 (1H, br m, $J$ = 18.4 Hz), 4.94 (1H, dd, $J$ = 8.1, 2.4 Hz); $^{13}$C NMR $\delta$ −3.5, −3.9, −0.7, 14.8, 18.7, 23.4, 27.5, 32.5, 34.7, 26.4, 29.8, 41.5, 48.1, 51.7, 107.1, 149.3, 211.4; HRMS calcd for $C_{21}H_{42}O_2Si_2$ 382.2723, found 382.2730.

**General Procedure for Transformation of Cycloheptenones 15 into Cycloheptenediones 25.** To a cooled (ice−water) solution of **15c** (100 mg, 260 $\mu$mol) in THF (2.6 mL) was added NBS (50 mg, 270 $\mu$mol), and then the reaction mixture was stirred at room temperature for 10 min. The mixture was cooled in an ice−water bath again before addition of TBAF (1.0 M in THF, 0.26 mL, 260 $\mu$mol). After being stirred at the same temperature for 10 min, the mixture was allowed to warm to room temperature, and then diluted with $Et_2O$ (20 mL) and water (30 mL). The phases were separated, and the aqueous phase was extracted with $Et_2O$ (20 mL × 2). The combined organic phases were washed with saturated brine (30 mL), dried, and concentrated. The residue was subjected to column chromatography (silica gel, 3.3 g; elution with 1:2 hexanes−$Et_2O$) to give **25c** (45 mg, 89%): a pale yellow oil; $R_f$ = 0.55 (hexane:AcOEt = 1:1); IR (film) 1715, 1670 cm$^{-1}$; $^1$H NMR $\delta$ 0.89 (3H, t, $J$ = 7.0 Hz), 1.28−1.44 (6H, m), 2.47 (1H, dd, $J$ = 17.1, 14.1 Hz), 2.69 (1H, dd, $J$ = 17.1, 3.4 Hz), 2.96−3.05 (1H, m), 3.58 (1H, dm, $J$ = 14.3 Hz), 4.10 (1H, d, $J$ = 14.3 Hz), 6.07 (1H, dm, $J$ = 12.0 Hz), 6.66 (1H, ddm, $J$ = 12.0, 4.3 Hz); $^{13}$C NMR $\delta$ 14.1, 18.0, 22.7, 26.6, 31.7, 35.5, 35.7, 47.1, 61.4, 131.9, 152.8, 192.3, 203.3; HRMS calcd for $C_{12}H_{18}O_2$ 194.1307, found 194.1267.

**General Procedure for Transformation of Cycloheptenones 23 into Cycloheptenediones 25.** To a cooled (ice−water) solution of **23c**

(54 mg, 90 μmol) in $CH_2Cl_2$ (0.45 mL) was added mCPBA (80%, 20 mg, 90 μmol), and then the solution was stirred at the same temperature for 15 min. The reaction mixture was concentrated, and the residue was subjected to column chromatography (silica gel, 4 g, elution with 1:1 hexanes−$Et_2O$) to give **25c** (16 mg, 89%).

**Trapping Experiment of the Cyclopropanolate Intermediate.** To a stirred and cooled (−80 °C) solution of LDA, prepared from diisopropylamine (124 μL, 882 μmol) and *n*-BuLi (1.45 M hexane solution, 610 μL, 882 μmol) in THF (1 mL), was added dropwise a solution of 2′-bromoacetophenone (176 mg, 882 μmol) in THF (1 mL). After being stirred at −80 °C for 30 min, the solution was added dropwise via a cannula to a cooled (−80 °C) solution of (*E*)-**12** (405 mg, 882 μmol) in THF (41 mL) over 2 min. The reaction mixture was allowed to warm to −45 °C over 40 min, and then quenched by acetic acid (52 mg, 882 μmol) in THF (1 mL). The mixture was extracted with $Et_2O$ (30 mL × 2) after addition of saturated aqueous $NH_4Cl$ solution (30 mL), and the combined organic phases were washed with saturated brine (20 mL), dried, and concentrated. The residual oil was subjected to column chromatography (silica gel, 40 g; elution with 20:1 hexanes−$Et_2O$) to give **33** (139 mg, 24%), **23g** (13 mg, 5%), **34** (93 mg, 16%), and 2′-bromoacetophenone (56 mg, 32%).

**33**: a pale yellow oil; $R_f$ = 0.40 (hexane:$Et_2O$ = 10:1); IR (film) 3530 $cm^{-1}$; $^1H$ NMR δ 0.15 and 0.18 (each 3H, s), 0.60−0.75 (6H, m), 0.84 (9H, t, *J* = 7.3 Hz), 0.97 (9H, s), 1.14−1.22 (6H, m), 1.25−1.32 (6H, m), 1.21 (1H, d, *J* = 7.5 Hz), 1.75 (1H, d, *J* = 7.5 Hz), 3.66 (1H, s), 5.62 (1H, d, *J* = 19.2 Hz), 5.90 (1H, d, *J* = 19.2 Hz), 7.07 (1H, ddd, *J* = 7.7, 7.7, 1.7 Hz), 7.19 (1H, ddd, *J* = 7.7, 7.7, 1.1 Hz), 7.29 (1H, dd, *J* = 7.7, 1.7 Hz), 7.49 (1H, dd, *J* = 7.7, 1.1 Hz); $^{13}C$ NMR δ −3.5, −3.1, 9.5, 13.9, 27.4, 29.1, 18.3, 23.4, 26.1, 63.6 and 64.9, 126.2, 126.7, 126.9, 129.3, 131.5, 133.2, 138.6, 146.0; HRMS calcd for $C_{29}H_{51}O_2BrSiSn$ 658.1864, found 658.1847.

