Chiral Lewis Acids. Haloorganotins Bearing Chiral Organic Groups

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A series of compounds in which chiral groups derived from readily available naturally occurring substances has been used for the preparation of chiral organotins. Starting compounds were α-pinene, carvone, verbenone, and myrtenal. α-Pinene was converted into 2-bromobornane and the bromine replaced by the trimethyltin group by reaction with (trimethylstannyl)lithium, yielding predominantly the exo isomer in good yield. Carvone, verbenone and *tert*-butyl myrtenate were subjected to Michael addition of (trimethylstannyl)lithium or -sodium to provide organofunctional organotins. These were converted to monochlorotins and/or dichlorotins. The stereochemistry of each of the products was determined by ^1H or ^{13}C NMR spectroscopy. The β-chlorotin and dichlorotin derivatives derived from *tert*-butyl myrtenate showed intramolecular coordination between the tins and the ester carbonyls as revealed from the IR spectra. Such coordination rendering the tin pentacoordinate ($abcd_2Sn$) creates a chiral tin center.

Chiral Lewis acids should be particularly useful in the synthesis and in separations of chiral compounds bearing donor groups. Ideally the Lewis acid center would also be the chiral center. However, this is not generally feasible with main-group Lewis acids such as those of boron, aluminum, titanium, or tin. The electronegative groups needed to confer Lewis acidity on the metal also confer stereochemical lability on the synthetic time scale in simple examples. Germane to the subject of this paper is the fact that organotins of the type RR′R″SnX racemize too rapidly to be of practical value.[1,2] Stereochemical stability can be imposed in cyclic structures when the coordination number of the tin atom is increased to five,[3] but the cost of this is diminution of Lewis acidity. Structures in which RR′R″SnX constitutes a chiral bicyclic system with the tin atom at the bridgehead should be suitable, but these appear to be inaccessible without extensive synthetic labor.

An alternative approach to the goal, but which would seem to be much less attractive, would be the use of compounds in which the chirality resides in the R groups. Nonetheless notable success has been achieved in asymmetric catalytic synthesis in a few cases. Perhaps the most familiar example is the Sharpless asymmetric epoxidation of allylic alcohols using a titanium tartrate complex as a catalyst.[4] Other examples include the use of chiral alkoxyaluminum chlorides for Friedel–Crafts catalysis of the Diels–Alder reaction[5] and the use of chiral zinc aryl dioxide for an alkylative intramolecular cyclization.[6]

Instead of having the chiral centers bound to the metal through oxygen the compounds described in this work involve bonding to tin through chiral carbon. Organotins with monocyclic and bicyclic groups bearing one or more chiral centers were the synthetic objectives of the study reported here. The organic groups used were derived from the commercially available naturally occurring chiral compounds α-pinene, carvone, verbenone, and myrtenal. The tin centers in the target compounds were converted into Lewis acids by replacement of methyl groups by chlorines.

Reaction of (+)-α-pinene with hydrogen bromide provided (+)-2-bromobornane which, upon treatment with (trimethylstannyl)sodium in ammonia/tetrahydrofuran (THF), yielded 77% of a 92:8 mixture of 2-bornyltrimethyltins. The high yield of substitution product formed by replacement of bromine on a highly hindered carbon of a rigid ring might not be expected, even though a very powerful nucleophile is involved. However, it can be understood if the reaction proceeds by a free-radical mechanism in which the first step is an electron transfer as shown in eq 1 (R = 2-bornyl).[7] The trimethyltin anion

$$Me_3SnNa + R\text{–}Br \rightarrow Me_3Sn^{\bullet}, Na^+, R^{\bullet}, Br^- \rightarrow Me_3Sn\text{–}R + NaBr \quad (1)$$

transfers an electron to the bromide which dissociates to form the carbon radical which can then lead to product as in eq 1 or by way of other processes such as the $S_{RN}1$ mechanism. This type of mechanism has been observed in the reactions of organotin anions with norbornenyl,[8] nortricyclyl,[8] substituted cyclohexyl,[7c,d] and adamantyl[7d] bromides for which compelling evidence for a free-radical mechanism has been obtained. It appears to show relatively low sensitivity to steric effects. The product-determining step from the radical would be expected to provide a mixture of epimers as observed. The major isomer, **1-x**, showed the trimethyltin carbon at −9.2 ppm (see Table I), and the minor one showed it at −8.1 ppm. The three-bond ^{13}C–^{119}Sn coupling constants (Table I) were used to assign the exo configuration for the trimethyltin group in **1-x**. This parameter showed a ^3J value of 41.5 Hz to the methylene carbon (labeled f in Table I), consistent with a dihedral angle approaching 180°; the coupling constant to the opposite bridgehead (a) carbon was 18.3 Hz as would be expected for a dihedral angle around 120°.[9] The corresponding coupling parameters for the minor isomer could not be observed, nor was any attempt made to isolate it; instead the mixture was treated

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(2) Gielen, M. *Topics in Stereochemistry*; Wiley: New York, 1980; Vol. 12, Chapter 5.
(3) (a) van Koten, G.; Noltes, J. G. *J. Am. Chem. Soc.* **1976**, *98*, 5393. (b) van Koten, G.; Jastrebski, J. T. B. H., Noltes, J. G., Pontenagel, W. M. G. F.; Kroon, J.; Spek, A. L. *J. Am. Chem. Soc.* **1978**, *100*, 5021.
(4) Sharpless, K. B.; Woodard, S. S.; Finn, M. G. *Pure and Appl. Chem.* **1983**, *55*, 1823.
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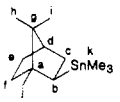
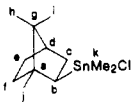
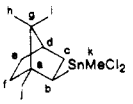
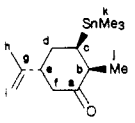
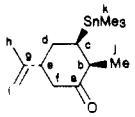
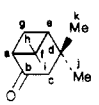
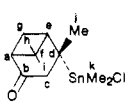
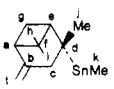
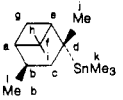
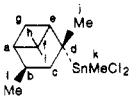
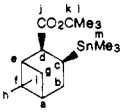
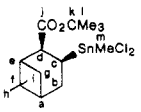
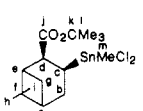
(6) Sakane, S.; Maruoka, K.; Yamamoto, M. *Tetrahedron Lett.* **1985**, 5535.
(7) (a) Smith, G. F.; Kuivila, H. G.; Simon, R.; Sultan, L. *J. Am. Chem. Soc.* **1981**, *103*, 833. Alnajjar, M. S.; Kuivila, H. G. *J. Am. Chem. Soc.* **1985**, *107*, 416. (b) Ashby, E. C.; DePriest, R. N.; Su, W-Y. *Organometallics* **1984**, *3*, 1718. (c) Lee, D-W.; San Filippo, J., Jr. *Organometallics* **1983**, *2*, 906. (d) Adcock, W.; Sankar-Iyer, V.; Kitching, W.; Young, D. *J. Org. Chem.* **1985**, *50*, 3706. These references contain citations to earlier work from each laboratory.
(8) Alnajjar, M. S.; Kuivila, H. G. *J. Org. Chem.* **1981**, *46*, 1053.
(9) Dodrell, D.; Burfitt, I.; Kitching, W.; Bullpit, M.; Lee, C. H.; Mynott, R. J.; Considine, J. L.; Kuivila, H. G.; Sarma, R. H. *J. Am. Chem. Soc.* **1974**, *96*, 1640.

