Extremely Efficient Chiral Induction in Conjugate Additions of *p*-Tolyl α-Lithio-*β*-(trimethylsilyl)ethyl Sulfoxide and Subsequent Electrophilic Trapping Reactions

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Reaction of *p*-tolyl α-lithio-*β*-(trimethylsilyl)ethyl sulfoxide with α,*β*-unsaturated esters gave the conjugate addition products as a single diastereomer. The intermediate enolates were subsequently trapped with various alkyl halides or aldehydes to give the products with extremely high stereoselectivity. The reaction with α,*β*-unsaturated ketones also proceeded with high diastereoselectivity. Protolysis of the enolates derived from the α-methyl-α,*β*-unsaturated esters gave the products with high stereoselectivity. The stereo- and regioselective elimination of the sulfinyl group gave chiral homoallylic carboxylates.

Introduction

The conjugate addition reaction of α-sulfinyl-stabilized carbanion to α,*β*-unsaturated carbonyl compounds is a useful method for the stereoselective formation of a C−C bond.[1,2] However, some limitations have precluded the general applicability of this method. Casey and coworkers have disclosed a reaction of *tert*-butylsulfinyl carbanions with α,*β*-unsaturated esters giving conjugate addition products with high stereoselectivity, whereas *p*-tolylsulfinyl carbanions give the adducts with low stereoselectivity.[2] These stereochemical features are similar to those obtained in the addition of α-sulfinyl carbanions to carbonyl compounds; e.g., *p*-tolyl or phenylsulfinyl carbanions generally give the products with low stereoselectivity and *tert*-butylsulfinyl carbanions show high stereoselectivity.[3] However, further transformation of the compounds having a *tert*-butylsulfinyl group often results in formation of complex products.[4] Thus, highly stereoselective reactions of readily obtainable arylsulfinyl carbanions have long been desired.

In the course of developing a new chiral vinyl anion equivalent, we found that reactions of the α-carbanion of *p*-tolyl 2-(trimethylsilyl)ethyl sulfoxide with aldehydes and ketones proceeded with extremely high stereoselection on the face of the α-carbanion, giving the products with stereochemistry different from that formed in the nucleophilic reaction of *tert*-butylsulfinyl carbanions.[5] We have reported in a preliminary communication that the reaction of the α-sulfinyl carbanion derived from *p*-tolyl *β*-(trimethylsilyl)ethyl sulfoxide with α,*β*-unsaturated carbonyl compounds gives the conjugate addition products with complete stereoselectivity.[5b] We now report in detail on the stereoselective conjugate additions of *p*-tolyl α-lithio-*β*-(trimethylsilyl)ethyl sulfoxide to α,*β*-unsaturated carbonyl compounds as well as subsequent stereoselective electrophilic reactions to the generated enolates. We also describe the transformation of the products into olefins.

Results

Conjugate Addition Reaction. The conjugate addition reactions of the α-sulfinyl carbanion, derived from *p*-tolyl 2-(trimethylsilyl)ethyl sulfoxide[6] **1**, to α,*β*-unsaturated esters were examined. The results are summarized in Table 1.

The sulfoxide **1** was added to a THF solution of lithium diisopropylamide at −78 °C. After 5 min, methyl acrylate was added rapidly, and the mixture was stirred for 15 min. The addition product was found to be a single isomer **3a** by careful analysis of the ^{1}H NMR spectra and HPLC

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(2) (a) Casey, M.; Manage, A. C.; Nezhat, L. *Tetrahedron Lett.* **1988**, *29*, 5821. (b) Casey, M.; Manage, A. C.; Gairns, R. S. *Tetrahedron Lett.* **1989**, *30*, 6919.

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(6) For the preparation of **1**, see ref 5a.

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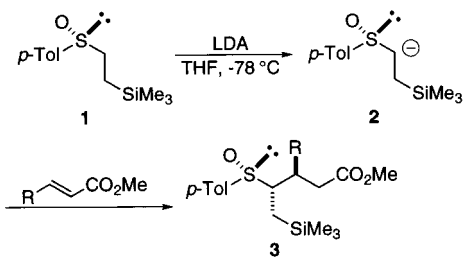
Table 1. Stereoselective Conjugate Addition of *p*-Tolyl α-Lithio-*β*-silylethyl Sulfoxide 2 to α,*β*-Unsaturated Esters



entry	R	product	yield (%)	diastereomer ratio[a]
1	H[b]	**3a**	64	>98:2[c]
2	Me[b]	**3b**	95	>98:2
3	Et[b]	**3c**	97	>98:2
4	Ph	**3d**	96	>98:2[c]

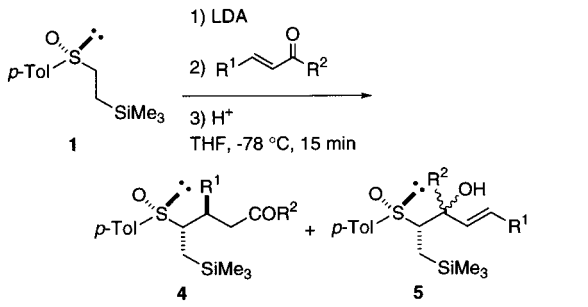
[a] Determined by ^{1}H NMR. [b] A THF solution of the α,*β*-unsaturated ester was cooled to −78 °C before addition. [c] The ration was also confirmed by HPLC (COSMOSIL, hexane/ethyl acetate = 75:25).

data (Table 1, entry 1). This surprisingly high stereoselection was also observed in the reaction of the α-sulfinyl carbanion **2** with other *β*-substituted α,*β*-unsaturated esters such as methyl crotonate, methyl (*E*)-2-pentenoate, and methyl cinnamate. The conjugate addition products **3b**−**d** were obtained as single stereoisomers (Table 1, entries 2−4). In these reactions, the diastereoselectivity was determined by the ^{1}H NMR spectra of the crude mixture. The X-ray crystallography of the adduct **3a** established the relative syn configuration between the sulfinyl oxygen and the trimethylsilylmethyl group, which was in accord with the stereochemistry on the α position of the compounds stereoselectively formed in the reaction of the α-sulfinyl carbanion **2** and aldehydes,[5a,c] but different from the anti configuration formed in the reaction of *tert*-butylsulfinyl carbanions with electrophiles such as aldehydes or α,*β*-unsaturated esters.[2,3] By the X-ray crystallography, the stereochemistry of **3b** was assigned to be (R_S,3*S*,4*R*).

The α-sulfinyl carbanion **2** was reacted with α,*β*-unsaturated ketones to give the conjugate and/or carbonyl addition products **4** and **5**, respectively. The results are summarized in Table 2.

The reaction of **2** with α,*β*-unsaturated ketones was performed in a manner similar to the reaction with α,*β*-unsaturated esters. The reaction with 3-buten-2-one afforded 38% yield of the carbonyl adduct **5a** with low stereoselectivity together with recovery of a large amount of the starting sulfoxide **1** due to deprotonation from the ketone. The product **5a** was produced in 54% yield when a THF solution of the lithium carbanion was added to a solution of 3-buten-2-one (Table 2, entry 1). Reaction with 1-phenyl-3-buten-1-one and 1,3-diphenyl-2-propen-1-one gave the conjugate adducts as a major product with high stereoselectivity (Table 2, entries 2 and 3). The stereochemistry of **4b** and **4c** was tentatively assigned as (R_S,3*S*,4*R*) and (R_S,3*R*,4*R*), respectively, as in the case of *β*-substituted α,*β*-unsaturated esters. The carbonyl addition products **5b** and **5c** were always obtained without selectivity. It is noteworthy that the reaction with 2-cyclopentenone yielded the carbonyl addition product **5d** with complete stereoselectivity, although the stereochemistry has not yet been determined (Table 2, entry 4).

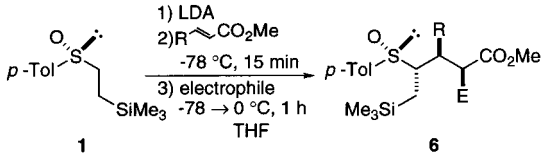
Table 2. Reaction of *p*-Tolyl α-Lithio-*β*-silylethyl Sulfoxide 2 with α,*β*-Unsaturated Ketones



entry	R^1	R^2	4	yield (%)	diastereomer ratio[a]	5	yield (%)	diastereomer ratio[a]
1	H	Me	**4a**	0		**5a**	38 (54)[b]	59:41
2	Me	Ph	**4b**	80	>98:2	**5b**	20	71:29
3	Ph	Ph	**4c**	57	96:4	**5c**	22	55:45
4	$-(CH_2)_2-$		**4d**	0		**5d**	82	>98:2

[a] Determined by ^{1}H NMR. [b] A THF solution of **2** was added to the enone at −78 °C.