**34**: a colorless oil; $R_f$ = 0.53 (hexane:$Et_2O$ = 10:1); IR (film) 1700 $cm^{-1}$; $^1H$ NMR δ 0.13 (6H, s), 0.63−0.85 (6H, m), 0.87 (9H, t, *J* = 7.3 Hz), 0.92 (9H, s), 1.21−1.30 (6H, m), 1.35−1.43 (6H, m), 1.58 (2H, d, *J* = 8.8 Hz), 3.63 (2H, s), 4.74 (1H, t, *J* = 8.8 Hz), 7.25 (1H, ddd, *J* = 7.9, 7.9, 1.9 Hz), 7.32 (1H, ddd, *J* = 7.9, 7.9, 1.1 Hz), 7.39 (1H, dd, *J* = 7.9, 1.9 Hz), 7.57 (1H, dd, *J* = 7.9, 1.1 Hz); $^{13}C$ NMR δ −3.7, 7.9, 9.4, 13.9, 27.5, 29.3, 18.4, 26.0, 50.9, 112.6, 119.0, 127.4, 129.4, 131.5, 133.7, 139.5, 141.2, 201.5; HRMS calcd for $C_{25}H_{42}O_2BrSiSn$ ($M^+ - C_4H_9$) 601.1159, found 601.1120.

**Reaction of 33 with LDA.** To a cooled (−30 °C) solution of **33** (114 mg, 173 μmol) in THF (8 mL) was added dropwise LDA (0.5 M THF−hexane solution, 359 μL, 173 μmol). After the reaction mixture was stirred at the same temperature for 10 min, the reaction was quenched by acetic acid (11 mg, 173 μmol) in THF (0.2 mL). The reaction mixture was extracted with $Et_2O$ (10 mL × 2) after addition of saturated aqueous $NH_4Cl$ solution (10 mL). The combined organic phases were washed with saturated brine (10 mL), dried, and concentrated. The residual oil was subjected to column chromatography (silica gel, 10 g; elution with 20:1 hexanes−$Et_2O$) to give **23g** (9 mg, 18%) and a mixture of **34** and **35** (65 mg, 48%; 11%).

**35**: a pale yellow oil; $R_f$ = 0.45 (hexane:$Et_2O$ = 10:1); IR (film) 1600 $cm^{-1}$; $^1H$ NMR δ 0.80−0.95 (15H, m), 0.98−1.11 (2H, m), 1.25−1.35 (6H, m), 1.40−1.60 (6H, m), 2.51−2.63 (2H, m), 5.98 (1H, s), 7.28 (1H, ddd, *J* = 8.1, 7.5 Hz), 7.37 (1H, ddd, *J* = 7.5, 1.1 Hz), 7.51 (1H, dd, *J* = 7.5, 1.9 Hz), 7.63 (1H, dd, *J* = 8.1, 1.1 Hz); $^{13}C$ NMR δ −4.4, 4.2, 9.2, 13.9, 27.6, 29.4, 36.4, 100.6, 120.3, 127.6, 130.1, 131.6, 134.0, 138.0, 185.4 and 198.5; HRMS calcd for $C_{23}H_{37}O_2BrSn$ 544.0999, found 544.1025.

**(*E*)-3-(*tert*-Butyldimethylsiloxy)-1-(trimethylsilyl)buta-1,3-diene ((*E*)-39).** To a cooled (ice−water) solution of methyl phenyl sulfone (516 mg, 3.3 mmol) in THF (7 mL) was added dropwise *n*-BuLi (1.47 M hexane solution, 2.25 mL, 3.3 mmol). After being stirred at the same temperature for 1 h, the mixture was added dropwise to a cooled (−80 °C) solution of (*E*)-**11** (728 mg, 3.0 mmol) in THF (7 mL). The reaction mixture was allowed to warm to −30 °C over 1 h, and then quenched by saturated aqueous $NH_4Cl$ solution (15 mL). The phases were separated, and the aqueous phase was extracted with $Et_2O$ (10 mL × 2). The combined organic phases were washed with saturated brine (10 mL), dried, and concentrated. The residual oil was subjected to column chromatography (silica gel, 36 g; elution with hexane) to give (*E*)-**39** (562 mg, 73%): a colorless oil; $R_f$ = 0.39 (hexane); IR (neat) 1250 $cm^{-1}$; $^1H$ NMR δ 0.09 (9H, s), 0.17 (6H, s), 0.97 (9H, s), 4.35 and 4.37 (each 1H, br s), 6.18 (1H, d, *J* = 18.6 Hz), 6.34 (1H, d, *J* = 18.6 Hz); $^{13}C$ NMR δ −4.5, −1.1, 18.5, 26.0, 96.7, 130.1, 141.4, 155.8; HRMS calcd for $C_{13}H_{28}OSi_2$ 256.1679, found 256.1657.

**(*Z*)-3-(*tert*-Butyldimethylsiloxy)-1-(trimethylsilyl)buta-1,3-diene ((*Z*)-39).** (*Z*)-**39** was obtained from (*Z*)-**11** in 85% yield by the procedure described above for (*E*)-**39**: a colorless oil; $R_f$ = 0.50 (hexane); IR (neat) 1250 $cm^{-1}$; $^1H$ NMR δ 0.14 (9H, s), 0.20 (6H, s), 0.95 (9H, s), 4.35 and 4.36 (each 1H, br s), 5.61 (1H, d, *J* = 15.2 Hz), 6.52 (1H, d, *J* = 15.2 Hz); $^{13}C$ NMR δ −3.6, 0.4, 19.0, 26.4, 95.8, 132.4, 143.9, 157.1; HRMS calcd for $C_{13}H_{28}OSi_2$ 256.1679, found 256.1643.

**Reaction of Enol Silyl Ether (*E*)-39 with Fischer Carbene Complex 40.** To a suspension of $Cr(CO)_6$ (440 mg, 2.00 mmol) in $Et_2O$ (40 mL) was added 2-methylpropen-1-yllithium, prepared from 1-bromo-2-methyl-1-propene (270 mg, 2 mmol) and *tert*-butyllithium (1.50 M pentane solution, 3 mL, 5 mmol), at room temperature over 10 min. After being stirred at room temperature for 30 min, the mixture was concentrated. Water (20 mL) was added to the residue, and the insoluble material was filtered out through Celite. To the filtrate was added an aqueous solution (2 mL) of $Me_4NBr$ (460 mg, 3.00 mmol). The mixture was extracted with $CH_2Cl_2$ (20 mL × 3), and the combined organic phases were washed with brine (10 mL), dried, and concentrated to give the complex **40** (480 mg) as a red solid. To a solution of this compound (480 mg, 1.37 mmol) in $CH_2Cl_2$ (3 mL) was added acetyl bromide (115 μL, 1.51 mmol) at −40 °C. After the mixture was stirred at the same temperature for 1 h, a solution of (*E*)-**39** (440 mg, 1.71 mmol) in $CH_2Cl_2$ (20 mL) was added over 10 min. The solution was allowed to warm to 10 °C over 2.5 h, and then poured into aqueous saturated $NaHCO_3$ (30 mL). The phases were separated, and the aqueous phase was extracted with hexane (30 mL × 3). The combined organic phases were washed with saturated brine (30 mL), dried, and then concentrated. The residue was subjected to column chromatography (silica gel, 25 g; elution with 20:1 hexanes−$Et_2O$) followed by MPLC (10 μm silica gel; elution with 55:1 hexanes−$Et_2O$) to give **41** (40 mg, 8%) and **42** (12 mg, 2%).