0022-3263/86/1951-4947$01.50/0

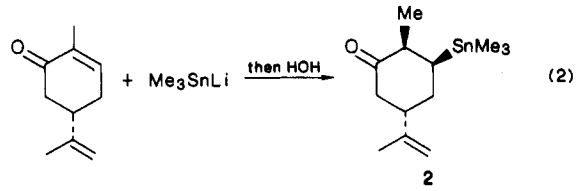
Table I. ^{13}C Chemical Shifts and Coupling Constants

compd	carbon, δ (n_J, Hz) of carbon											
	a	b	c	d	e	f	g	h	i	j	k	l
1-**x** 	(or g) 49.1	35.2 (408.9)	33.1	45.9 (18.3)	28.6	37.0 (41.5)	(or a) 48.1	(or i) 19.0	(or h) 16.3	19.7	−9.2 (306.4)	
1-**x**-Cl 	(or g) 49.1	44.2 (470.0)	32.0	45.5 (23.2)	28.2	37.9 (57.4)	(or a) 48.3	(or i) 18.7	(or h) 16.1	19.4	−0.38 (311.1) −1.29 (322.1)	
1-**x**-Cl_2 	(or g) 49.4	54.2 (546.9)	31.2 (14.6)	45.2 (30.5)	27.8	38.9 (73.2)	(or a) 48.5	(or i) 18.7	(or h) 16.1	19.4 (11.0)	7.4 (361.3)	
2 	211.0	48.4	33.3 (365.0)	35.3 (10.4)	46.9 (20.2)	46.2	147.0	20.5	109.5	15.6 (19.5)	−8.9 (313.1)	
2-Cl 	210.8	47.7	42.2 (413.3)	34.0 (16.2)	47.1	46.4	146.7	20.8	110.2	15.7 (29.4)	(or l) 0.51 (334.1)	(or k) −0.03 (316.7)
3-**n** 	57.5	214.6 (26.7)	46.2 (9.2)	29.0 (435.8)	52.1 (14.7)	42.0 (71.6)	28.6 (32.3)	27.4 (7.6)	25.6	26.5	−9.8 (296.0)	
3-**x** 	58.2	214.8	46.2 (9.4)	29.0 (435.8)	52.7 (9.9)	41.3 (13.6)	22.7 (59.2)	26.6	23.7	28.7	−8.3 (307.2)	
3-**n**-Cl 	57.3	212.4 (35.9)	45.0 (8.8)	38.4 (485.3)	51.3 (18.2)	42.4 (95.2)	28.4 (42.7)	25.8	25.5	27.3 (11.2)	−2.5 (296.6)	
4 	51.7 (7.4)	152.6 (21.3)	37.8 (8.2)	32.5 (460.4)	52.2 (17.8)	42.4 (76.4)	33.1 (41.7)	27.3	25.3	27.9 (8.3)	−9.9 (285.6)	105.9
5 	36.9	47.6 (12.2)	40.7 (10.7)	35.5 (463.0)	53.1 (15.0)	42.0 (75.4)	37.1 (39.1)	27.9	25.3	30.3 (9.6)	−9.8 (281.4)	22.5
5-Cl_2 	36.2 (9.5)	47.4 (12.3)	38.8 (21.3)	59.3 (565.4)	51.9 (21.7)	42.2 (148.3)	38.6 (104.7)	27.0 (15.0)	24.8	22.9 (19.1)	6.2 (261.8)	21.8
7 	44.8 (24.9)	30.7 (13.7)	12.9 (394.8)	50.5 (17.2)	41.7 (23.1)	38.7	31.9	27.5	22.1	175.2 (15.4)	79.6	28.0 (m) −11.00 (312.5)
7-Cl 	44.3 (36.6)	29.8 (23.5)	23.0 (453.2)	49.7 (26.1)	41.6 (33.4)	38.7	32.6	27.8	22.5	175.6 (13.8)	80.9	28.0 (m) −2.1 (344.8)
7-Cl_2 	44.0 (57.3)	29.5 (39.1)	33.1 (572.8)	49.2 (41.1)	41.8 (56.1)	38.7	33.5	28.0	23.0	175.8 (22.7)	82.2	28.0 (m) 6.7 (432.5)

with 1 mol of tin tetrachloride in methylene chloride at 0 °C providing a mixture of the monochlorotin analogues. The major isomer 1-**x**-Cl showed diastereotopic methyl groups with ^{13}C chemical shifts at −0.38 and −1.29 ppm, respectively, and $^1J(^{13}C-^{119}Sn)$ of 318.6 and 323.5 Hz. Treatment of 1-**x** with 2 mol of tin tetrachloride provided pure 1-**x**-Cl_2 in 66% yield. Both 1-**x**-Cl and 1-**x**-Cl_2 showed the same pattern of $^3J(^{13}C-^{119}Sn)$ values as 1-**x** thus enhancing the validity of the configurational assignment.

α,β-Unsaturated carbonyl compounds constitute another class of available chiral substrates for introduction of organotin groups.[10,11] This can be achieved by the Michael

addition which often gives high yields of adduct. (−)-Carvone was treated with (trimethylstannyl)lithium in ammonia–THF, eq 2. Although two chiral centers are



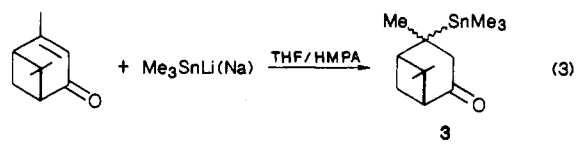
(2)

2

formed in this reaction, only a single diastereomer was isolated, in 92% yield. This stereoselectivity might be rationalized as follows. The trimethyltin anion attacks from the axial direction with the isopropenyl and methyl groups in the equatorial positions; axial protonation of the resulting enolate results in the cis relationship of the trimethyltin and methyl groups as in **2**. The NMR parameters of the product **2** confirm this rationale. The three-bond coupling constant between the methyl carbon j and the tin is 19.5 Hz (Table I); this is in the range to be expected for a gauche relationship.[9] More informative is the value for the three-bond coupling constant between the tin and the methine carbon bearing the isopropenyl group which is 20.2 Hz. An equatorial tin would give a value around 65 Hz. The NMR spectrum showed no indication of the presence of the epimer with the trimethyltin group in the equatorial orientation.

Reaction of **2** with tin tetrachloride to form the monochlorotin analogue **2**-Cl occurred in 83% yield. The NMR parameters confirm the stereochemical assignment made for **2**. When the conversion of **2**-Cl to the dichloro derivative was attempted by using 2 mol of tin tetrachloride, no reaction occurred. Evidently coordination with the carbonyl group and the lowered reactivity of the chlorotin group combine to deactivate **2**-Cl with respect to further methyl–chlorine exchange. Use of drastic conditions led to formation of tarry product.