Table 3. Conjugate Addition of α-Sulfinyl Carbanion 2 to α,*β*-Unsaturated Esters and Subsequent Stereoselective Trapping Reaction



entry	R	electrophile	product	yield (%)	diastereomer ratio[a]
1	H	MeI	**6a**	21	>98:2
2	Me	MeI	**6b**	59	>98:2
3	Et	MeI	**6c**	64	>98:2
4	Ph	MeI	**6d**	75	>98:2
5	Ph	CH_2=$CHCH_2Br$	**6e**	70	>98:2
6	Ph	$C_6H_5CH_2Br$	**6f**	74	>98:2
7	Ph	CH_3CH_2CHO	**6g**	32	>98:2
8	Ph	^{i}PrCHO	**6h**	90	>98:2
9	Ph	PhCHO	**6i**	98	>98:2

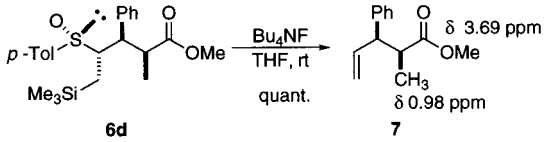
[a] Determined by ^{1}H NMR.

Trapping Reaction of the Enolates. We next explored trapping reactions of the intermediate enolates formed after conjugate addition to α,*β*-unsaturated esters (Table 3).

Reaction of the α-sulfinyl carbanion **2** and methyl acrylate afforded the intermediate enolate, which was reacted with methyl iodide. The product **6a** was obtained in 21% yield, because of the inevitable polymerization of methyl acrylate occurred during the reaction at the temperature in the region from −78 °C to 0 °C, but the product was a single diastereomer (Table 3, entry 1). Reaction of other intermediate enolates with various alkyl halides showed exclusive formation of the alkylated products **6a**−**f** composed of a single diastereomer (Table 3, entries 2−6). It was confirmed by ^{1}H NMR spectroscopy of the crude products that a single isomer was formed in each reaction. The reaction of the enolate derived from methyl cinnamate with propionaldehyde gave the product **6g** as a single diastereomer but in low yield due to the formation of a considerable amount of **3d** by the protonation of the enolate during the reaction (Table 3, entry 7). Reaction of the enolate with isobutyraldehyde and benzaldehyde gave the respective

products **6h** and **6i** in high yield and with complete stereoselectivity (Table 3, entries 8 and 9). Thus, the reaction with aldehydes proceeded with complete stereoselection not only on the enolate face, but also on the carbonyl face of the aldehyde. The stereochemistry of the addition product **6d** was proven by chemical transformation of **6d**: desilylsulfenylation of **6d** with tetrabutylammonium fluoride quantitatively yielded the elimination product **7** as a single diastereomer (Scheme 1).

Scheme 1



6d **7**

The ^{1}H NMR spectrum of **7** showed the methyl protons at 0.98 ppm and the methoxy protons at 3.69 ppm. On the other hand, the conjugate addition of a vinyl cuprate reagent to methyl cinnamate, followed by enolate trapping with methyl iodide, was performed to give an inseparable 76:24 mixture of two diastereomers of **7**, the minor component of which showed the methyl protons at 1.22 ppm and the methoxy protons at 3.42 ppm (Figure 1).

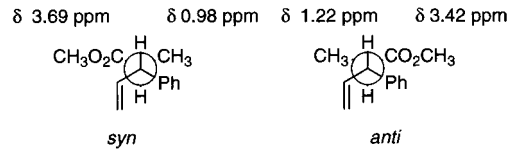
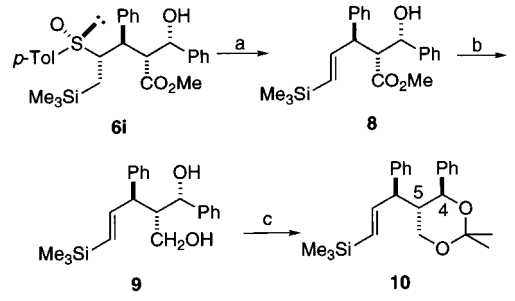


Figure 1. ^{1}H NMR assignment of **7**.

The anisotropy induced by the aromatic group leads to a specific upfield shift of the α-methyl group in the syn isomer and the corresponding upfield shift of the methyl ester in the anti isomer.[7] These data suggest the syn stereochemistry of **7**, and accordingly, the adduct **6d** is the (R_S,2*S*,3*R*,4*R*) isomer. The stereochemistry of other alkylated products shown in Table 3 was assumed to be the same as that of **6d**. The stereochemistry of the product **6i** obtained in the reaction of the enolate with benzaldehyde was proven by transformation of **6i** to the acetonide derivative **10** as shown in Scheme 2: thermal dehydrosulfenylation of the ester **6i** and reduction with $LiAlH_4$ gave the diol **9**, which was then converted to the acetonide **10**.

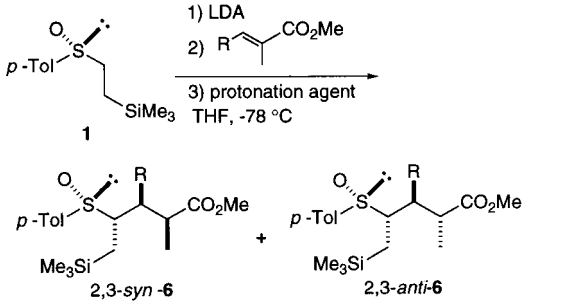
Scheme 2



6i **8** **9** **10**

The stereochemistry of **10** was confirmed on the basis of the vicinal coupling constant $J_{\alpha\beta}$ between C4-H and C5-H. The observed *J* value of 10.4 Hz suggests an axial–axial coupling showing the trans configuration in **10**. Hence, the absolute configuration of **6i** was assigned to be (R_S,1′*S*,2*R*,3*R*,4*R*) as shown in Scheme 2.[8]

Table 4. Conjugate Addition of α-Sulfinyl Carbanion 2 to α,β-Unsaturated Esters and Subsequent Stereoselective Protonation



entry	R	protonation agent	product	yield (%)	ratio syn/anti[a]
1	H	H_2O	**6a**	53	42:58
2	H	isopropyl salicylate[b]	**6a**	63	13:87
3	Me	H_2O	**6b**	92	31:69
4	Me	ethyl salicylate	**6b**	95	19:81
5	Me	*iso*propyl salicylate	**6b**	93	16:84
6	Me	isopropyl salicylate[b]	**6b**	98	10:90
7	Me	ethanolamine	**6b**	90	17:83
8	Me	2-aminophenol	**6b**	90	20:80
9	Me	2,6-di-*tert*-butylphenol	**6b**	100	66:34

[a] Determined by ^{1}H NMR. [b] The protonation reaction was carried out at −100 °C.

When the enolates derived from the reaction of **2** with methyl methacrylate and methyl tiglate were treated with water, nonstereoselective protonation occurred (Table 4, entry 1). The protonation reaction of the enolate with isopropyl salicylate at −100 °C gave the 2,3-syn/2,3-anti products in a ratio of 13:87 (Table 4, entry 2). A similar result was obtained for the protonation of the enolate derived from the reaction of **2** with methyl tiglate (Table 4, entry 6). The protonation reaction afforded products having stereochemistry different from that of products obtained in the reaction of the enolate with methyl iodide (Table 3, entries 1 and 2). In contrast, the protonation reaction with 2,6-di-*tert*-butylphenol gave a product with moderately reversed diastereoselectivity in comparison with products obtained with other protonation agents.

Intramolecular Cyclization. We next studied stereoselective intramolecular cyclization using the β-silylethyl sulfoxide and ω-halo-α,β-unsaturated esters (Table 5).

The reaction of the α-sulfinyl carbanion **2** with ethyl 4-bromo-2-butenoate was performed at −78 °C for 15 min to give the cyclopropanecarboxylate **11a** in 80% yield as

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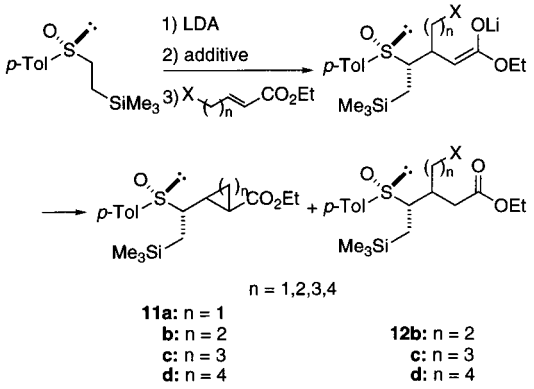
(8) We reasonably assumed that the aldehyde approaches to the enolate from the endo direction of the bicyclic intermediate, shown in Figure 5, as in the reaction with alkyl halides. The trapping reactions of ester enolates with alkyl halides and aldehydes generally occur from the same direction; see the following. Alkylations: (a) Caine, D. In *Comprehensive Organic Synthesis*; Trost, B. M., Fleming, I., Eds.; Pergamon Press: Oxford, 1991; Vol. 3, pp 1−64. (b) Frater, G. In *Stereoselective Synthesis*; Helmchen, G., Hoffmann, R. W., Mulzer, J., Schaumann, E., Eds.; Houben-Weyl: New York, 1996; Vol. 2, pp 723−791. Aldol reactions: (c) Braun, M. In *Stereoselective Synthesis*; Helmchen, G., Hoffmann, R. W., Mulzer, J., Schaumann, E., Ed.; Houben-Weyl: New York, 1996; Vol. 3, pp 1612−1667.