**41**: a colorless oil; $R_f$ = 0.39 (hexane:$Et_2O$ = 10:1); IR (film) 1750 $cm^{-1}$; $^1H$ NMR δ 0.06 (9H, s), −0.03 and 0.07 (each 3H, s), 0.84 (9H, s), 1.17 (1H, d, *J* = 7.4 Hz), 1.50 (1H, d, *J* = 7.4 Hz), 1.71 (3H, d, *J* = 1.4 Hz), 1.75 (3H, d, *J* = 1.4 Hz), 1.89 (3H, s), 5.68 (1H, br m), 5.80 (1H, d, *J* = 18.8 Hz), 5.98 (1H, d, *J* = 18.8 Hz); $^{13}C$ NMR δ −3.1, −2.1, −0.2, 19.0, 20.4, 22.0, 26.3, 26.7, 27.5, 64.3, 64.8, 121.4, 129.3, 142.1, 145.7, 171.1; HRMS calcd for $C_{20}H_{38}O_3Si_2$ 382.2360, found 382.2353.

**42**: a pale yellow oil; $R_f$ = 0.45 (hexane:$Et_2O$ = 10:1); IR (film) 1755 $cm^{-1}$; $^1H$ NMR δ 0.08 (9H, s), 0.14 (6H, s), 0.90 (9H, s), 1.09 (3H, s), 1.22 (3H, s), 1.55 (1H, d, *J* = 9.2 Hz), 2.08 (3H, s), 2.69 (1H, d, *J* = 20.6 Hz), 3.34 (1H, br d, *J* = 20.6 Hz), 4.97 (1H, d, *J* = 9.2 Hz), 5.20 (1H, d, *J* = 2.1 Hz); $^{13}C$ NMR δ −4.3, −4.2, 0.9, 18.1, 21.3, 25.9, 30.8, 32.3, 36.4, 37.6, 38.1, 109.3, 129.3, 135.3, 143.1, 170.0; HRMS calcd for $C_{20}H_{38}O_3Si_2$ 382.2360, found 382.2346.

**Reaction of Enol Silyl Ether (*Z*)-39 with Fischer Carbene Complex 40.** To a solution of the **40** (1.20 g, 3.43 mmol) described above in $CH_2Cl_2$ (8 mL) was added acetyl bromide (305 μL, 4.10 mmol) at −40 °C. After the mixture was stirred at the same temperature for 1 h, a solution of (*Z*)-**39** (1.75 g, 6.82 mmol) in $CH_2Cl_2$ (56 mL) was added over 35 min. The solution was allowed to warm to 10 °C over 2 h, and then poured into aqueous saturated $NaHCO_3$ (30 mL). The phases were separated, and the aqueous phase was extracted with hexane (100 mL × 1, 50 mL × 2). The combined organic phases were washed with saturated brine (100 mL), dried, and then concentrated. The residue was subjected to column chromatography (silica gel, 90 g; elution with 20:1 hexanes−$Et_2O$) followed by MPLC (10 μm silica gel; elution with 55:1 hexanes−$Et_2O$) to give **44** (28 mg, 2%) and **45** (53 mg, 4%).

**44**: a colorless oil; $R_f$ = 0.45 (hexane:$Et_2O$ = 10:1); IR (film) 1755 $cm^{-1}$; $^1H$ NMR δ 0.09 (9H, s), 0.07 and 0.10 (each 3H, s), 0.84 (9H, s), 1.34 (1H, d, *J* = 7.5 Hz), 1.41 (1H, d, *J* = 7.5 Hz), 1.65 (3H, d, *J* = 1.3 Hz), 1.76 (3H, d, *J* = 1.3 Hz), 2.00 (3H, s), 5.36 (1H, br m),

5.63 (1H, d, $J$ = 15.2 Hz), 6.56 (1H, br d, $J$ = 15.2 Hz); $^{13}$C NMR $\delta$ −3.4, −2.9, 0.4, 18.1, 19.2, 21.2, 25.6, 25.8, 26.4, 61.0, 61.5, 121.0, 132.3, 140.5, 145.7, 170.4; HRMS calcd for $C_{20}H_{38}O_3Si_2$ 382.2360, found 382.2371.

**45**: a colorless oil; $R_f$ = 0.46 (hexane:$Et_2O$ = 10:1); IR (film) 1750 cm$^{-1}$; $^1$H NMR $\delta$ 0.15 (9H, s), 0.03 and 0.12 (each 3H, s), 0.81 (9H, s), 1.14 (3H, dd, $J$ = 7.3, 1.3 Hz), 1.56 (1H, d, $J$ = 7.3 Hz), 1.71 (3H, d, $J$ = 1.3 Hz), 1.77 (3H, d, $J$ = 1.3 Hz), 1.90 (3H, s), 5.65 (1H, br s), 5.67 (1H, d, $J$ = 15.0 Hz), 6.52 (1H, dd, $J$ = 15.0, 1.3 Hz); $^{13}$C NMR $\delta$ −3.2, −2.9, 0.6, 18.1, 19.4, 21.2, 25.7, 25.8, 26.9, 62.2, 62.4, 120.7, 133.6, 140.1, 144.6, 170.6; HRMS calcd for $C_{20}H_{38}O_3Si_2$ 382.2360, found 382.2402.