Pure (+)-verbenone was obtained by oxidation of a commercial sample mixed with 35% verbenol with 2,3-dichloro-5,6-dicyanobenzoquinone. Reaction of (+)-verbenone with (trimethylstannyl)lithium did not occur satisfactorily in the ammonia–THF mixture used for carvone, but the addition of 10% by volume of hexamethylphosphoramide resulted in the formation of the adduct **3-n** in 98% yield, eq 3. This proved to be a single stereoisomer. The $^{13}C-^{119}Sn$ three-bond coupling constants again made assignment of the stereochemistry possible. The dihedral angle between the tin and the bridging isopropylidene carbon f at 42.0 ppm is close to 180°, and its coupling constant should be the largest of the three-bond couplings to tin; it is 71.6 Hz. Coupling to the methylene bridge carbon at 28.6 ppm is 32.3 Hz and to the carbonyl carbon at 214.6 ppm is 26.7 Hz. Interestingly a four-bond 'W' coupling of 7.6 Hz to an isopropylidene methyl is also observed. Formation of this isomer can be visualized as the result of axial attack on the β-carbon at the enone unit by the trimethyltin anion from the less hindered side which yields the endo epimer when the verbenone is in a twist-chair conformation.



(3)

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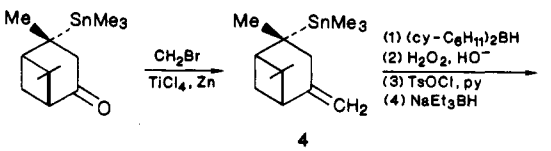
When (trimethylstannyl)sodium in ammonia–THF was used with (−)-verbenone instead of (trimethylstannyl)lithium as the stannylating agent, the product was a 1/1 mixture of the epimers **3-n** and **3-x** (proton NMR). The carbon atom of **3-x** at 22.7 ppm in the ^{13}C spectrum, assigned to the methylene bridge, showed the three-bond coupling to ^{119}Sn of 59.2 Hz consistent with the dihedral angle approaching 180°. The carbon of the isopropylidene bridge appeared at 41.3 ppm with a coupling constant of 13.6 Hz, and the carbonyl carbon appered at 214.8, but the weak signal precluded observation of the ^3J value.

Treatment of **3-n** with 1 molar equiv of tin tetrachloride as described for carvone provided the monochlorotin derivative, **3-n**-Cl. The three-bond $^{13}C-^{119}Sn$ coupling constants fully confirm the configuration assigned for the tin-bearing carbon. An unusually large value of 95.2 Hz to the isopropylidene carbon and the smaller values of 35.9 Hz to the carbonyl carbon and 42.7 Hz to the methylene bridging carbon were observed. Quite remarkably the one-bond coupling to the tin–methyl carbon was virtually the same as that for the trimethyltin analogue (296.0 Hz). Normally the monochloro analogue has a value of 20 to 40 Hz larger. We have no explanation for this apparent anomaly.

Attempts to prepare the dichlorotin derivative met with the same fate as was encountered with **1**. Therefore, it was decided to eliminate the carbonyl group to establish whether it was, in fact, the cause of the difficulty. The procedure was to treat the ketone with methylene bromide, titanium tetrachloride, and zinc dust to produce methylene derivative **4**. Hydroboration–oxidation, followed by tosylation and reduction of the tosylate provided the exo methyl derivative **5**, eq 4. Use of diborane for hydroboration provided a 90:10 mixture of epimers, but use of dicyclohexylborane yielded only **5**. The methyl group is placed in the exo configuration as a result of endo attack by R_2B-H in the hydroboration.[12] This is based on analogy with the hydroboration of β-pinene which has been reported by Brown to follow this stereochemical course.[13]



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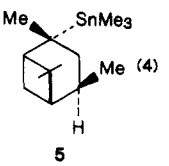

(4)

5

Each of the two- and three-bond couplings between tin and carbon is observed in the ^{13}C spectrum. Noteworthy is the large value of 74.5 Hz of ^3J for the isopropylidene carbon. On the other hand, the one-bond coupling between the methyl carbon and tin of 281.4 Hz is smaller than is usually observed.

(10) Still, W. C. *J. Am. Chem. Soc.* **1977**, *99*, 4836; **1978**, *100*, 1481.
(11) Kuivila, H. G.; Lein, G. J., Jr. *J. Org. Chem.* **1978**, *43*, 750.
(12) Zweifel, G.; Alnajjar, N. R.; Brown, H. C. *J. Am. Chem. Soc.* **1963**, *85*, 2072.
(13) Zweifel, G.; Brown, H. C. *J. Am. Chem. Soc.* **1964**, *86*, 393.
(14) Holden, C. M.; Whittaker, D. *Org. Magn. Reson.* **1975**, *7*, 125.
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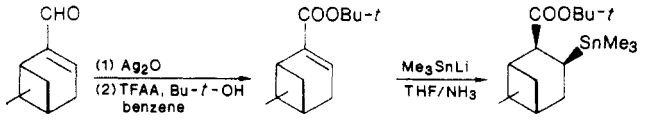
(16) (a) Hoshida, M.; Ueki, T.; Yasuoka, N.; Kasai, N.; Kakudo, M.; Omae, I.; Kikkawa, S.; Matsuda *Bull. Chem. Soc. Jpn.* **1968**, *41*, 1113. (b) Kimura, T.; Ueki, T.; Yasuoka, N.; Kasai, N.; Kakudo, M. *Bull. Chem. Soc. Jpn.* **1969**, *42*, 2479. (c) Harrison, P. G.; King. T. J.; Healy, M. A. *J. Organomet. Chem.* **1979**, *182*, 17. (d) Haigh, R. M.; Davies, A. G.; Tse, M. W. *J. Organomet. Chem.* **1979**, *174*, 163. (e) Maughan, D.; Wardell, J. L.; Burley, J. W. *J. Organomet. Chem.* **1981**, *212*, 59.

As anticipated, absence of the carbonyl group made possible conversion of **5** to the dichlorotin derivative **5**-Cl_2 under the conditions used for the bornyl analogue. Here all of the tin–carbon couplings observed for **5** were observed along with a four-bond coupling between tin and the opposite bridgehead carbon of 9.5 Hz, and another of 15.0 Hz to one of the methyls of the isopropylidene bridge. The values are uniformly larger than for **5** except for the one-bond value for methyl bonded to tin which is, unaccountably, smaller than that for **5** by 20 Hz.

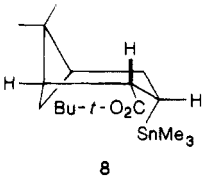
Attempts to convert **4** to chlorotins led to the formation of intractable mixtures. Presumably their formation is initiated by attack of the tin tetrachloride on the double bond leading to the formation of reactive cationic intermediates.

Another chiral moiety which provided a substrate which could be readily bonded to tin was provided by myrtenal. (−)-Myrtenal (**6**) was oxidized to myrtenic acid, which was converted to the *tert*-butyl ester; this was allowed to react with (trimethylstannyl)lithim in THF–ammonia, eq 5, to



6 7 (5)

produce the Michael adduct in 80% yield. This consisted of a single diastereomer (**7**) as could be established by the NMR spectra.[17] The ^{13}C–^{119}Sn three-bond coupling constants were all small, ranging from 15.4 to 24.9 Hz. This indicated that none of these carbons formed a dihedral angle approaching 180° with the tin atom. On the other hand, the coupling constants involving the proton on the methine carbon labeled d bearing the ester group provided a clear indication of the stereochemistry. The three-bond coupling constant to tin was 90.5 Hz, establishing a large dihedral angle. Proton–proton couplings of 6.6 and 2.5 Hz involving this methine proton were observed. These can be assigned to coupling to the equatorial proton on the carbon bearing the tin atom and the proton on the adjacent bridgehead carbon with a dihedral angle near 90°, respectively. These are consistent with a structure (**8**) in



8

which the axial trimethyltin and equatorial ester groups are cis to each other, and the ring is in the chair conformation shown. The Sn–C–C–H^d dihedral angle is near 180°. The values of the coupling constants would be quite different in the alternative boat[14] or the Y[14] conformations.