Table 5. Stereoselective Cyclization through the Conjugate Addition of the α-Sulfinyl Carbanion 2 to ω-Halo-α,β-unsaturated Esters[a]



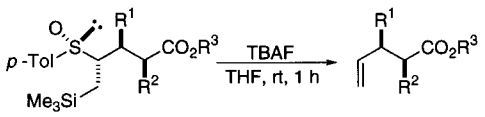
					products			
entry	n	X	*T* (°C)	additive	**11**	yield (%)	**12**	yield (%)
1	1	Br	−78		**11a**	80	**12a**	0
2	2	Br	−78		**11b**	0	**12b** (X = Br)	87
3	2	Br	−78→ 0	HMPA	**11b**	49	**12b** (X = Br)	29
4	2	I	−78		**11b**	28	**12b** (X = I)	59
5	2	I	−78→ 0		**11b**	51		43
6	2	I	−78→ 0	HMPA	**11b**	66	**12b** (X = I)	22
7	3	Br	−78		**11c**	72	**12c** (X = Br)	18
8	3	Br	−105		**11c**	49	**12c** (X = Br)	49
9	3	Br	0		**11c**	60	**12c** (X = Br)	5
10	3	Br	−78[b]		**11c**	88	**12c** (X = Br)	4
11	4	Br	−78		**11**	0	**12d** (X = Br)	quant
12	4	Br	−78→ 0		**11d**	93	**12d** (X = Br)	7
13	4	I	−78		**11d**	80	**12d** (X = I)	8

[a] Lithium diisopropylamide (1.25 equiv) was used for lithiation unless otherwise noted. [b] Lithium diisopropylamide (2 equiv) was used.

a single diastereomer (Table 5, entry 1). Intramolecular cyclization to cyclobutanecarboxylate was rather difficult. The reaction of **2** with ethyl 5-bromo-2-pentenoate at −78 °C for 1 h only gave the conjugate addition product **12b** in 87% yield (Table 5, entry 2). When HMPA was added to the reaction mixture and warmed to 0 °C, the cyclobutanecarboxylate **11b** was obtained in 49% yield (Table 5, entry 3). After several attempts to effect cyclization, the reaction with ethyl 5-iodo-2-pentenoate in the presence of HMPA at 0 °C led to 66% yield of **11b** (Table 5, entry 6). The reaction with ethyl 6-bromo-2-hexenoate at −78 °C for 15 min afforded the cyclopentanecarboxylate **11c** together with a considerable amount of the uncyclized product **12c**, the latter of which was possibly formed by the protonation from the cyclized product. Thus, almost selective formation of **11c** could be achieved in 88% yield when 2.0 equiv of LDA was used. The reaction was also completely diastereoselective (Table 5, entry 10). The reaction of **2** with ethyl 7-bromo-2-heptenoate was performed at −78 °C for 1 h to give the conjugate addition product **12d** quantitatively as a single diastereomer (Table 5, entry 11). The intramolecular cyclization proceeded smoothly as the reaction temperature was raised to 0 °C, giving the cyclohexanecarboxylate **11d** in 93% yield (Table 5, entry 12). The stereochemistry of cyclopropane and cyclopentanecarboxylates **11a**,**c** and the cyclohexanecarboxylic acid derivative derived from **11d** was confirmed to be (R_S,1*S*,1′*R*,2*S*) by their X-ray crystal structure analyses.

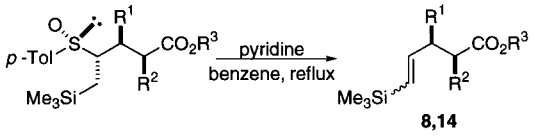
Elimination of the Sulfinyl Group. The chiral sulfinyl group together with the β-trimethylsilyl group functions as a vinyl anion equivalent,[5] not only inducing the stereoselectivity in the conjugate addition reaction as well as in the enolate trapping reaction, but also forming a double bond regioselectively from the products. The obtained optically active homoallylic carboxylates are useful in a variety of organic transformations.[9] The conjugate addition products were treated with tetrabutylammonium fluoride or refluxed in benzene in the presence of pyridine to effect elimination of the sulfinyl group. Treatment of **3d** with tetrabutylammonium fluoride in THF at room temperature afforded the olefin **13a** quantitatively through β-elimination of the trimethylsilyl and *p*-tolyl sulfinyl groups starting with an initial attack of a fluoride ion on the silicon. Other products also yielded the homoallylic carboxylates in good to excellent yields as shown in Table 6.

Table 6. Treatment of the Addition Products with TBAF into Homoallylic Carboxylates



entry	substrate	R^1	R^2	R^3	product	yield (%)
1	**3d**	Ph	H	Me	**13a**	quant
2	**6d**	Ph	Me	Me	**7**	quant
3	**6i**	Ph	CH(OH)Ph	Me	**13b**	85
4	**11a**		$-CH_2-$	Et	**13c**	56
5	**11b**		$-(CH_2)_2-$	Et	**13d**	83
6	**11c**		$-(CH_2)_3-$	Et	**13e**	92
7	**11d**		$-(CH_2)_4-$	Et	**13f**	94

Table 7. Thermal Treatment of the Addition Products into Homoallylic Carboxylates



entry	substrate	R^1	R^2	R^3	product	yield (%)	ratio *E*/*Z*
1	**3b**	Me	H	Me	**14a**	86	>98:2
2	**3d**	Ph	H	Me	**14b**	95	>98:2
3	**6a**	Me	Me	Me	**14c**	98	>98:2
4	**6d**	Ph	Me	Me	**14d**	90	>98:2
5	**6e**	Ph	$CH_2CH{=}CH_2$	Me	**14e**	99	>98:2
6	**6f**	Ph	CH_2Ph	Me	**14f**	99	>98:2
7	**6i**	Ph	CH(OH)Ph	Me	**8**	94	>98:2
8	**11a**		$-CH_2-$	Et	**14g**	56	83:17
9	**11b**		$-(CH_2)_2-$	Et	**14h**	83	>98:2
10	**11c**		$-(CH_2)_3-$	Et	**14i**	92	>98:2
11	**11d**		$-(CH_2)_4-$	Et	**14j**	94	>98:2

A benzene solution of **3b** was heated for 1 h in the presence of pyridine to give the (*E*)-vinylsilane **14a** in 86% yield (Table 7). All thermal elimination reactions exclusively formed the *E*-stereoisomers except for **11a** in which **14g** was obtained as an *E*/*Z* mixture of 83:17 (Table 7, entry 8). By examination of the vicinal coupling constants of the ring protons in the ^{1}H NMR spectra, no epimerization was confirmed to occur during the conversion of the adducts into homoallylic carboxylates.

Discussion

Alkylation of the enolates derived from the α,β-unsaturated esters having a substituent at the β-position

(9) For recent reviews of iodolactonizations, see: Cardillo, G.; Orena, M. In *Stereoselective Synthesis*; Helmchen, G., Hoffmann, R. W., Mulzer, J., Schaumann, E., Eds.; Houben-Weyl: New York, 1996; Vol. 8, pp 4698−4750.

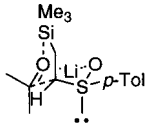


Figure 2. Plausible transition state in the reaction of α-sulfinyl carbanion **2** and a carbonyl compound.

shows high stereoselectivity and gives products having the stereochemistry predicted from the Felkin−Anh model.[8,10] The addition of the α-sulfinyl carbanion **2** to methyl crotonate and the subsequent alkylation gave products having the same stereochemistry as that predicted from the Felkin−Anh model. However, the trapping reaction of the enolate, derived from the reaction of **2** with acrylate, with methyl iodide also gave a single diastereomer of the product. This fact is not in accord with the results from the Felkin−Anh model, which usually show low stereoselectivity in alkylation of the enolates derived from γ-substituted carboxylates.[11] Recently, we demonstrated that a silicon−oxygen interaction plays an important role in stabilizing the transition state for the highly stereoselective reaction of α-lithio-β-silylethyl sulfoxides with carbonyl compounds.[5c] Figure 2 shows a plausible transition state that we have proposed on the basis of the stereochemical outcome as well as the MO calculation.

In these reactions, the trialkylsilyl group at the position β to the sulfinyl is essential to induce high stereoselectivity. Obviously, the excellent stereochemical outcome in the present conjugate addition is also ascribed to the presence of the β-trimethylsilyl group, since the reaction of the carbanion derived from 3,3-dimethylbutyl *p*-tolyl sulfoxide with methyl crotonate gave a diastereomeric mixture in a 69:31 ratio.[5b] In addition, the stereochemistry at the carbon α to the sulfinyl group is the same as that of the products obtained in both reactions with carbonyl compounds and with α,β-unsaturated carbonyl compounds. Therefore, we have assumed that the conjugate addition reaction proceeds via a bicyclic transition state that consists of the α-sulfinyl carbanion and the α,β-unsaturated carbonyl compound having an s-cis conformation and includes the silicon−oxygen interaction (Figure 3). There are several discussions about the transition state in the conjugate addition of α-sulfinyl carbanions derived from allyl sulfoxide[1f,g] and ketimine sulfoxide[1i,j,k] to α,β-unsaturated carbonyl compounds. In these papers, the reactions proceed via the 8- or 10-membered cyclic transition state, in which the α,β-unsaturated carbonyl compound has an s-trans conformation. However, the reaction of the α-sulfinyl carbanion **2** with 2-buten-4-olide as an s-trans ester gave neither a conjugate nor a carbonyl addition product, but led to recovery of the starting sulfoxide **1**. Furthermore,

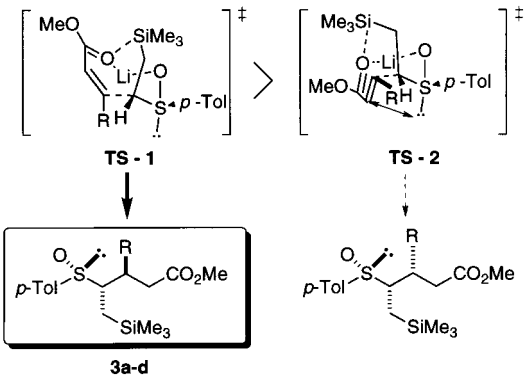


Figure 3. Transition states for stereoselective conjugate addition of **1**.