**Thermal Cope Rearrangement of 41, 44, and 45.** This procedure is representative for the thermal Cope rearrangement of the cyclopropyl acetates. A solution of **41** (9.1 mg, 23.8 μmol) in benzene (2.4 mL) was refluxed for 1.5 h. Concentration of the solution gave pure **42** (9.1 mg, 100%).

**Reaction of Cyclopropyl Acetates 41 with MeLi.** To a cooled (−80 °C) solution of **41** (21.1 mg, 55.1 μmol) in THF (2.8 mL) was added dropwise MeLi (1.07 M in $Et_2O$, 114 μL, 122 μmol). After the reaction mixture was stirred at −80 °C for 5 min, the reaction was quenched by addition of AcOH (7.4 mg, 123 μmol) in THF (0.5 mL). The mixture was diluted with saturated aqueous $NH_4Cl$ solution (5 mL), and then extracted with $Et_2O$ (5 mL × 3). The combined organic phases were washed with saturated brine (5 mL), dried, and concentrated. The residue was subjected to MPLC (5 μm silica gel, elution with 40:1 hexanes−$Et_2O$) to give **15d** (13.4 mg, 71%) and **41** (2.9 mg, 14%).

**Reaction of Cyclopropyl Acetates 44 and 45 with MeLi.** The following procedure for **45** is representative: To a cooled (−80 °C) solution of **45** (12.6 mg, 32.9 μmol) in THF (1.6 mL) was added dropwise MeLi (1.00 M in $Et_2O$, 73 μL, 73.0 μmol). After the reaction mixture was stirred at −80 °C for 5 min, the reaction was quenched by addition of AcOH (4.4 mg, 73.3 μmol) in THF (0.2 mL). The mixture was diluted with saturated aqueous $NH_4Cl$ solution (3 mL), and then extracted with $Et_2O$ (3 mL × 3). The combined organic phases were washed with saturated brine (5 mL), dried, and concentrated. The residue was filtered through a short pad of silica gel (120 mg) to give a mixture (12.1 mg) of **48**, **15d**, and **45**. Attempted purification of this mixture by MPLC led to complete decomposition of **48**; the characterization was made by the comparison of its $^1$H NMR with those of **58** and related compounds.

**Reaction of Enol Silyl Ether (*E*)-39 with Fischer Carbene Complex 50.** To a suspension of $Cr(CO)_6$ (360 mg, 1.63 mmol) in $Et_2O$ (10 mL) was added 1-propenyllithium (0.018 M $Et_2O$ solution, 90 mL, 1.62 mmol), prepared from 1-bromo-1-propene with *tert*-butyllithium, at room temperature over 10 min. After being stirred at room temperature for 1 h, the mixture was concentrated. Water (20 mL) was added to the residue, and the insoluble material was filtered out through Celite. To the filtrate was added an aqueous solution (1.6 mL) of $Me_4NBr$ (380 mg, 2.44 mmol). The mixture was extracted with $CH_2Cl_2$ (20 mL × 3), and the combined organic phases were washed with brine (10 mL), dried, and concentrated. The residual solid was recrystallized from $CH_2Cl_2$−$Et_2O$ to give tetramethylammonium (propenyl(oxido)carbene)pentacarbonyl-chromium (320 mg, 59%): red needles; mp 112−113 °C dec. Anal. Calcd for $C_{13}H_{17}O_6NCr$: C, 46.56; H, 5.11; N, 4.18. Found: C, 46.28; H, 4.98; N, 3.99.

To a cooled (−40 °C) solution of the above carbene complex (195 mg, 580 μmol) in $CH_2Cl_2$ (1.2 mL) was added dropwise acetyl bromide (48 μL, 640 μmol), and then the reaction mixture was stirred at the same temperature for 1 h. To this mixture was added dropwise a solution of (*E*)-**39** (300 mg, 1.16 mmol) in $CH_2Cl_2$ (9.4 mL) over 10 min. The reaction mixture was allowed to warm to 10 °C over 2 h. The mixture was poured into saturated aqueous $NaHCO_3$ solution (15 mL), and extracted with hexane (10 mL × 3). The combined organic phases were washed with saturated brine (10 mL), dried, and concentrated. The residual oil was subjected to column chromatography (silica gel, 20 g; elution with 20:1 hexanes−$Et_2O$) followed by MPLC (elution with 50:1 hexanes−$Et_2O$) to give **51** (48 mg, 23%), a 1:1 mixture of **52** and **i** (35 mg, 16%), and 2-acetoxy-5-(*tert*-butyldimethylsiloxy)-7-methyl-3-(trimethylsilyl)cyclohepta-1,4-diene (17 mg, 8%). The mixture of **52** and **i** was separated by resubjecting it to the MPLC.

**51**: a colorless oil; $R_f$ = 0.38 (hexane:$Et_2O$ = 10:1); IR (film) 1760 cm$^{-1}$; $^1$H NMR $\delta$ 0.06 (9H, s), 0.04 and 0.08 (each 3H, s), 0.87 (9H, s), 1.35 (1H, d, $J$ = 7.7 Hz), 1.51 (1H, d, $J$ = 7.7 Hz), 1.73 (3H, dd, $J$ = 6.4, 1.5 Hz), 1.94 (3H, s), 5.55 (1H, dq, $J$ = 15.6, 6.4 Hz), 5.66 (1H, dq, $J$ = 15.6, 1.5 Hz), 5.73 (1H, d, $J$ = 18.8 Hz), 6.04 (1H, d, $J$ = 18.8 Hz); $^{13}$C NMR $\delta$ −3.7, −2.9, −1.1, 18.2, 18.2, 21.2, 25.4, 25.9, 65.9, 66.1, 125.8, 126.5, 129.0, 144.0, 169.9; HRMS calcd for $C_{19}H_{36}O_3Si_2$ 368.2203, found 368.2178.