Replacement of one or two methyl groups of **7** by chlorine with mercuric chloride occurred with considerably greater ease than is usual for simple methyltins. This can be attributed to the ability of the carbonyl group of the ester to approach the tin atom and provide nucleophilic catalysis for the formal electrophilic substitution, as has been observed previously.[15] Several studies have shown that a halotin group β to the carbonyl group leads to a coordinative interaction.[16] The chlorotins **7**-Cl and **7**-Cl_2 show such interaction as revealed most clearly in a shift in the carbonyl stretching frequency in the infrared from 1729 cm^{-1} in **7** to 1673 and 1672 cm^{-1}, in **7**-Cl and **7**-Cl_2, respectively. Pentacoordinate tin is also indicated by data from the NMR spectra on the ^{13}C–^{119}Sn one-bond coupling constants involving the tin methyls which are somewhat larger for these chlorides than those bearing tetracoordinate tin.

On the IR time scale all of the molecules of **7**-Cl and **7**-Cl_2 show the cyclic coordinated structure within the sensitivity of measurement because none of the carbonyl band at 1729 cm^{-1} is evident. The pentacoordinate tin in these compounds must be chiral. This follows from the normal trigonal pyramidal geometry for pentacoordinate tin; in this case the structure is of the type $abcd_2Sn$, which must be chiral.

Experimental Section

Magnetic resonance spectra were obtained on a Varian EM 360A, a Bruker WH-90, or a Varian XL-300 instrument, depending upon need. Internal tetramethylsilane was used as the standard for the ^1H and ^{13}C spectra and internal tetramethylstannane for the ^{119}Sn spectra. $CDCl_3$ was used as the solvent and as an internal lock except as otherwise indicated. Gas chromatographic analyses were performed on a Hewlett-Packard 5750 instrument equipped with a 12 ft × $^1/_4$ in. stainless steel column packed with 15% SE-30 on chromosorb W, 60–80 mesh. IR spectra were recorded on a Perkin-Elmer 283-B instrument. Mass spectral data were obtained on a AEI NS-902 instrument at 90 volts. Melting and boiling points are uncorrected. Flash column chromatography was performed on silica gel, Davisil 200–425 mesh (Aldrich). Thin-layer chromatography (TLC) was performed on E. Merck precoated silica gel plates (60F-254).

(+)-α-Pinene, (−)-carvone, (−)-verbenone, and (−)-myrtenal were purchased from Aldrich Chemical Co. and used without further purification. (+)-Verbenone was obtained as a 35:65 mixture of verbenol and verbenone respectively from SCM Organic Chemicals. Elemental Analyses were performed by Galbraith Laboratories, Inc., Knoxville, TN. All operations involving air- and moisture-sensitive materials were conducted under dry nitrogen.

Not all the chiral compounds used were optically pure. Therefore the products obtained in the syntheses would not be optically pure even though the reactions were generally stereospecific.

(+)-2-Bromobornane. A solution of 45.5 g (0.334 moles) of (+)-α-pinene ($[\alpha]^{25}_D$ +47.10° (neat); lit.[18] $[\alpha]_D$ 51.50°) in 400 mL of chloroform was treated with hydrogen bromide over approximately 1.5 h at 0 °C until a TLC check of the reaction mixture showed complete disappearance of pinene. The solvent was then rotary evaporated, and the residual oil was trap-to-trap distilled at 50 °C (oil bath) at 0.05 torr to give a viscous colorless material as the distillate, which was crystallized from methanol. Further recrystallization of the crude product from methanol gave 53.0 g (70%) of the product as a white crystalline material, mp 93–4 °C (lit.[19] mp 90 °C); $[\alpha]^{21}_D$ +26.95° (*c* 5.44, $CHCl_3$).

2-(Trimethylstannyl)bornanes (1). A flame-dried 2-L flask, fitted with a stirrer and dry ice cooled cold finger was charged with 78.5 g (394 mmol) of trimethyltin chloride and 120 mL of hexane. The flask was cooled to −78 °C and ammonia was introduced until the flask was about half full. Sodium (18.5 g; 805 mmol) was then introduced in small pieces. The ammonia was allowed to evaporate, and 175 mL of dry THF was added. The flask was cooled in an ice-water bath, and 45 g (207 mmol) of (+)-2-bromobornane in 85 mL of THF was added dropwise over 10 min. After 1.5 h no bromide remained, and the mixture was quenched with 55 mL of 30% H_2O_2, added *very carefully* because of the vigorous reaction, and stirred for 1 h. The resultant product was poured into 300 mL of water and the water layer extracted with hexanes (2 × 150 mL). The extracts were washed with 200 mL of 15% H_2SO_4, water (2 × 200 mL), and saturated aqueous NH_4Cl and dried over $MgSO_4$. After removal of the solvent at

(17) The *tert*-butyl ester was used because the methyl and ethyl esters gave mixtures of diastereoisomers.

(18) Thurber, F. H.; Thielke, R. C. *J. Am. Chem. Soc.* **1931**, *53*, 1030.
(19) Carman, R. M.; Walker, G. J. *Aust. J. Chem.* **1977**, *30*, 1393.

reduced pressure the residual oil was distilled yielding 55.8 g (77%) of (+)-2-(trimethylstannyl)bornane (1): bp 52 °C (0.05 torr); $[\alpha]^{22}_D$ +1.50° (*c* 3.74, $CHCl_3$); ^1H NMR (60 MHz, CCl_4) δ 0.07 (s, 9, $^2J(^{119}SnCH)$ = 49 Hz, $Sn(CH_3)_3$, 0.80 (s, 3, CH_3), 0.85 (s, 6), 0.93–1.93 (m); mass spectrum, *m/z* 302 (M^+), 165 (Me_3Sn^+).

Anal. Calcd for $C_{13}H_{26}Sn$: C, 51.84; H, 8.71. Found: C, 51.74; H, 8.64.

This mixture of epimers was converted to the dichlorotin derivative 1-**x**-Cl_2 by the procedure described below, and converted back to 1 by the following procedure. Into a 250-mL 3-neck flask was placed 10.0 g (29.25 mmol) of (+)-1-**x**-Cl_2 ($[\alpha]^{19}_D$ +13.83° (*c* 3.67, $CHCl_3$)) and dissolved in 80 mL of a 1:1 mixture of diethyl ether and tetrahydrofuran. The solution was cooled to 0 °C and treated with 65 mL (70 mmol) of 1.1 M methyllithium in ether over 10 min. The ice bath was removed, and the reaction mixture was stirred at room temperature. After 2.5 h, the flask was cooled to 0 °C, and 5 mL of water was carefully added. The mixture was then extracted with 80 mL of pentane, and the organic layer was separated and washed with brine, dried ($MgSO_4$), and concentrated. Distillation under reduced pressure provided 7.9 g (90%) of the product as a colorless liquid, bp 96 °C (1 torr); $[\alpha]^{21}_D$ +20.55° (*c* 2.54, $CHCl_3$).