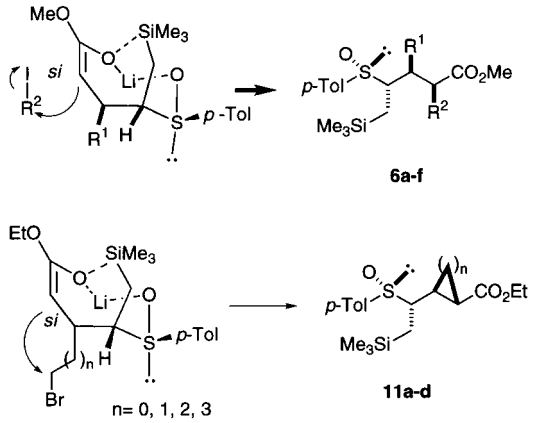


Figure 4. Intra- and intermolecular stereoselective alkylation of the enolates.

the reaction with 2-cyclopentenone as an s-trans ketone formed the carbonyl addition product **3d** in high yield without formation of the conjugate addition product (Table 2, entry 4). These results suggest that the s-cis conformation of α,β-unsaturated carbonyl compounds should be important at the transition state for the conjugate addition in the present reaction.

Figure 3 shows two possible transition states **TS-1** and **TS-2** stabilized by the silicon−oxygen interaction as proposed in the transition state for the reaction of the α-sulfinyl carbanion with ketones, aldehydes, or trimethyl phosphate (see Figure 2).[5c] Repulsion between the π-electrons of the α,β-unsaturated ester and the sulfinyl lone pair of electrons would develop in **TS-2**, whereas no such repulsive effect is expected in **TS-1**. Thus, the conjugate addition reaction gives the products **3a**−**d** with high stereoselectivity through the more preferable transition state **TS-1**. The high diastereoselectivity observed in the alkylation of the intermediate enolates with alkyl halides can also be explained by the intermediate structure formed through **TS-1**. The exo face of the bicyclic intermediate enolate is highly hindered by the trimethylsilylmethyl group (Figure 4).[12] An alkyl halide approaches only from the less hindered endo direction (the *si* face) to the enolate to give the products **6a**−**f** exclusively. Intramolecular cyclization also occurs on the *si* face of the enolate in the intermediate from the less hindered direction to avoid the trimethylsilylmethyl group, giving a trans compound **11a**−**d**.

(10) (a) Hoffmann, R. W. *Chem. Rev.* **1989**, *89*, 1841. (b) Bernhard, W.; Fleming, I.; Waterson, D. *J. Chem. Soc., Chem. Commun.* **1984**, 28. (c) Yamamoto, Y.; Maruyama, K. *J. Chem. Soc., Chem. Commun.* **1984**, 904. (d) Fleming, I.; Lewis, J. J. *J. Chem. Soc., Chem. Commun.* **1985**, 149. (e) Yamaguchi, M.; Hasebe, K.; Tanaka, S.; Minami, T. *Tetrahedron Lett.* **1986**, *27*, 959. (f) Yamaguchi, M.; Hasebe, M.; Nakashima, H.; Minami, T. *Tetrahedron Lett.* **1987**, *28*, 1785. (g) Kawasaki, H.; Tomioka, K.; Koga, K. *Tetrahedron Lett.* **1985**, *26*, 3031. (h) McGarvey, G. J.; Williams, J. M. *J. Am. Chem. Soc.* **1985**, *107*, 1435. (i) Fleming, I.; Hill, J. H. M.; Parker, D.; Waterson, D. *J. Chem. Soc., Chem. Commun.* **1985**, 318. (j) Tomioka, K.; Kawasaki, H.; Koga, K. *Tetrahedron Lett.* **1985**, *26*, 3027.

(11) (a) Kuehne, M. E.; Nelson, J. A. *J. Org. Chem.* **1970**, *35*, 161. (b) Krapcho, A. P.; Dundulis, E. A. *J. Org. Chem.* **1980**, *45*, 3236.

(12) The eight-membered ring chelation of sulfinyl oxygen and ester enolate has been postulated in the reaction of; Yoshizaki, H.; Tanaka, T.; Yoshii, E.; Koizumi, T.; Takeda, K. *Tetrahedron Lett.* **1998**, *39*, 47.

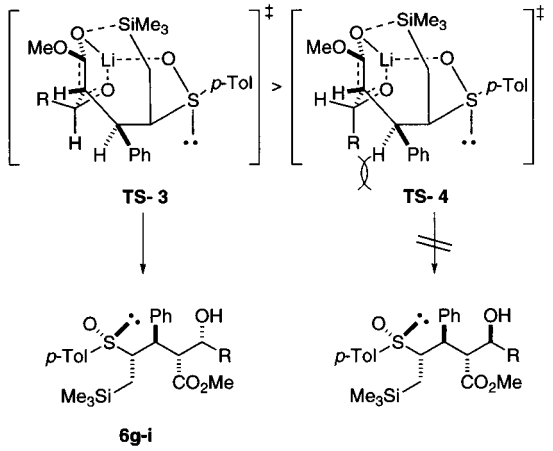


Figure 5. Transition states for the reaction of the enolates with aldehydes.

The highly stereoselective aldol reaction can be rationalized by the transition state developed by the addition of an aldehyde to the intermediate enolate as shown in Figure 5. If the reaction proceeds through a chairlike form at the transition state, there would be severe steric interaction in the concave ring. To avoid this hindrance, the aldehyde should approach by taking a boatlike form. Such transition states are depicted as **TS-3** or **TS-4** in Figure 5.

A significant steric interaction is anticipated to arise in **TS-4**, where the substituent R on the carbaldehyde such as the ethyl, isopropyl, or phenyl group is located close to the methine proton. Accordingly, the reaction proceeds preferentially through **TS-3** to give the aldol product **6g**−**i**.[13] The stereochemical outcome in protolysis of the enolates may be also explained through the bicyclic intermediate. Protonation with agents capable of forming a chelating complex with the enolate, shows particularly high diastereoselectivity in the kinetically controlled protonation.[14] Recently, Krause and co-workers have reported highly stereoselective protonation of enolates with ethyl salicylate which are capable of forming a chelating complex. In our reaction, isopropyl salicylate gave 2,3-anti-**6** with high stereoselectivity. Protonation with ethanolamine or 2-aminophenol also proceeded to give the product with high selectivity, whereas protonation with H_2O or nonchelating 2,6-di-*tert*-butylphenol showed low stereoselectivity.

Easy elimination of the sulfinyl group and high *E* selectivity of the products are apparently due to the effect of the vicinal silyl group.[15] Under thermal conditions, the silyl group accelerates the elimination, since the silyl group is a conjugatively electron-withdrawing group.[15b] Thus, the elimination proceeded with complete regioselectivity. The *E*-olefins were exclusively formed in most reactions because the syn elimination proceeds through a transition state avoiding the steric interaction between the trimethylsilyl group and the cycloalkane ring. However, this is not the case in the elimination reaction of the cyclopropanecarboxylate **11a**, where small interaction relative to other cycloalkanecarboxylates **11b**−**d** would occur between the trimethylsilyl and cyclopropyl groups at the transition state **TS-8** to give a mixture of the *E*- and *Z*-olefins (Figure 6).

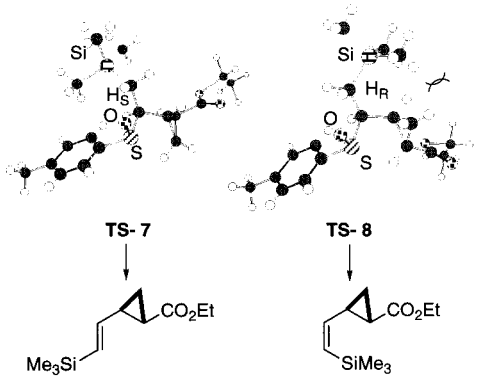


Figure 6. Elimination reaction of **11a**.

In summary, *p*-tolyl 2-(trimethylsilyl)ethyl sulfoxide is demonstrated to be a powerful chiral vinyl anion equivalent that may be used to construct new chiral centers. This reaction of *p*-tolyl 2-(trimethylsilyl)ethyl sulfoxide with α,*β*-unsaturated esters provides a convenient method for the preparation of optically pure homoallylic carboxylates, which have three or four chiral centers, via subsequent thermal elimination of the sulfinyl group or concurrent elimination of the sulfinyl and silyl groups.