**52**: a colorless oil; $R_f$ = 0.56 (hexane:$Et_2O$ = 5:1); IR (film) 1755 cm$^{-1}$; $^1$H NMR $\delta$ 0.04 (9H, s), 0.13 and 0.14 (each 3H, s), 0.91 (9H, s), 1.01 (3H, d, $J$ = 7.3 Hz), 1.85 (1H, br d, $J$ = 7.5 Hz), 2.09 (3H, s), 2.39 (1H, d, $J$ = 19.5 Hz), 2.64−2.74 (1H, br s), 3.75 (1H, d, $J$ = 19.5 Hz), 4.91 (1H, dd, $J$ = 7.5, 1.7 Hz), 5.30 (1H, dd, $J$ = 5.9, 2.5 Hz); $^{13}$C NMR $\delta$ −4.4, −4.3, −1.1, 18.1, 21.2, 23.3, 25.9, 32.5, 29.4, 38.0, 107.2, 125.5, 144.0, 169.8; HRMS calcd for $C_{19}H_{36}O_3Si_2$ 368.2203, found 368.2200.

**2-Acetoxy-5-(*tert*-butyldimethylsiloxy)-7-methyl-3-(trimethylsilyl-)cyclohepta-1,4-diene:** a colorless oil; $R_f$ = 0.45 (hexane: $Et_2O$ = 10:1); IR (film) 1760 cm$^{-1}$; $^1$H NMR $\delta$ 0.00 (9H, s), 0.12 and 0.12 (each 3H, s), 0.91 (9H, s), 1.11 (3H, d, $J$ = 6.4 Hz), 1.88 (1H, dddd, $J$ = 16.7, 11.8, 2.8, 2.1 Hz), 2.07 (1H, dd, $J$ = 16.7, 5.8 Hz), 2.11 (3H, s), 2.42 (1H, dddd, $J$ = 11.8, 6.4, 5.8, 1.9 Hz); 2.92 (1H, dd, $J$ = 4.3, 2.8 Hz), 4.77 (1H, dd, $J$ = 4.3, 2.1 Hz), 6.95 (1H, d, $J$ = 1.9 Hz). $^{13}$C NMR $\delta$ −4.2, −4.1, −2.1, 17.4, 18.2, 21.1, 25.9, 28.7, 30.9, 39.6, 102.9, 126.2, 127.2, 147.6, 168.3; HRMS calcd for $C_{19}H_{36}O_3Si_2$ 368.2203, found 368.2193.

**i**: colorless plates; mp 65 °C (petroleum); $R_f$ = 0.56 (hexane:$Et_2O$ = 5:1); IR (KBr) 1745 cm$^{-1}$; $^1$H NMR $\delta$ −0.02 (9H, s), 0.11 and 0.11 (each 3H, s), 0.81 (1H, dd, $J$ = 6.4, 4.3 Hz), 0.91 (9H, s), 1.08 (3H, d, $J$ = 6.8 Hz), 1.80 (1H, ddd, $J$ = 15.8, 8.6, 1.9 Hz), 1.86 (1H, dd, $J$ = 15.8, 5.6 Hz), 1.99 (1H, dddd, $J$ = 8.6, 6.8, 5.6, 4.3 Hz), 2.02 (3H, s), 3.88 (1H, d, $J$ = 6.4 Hz), 4.57 (1H, d, $J$ = 1.9 Hz); $^{13}$C NMR $\delta$ −4.2, −4.2, −3.4, 18.2, 21.1, 23.0, 23.4, 25.7, 25.9, 37.3, 60.5, 98.3, 153.5, 171.9. Anal. Calcd for $C_{19}H_{36}O_3Si_2$: C, 61.92; H, 9.85. Found: C, 62.07; H, 9.93.

**Reaction of Enol Silyl Ether (*Z*)-39 with Fischer Carbene Complex 50.** To a cooled (−40 °C) solution of the above carbene complex (160 mg, 477 μmol) in $CH_2Cl_2$ (1.2 mL) was added dropwise acetyl bromide (39 μL, 525 μmol), and then the reaction mixture was stirred at the same temperature for 1 h. To this mixture was added dropwise a solution of (*Z*)-**39** (245 mg, 954 μmol) in $CH_2Cl_2$ (7.6 mL) over 6 min. The reaction mixture was allowed to warm to −20 °C over 2 h. The mixture was poured into saturated aqueous $NaHCO_3$ solution (10 mL), and extracted with hexane (10 mL × 3). The combined organic phases were washed with saturated brine (10 mL), dried, and concentrated. The residual oil was subjected to column chromatography (silica gel, 15 g; elution with 20:1 hexanes−$Et_2O$) followed by MPLC (elution with 50:1 hexanes−$Et_2O$) to give **53** (21 mg, 12%), **54** (16 mg, 8%), and **i** (36 mg, 21%).

**53**: a colorless oil; $R_f$ = 0.57 (hexane:$Et_2O$ = 5:1); IR (film) 1760 cm$^{-1}$; $^1$H NMR $\delta$ 0.14 (9H, s), 0.07 and 0.09 (each 3H, s), 0.84 (9H, s), 1.36 (1H, d, $J$ = 7.7 Hz), 1.41 (1H, d, $J$ = 7.7 Hz), 1.73 (3H, dd, $J$ = 6.4, 1.5 Hz), 2.00 (3H, s), 5.48 (1H, dq, $J$ = 15.6, 6.4 Hz), 5.58 (1H, dq, $J$ = 15.6, 1.5 Hz), 5.80 (1H, d, $J$ = 14.7 Hz), 6.52 (1H, d, $J$ = 14.7 Hz); $^{13}$C NMR $\delta$ −3.0, −2.9, −1.1, 18.1, 18.2, 21.4, 25.9, 25.9, 63.4, 64.9, 125.3, 126.8, 136.7, 143.8, 170.3; HRMS calcd for $C_{19}H_{36}O_3Si_2$ 368.2203, found 368.2234.

**54**: a colorless oil; $R_f$ = 0.58 (hexane:$Et_2O$ = 5:1); IR (film) 1755 cm$^{-1}$; $^1$H NMR $\delta$ 0.04 (9H, s), 0.13 and 0.15 (each 3H, s), 0.91 (9H, s), 1.21 (3H, d, $J$ = 7.1 Hz), 1.42 (1H, dd, $J$ = 8.9, 3.5 Hz), 2.08 (3H, s), 2.41−2.49 (1H, m), 2.88 (1H, d, $J$ = 21.6 Hz), 3.16 (1H, d, $J$ = 21.6 Hz), 5.02 (1H, dd, $J$ = 8.9, 0.5 Hz), 5.53 (1H, dd, $J$ = 8.6, 1.9 Hz); $^{13}$C NMR $\delta$ −4.3 and −4.2, −1.6, 18.1, 21.3, 22.9, 25.9, 30.2, 32.9, 39.0, 108.0, 123.0, 143.4, 144.7, 169.7; HRMS calcd for $C_{19}H_{36}O_3Si_2$ 368.2203, found 368.2175.