2-Methyl-4-(2-propenyl)-3-(trimethylstannyl)cyclohexanone (2). (Trimethylstannyl)lithium was prepared from 22.9 g (115 mmol) of trimethyltin chloride and 1.67 g (230 mmol) of lithium in liquid ammonia and then concentrated to about 50 mL. To this was added 55 mL of THF and a solution of 12.5 g (83.2 mmol) of l-carvone ($[\alpha]^{22}_D$ −58.00° (neat); lit.[20] $[\alpha]^{22}_D$ −62.46° (neat)) in 80 mL of THF. The mixture was warmed to 0 °C, treated with 250 mL of hexanes, washed successively with 200 mL of 0.1 M H_2SO_4, 100 mL saturated aqueous NaCl, and 2 × 200 mL of water. After being dried over $MgSO_4$ and concentrated, the product was distilled as a colorless liquid, 23.8 g (92%): bp 71–72 °C (0.1 torr); $[\alpha]^{22}_D$ −49.80° (*c* 8.25, $CHCl_3$); ^1H NMR (60 MHz, CCl_4) δ 0.07 (s, 9, $^2J(^{119}SnCH_3)$ = 49.5 Hz), 0.98 (d, 3, CH_3CH), 1.68 (t, 3, *J* = 1 Hz, $CH_3C{=}CH_2$), 1.9–2.9 (m, 7), 4.60 (q, 2, $CH_2{=}C$), IR (neat) 1715 cm^{-1} (C=O), 1647 (C=C), 770, 520 cm^{-1}; mass spectrum, *m/z* 316 (M^+), 165 Me_3Sn^+.

Anal. Calcd for $C_{13}H_{24}SnO$: C, 49.57; H, 7.68. Found: C, 49.75; H, 7.59.

(+)-Verbenone. The procedure of Iwamura[21] was used to oxidize the verbenol in 29.0 g of the verbenol/verbenone mixture (35/65) (SCM Organic Chemicals) with 15.3 g (67 mmol) of 2,3-dichloro-5,6-dicyano-1,4-benzoquinone. Verbenone (24.3 g, (94%)) was obtained as a pale yellow oil: bp 48 °C (0.15 torr); $[\alpha]^{25}_D$ +113.40° (*c* 9.80, $CHCl_3$); bp 100 °C (11 torr); lit.[22] $[\alpha]^{25}_D$ +282.00° (neat); ^1H NMR (CCl_4) δ 0.97 (s, 3, CH_3), 1.45 (s, 3, CH_3), 1.92 (d, 3, *J* = 2 Hz), 2.10–2.83 (m, 4), 5.40 (q, 1, $CH{=}CCH_3$).

Reaction of (+)-Verbenone with (Trimethylstannyl)lithium. (Trimethylstannyl)lithium prepared from 272 mmol of trimethyltin chloride in a solvent mixture of 100 mL of ammonia, 100 mL of THF, and 13 mL of hexamethylphosphoramide was treated with a solution of 35 g (233 mmol) of (+)-verbenone $[\alpha]^{25}_D$ +113.40° (*c* 9.80, $CHCl_3$) in 50 mL of THF. The mixture was warmed to 0 °C and stirred for 1 h. It was treated with 30 mL of saturated NH_4Cl and was extracted with 200 mL of hexanes and then with 100 mL. The combined hexane extracts were washed with 150 mL of dilute H_2SO_4, then 2 × 100 mL of water, and 200 mL of saturated NH_4Cl. After drying over $MgSO_4$ the solvent was removed and the oily residue maintained at 0.1 torr and 45 °C to remove volatiles leaving 71.7 g (98%) of the crude product as an oil which solidified at room temperature. Chromatography of a portion using silica gel with hexanes/ether (80/20) as eluant provided **3-h** as a waxy white solid, mp 30–40 °C: $[\alpha]^{24}_D$ +23.39° (*c* 5.02 $CHCl_3$); ^1H NMR (60 MHz, $CDCl_3$) δ 0.07 (s, 9, $^2J(^{119}SnCCH_3)$ = 49.5 Hz), 1.06 (s, 3), 1.34 (s, 3) 1.42 (s, 3, $^3J(^{119}SnCCH_3)$ = 71.9 Hz), 2.03–3.00 (m, 6); ^{119}Sn NMR (112 MHz, $CDCl_3$) δ 29.3; IR (neat) 1716 (C=O), 1370–88, 746 cm^{-1}; mass spectrum, *m/z* 315 (M^+), 165 (Me_3Sn^+), 150 (Me^2Sn^+).

Anal. Calcd for $C_{13}H_{24}SnO$: C, 49.57; H, 7.68. Found: C, 49.70, H, 7.71.

Reaction of (−)-Verbenone with (Trimethylstannyl)sodium. Into a three-neck 1-L flask fitted with a mechanical wire stirrer and a dry ice cold finger was placed 18.5 g (93.0 mmol) of trimethyltin chloride. The flask was cooled with a dry ice–acetone bath, and ammonia gas was condensed in with good stirring until about 500 mL had been condensed. To the well-stirred solution was added 4.3 g (186.0 mmol) of sodium metal in small pieces over 10 min. A bright yellow solution of the (trimethylstannyl)sodium resulted. The dry ice bath was then removed, and about 400 mL of ammonia was allowed to evaporate. Then 70 mL of THF was added followed by 15 mL of dry hexamethylphosphoramide. To this mixture was then added with good stirring a solution of 9.0 g (60.0 mmol) of (−)-verbenone ($[\alpha]_D$ −192.00° (neat)) in 50 mL of THF. After addition, the flask was immersed in an ice bath and stirred for 1 h. Then 100 mL of saturated ammonium chloride solution was added and the mixture was extracted with 250 mL of hexanes. The organic layer was separated and washed with 2 × 200 mL of water, dried ($MgSO_4$), and concentrated to give a viscous yellow oil. Attempted purification of the crude product by distillation resulted in significant decomposition at the boiling point. The yield of the distilled product was 14.0 g (73%), bp 96–8 °C dec (0.2 torr), and was >95% pure by vpc analysis. The ^1H and ^{13}C NMR spectra of the product indicated it to be a 1:1 mixture of the two stereoisomeric 1,4-addition roducts **3-n** and **3-x**. No 1,2-addition was observed (absence of O–H stretch in the IR spectrum). ^1H NMR (300 MHz, $CDCl_3$): δ 0.07 (s, 9, $^2J(^{119}SnCH)$ = 49.5 Hz, $SnMe_3$), 0.09 (s, 9, $^2J(^{119}SnCH)$ = 48.7 Hz, $SnMe_3$), 0.89 (s, 3, Me), 1.06 (s, 3, Me), 1.30 (s, 3, $^3J(^{119}SnCCH)$ = 64.8 Hz, ($MeCSnMe_3$), 1.34 (s, 3, Me), 1.36 (s, 3, Me), 1.44 (s, 3, $^3J(^{119}SnCCH)$ = 71.9 Hz, ($MeCSnMe_3$)), 1.8–3.0 (m, 12). ^{119}Sn NMR (112 MHz, $CDCl_3$) δ 29.3, 30.5.