Experimental Section

Representative Procedure for the Reaction of *p*-Tolyl α-Lithio-(*β*-trimethylsilyl)ethyl Sulfoxides with α,*β*-Unsaturated Esters. Methyl (*R*$_S$,3*S*,4*R*)-3-Methyl-4-(*p*-tolylsulfinyl)-5-trimethylsilylpentanoate (3b). To a solution of diisopropylamine (0.040 mL, 0.285 mmol) in THF (0.40 mL) was added *n*-butyllithium (1.46 mol L^{-1}, 0.18 mL, 0.263 mmol) at 0 °C, and the mixture was stirred for 10 min. The reaction mixture was then cooled to −78 °C, and a solution of *p*-tolyl (*R*)-2-(trimethylsilyl)ethyl sulfoxide[5a] (**1**) (49.8 mg, 0.207 mmol) in THF (0.40 mL) was added. After being stirred for 5 min, the solution of methyl crotonate (0.030 mL, 0.283 mmol) in THF (0.4 mL) was added at −78 °C, and the mixture was stirred for additional 15 min. Saturated aqueous NH_4Cl (20 mL) was added, and the mixture was extracted with CH_2Cl_2. The combined organic extracts were washed with brine, dried over Na_2SO_4, and concentrated under reduced pressure to leave a residue that was purified by column chromatography (silica gel 10 g, hexane/ethyl acetate = 88:12) to give **3b** (67.0 mg, 95%): TLC R_f = 0.36 (hexane/ethyl acetate = 70/30); $[\alpha]^{26}_D$ +58.1 (*c* 0.310, $CHCl_3$); ^{1}H NMR δ −0.15 (s, 9H), 0.68 (dd, 1H, *J* = 2.9, 15.3 Hz), 0.93 (dd, 1H, *J* = 11.2, 15.3 Hz), 0.90−1.10 (m, 1H), 1.23 (d, 3H, *J* = 7.0 Hz), 2.41 (s, 3H), 2.55−2.75 (m, 2H), 2.87 (dd, 1H, *J* = 9.2, 15.2 Hz), 3.73 (s, 3H), 7.30 (d, 2H, *J* = 8.3 Hz), 7.38 (d, 2H, *J* = 8.3 Hz); ^{13}C NMR δ −1.4, 7.8, 15.9, 21.3, 33.9, 40.3, 51.7, 67.2, 124.1, 129.6, 140.2, 172.7; IR (KBr) 2950, 1750, 1060 cm^{-1}; SIMS *m*/*z* (rel intensity) 340.2 (M^+, 23), 200.2 (100). Anal. Calcd for $C_{17}H_{28}O_3SSi$: C, 59.96; H, 8.29. Found: C, 59.96; H, 8.29.

Trapping Reaction of the Enolate Derived from the Reaction of *p*-Tolyl α-Lithio-(*β*-trimethylsilyl)ethyl Sulfoxide and α,*β*-Unsaturated Esters. Methyl (*R*$_S$,2*S*,3*R*,4*R*)-2-Methyl-3-phenyl-4-(*p*-tolylsulfinyl)-5-trimethylsilylpentanoate (6d). To a solution of diisopropylamine (0.090 mL, 0.640 mmol) in THF (0.60 mL) was added *n*-butyllithium (1.46

(13) It was not successful to obtain the silylated ester enolate by treatment of the enolate with TMSCl, giving complex products presumably because of the sila-Pummerer reaction; see: Kita, Y.; Shibata, N. *Synlett* **1996**, 289.

(14) (a) Awandi, D.; Henin, F.; Muzart, J.; Pete, J.-P. *Tetrahedron: Asymmetry* **1991**, *2*, 1011. (b) Krause, N. *Angew. Chem., Int. Ed. Engl.* **1994**, *33*, 1764. (c) Fehr, C. *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 2566. (d) Krause, N.; Ebert, S.; Haubrich, A. *Liebigs Ann.* **1997**, 2409. (e) Eames, J. *Tetrahedron Lett.* **1999**, *40*, 5787.

(15) (a) Ochiai, M.; Tada, S.; Sumi, K.; Fujita, E. *J. Chem. Soc., Chem. Commun.* **1982**, 281. (b) Fleming, I.; Goldhill, J.; Perry, D. A. *J. Chem. Soc., Perkin. Trans. 1* **1982**, 1563.

mol L^{-1}, 0.40 mL, 0.584 mmol) at 0 °C, and the mixture was stirred for 10 min. The reaction mixture was then cooled to −78 °C. A solution of the sulfoxide **1** (111.2 mg, 0.462 mmol) in THF (0.50 mL) was added, and the mixture was stirred for 5 min. The solution of methyl cinnamate (97.8 mg, 0.601 mmol) in THF (0.6 mL) was added, and the mixture was stirred for an additional 15 min. Methyl iodide (0.06 mL, 0.963 mmol) was then added. The cooling bath was changed to an ice−water bath, and the mixture was stirred for 30 min at 0 °C. Usual workup gave a reduced pressure to leave an oil that was purified by column chromatography (silica gel 30 g, CH_2Cl_2/Et_2O = 99:1) to give **6d** (145.2 mg, 75%) and **3d** (26.1 mg, 14%). **6d**: TLC R_f = 0.42 (hexane/ethyl acetate = 80:20 × 2); $[\alpha]^{26}_D$ +71.8 (*c* 0.266, $CHCl_3$); ^{1}H NMR δ −0.20 (s, 9H), 0.49 (dd, 1H, *J* = 10.6, 15.6 Hz), 0.73 (dd, 1H, *J* = 1.7, 15.6 Hz), 1.06 (d, 3H, *J* = 6.9 Hz), 2.40 (s, 3H), 2.73 (ddd, 1H, *J* = 1.7, 3.6, 10.6 Hz), 3.19 (dd, 1H, *J* = 3.6, 10.8 Hz), 3.66 (dd, 1H, *J* = 6.9, 10.8 Hz), 3.81 (s, 3H), 7.19−7.43 (m, 9H); ^{13}C NMR δ −1.5, 8.4, 16.8, 20.7, 43.5, 51.9, 52.1, 67.1, 124.1, 127.7, 127.9, 128.4, 128.6, 129.6, 130.1, 179.5; IR (KBr) 1730, 1090 cm^{-1}; SIMS *m*/*z* (rel intensity) 416.2 (M^+, 7), 276.2 (100). Anal. Calcd for $C_{23}H_{32}O_3SSi$: C, 66.30; H, 7.74. Found: C, 66.12; H, 7.81.

Methyl (*R*$_S$,2*R*,3*R*,4*R*)-3-Phenyl-2-[(*S*)-phenylhydoxymethyl]-4-(*p*-tolylsulfinyl)-5-(trimethylsilyl)pentanoate (6i). The reaction was carried out as described above using **1** (140.2 mg, 0.583 mmol), methyl cinnamate (125.0 mg, 0.771 mmol), and benzaldehyde (0.12 mL, 1.18 mmol). Purification by column chromatography (hexane/ethyl acetate = 85:15) afforded **6i** (290.7 mg, 98%). **6i**: TLC R_f = 0.79 (CH_2Cl_2/Et_2O = 90:10); $[\alpha]^{20}_D$ +57.6 (*c* 0.180, $CHCl_3$); ^{1}H NMR δ −0.17 (s, 9H), 0.58 (dd, 1H, *J* = 10.5, 15.7 Hz), 0.73 (dd, 1H, *J* = 2.1, 15.7 Hz), 1.70 (br, 1H), 2.38 (s, 3H), 2.56 (ddd, 1H, *J* = 2.1, 2.7, 10.5 Hz), 3.57 (s, 3H), 3.75 (dd, 1H, *J* = 2.7, 12.1 Hz), 4.00 (dd, 1H, *J* = 3.0, 12.1 Hz), 4.60−4.67 (m, 1H), 7.12−7.63 (m, 14H); ^{13}C NMR δ −1.5, 8.4, 21.3, 48.3, 51.7, 56.3, 67.3, 71.5, 124.0, 124.8, 124.9, 125.1, 127.5, 128.1, 128.3, 128.4, 128.8, 129.0, 129.6, 130.0, 185.5; IR (KBr) 3400, 1730, 1090 cm^{-1}; SIMS *m*/*z* (rel intensity) 508.2 (M^+, 8), 368.2 (45), 184.0 (100). Anal. Calcd for $C_{29}H_{36}O_4SSi$: C, 68.47; H, 7.13. Found: C, 68.50; H, 7.29.

Representative Procedure for the Conversion of 6d into the Homoallylic Esters 7 with Tetrabutylammonium Fluoride. Methyl (2*S*,3*R*)-2-Methyl-3-phenyl-4-pentenoate (7). To a solution of **6d** (61.0 mg, 0.146 mmol) in THF (1.0 mL) was added a THF solution of tetrabutylammonium fluoride (TBAF) (1.0 mol L^{-1}, 0.30 mL, 0.30 mmol) at 0 °C, and the mixture was stirred for 1 h. THF was then evaporated under reduced pressure, and the residue was purified by column chromatography (silica gel 5 g, hexane/CH_2Cl_2 = 80:20) to give **7** (30.2 mg, 100%): TLC R_f = 0.76 (CH_2Cl_2); $[\alpha]^{26}_D$ +58.8 (*c* 0.26, $CHCl_3$); ^{1}H NMR δ 0.98 (d, 3H, *J* = 6.9 Hz), 2.84 (dq, 1H, *J* = 6.9, 10.4 Hz), 3.45 (dd, 1H, *J* = 8.3, 10.4 Hz), 3.69 (s, 3H), 4.97−5.12 (m, 2H), 6.01 (ddd, 1H, *J* = 8.3, 10.2, 17.1 Hz), 7.14−7.38 (m, 5H); ^{13}C NMR δ 15.9, 45.2, 51.5, 53.8, 115.4, 126.7, 128.1, 128.7, 139.7, 141.3, 176.1; IR (neat) 1740, 920 cm^{-1}; EIMS *m*/*z* (rel intensity) 204.1 (M^+, 23), 27.9 (100). Anal. Calcd for $C_{13}H_{16}O_2$: C, 76.44; H, 7.89. Found: C, 76.31; H, 8.02.