**Reaction of 51 with MeLi.** This procedure is representative of reactions of **51** and **53** with MeLi: To a cooled (−80 °C) solution of **24** (21 mg, 55.6 μmol) in THF (2.8 mL) was added dropwise MeLi (1.07 M in $Et_2O$, 115 μL, 123 μmol). After the reaction mixture was stirred at −80 °C for 5 min, the reaction was quenched by addition of AcOH (7.4 mg, 123 μmol) in THF (0.5 mL). The mixture was diluted

with saturated aqueous $NH_4Cl$ solution (5 mL), and then extracted with $Et_2O$ (5 mL × 3). The combined organic phases were washed with saturated brine (10 mL), dried, and concentrated. The residue was subjected to MPLC (5 μm silica gel, elution with 50:1 hexanes−$Et_2O$) to give **55** (7.0 mg, 39%) and **56** (6.5 mg, 35%).

**55**: a colorless oil; $R_f$ = 0.48 (hexane:$Et_2O$ = 5:1); IR (film) 1710 $cm^{-1}$; $^1H$ NMR δ 0.02 (9H, s), 0.14 and 0.17 (each 3H, s), 0.92 (9H, s), 0.95 (3H, d, $J$ = 6.6 Hz), 1.60 (1H, dd, $J$ = 7.9, 3.2 Hz), 2.37 (1H, dd, $J$ = 11.1, 6.2 Hz), 2.44−2.50 (1H, m), 2.62 (1H, dd, $J$ = 11.1, 9.8 Hz), 2.82 (1H, d, $J$ = 18.6 Hz), 3.43 (1H, dm, $J$ = 18.6 Hz), 4.92 (1H, dd, $J$ = 7.9, 2.4 Hz); $^{13}C$ NMR δ −4.4, −4.1, −1.6, 18.2, 19.3, 25.8, 28.7, 36.1, 50.4, 51.0, 105.5, 149.6, 208.9; HRMS calcd for $C_{17}H_{34}O_2Si_2$ 326.2097, found 326.2069.

**56**: a pale yellow oil; $R_f$ = 0.53 (hexane:$Et_2O$ = 5:1); IR (film) 1700 $cm^{-1}$; $^1H$ NMR δ 0.00 (9H, s), 0.12 (6H, s), 0.88 (9H, s), 1.31 (2H, d, $J$ = 8.5 Hz), 1.88 (3H, dd, $J$ = 6.8, 1.7 Hz), 3.21 (2H, s), 4.79 (1H, t, $J$ = 8.5 Hz), 6.25 (1H, dq, $J$ = 15.6, 1.7 Hz), 6.90 (1H, dq, $J$ = 15.6, 6.8 Hz); $^{13}C$ NMR δ −4.3, −1.6, 16.7, 18.2, 18.4, 25.9, 44.7, 106.4, 130.7, 143.0, 143.8, 197.0; HRMS calcd for $C_{17}H_{34}O_2Si_2$ 326.2097, found 326.2076.

**57**: a colorless oil; $R_f$ = 0.47 (hexane:$Et_2O$ = 5:1); IR (film) 1710 $cm^{-1}$; $^1H$ NMR δ 0.07 (9H, s,), 0.12 (6H, s), 0.90 (9H, s), 1.05 (3H, d, $J$ = 6.8 Hz), 1.35 (1H, ddd, $J$ = 9.2, 7.5, 1.0 Hz), 2.52 (1H, dd, $J$ = 14.1, 8.1 Hz), 2.16−2.24 (1H, m), 2.62 (1H, dd, $J$ = 14.1, 4.1 Hz), 2.95 (1H, d, $J$ = 17.5 Hz), 3.35 (1H, ddd, $J$ = 17.5, 1.3, 1.1 Hz), 4.99 (1H, dd, $J$ = 7.5, 1.3 Hz); $^{13}C$ NMR δ −4.2, −4.2, −1.4, 18.1, 23.9, 25.8, 33.3, 31.5, 50.4, 49.9, 109.3, 144.2, 209.2; HRMS calcd for $C_{17}H_{34}O_2Si_2$ 326.2097, found 326.2118.

**58**: a colorless oil; $R_f$ = 0.27 (hexane:$Et_2O$ = 5:1); IR (film) 1720 $cm^{-1}$; $^1H$ NMR δ −0.03 (9H, s), 0.16 and 0.17 (each 3H, s), 0.93 (9H, s), 1.72 (3H, dd, $J$ = 6.0, 1.3 Hz), 1.89 (2H, dd, $J$ = 2.8, 0.9 Hz), 2.15 (1H, d, $J$ = 16.2 Hz), 2.23 (1H, s), 2.67 (1H, ddd, $J$ = 16.2, 2.4, 1.5 Hz), 4.64 (1H, ddd, $J$ = 2.8, 2.4, 0.9 Hz), 5.65 (1H, dd, $J$ = 15.4, 1.3 Hz), 5.72 (1H, dq, $J$ = 15.4, 6.0 Hz); HRMS calcd for $C_{17}H_{34}O_2Si_2$ 326.2097, found 326.2100.

**Low-Temperature Quenching of Reactions of (*E*)- and (*Z*)-11 with 13c.** To a stirred and cooled (−80 °C) solution of lithium diisopropylamide prepared from diisopropylamine (572 μL, 413 mg, 4.08 mmol) and *n*-BuLi (1.28 M in hexane, 3.19 mL, 4.08 mmol) in THF (2 mL) was added dropwise a solution of 3-nonen-2-one (614 μL, 521 mg, 3.71 mmol) in THF (2 mL). After being stirred at −80 °C for 30 min, the solution was added dropwise via a cannula to a cooled (−80 °C) solution of **(*E*)-11** (900 mg, 3.71 mmol) in THF (170 mL). After the reaction mixture was stirred at the same temperature for 30 min, the reaction was quenched by acetic acid (234 μL, 245 mg, 4.08 mmol) in THF (1 mL). The mixture was diluted with saturated aqueous $NH_4Cl$ solution (40 mL), and then extracted with $Et_2O$ (40 mL × 3). The combined organic phases were washed with saturated brine (50 mL), dried, and concentrated. The residual oil was subjected to column chromatography (silica gel, 150 g; elution with 30:1 hexane−AcOEt) to give **(*E*)-63** (613 mg, 43%), **(*E*)-11** (155 mg, 17%), 3-nonen-2-one (182 mg, 35%), and **15c** (172 mg, 12%).