4-n. Following the procedure of Lombardo[23] 57.7 g (0.88 mol) of zinc dust, 500 mL of dry THF, 20.2 mL (0.288 mol) of dibromomethane, and 23 mL (0.209 mol) of titanium tetrachloride were used to prepare the methylenation slurry. To a solution of 15.0 g (47.6 mol) of (+)-**2-n** was added 240 mL of the slurry with stirring at room temperature. A TLC assay showed the reaction to be complete in 50 min. The reaction mixture was poured into a mixture of 250 mL of ether, 250 mL of saturated $NaHCO_3$, and 125 mL of water and filtered through a bed of Celite. The organic layer was separated, washed with 350 mL of saturated NH_4Cl, dried over $MgSO_4$, and concentrated. Distillation of the residual oil provided 13.3 g (90%) of (+)-**4-n** as a colorless oil: bp 64–65 °C (0.5 torr); $[\alpha]^{25}_D$ +19.70 (*c* 2.85, $ChCl_3$); ^1H NMR (60 MHz, CCl_4) δ 0.00 (s, 9, $^2J(^{119}Sn^1H)$ = 47 Hz, $SnMe_3$), 0.94 (s, 3), 1.21 (s, 3), 1.31 (s, 3, $^3J(^{119}Sn^1H)$ = 74 Hz, $SnCCH_3$), 1.96–2.84 (m, 6), 4.53 (t, 2, *J* = ca. 2 Hz); IR (neat) 3080, 1642, 765 cm^{-1}; mass spectrum, *m/z* 313 (M^+, weak), 298, 165.

Anal. Calcd for $C_{14}H_{26}Sn$: C, 53.71; H, 8.37. Found: C, 53.70, H, 8.45.

Compound 5. Hydroboration–Oxidation of 4, Tosylation, and Reduction. To a solution of dicyclohexylborane in 220 mL of diglyme prepared from 19.9 g (162 mmol) of boron trifluoride etherate, 4.60 g (121 mmol) of sodum borohydride, and 32.8 mL (324 mmol) of cyclohexene was added at room temperature 21.2 g (67.7 mmol) of (+)-4 in 50 mL of diglyme. After the mixture had stirred for 20 h, 1.7 mL of water was added followed by 48 mL of 3 N NaOH and 48 mL of 30% hydrogen peroxide. After heating for 1 h to 50 °C, the mixture was poured into 150 mL of water and extracted with ether (2 × 200 mL). The ether extracts wee washed with water (3 × 150 mL) and 200 mL of saturated NH_4Cl. Drying ($MgSO_4$) was followed by removal of solvent and heating to 65 °C at 0.05 torr to remove other volatiles, leaving 20.9 g (93%) of alcohol, pure by NMR: ^1H NMR (60 MHz, CCl_4) δ 0.02 (s, 9, $^2J(^{119}SnCH_3)$ = 47.0 Hz), 1.09 (s, 3), 1.19 (s, 3), 1.28 (s, 3, $^3J(^{119}SnCCH_3)$ = 74 Hz), 3.38 (d, 2, *J* = ca. 6.5 Hz, $HOCH_2CH$); IR (neat) 3331, 1386–1367, 761 cm^{-1}.

The alcohol was treated with 29.8 g (156 mmol) of *p*-toluenesulfonyl chloride in 180 mL of dry pyridine at 3 °C; after 28 h the reaction mixture was poured into 150 mL of ice-water and extracted with 400 mL of ether which was then washed with 150 mL of 20% HCl and with water (3 × 150 mL). After drying ($MgSO_4$), solvent was removed in vacuo (0.05 torr) briefly; yield

(20) Simonsen, J. L. *The Terpenes*; University: Cambridge, 1947; p 396.
(21) Iwamura, J. *Nippon Kagaku Kaishi* **1978**, 846.
(22) Banthorpe, D. V.; Whittaker, D. *Chem. Rev.* **1966**, *66*, 643.
(23) Lombardo, L. *Tetrahedron Lett.* **1982**, 4293.

30.5 g (100%) pure by NMR. ^{1}H NMR (60 MHz, CCl_4): δ 0.00 (s, 9, $^2J(^{119}SnCH_3)$ = 47 Hz), 0.97 (s, 3), 1.10 (s, 3), 2.35 (s, 3,), 3.73 (d, 2, ^2J = ca. 6 Hz, $CHCH_2OTs$), 7.00–7.57 (2 doublets, $^3J(HCCH)$ = 8 Hz).

Treatment of the tosylate in 115 mL of THF with 200 mL of a 1 M solution of $LiBEt_3H$ (super hydride) with cooling, and refluxing for 26 h was followed by cooling in an ice-water bath and addition of 64 mL of 3 N NaOH and 64 mL of 30% hydrogen peroxide dropwise. After 45 min the mixture was poured into 300 mL of water and extracted with hexanes (2 × 250 mL) which were washed with water (2 × 300 mL), dried ($MgSO_4$), and distilled through a Vigreux column yielding 16.5 g (84%) (from the alcohol) of (+)-**5** as a colorless oil: bp 51–52 °C (0.05 torr); $[\alpha]^{25}_D$ +8.96° (*c* 2.97, CH_2Cl_2); ^{1}H NMR (CCl_4) δ 0.00 (s, 9, $^2J(^{119}SnCH_3)$ = 46 Hz, 0.98 (d, 3, $J(HCCH_3)$ = 6 Hz), 1.13 (s, 3), 1.18 (s, 3), 1.25 (s, 3, $^3J(^{119}SnCCH_3)$ = 72 Hz); mass spectrum, *m/z* 315 (M^+, weak), 165, 150.

Anal. Calcd for $C_{14}H_{28}Sn$: C, 53.37; H, 8.96. Found: C, 53.51; H, 9.00.

Preparation of (1*R*)-(−)-Myrtenic Acid. Following the procedure of Borowiecki et al.,[24] (−)-myrtenal ($[\alpha]_D$ −15.0° (neat), lit[22] $[\alpha]^{20}_D$ −18.60°) was oxidized to (−)-myrtenic acid in 83% yield, bp 108–10° (0.15 torr) (lit.,[22] bp 131 °C (4 torr)); $[\alpha]^{24}_D$ −60.44° (*c* 4.36, C_2H_5OH).

Preparation of (1*R*)-(−)-*tert*-Butyl Myrtenate (6). A modification of the method of Parish et al.[25] was used. To a solution of 3.6 g (21.66 mmol) of (−)-myrtenic acid in 30 mL of benzene was added 12.2 mL (18.2 g, 86.6 mmol) of trifluoracetic anhydride. The resulting homogeneous solution was stirred for 25 min and then treated with 26.0 g (348 mmol) of *tert*-butyl alcohol. The resulting yellow solution was stirred for 3.5 h at room temperature. Then 40 mL of 10% aqueous sodium hydroxide and 50 mL of benzene were added, and the benzene layer was separated, washed with 2 × 70 mL of water and 70 mL of saturated ammonium chloride solution, then dried, and concentrated to give 4.7 g (98%) of the ester as a pale yellow oil which was spectroscopically pure. The sample was further purified by silica gel flash column chromatography (90/10 hexanes/ether) to afford 4.32 g (90%) of the pure ester as a colorless oil, $[\alpha]^{25}_D$ −34.05° (*c* 3.34, $CHCl_3$). IR (neat): 1708, 1627, 1366 cm^{-1}. ^{1}H NMR (300 MHz, $CDCl_3$): 0.79 (s, 3, Me), 1.11 (d, 1, J_{gem} = 9.6 Hz), 1.32 (s, 3, Me), 1.48 (2, 9, $C(Me)_3$), 2.11 (br m, 1) 2.42 (m, 3), 2.75 (dt, 1, *J* = 5.8, 1.9 Hz), 6.71 (m, 1). ^{13}C NMR ($CDCl_3$): 165.8, 141.6, 135.1, 79.7, 41.2, 40.8, 37.6, 32.0, 31.4, 28.2, 26.0, 20.9.