Representative Procedure for the Conversion of 6i into the Homoallylic Ester 8 under Thermal Conditions. Methyl (2*R*,3*S*)-(*E*)-2-[(*S*)-Hydroxyphenylmethyl]-3-phenyl-5-trimethylsilyl-4-pentenoate (8). A solution of **6i** (60.0 mg, 0.118 mmol) and pyridine (0.048 mL, 0.590 mmol) in benzene (2.0 mL) was heated under reflux for 1 h. After the mixture was cooled, the solvent was evaporated under reduced pressure and the residue was purified by column chromatography (silica gel 10 g, hexane/CH_2Cl_2 = 80:20) to give **8** (41.0 mg, 94%) as a colorless oil: TLC R_f = 0.43 (hexane/ethyl acetate = 80:20); $[\alpha]^{26}_D$ +36.5 (*c* 0.43, $CHCl_3$); ^{1}H NMR δ 0.02 (s, 9H), 3.15 (dd, 1H, *J* = 3.0, 11.0 Hz), 3.47 (s, 3H), 3.87 (d, 1H, *J* = 9.9 Hz), 3.93 (dd, 1H, *J* = 8.5, 11.0 Hz), 4.44 (dd, 1H, *J* = 3.0, 9.9 Hz), 5.75 (d, 1H, *J* = 18.4 Hz), 6.20 (dd, 1H, *J* = 8.5, 18.4 Hz), 7.15−7.45 (m, 5H); ^{13}C NMR δ −1.4, 51.3, 53.0, 57.8, 71.8, 125.0, 125.1, 127.0, 127.3, 128.1, 128.3, 129.0, 132.2, 142.5, 145.8, 174.6; IR (neat) 3500, 1720, 1250, 970 cm^{-1}; EIMS *m*/*z* (rel intensity) 368.1 (M^+, 0.6), 262.2 (20), 73.1 (100). Anal. Calcd for $C_{22}H_{28}O_3Si$: C, 71.70; H, 7.66. Found: C, 71.48; H, 7.88.

(1*S*,2*S*)-2-1-Phenyl-[(3*S*)-3-(3-phenyl-1-trimethylsilyl-1-propenyl)]-1,3-propanediol (9). To a solution of $LiAlH_4$ (110.0 mg, 2.90 mmol) in Et_2O (5.0 mL) was added a solution of **8** (227.9 mg, 0.618 mmol) in Et_2O (2.0 mL) at 0 °C. The reaction mixture was then warmed to room temperature and stirred for 1 h. Saturated aqueous NH_4Cl (20 mL) was added, and the mixture was extracted with CH_2Cl_2. The combined organic extracts were washed with brine and dried over Na_2SO_4. The solvent was removed under reduced pressure to leave a residue that was purified by column chromatography (silica gel 15 g, hexane/ethyl acetate = 90:10) to give **9** (201.5 mg, 95%): TLC R_f = 0.33 (hexane/ethyl acetate = 80:20); $[\alpha]^{20}_D$ +56.1 (*c* 0.746, $CHCl_3$); ^{1}H NMR δ 0.06 (s, 9H), 1.97−2.10 (m, 1H), 2.78 (br, 1H), 3.45 (br, 1H), 3.70−3.92 (m, 3H), 4.57−4.67 (m, 1H), 5.84 (d, 1H, *J* = 18.4 Hz), 6.22 (dd, 1H, *J* = 8.8, 18.4 Hz), 7.20−7.42 (m, 10H); ^{13}C NMR δ −1.2, 50.6, 60.6, 75.2, 125.5, 126.4, 127.1, 128.0, 128.3, 128.8, 132.3, 142.8, 143.8, 147.0; IR (neat) 3350, 1250, 880 cm^{-1}; EIMS *m*/*z* (rel intensity) 340.2 (M^+, 21), 187.2 (82), 73.1(100). Anal. Calcd for $C_{21}H_{28}O_2Si$: C, 74.07; H, 8.29. Found: C, 73.80; H, 8.56.

(4*S*,5*S*)-2,2-Dimethyl-4-phenyl-5-[(*S*)-1-phenyl-3-trimethylsilyl-2-propenyl]-1,3-dioxane (10). A solution of **9** (23.4 mg, 0.068 mmol), 2,2-dimethoxypropane (0.060 mL, 0.488 mmol), and a catalytic amount of *p*-toluenesulfonic acid in DMF (5.0 mL) was heated under reflux for 3 h. After the mixture was cooled, CH_2Cl_2 was added. The organic solution was washed with water and brine and dried over Na_2SO_4. The solvent was removed under reduced pressure to leave a residue that was purified by column chromatography (silica gel 3 g, hexane/ethyl acetate = 98:2) to give **10** (23.3 mg, 89%): TLC R_f = 0.73 (hexane/ethyl acetate = 80:20); $[\alpha]^{20}_D$ +105.2 (*c* 0.88, $CHCl_3$); ^{1}H NMR δ 0.07 (s, 9H), 1.36 (s, 3H), 1.46 (s, 3H), 2.31−2.47 (m, 1H), 3.16 (dd, 1H, *J* = 4.1, 9.4 Hz), 3.74 (dd, 1H, *J* = 5.2, 11.9 Hz), 3.92 (dd, 1H, *J* = 11.8, 11.9 Hz), 4.67 (d, 1H, *J* = 10.4 Hz), 5.65 (d, 1H, *J* = 18.4 Hz), 6.23 (dd, 1H, *J* = 9.4, 18.4 Hz), 6.83−7.33 (m, 10H); ^{13}C NMR δ −1.2, 19.7, 29.1, 45.6, 50.7, 60.6, 75.5, 98.8, 126.2, 127.5, 127.8, 128.0, 128.2, 128.3, 128.5, 135.1, 140.0, 141.9, 143.4; IR (neat) 1250, 1230, 1170, 880 cm^{-1}; EIMS *m*/*z* (rel intensity) 380.2 (M^+, 100), 365.2 (50), 73.1 (100). Anal. Calcd for $C_{24}H_{32}O_2Si$: C, 75.74; H, 8.47. Found: C, 75.50; H, 8.71.

Representative Procedure for Protonation of the Intermediate Enolates. Methyl (*R*$_S$,2*S*,3*S*,4*R*)- and (*R*$_S$,2*R*,-3*S*,4*R*)-2,3-Dimethyl-4-(*p*-tolylsulfinyl)-5-trimethylsilylpentanoate (6b). To a solution of diisopropylamine (0.040 mL, 0.285 mmol) in THF (0.40 mL) was added *n*-butyllithium (1.37 mol L^{-1}, 0.17 mL, 0.233 mmol) at 0 °C, and the mixture was stirred for 10 min. The reaction mixture was then cooled to −78 °C, and a solution of the sulfoxide **1** (43.2 mg, 0.180 mmol) in THF (0.40 mL) was added. After the mixture was stirred for 5 min, a solution of methyl tiglate (26.7 mg, 0.234 mmol) in THF (0.4 mL) was added, and the mixture was stirred for an additional 15 min. The reaction mixture was then cooled to −100 °C. A solution of isopropyl salicylate (116.0 mg, 0.644 mmol) in THF (0.4 mL) was added, and the mixture was stirred for 15 min. Usual workup gave a residue that was purified by column chromatography (silica gel 12 g, hexane/CH_2Cl_2/Et_2O = 50:35:15) to give *syn*-**6b** (6.4 mg, 10%) and *anti*-**6b** (56.1 mg, 88%). The syn/anti ratio was determined to be 10:90 by the ^{1}H NMR analysis of the crude product. *syn*-**6b**: TLC R_f = 0.42 (hexane/ethyl acetate = 70:30); $[\alpha]^{27}_D$ +35.2 (*c* 1.05, $CHCl_3$); ^{1}H NMR δ −0.16 (s, 9H), 0.71 (dd, 1H, *J* = 2.7, 15.3 Hz), 0.93 (dd, 1H, *J* = 11.3, 15.3 Hz), 1.19 (d, 3H, *J* = 6.9 Hz), 1.30 (d, 3H, *J* = 7.0 Hz), 2.00−2.20 (m, 1H), 2.41 (s, 3H), 2.73 (ddd, 1H, *J* = 2.7, 2.7, 11.3 Hz), 2.92 (dq, 1H, *J* = 7.0, 8.6 Hz), 3.73 (s, 3H), 7.30 (d, 2H, *J* = 7.5 Hz), 7.38 (d, 2H, *J* = 7.5 Hz); ^{13}C NMR δ −1.4, 8.1, 13.4, 15.8, 21.2, 40.1, 44.3, 51.6, 65.0, 123.9, 129.7, 140.3, 140.5, 176.0; IR (KBr) 1740, 1060, cm^{-1}; SIMS *m*/*z* (rel intensity) 354.2 (M^+, 10), 214.2 (75), 92.4 (100). Anal. Calcd for $C_{18}H_{30}O_3SSi$: C, 60.97; H, 8.53. Found: C, 60.99; H, 8.30. *anti*-**6b**: TLC R_f = 0.42 (hexane/ethyl acetate = 70:30); ^{1}H NMR δ −0.18 (s, 9H), 0.65 (dd, 1H, *J* = 2.5, 15.2