**(*E*)-63**: a colorless oil; $R_f$ = 0.29 (hexane: $Et_2O$ = 15:1); IR (film) 3645, 1665 (weak) $cm^{-1}$; $^1H$ NMR δ −0.01 (9H, s), 0.01 (6H, s), 0.89 (3H, t, $J$ = 6.8 Hz), 0.95 (9H, s), 1.26−1.35 (4H, m), 1.46 (2H, br tt, $J$ = 6.8, 6.8 Hz), 2.20 (2H, dt, $J$ = 6.8, 6.8 Hz); 2.72 (1H, d, $J$ = 15.4 Hz), 3.04 (1H, d, $J$ = 15.4 Hz), 3.79 (1H, s), 5.67 (1H, d, $J$ = 19.0 Hz), 6.02 (1H, dt, $J$ = 15.0, 1.5 Hz), 6.12 (1H, d, $J$ = 19.0 Hz), 6.77 (1H, dt, $J$ = 15.8, 6.8 Hz); $^{13}C$ NMR δ −7.7, −7.4, −1.0, 14.1, 18.5, 28.0, 22.6, 29.9, 31.6, 32.6, 44.9, 73.9, 124.9, 131.6, 148.9, 150.1, 202.1; HRMS calcd for $C_{21}H_{42}O_2Si_2$ 382.2723, found 382.2710.

To a stirred and cooled (−80 °C) solution of lithium diisopropylamide prepared from diisopropylamine (191 μL, 138 mg, 1.36 mmol) and *n*-BuLi (1.28 M in hexane, 1.06 mL, 1.36 mmol) in THF (1 mL) was added dropwise a solution of 3-nonen-2-one (205 μL, 174 mg, 1.24 mmol) in THF (1 mL). After being stirred at −80 °C for 30 min, the solution was added dropwise via a cannula to a cooled (−80 °C) solution of **(*Z*)-11** (300 mg, 1.24 mmol) in THF (58 mL). After the reaction mixture was stirred at the same temperature for 30 min, the reaction was quenched by acetic acid (78 μL, 82 mg, 1.36 mmol) in THF (1 mL). The mixture was diluted with saturated aqueous $NH_4Cl$ solution (10 mL), and then extracted with $Et_2O$ (20 mL × 3). The combined organic phases were washed with saturated brine (20 mL), dried, and concentrated. The residual oil was subjected to column chromatography (silica gel, 50 g; elution with 20:1 hexane−AcOEt) to give **(*Z*)-63** (20 mg, 4%), **(*Z*)-11** (231 mg, 77%), and 3-nonen-2-one (127 mg, 73%).

**(*Z*)-63**: a colorless oil; $R_f$ = 0.59 (hexane:AcOEt = 10:1); IR (film) 3435, 1655 (weak) $cm^{-1}$; $^1H$ NMR δ −0.07 and 0.02 (each 3H, s), 0.11 (9H, s), 0.89 (3H, t, $J$ = 6.2 Hz), 0.99 (9H, s), 1.25−1.40 (4H, m), 1.46 (2H, br tt, $J$ = 7.5, 7.5 Hz), 2.21 (2H, dt, $J$ = 7.1, 7.1 Hz), 2.72 (1H, d, $J$ = 15.0 Hz), 2.99 (1H, d, $J$ = 15.0 Hz), 3.91 (1H, s), 5.36 (1H, d, $J$ = 14.3 Hz), 6.02 (1H, dd, $J$ = 15.8, 0.9 Hz), 6.25 (1H, dd, $J$ = 14.3, 0.6 Hz), 6.78 (1H, dt, $J$ = 15.8, 7.1 Hz); $^{13}C$ NMR δ −6.9, −6.8, 2.2, 14.1, 18.6, 28.1, 22.6, 31.5, 27.9, 32.7, 45.0, 75.9, 125.8, 131.5, 149.5, 150.6, 202.2; HRMS calcd for $C_{21}H_{42}O_2Si_2$ 382.2723, found 382.2730.

**Reactions of (*E*)- and (*Z*)-63 with LDA.** To a cooled (−80 °C) solution of **(*E*)-63** (186 mg, 486 μmol) in THF (21 mL) was added dropwise a solution of lithium diisopropylamide prepared from diisopropylamine (68 μL, 49 mg, 486 μmol) and *n*-BuLi (1.28 M in hexane, 380 μL, 486 μmol) in THF (3 mL). After the reaction mixture was stirred at the same temperature for 30 min, the reaction was quenched by acetic acid (28 μL, 29 mg, 483 μmol) in THF (1 mL). The mixture was diluted with saturated aqueous $NH_4Cl$ solution (8 mL), and then extracted with $Et_2O$ (20 mL × 3). The combined organic phases were washed with saturated brine (10 mL), dried, and concentrated. The residual oil was subjected to column chromatography (silica gel, 18 g; elution with 15:1 hexanes−$Et_2O$) to give **15c** (69 mg, 37%), **(*E*)-64** (19 mg, 16%), and 3-nonen-2-one (25 mg, 36%).

**(*E*)-64**: a colorless oil; $R_f$ = 0.34 (hexane:AcOEt = 15:1); IR (film) 3435 $cm^{-1}$; $^1H$ NMR δ −0.05 and −0.02 (each 3H, s), 0.06 (9H, s), 0.95 (9H, s), 4.21 (1H, dd, $J$ = 4.7, 2.1 Hz), 5.67 (1H, dd, $J$ = 18.8, 2.1 Hz), 6.28 (1H, dd, $J$ = 18.8, 4.7 Hz); $^{13}C$ NMR δ −8.7, −7.4, −0.9, 17.3, 27.1, 69.6, 122.9, 148.6; HRMS calcd for $C_{12}H_{28}OSi_2$ 244.1679, found 244.1654.