Preparation of (1*S*,2*S*,3*S*,5*S*)-(+)-*exo*-2-(*tert*-Butoxycarbonyl)-*exo*-3-(trimethylstannyl)-6,6-dimethylbicyclo[3.1.1]heptane (7). (Trimethylstannyl)lithium was prepared in liquid ammonia from 7.14 g (37.14 mmol) of trimethyltin chloride in 10 mL of tetrahydrofuran and 0.62 g (75.0 mmol) of lithium at −78 °C. The dry ice bath was removed; 25 mL of tetrahydrofuran and a solution of 4.1 g (18.44 mmol) of the (+)-ester (**6**) in 10 mL of tetrahydrofuran were added. The ammonia was then allowed to escape over 1.5 h, and the flask was then immersed in an ice bath. After 2 h, 10 mL of saturated aqueous ammonium chloride was added, and the ice bath was removed. The reaction mixture was treated with 50 mL of hexanes, and the aqueous layer was extracted with 20 mL of hexanes. The combined organic layer was washed successively with 70 mL of 10% sulfuric acid, (2 × 70 mL) of water, and 70 mL of saturated aqueous ammonium chloride solution, dried ($MgSO_4$), concentrated, and briefly placed under 0.1 torr to afford 6.3 g (88%) of **7** as a pale yellow oil which was spectroscopically pure. Further purification by silica gel flash column chromatography (98/2 hexanes/ether) gave 5.7 g (80%) of **7** as a colorless oil, $[\alpha]^{25}_D$ +52.68° (*c* 4.62, $CHCl_3$). IR (neat): 1729, 1366, 1150, 785 cm^{-1}. ^{1}H NMR (300 MHz, $CDCl_3$): δ 0.07 (s, 9, $^2J(^{119}SnCH)$ = 51.8 Hz, $SnMe_3$), 0.92 (d, 1, *J* = 9.2 Hz), 0.98 (s, 3, Me), 1.19 (s, 3, Me), 1.44 (s, 9, $C(Me)_3$), 1.93 (m, 2), 2.22 (m, 2), 2.37 (m, 2), 2.90 (dd, *J* = 6.6, 2.5 Hz $HCCO_2Bu$), $^3J(^{119}SnCH)$ = 90.5 Hz).

Anal. Calcd for $C_{17}H_{32}SnO_2$: C, 52.74; H, 8.33. Found: C, 53.41; H, 8.63.

Trialkyltin Monochlorides. General Procedure. The reactions were conducted in dichloromethane using equimolar amounts of the tetraalkyltin and tin tetrachloride at 0 °C in 1 M concentration. The course of the reaction was monitored by ^{1}H NMR and shown to be complete in about 45 min. Solvent was removed at reduced pressure and then the methyltin trichloride by heating to 60 °C at 0.05 torr.

1-x-Cl. The solid remaining after removal of the $MeSnCl_3$ was sublimed by warming with a heat gun at 0.05 torr; 95% yield, mp 70–1 °C; $[\alpha]^{21}_D$ +20.50° (*c* 3.61, $CHCl_3$); ^{1}H NMR (CCl_4) δ 0.59 (s, 6, $^2J(^{119}SnCH_3)$ = 50.0 Hz), 0.88 (s, 6), 0.90 (s, 3), 0.91–2.00 (m, 8), IR (KBr) 1370–90, 770, 530 cm^{-1}; mass spectrum, *m/z* 321 (M^+), 184 (Me_2SnCl^+).

Anal. Calcd for $C_{12}H_{23}SnCl$: C, 44.84; H, 7.21. Found: C, 45.01; H, 7.23.

2-Cl. Recrystallization from CCl_4 provided 83% yield, mp 135.5–136.5 °C, $[\alpha]^{24}_D$ −41.13° (*c* 2.05, $CHCl_3$). ^{1}H NMR ($CDCl_3$): δ 0.63 (br s, 6, $^2J(^{119}SnCH_3)$ = 53.0 Hz), 1.08, (d, 3, ^3J = 6 hz), 1.72 (br, 3), 4.67 (q, 2). IR (Kbr): 3080, 1690, 775, 520 cm^{-1}. Mass spectrum: *m/z* 335 (M^+), 320 ($MCH_3)^+$, 185 ($SnMe_2Cl^+$), 150 (Me_2Sn^+).

Anal. Calcd for $C_{12}H_{21}SnC10$: C, 42.97; H, 6.31. Found: C, 43.52; H, 6.33.

3-n-Cl. Recrystallization from CCl_4 provided 85%: mp 152–3 °C; $[\alpha]^{21}_D$ +31.47° (*c* 3.69, $CHCl_3$); ^{1}H NMR ($CDCl_3$) δ 0.65 (s, 6, $^2J(^{119}SnCH_3)$ = 53 Hz), 1.07 (s, 3), 1.36 (s, 3) 1.57 (s, 3, $^3J(^{119}SnCCH_3)$ = 96 Hz); IR (KBr) 1691 cm^{-1}, 785, 540; mass spectrum, *m/z* 335 (M^+, weak), 320 $(MCH_3)^+$, 185 ($SnMe_2Cl^+$).

Anal. Calcd for $C_{12}H_{21}SnC10$: C, 42.97; H, 6.31. Found: C, 42.72; H, 6.14.

Dialkyltin Dichlorides. General Procedure. The tetraalkyltin compound was first treated with 1 equiv of tin tetrachloride at 0 °C to give the monochlorotin derivative. Then another equivalent of tin tetrachloride was added and the mixture heated under reflux for about 30 h. The solvent was removed in vacuo, and the methyltin trichloride and other volatiles were removed by heating at 50–60 °C at 0.05 torr. The residue was taken up in a CCl_4–CH_2Cl_2 mixed solvent, treated with activated charcoal, filtered, and evaporated to give the crude product. This was then recrystallized from hexanes to yield the pure product.

1-x-Cl$_2$. This was obtained as colorless needles in 66% yield: mp 85–86 °C; $[\alpha]^{21}_D$ +13.83° (*c* 5.81, $CHCl_3$); ^{1}H NMR (60 MHz, CCl_4) δ 0.92 (s, 6), 1.03 (s, 3), 1.10 (s, 3, $^2J(^{119}SnCH_3)$ = 56 Hz); IR (KBr) 1370–90, 770, 530 cm^{-1}; mass spectrum, *m/z* 342 (M^+, weak), 205, 137.

Anal. Calcd for $C_{11}H_{20}SnCl_2$: C, 38.65; H, 5.90. Found: C, 38.73; H, 5.96.

5-Cl$_2$. This was obtained as colorless needles in 70% yield, mp 56–57 °C, $[\alpha]^{25}_D$ +7.10° (*c* 4.38, $CHCl_3$); ^{1}H NMR (60 MHz, $CDCl_3$) δ 0.98 (s, 3, $^2J(^{119}SnCH_3)$ = 48 Hz), 1.05 (d, 3, $^3J(HCCH)$ = 6 Hz, CH_3CH), 1.17 (s, 3), 1.25 (s, 3), 1.60 (s, 3, $SnCCh_3$), 1.72–2.88 (m), $^3J(^{119}SnCCH_3)$ = 148.1 Hz. Mass spectrum, *m/z* 356 (M^+, absent), 205, 151; IR (KBr) 1370–90, 760, 520 cm^{-1}.

Anal. Calcd for $C_{12}H_{22}SnCl_2$: C, 40.50; H, 6.23. Found: C, 40.62; H, 6.15.