Hz), 0.93 (dd, 1H, J = 11.3, 15.2 Hz), 0.90−1.15 (m, 1H), 1.22 (d, 3H, J = 7.1 Hz), 1.30 (d, 3H, J = 6.9 Hz), 2.40 (s, 3H), 2.49 (ddd, 1H, J = 2.4, 2.5, 11.3 Hz), 3.02 (dq, 1H, J = 6.9, 10.2 Hz), 3.70 (s, 3H), 7.25−7.45 (m, 4H); ^{13}C NMR δ −1.5, 7.9, 12,4, 16.0, 21.3, 40.0, 44.9, 51.6, 67.0, 124.0, 129.5, 140.3, 176.5; IR (KBr) 1740, 1070, cm^{-1}; SIMS m/z (rel intensity) 354.2 (M$^+$, 11), 214.2 (100), 136.0 (100), 110.3 (100). Anal. Calcd for $C_{18}H_{30}O_3SSi$: C, 60.97; H, 8.53. Found: C, 61.04; H, 8.46.

Stereoselective Cyclization Reaction through the Conjugate Addition of the Sulfinyl Carbanion 2 to ω-Halo-α,β-unsaturated Esters. Ethyl (R_S,1*S*,2*S*)-2-[(1*R*)-1-(*p*-Tolylsulfinyl)-2-(trimethylsilyl)ethyl]cyclopropanecarboxylate (11a). To a solution of diisopropylamine (0.040 mL, 0.285 mmol) in THF (0.28 mL) was added *n*-butyllithium (1.44 mol L^{-1}, 0.175 mL, 0.252 mmol) at 0 °C, and the mixture was stirred for 10 min. The reaction mixture was then cooled to −78 °C, a solution of sulfoxide **1** (48.3 mg, 0.201 mmol) in THF (0.20 mL) was added, and the mixture was stirred for 5 min. The solution of ethyl 4-bromo-2-butenoate (0.040 mL, 0.290 mmol) in THF (0.23 mL) was then added. After the mixture was stirred for an additional 15 min, saturated aqueous NH_4Cl (20 mL) was added. Usual workup gave a residue that was purified by column chromatography (silica gel 15 g, hexane/CH_2Cl_2 = 80:20) to give **11a** (56.4 mg, 80%): TLC R_f = 0.19 (CH_2Cl_2/Et_2O/hexane = 35:15:50); $[\alpha]^{20}_D$ +166.3 (*c* 0.22, $CHCl_3$); ^{1}H NMR δ 0.00 (s, 9H), 0.80−0.91 (m, 2H), 1.10−1.45 (m, 3H), 1.24 (t, 3H, J = 7.1 Hz), 1.50−1.65 (m, 1H), 2.19 (ddd, 1H, J = 7.4, 7.4, 9.1 Hz), 2.43 (s, 3H), 4.11 (q, 2H, J = 7.1 Hz), 7.32 (d, 2H, J = 8.1 Hz), 7.48 (d, 2H, J = 8.1 Hz); ^{13}C NMR δ −0.9, 14.0, 14.2, 14.6, 20.6, 21.4, 23.1, 60.7, 66.0, 125.1, 129.6, 139.3, 141.4, 173.1; IR (KBr) 1730, 1090 cm^{-1}; SIMS m/z (rel intensity) 352.2 (M$^+$, 5), 212.2 (41), 93.2 (100). Anal. Calcd for $C_{18}H_{28}O_3SSi$: C, 61.32; H, 8.00. Found: C, 61.49; H, 8.17.

Ethyl (R_S,1*S*,2*S*)-2-[(1*R*)-1-(*p*-Tolylsulfinyl)-2-(trimethylsilyl)ethyl]cyclobutanecarboxylate (11b). (1) Reaction with Ethyl 5-Bromo-2-pentenoate. To a solution of diisopropylamine (0.045 mL, 0.320 mmol) in THF (0.30 mL) was added *n*-butyllithium (1.49 mol L^{-1}, 0.190 mL, 0.283 mmol) at 0 °C, and the mixture was stirred for 10 min. The reaction mixture was then cooled to −78 °C, and a solution of the sulfoxide **1** (54.0 mg, 0.225 mmol) in THF (0.23 mL) was added. After the mixture was stirred for 5 min, a solution of ethyl 5-bromo-2-pentenoate (81.6 mg, 0.394 mmol) in THF (0.20 mL) and subsequently HMPA (0.05 mL, 0.297 mmol) were added. The mixture was warmed to room temperature and stirred for 15 min. Usual workup gave a residue that was purified by column chromatography (silica gel 12 g, hexane/ethyl acetate = 85:15) to give **11b** (40.3 mg, 49%) and **12b** (X = Br) (29.6 mg, 29%). **11b**: TLC R_f = 0.40 (CH_2Cl_2/Et_2O = 97:3); $[\alpha]^{20}_D$ +145.0 (*c* 0.65, $CHCl_3$); ^{1}H NMR δ −0.18 (s, 9H), 0.62 (dd, 1H, J = 9.1, 15.4 Hz), 0.78 (dd, 1H, J = 3.7, 15.4 Hz), 1.28 (t, 3H, J = 7.1 Hz), 1.95−2.28 (m, 4H), 2.41 (s, 3H), 2.61 (ddd, 1H, J = 3.7, 5.8, 9.1 Hz), 2.80−3.01 (m, 1H), 3.30−3.50 (m, 1H), 4.16 (q, 2H, J = 7.1 Hz), 7.34 (d, 2H, J = 7.1 Hz), 7.39 (d, 2H, J = 7.1 Hz); ^{13}C NMR δ −1.4, 8.2, 14.3, 21.3, 21.7, 22.2, 41.8, 41.9, 60.5, 66.0, 124.3, 129.7, 130.2, 139.4, 178.2; IR (neat) 1730, 1090 cm^{-1}; SIMS m/z (rel intensity) 226.2 (69), 185.0 (42), 91.0 (100). Anal. Calcd for $C_{19}H_{30}O_3SSi$: C, 62.24; H, 7.85. Found: C, 62.46; H, 7.99. **12b** (X = Br): TLC R_f = 0.25 (CH_2Cl_2/Et_2O = 97:3); ^{1}H NMR δ −0.17 (s, 9H), 0.68−1.02 (m, 2H), 1.32 (t, 3H, J = 7.1 Hz), 1.90 (ddd, 1H, J = 5.8, 10.8, 19.7 Hz), 2.28−2.45 (m, 2H), 2.40 (s, 3H), 2.47−2.89 (m, 3H), 3.40 (ddd, 1H, J = 5.2, 10.8, 11.0 Hz), 3.62 (ddd, 1H, J = 4.5, 5.8, 11.0 Hz), 4.20 (q, 2H, J = 7.1 Hz), 7.30 (d, 2H, J = 7.3 Hz), 7.38 (d, 2H, J = 7.3 Hz); ^{13}C NMR δ −1.5, 8.0, 14.3, 21.3, 31.5, 32.3, 37.3, 60.9, 66.2, 124.1, 129.7, 139.9, 140.7, 172.1; IR (neat) 1740, 1090 cm^{-1}; SIMS m/z (rel intensity) 448.1 (M$^+$ + 2, 18), 446.1 (M$^+$, 18), 308.1 (100), 306.1 (100). Anal. Calcd for $C_{19}H_{31}BrO_3SSi$: C, 50.99; H, 6.98. Found: C, 51.17; H, 6.70.

(2) Reaction with Ethyl 5-Iodo-2-pentenoate. The reaction was carried out as described above using **1** (48.0 mg, 0.200 mmol), ethyl 5-iodo-2-pentenoate (70.2 mg, 0.272 mmol), and HMPA (0.045 mg, 0.259 mmol). Purification by column chromatography (silica gel 10 g, hexane/ethyl acetate = 85:15) afforded **11b** (48.1 mg, 66%) and **12b** (X = I) (22.0 mg, 22%). **12b** (X = I): TLC R_f = 0.52 (hexane/ethyl acetate = 70:30); ^{1}H NMR δ 0.17 (s, 9H), 0.73−0.81 (m, 2H), 1.32 (t, 3H, J = 7.1 Hz), 1.92−2.10 (m, 1H), 2.24−2.47 (m, 2H), 2.40 (s, 3H), 2.58 (m, 3H), 3.13 (ddd, 1H, J = 6.0, 9.9, 10.1 Hz), 3.42 (ddd, 1H, J = 4.5, 6.7, 10.1 Hz), 4.08−4.32 (m, 2H), 7.28 (d, 2H, J = 8.5 Hz), 7.38 (d, 2H, J = 8.5 Hz); ^{13}C NMR δ −1.5, 4.5, 7.9, 14.3, 21.3, 32.9, 37.0, 39.5, 60.9, 66.1, 124.1, 129.6, 139.9, 140.7, 172.2; IR (neat) 1730, 1080 cm^{-1}; SIMS m/z (rel intensity) 494.1 (M$^+$, 5), 354.1 (100). Anal. Calcd for $C_{19}H_{31}IO_3SSi$: C,46.15; H, 6.32. Found: C, 46.23; H, 6.22.