To a cooled (−80 °C) solution of **(*Z*)-63** (57 mg, 149 μmol) in THF (6.5 mL) was added dropwise a solution of lithium diisopropylamide prepared from diisopropylamine (21 μL, 15 mg, 149 μmol) and *n*-BuLi (1.28 M in hexane, 116 μL, 149 μmol) in THF (1 mL). After the reaction mixture was stirred at the same temperature for 30 min, the reaction was quenched by acetic acid (9 μL, 9 mg, 149 μmol) in THF (1 mL). The mixture was diluted with saturated aqueous $NH_4Cl$ solution (3 mL), and then extracted with $Et_2O$ (7 mL × 3). The combined organic phases were washed with saturated brine (5 mL), dried, and concentrated. The residual oil was subjected to column chromatography (silica gel, 6.5 g; elution with 30:1 hexane−AcOEt) to give **22c** (1.7 mg, 3%), **(*Z*)-11** (27 mg, 75%), and 3-nonen-2-one (9.8 mg, 47%).

**General Procedure for the Reaction of 70 with the Lithium Enolate of 3-Nonen-2-one (13c).** This procedure is representative of reactions of **70** with the lithium enolate of 3-nonen-2-one. To a stirred and cooled (−80 °C) solution of lithium diisopropylamide (LDA) prepared from diisopropylamine (146 μL, 105 mg, 1.04 mmol) and *n*-BuLi (1.47 M in hexane, 708 μL, 1.04 mmol) in THF (1 mL) was added dropwise a solution of 3-nonen-2-one (157 μL, 133 mg, 0.948 mmol) in THF (1 mL). After being stirred at −80 °C for 30 min, the solution was added dropwise via a cannula to a cooled (−80 °C) solution of **70c** (168 mg, 0.791 mmol) in THF (44 mL). The reaction mixture was allowed to warm to 0 °C over 1 h, and then quenched by saturated aqueous $NH_4Cl$ solution (30 mL). The mixture was extracted with $Et_2O$ (20 mL × 2), and the combined organic phases were washed with saturated brine (30 mL), dried, and concentrated. The residual oil was subjected to column chromatography (silica gel, 35 g; elution with 20:1 hexane−AcOEt) to give **71c** (225 mg, 65% as a colorless oil): a colorless oil; $R_f$ = 0.38 (hexane:AcOEt = 15:1); IR (film) 1710, 1655, 1250 $cm^{-1}$; $^1H$ NMR δ 0.14 and 0.17 (each 3H, s, $SiMe_2$), 0.86 (3H, t, $J$ = 7.1 Hz, H-5″), 0.92 and 0.93 (each 9H, s), 1.10−1.48 (8H, m), 2.14 (1H, dd, $J$ = 7.7, 2.8 Hz), 2.31−2.38 (1H, m), 2.44 (1H, dd, $J$ = 11.3, 6.4 Hz), 2.58 (1H, dd, $J$ = 11.3, 7.1 Hz), 2.77 (1H, d, $J$ = 16.9 Hz), 3.52 (1H, dd, $J$ = 16.9, 2.1 Hz), 4.96 (1H, dd, $J$ = 7.7, 2.1 Hz); $^{13}C$ NMR δ −4.3, −4.0, 14.3, 18.1, 22.9, 27.2, 30.8, 32.2, 25.8,

29.2, 33.5, 42.2, 49.1, 49.8, 51.3, 108.2, 147.2, 209.4; HRMS calcd for $C_{22}H_{42}O_2Si$ 366.2954, found 366.2964.

**General Procedure for the [3 + 4] Annulation Using Acylsilanes 74.** This procedure is representative of reactions of **74** with the lithium enolate of 3-nonen-2-one (**13c**): To a stirred and cooled (−80 °C) solution of lithium diisopropylamide (LDA) prepared from diisopropylamine (84 μL, 61 mg, 0.603 mmol) and *n*-BuLi (1.41 M in hexane, 426 μL, 0.600 mmol) in THF (0.5 mL) was added dropwise a solution of 3-nonen-2-one (99 μL, 84 mg, 0.600 mmol) in THF (1 mL). After being stirred at −80 °C for 30 min, the solution was added dropwise via a cannula to a cooled (0 °C) solution of **74** (125 mg, 0.542 mmol) in THF (24 mL). The reaction mixture was stirred at 0 °C for 30 min, and then quenched by acetic acid (36 mg, 0.600 mmol). The mixture was concentrated, and then the residue was subjected to column chromatography (silica gel, 10 g; elution with 10:1 hexane−AcOEt) to give **76a** (164 mg, 82%): a colorless oil; $R_f = 0.26$ (hexane:AcOEt = 20:1); IR (film) 1705, 1685, 1250 $cm^{-1}$; $^1H$ NMR δ 0.47 and 0.46 (each 3H, s), 0.89 (3H, t, $J = 7.1$ Hz), 0.08−1.42 (9H, m), 1.42−1.52 (1H, m), 1.62−1.65 (1H, m), 1.80−1.87 (1H, m), 1.94−2.00 (1H, m), 1.99−2.08 (1H, br m), 2.35−2.42 (1H, m), 2.47 (2H, d, $J = 5.8$ Hz), 2.81−2.86 (1H, br m), 2.82 (1H, d, $J = 15.0$ Hz), 3.53 (1H, dm, $J = 15.0$ Hz), 7.35−7.42 (3H, m, Ar), 7.52−7.62 (2H, m, Ar); $^{13}C$ NMR δ −0.6, 14.3, 22.8, 25.3, 27.4, 29.0, 31.2, 31.3, 32.2, 41.1, 44.5, 48.4, 51.5, 125.7, 128.0, 130.0, 133.6, 136.0, 137.4, 207.4; HRMS calcd for $C_{23}H_{34}O_2Si$ 370.2328, found 370.2330.

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**Supporting Information Available:** Full experimental details and characterization data for all new compounds described in the text and X-ray structural information on **15f** and **77f** (25 pages, print/PDF). See any current masthead page for ordering information and Web access instructions.

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