7-Cl. To a solution of 0.137 g (0.353 mmol) of (+)-**7** in 1.4 mL of dichloromethane and 0.7 mL of tetrrahydrofuran was added 0.0984 g (0.362 mmol) of mercuric chloride. After being stirred for 2 h, the turbid solution was filtered through celite, and the filtrate was concentrated. The residue was stirred under 0.005 torr with gradual warming to 90 °C (oil bath) over 1 h, whereupon the product was collected as a white crystalline sublimate in a yield of 0.122 g (87%), mp 88.5–9.5 °C, $[\alpha^{25}_D$ +52.04° (*c* 1.66, $CHCl_3$). Further recrystallization from hexanes gave the analytical sample as colorless needles, mp 91–2 °C, $[\alpha]^{25}_D$ +53.05° (*c* 1.24, $CHCl_3$). ^{1}H NMR ($CDCl_3$): 0.60 (s, 3, $^2J(^{119}SnCH)$ = 52.7 Hz; *SnMe*), 0.67 (s, 3, $^2J(^{119}SnCH)$ = 52.6 Hz; Sn*Me*), 1.00 (s, 3, Me), 1.05 (d, 1, *J* = 9.9 Hz), 1.23 (s, 3 Me), 1.45 (s, 9, $C(Me)_3$), 2.01 (m, 1), 2.26 (dd, 1, *J* = 2.5, 9.6 Hz), 2.46 (m, 4), 3.11 (dd, 1, *J* = 2.4, 9.1 Hz, $HCCO_2Bu$, $^3J(^{119}SnCCH)$ = 113.2 Hz). IR (KBr): 1673, 1366, 1153, 758, 540, 513, 291 cm^{-1}.

Anal. Calcd for $C_{16}H_{29}SnO_2Cl$: C, 47.15; H, 7.17. Found: C, 47.17; H, 7.48.

7-Cl$_2$. A solution of 1.8242 g (4.71 mmol) of (+)-**7** in 4 mL of dichloromethane and 6 mL of tetrahydrofuran was treated with 2.85 g (10.5 mmol) of mercuric chloride. The solution was refluxed for 2.5 days when an ^{1}H NMR check of the reaction mixture showed complete formation of the dichloride. The reaction

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mixture was suction filtered over celite, and the filtrate was concentrated. The residual solid was then stirred under 0.005 torr with gradual warming to 90 °C (oil bath) to remove MeHgCl. The residue in the flask was then dissolved in 50 mL of hexanes and suction filtered through Celite. Rotary evaporation of the filtrate gave 1.25 g (63%) of the product as a white crystalline solid, mp 64–6 °C, $[\alpha]^{25}_D$ +53.52° (c 2.78, $CHCl_3$). Recrystallization from hexanes afforded the analytical sample, mp 71–2 °C. ^1H NMR ($CDCl_3$): 1.02 (s, 3, Me), 1.04 (d, 1, J = 9.1 Hz), 1.25 (s, 3, $^2J(^{119}SnCH)$ = 65.9 Hz, $SnMeCl_2$), 1.27 (s, 3, Me), 1.46 (s, 9, $C(Me)_3$), 2.10 (br m, 1), 245 (m, 4), 2.93 (dd, 1, J = 19.0, 10.2 Hz), 3.33 (dd, 1, J = 9.3, 2.3 Hz, $HCCO_2Bu$, $^3J(^{119}SnCCH)$ = 163.5 Hz). IR (KBr): 1672, 1367, 1157, 776, 542, 527, 313 cm^{-1}.

Anal. Calcd for $C_{15}H_{26}SnO_2Cl_2$: C, 42.10; H, 6.12. Found: C, 42.16; H, 6.10.

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Asymmetric Induction with Amidocuprates

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Optically active amines such as (*R*)- or (*S*)-α-methylbenzylamine and (4*S*,5*S*)-(+)-5-amino-2,2-dimethyl-4-phenyl-1,3-dioxane can be lithiated with an alkyllithium and added to an organocopper(I) compound, prepared from a lithium reagent and CuI, to give a chiral organocuprate. The 3-phenylcyclohexanone obtained from such a phenyl cuprate and 2-cyclohexenone has up to 50% ee. Running the reaction in the presence of chlorotrimethylsilane improved the results in some cases. The counterion in the Cu(I) precursor, the cation (Li^+ or Mg^{2+}), the solvent, and the temperature also have important effects.

Organocopper reagents are among the most useful of C–C bond forming reagents, and a chiral organocopper reagent that would give high levels of asymmetric induction would be an especially valuable addition to existing methodology for the synthesis of optically active products. Pioneering work toward this goal has been done by a number of groups. Kretchmer[1] used the alkaloid (–)-sparteine as a complexing agent with organocopper(I) compounds of the type $RCuMgX_2$ in the conjugate addition reaction of α,β-unsaturated ketones and obtained products of low optical purity (<10%). Low optical purity (≤27%) was also characteristic of the products of organocopper conjugate additions run in the presence of the chiral cosolvents (*R*,*R*)- or (*S*,*S*)-1,4-(dimethylamino)-2,3-dimethoxybutane by Langer and Seebach.[2]

As far as heterocuprates[3] R(Het)CuLi are concerned, Crabbé and co-workers[4] investigated the alcoholates of (–)-*N*-methylephedrine and 1,2:5,6-di-*O*-isopropylidine-α-D-glucofuranose as chiral auxiliary ligands (Het), and they likewise observed very low optical purities from reactions with α-enones. The best results with such a heterocuprate coordinated by oxygen (*O*-heterocuprate for abbreviation[5]) are due to Huché et al.,[6] who obtained a 34% ee for the methylated product from chalcone. Crabbé et al.[7] also studied *N*-heterocuprates; again the optical yields were low (<5%).

The Swedish school of Gustafsson, Ullenius, Nilsson, and co-workers have studied mixed cuprates RR*CuLi, where R* = (–)-2-[1-(dimethylamino)ethyl]phenyl[8] or *o*-[cyclohexyl(dimethylamino)methyl]phenyl,[9] and their results for the conjugate addition reactions of α,β-unsaturated ketones and esters were also disappointing (<5% ee). They also prepared *S*-heterocuprates[5] from the thiols (+)-neomenthylthiol and (+)-α-cyclohexylbenzenemethanethiol and observed ee's of 15% and 0%, respectively, for the addition of butyl to 2-cyclohexenone.[10]

In certain situations, much higher optical yields have been recorded. Imamoto and Mukaiyama[11] obtained 61–68% optical yields in the conjugate addition of MeMgBr to chalcone in the presence of CuBr and (*S*)-*N*-methylprolinol (reactant ratio 8.8:1.0:4.0:5.6). Leyendecker and co-workers reinvestigated this reaction and obtained an 88% ee under more dilute conditions.[12] The (4*S*)-*tert*-butylthio-(*S*)-prolinol derivatives have also been introduced by this group,[13] who observed as high as 94% ee in the methylation of chalcone using Me_2CuLi and one such chiral auxiliary.

In addition to these approaches based on attaching the chiral auxiliary to the cuprate, several research groups have attached it to the substrate; e.g., Posner's group has studied optically pure α-carbonyl-α,β-ethylenic sulfoxides,[14] and Oppolzer's has focused on (–)-*trans*-8-phenylmenthyl enoates.[15] The ee's in these well-engineered systems are usually very good; in some cases >99% enantiomeric purity has been observed.

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