Ethyl (R_S,1*S*,2*S*)-2-[(1*R*)-1-(*p*-Tolylsulfinyl)-2-(trimethylsilyl)ethyl]cyclopentanecarboxylate (11c). To a solution of diisopropylamine (0.065 mL, 0.462 mmol) in THF (0.45 mL) was added *n*-butyllithium (1.49 mol L^{-1}, 0.290 mL, 0.432 mmol) at 0 °C, and the mixture was stirred for 10 min. The reaction mixture was then cooled to −78 °C, a solution of sulfoxide **1** (51.5 mg, 0.214 mmol) in THF (0.22 mL) was added, and the mixture was stirred for 5 min. The solution of ethyl 6-iodo-2-hexenoate (77.8 mg, 0.352 mmol) in THF (0.23 mL) was then added. After the mixture was stirred for an additional 15 min, saturated aqueous NH_4Cl (20 mL) was added. Usual workup gave a residue that was purified by column chromatography (silica gel 20 g, hexane/ethyl acetate = 90:10) to give **11c** (71.7 mg, 88%) and **12c** (4.2 mg, 4%). **11c**: TLC R_f = 0.49 (hexane/ethyl acetate = 70:30); $[\alpha]^{20}_D$ +108.8 (*c* 0.332, $CHCl_3$); ^{1}H NMR δ −0.17 (s, 9H), 0.73 (dd, 1H, J = 3.1, 15.6 Hz), 0.87 (dd, 1H, J = 11.0, 15.6 Hz), 1.31 (t, 3H, J = 7.1 Hz), 1.62−2.18 (m, 6H,), 2.41 (s, 3H), 2.49 (dddd, 1H, J = 3.1, 8.7, 9.0, 9.0 Hz), 2.82 (ddd, 1H, J = 3.1, 3.1, 11.0 Hz), 3.19 (ddd, 1H, J = 8.3, 8.7, 10.1 Hz), 4.19 (q, 2H, J = 7.1 Hz), 7.28 (d, 2H, J = 8.3 Hz), 7.35 (d, 2H, J = 8.3 Hz); ^{13}C NMR δ −1.4, 9.2, 14.3, 21.3, 24.4, 27.5, 29.4, 47.8, 48.0, 60.6, 65.8, 123.9, 130.0, 140.3, 175.4; IR (KBr) 1730, 1090 cm^{-1}; SIMS m/z (rel intensity) 380.2 (M$^+$, 21), 240.2 (100). Anal. Calcd for $C_{20}H_{32}O_3SSi$: C, 63.11; H, 8.47. Found: C, 63.35; H, 8.23. **12c**: TLC R_f = 0.43 (hexane/ethyl acetate = 70:30); ^{1}H NMR δ −0.15 (s, 9H), 0.47 (dd, 1H, J = 4.0, 14.7 Hz), 0.63 (dd, 1H, J = 9.8, 14.7 Hz), 1.29 (t, 3H, J = 7.2 Hz), 1.60−2.10 (m, 5H), 2.42 (s, 3H), 2.50−2.80 (m, 2H), 3.13 (ddd, 1H, J = 2.7, 4.0, 9.8 Hz), 3.50−3.65 (m, 2H), 4.16 (q, 2H, J = 7.2 Hz), 7.29 (d, 2H, J = 8.2 Hz), 7.59 (d, 2H, J = 8.2 Hz); IR (KBr) 2940, 1730, 1480, 1430, 1420, 1390, 1250, 1190, 1100, 1090, 1030, 870, 860, 800 cm^{-1}; SIMS m/z (rel intensity) 460.1 (M$^+$, 11), 320.1 (9), 241.0 (100), 147.0 (100). Anal. Calcd for $C_{20}H_{33}BrO_3SSi$: C, 52.05; H, 7.21. Found: C, 52.32; H, 6.94.

Ethyl (R_S,1*S*,2*S*)-2-[(1*R*)-1-(*p*-Tolylsulfinyl)-2-(trimethylsilyl)ethyl]cyclohexanecarboxylate (11d). To a solution of diisopropylamine (0.080 mL, 0.562 mmol) in THF (0.56 mL) was added *n*-butyllithium (1.49 mol L^{-1}, 0.36 mL, 0.536 mmol) at 0 °C, and the mixture was stirred for 10 min. The reaction mixture was then cooled to −78 °C. A solution of the sulfoxide **1** (103.6 mg, 0.431 mmol) in THF (0.40 mL) was added, and the mixture was stirred for 5 min. The solution of ethyl 6-bromo-2-hexenoate (144.6 mg, 0.615 mmol) in THF (0.50 mL) was added, and the mixture was stirred for an additional 15 min. The cooling bath was changed to an ice−water bath, and the mixture was stirred for 15 min at 0 °C. Usual workup gave a reduced pressure to leave an oil that was purified by column chromatography (silica gel 15 g, hexane/ethyl acetate = 80:20) to give **11d** (158.4 mg, 93%) and **12d** (X = Br) (15.5 mg, 7%). **11d**: TLC R_f = 0.49 (hexane/ethyl acetate = 70:30); $[\alpha]^{20}_D$ +34.1 (*c* 0.346, $CHCl_3$); ^{1}H NMR δ −0.14 (s, 9H), 0.56 (dd, 1H, J = 2.7, 15.0 Hz), 1.03 (dd, 1H, J = 11.9, 15.0 Hz), 1.32 (t, 3H, J = 7.1 Hz), 1.15−2.10 (m, 9H), 2.40 (s, 3H), 2.51 (ddd, 1H, J = 2.4, 2.7, 11.9 Hz), 2.99 (ddd, 1H, J = 3.8, 11.3, 11.3 Hz), 4.19 (q, 2H, J = 7.1 Hz), 7.29 (d, 2H, J = 8.3 Hz), 7.37 (d, 2H, J = 8.3 Hz); ^{13}C NMR δ −1.4, 6.8, 14.3, 21.3, 25.3, 25.9, 26.2, 30.5, 42.8, 48.4, 60.5, 66.9, 124.0, 129.5, 140.3, 140.4, 175.4; IR (KBr) 1720, 1050 cm^{-1}; SIMS m/z (rel intensity) 394.2 (M$^+$, 10), 254.2 (100). Anal. Calcd for $C_{21}H_{34}O_3SSi$: C, 63.91; H, 8.68. Found: C, 64.18; H, 8.51. **12d** (X = Br): TLC R_f = 0.38 (hexane/ethyl acetate = 70:30); ^{1}H NMR δ −0.15 (s, 9H), 0.69 (dd, 1H, J = 3.1, 15.4 Hz), 0.88 (dd, 1H, J = 11.0, 15.0 Hz), 1.31 (t, 3H, J = 7.1 Hz), 1.20−1.95 (m, 7H), 2.20−2.40 (m, 1H),

2.41 (s, 3H), 2.66−2.85 (m, 2H), 3.44 (m, 2H), 4.19 (q, 2H, J = 7.1 Hz), 7.30 (d, 2H, J = 7.4 Hz), 7.38 (d, 2H, J = 7.4 Hz); IR (neat) 1730, 1280, 1040 cm^{-1}; SIMS m/z (rel intensity) 476.1 ($M^+ + 2$, 1), 474.1 (M^+, 5), 336.1 (32), 334.1 (100). Anal. Calcd for $C_{21}H_{35}BrO_3SSi$: C, 53.04; H, 7.42. Found: C, 52.82; H, 7.64. **12d** (X = I): TLC R_f = 0.38 (hexane/ethyl acetate = 70:30); ^1H NMR δ −0.15 (s, 9H), 0.69 (dd, 1H, J = 3.0, 15.2 Hz), 0.88 (dd, 1H, J = 11.0, 15.2 Hz), 1.31 (t, 3H, J = 7.1 Hz), 1.20−2.50 (m, 8H), 2.20−2.40 (m, 1H), 2.41 (s, 3H), 2.63−2.83 (m, 2H), 3.17−3.28 (m, 2H), 4.19 (q, 2H, J = 7.1 Hz), 7.28 (d, 2H, J = 7.8 Hz), 7.36 (d, 2H, J = 7.8 Hz); IR (neat) 1730, 1220, 1070 cm^{-1}; SIMS m/z (rel intensity) 522.1 (M^+, 2), 382.1 (60), 149.1 (100). Anal. Calcd for $C_{21}H_{35}IO_3SSi$: C, 48.27; H, 6.75. Found: C, 48.01; H, 6.55.

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Supporting Information Available: Spectroscopic characterization for the products **3a**,**c**,**d**, **4b**,**c**, **5a**−**d**, **6a**−**c**,**e**−**h**, **13a**−**f**, and **14a**−**i** and X-ray crystallographic data for **11a**,**c** and the hydrolyzed **11d**. This material is available free of charge via the Internet at http://pubs.acs.org.

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