Regio- and Enantioselective Substitution of Primary Endocyclic Allylic Sulfoximines with Organocopper and Organocuprate Reagents. The Importance of Iodide for the Allylic Substitution with Organocopper Compounds

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Received September 12, 1994⊗

Abstract: The endocyclic *N*-substituted allylic sulfoximines **17**–**20** and **26** were synthesized from the corresponding cycloalkanones and the various (*S*)-*S*-(lithiomethyl)-*S*-phenylsulfoximines in enantiomerically pure form in yields of 60–70% in a process involving the isomerization of the intermediate vinylic sulfoximines. Desilylation of **26** gave the parent *N*-H sulfoximine **27** from which the *N*-sulfonylsulfoximines **28** and **29** were prepared. The X-ray crystal structure of **28** was determined. The allylic sulfoximines **17**–**20** and **26**–**29** did not racemize or rearrange thermally to the corresponding allylic sulfinamides. Reaction of the allylic sulfoximines **18**, **28**, and **29** with the organocuprate reagents **2**/LiI, **35**/LiI, and **47**/LiI led with α-selectivities of 92:8 to 99:1 to the endocyclic alkenes **39** in good to high yields. Reaction of **17**–**20**, **28**, and **29** with the organocopper reagents **5**/LiI, **30**/LiI, **31**/LiI, **32**/LiI, **33**/LiI, **34**/LiI, and **37**/LiI in the presence of BF_3 resulted in the formation of the exocyclic alkenes **38**, **41**, **43**, and **45**, respectively, in good to high yields with γ-selectivities of 80:20 to 99:1. The sulfonimidoyl group imparts asymmetric induction to the substitution in the range of 27–90% ee. The (*S*)-sulfonimidoyl group leads to a preferential bond formation from the *si* side of the double bond. From the sulfoximines **18** and **26**–**29** the *N*-methylsulfoximine **18** and the *N*-tosylsulfoximine **28** showed the highest and lowest reactivity with the butylcopper reagent **32**/LiI in the presence of BF_3, respectively, while in the absence of BF_3 only **29** reacted. The Lewis acid most likely serves to activate the *N*-methyl- and *N*-tosylsulfoximines or intermediates thereof through coordination at the sulfonimidoyl and sulfonyl group. Reaction of the sulfoximines **18** and **29** with pure Me_3SiCH_2Cu (**34**) revealed a strong rate acceleration by LiI and an even stronger one by Bu_4NI. This points to the existence of a heteroleptic cuprate or a related compound as reactive species. In substitutions with the Yamamoto reagents RCu/MX/BF_3, the halide is important and a reaction between RCu and BF_3 does not have, at least in the case of allylic sulfoximines, to be invoked. In reactions of **17**–**20** besides the alkenes, the sulfinamide *ent*-**4** was formed with an ee value of 97% in high yield with retention of configuration. The absolute configuration of the exocyclic alkenes **38**, **41**, and **45** was determined by ozonolysis to the corresponding cycloalkanones followed by their conversion to the corresponding lactones and/or CD measurement of the former.

Introduction

The creation of central chirality by the γ-substitution of an allylic substrate with an organocopper or an organocuprate reagent constitutes an important process in organic synthesis.[1-4] Whereas the asymmetric induction in such reactions by chirality residing in the allylic moiety has been investigated intensively, the one caused by chirality contained in the nucleofuge has received less attention. However, studies of the reaction of chiral nucleofuge-containing allylic acetals, carbamates, pyrrolidines, and sulfides with copper organyls by Alexakis et al.,[5] Denmark et al.,[6] Tamura et al.,[7] and Caló et al.,[8] respectively, revealed high asymmetric inductions. A synthetically most interesting group of chiral allylic substrates are sulfoxides[9a,b] since the center of chirality is directly connected with the allylic fragment and the sulfinyl group is not only a chiral nucleofuge[10] but also a chiral carbanion-stabilizing moiety. While the asymmetric induction by the sulfinyl group in reactions of lithioallyl sulfoxides with electrophiles has been investigated thoroughly,[9a,b] the asymmetric induction in the γ-substitution of allylic sulfoxides with copper organyls has apparently not been explored.[1,2,10] The loss of the chirality of the nucleofuge and the aptness of allylic sulfoxides for thermal racemization[11]

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⊗ Abstract published in *Advance ACS Abstracts*, February 1, 1995.

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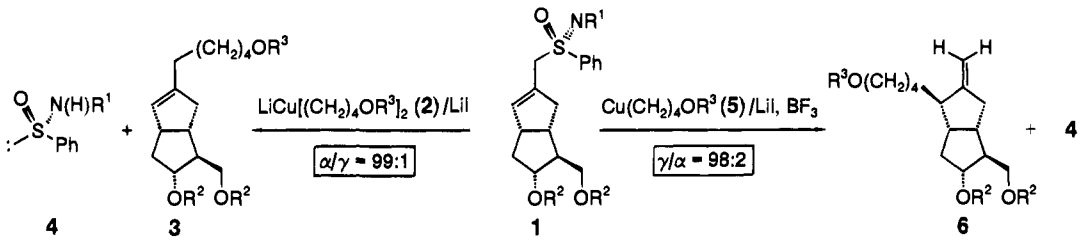
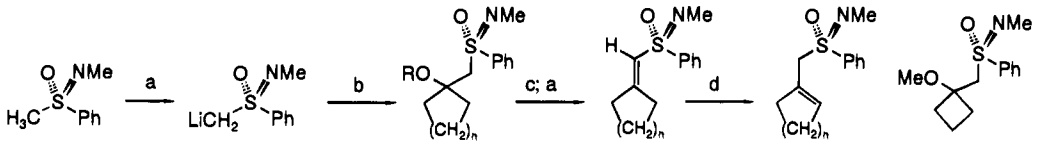
Scheme 1[a]



[a] R^1 = Me, R^2 = Si*t*-BuMe$_2$, and R^3 = CH(Me)OEt.

Scheme 2[a]



[a] Reagents: (a) *n*-BuLi; (b) cycloalkanone; (c) Me_3SiCl; (d) LiOMe (n = 1, 2, 4) or KOMe (n = 3).

may perhaps be responsible for this void. Structurally analogous to allylic sulfoxides are allylic sulfoximines, a class of chiral allylic substrates that were virtually unknown and deemed unstable[12] until recently when we prepared in the course of an isocarbacyclin synthesis the stable endocyclic allylic sulfoximine **1** (Scheme 1).[13] We found that **1** reacts readily with high regioselectivity with the organocuprate reagent **2**/LiI at the α-position to give the endocyclic alkene **3** and with the organocopper reagent **5**/LiI in the presence of BF_3 with equally high regioselectivity at the γ-position to give the exocyclic alkene **6**. In both cases, the chirality of the nucleofuge is retained as the isolation of the enantiomerically pure sulfinamide **4** revealed. In these reactions, **1** behaves like the corresponding allylic acetate[14] and as the various primary allylic substrates that give with organocuprates preferentially the α-substitution product and with organocopper reagents in the presence of BF_3, see so-called Yamamoto reagents,[3] preferentially the γ-substitution product.[1,2] Besides substitution, deprotonation of allylic sulfoximines is feasible also. Allylic sulfoximine **1** is readily deprotonated at the α-position by *n*-BuLi with formation of the corresponding (lithioallyl)sulfoximine which is stable in solution.[13] Several other cyclic and acyclic (lithioallyl)sulfoximines have been prepared,[15-18] spectroscopically characterized,[16a,c] and shown to react readily with electrophiles.[15-18] Allylic sulfoximines are thus another class of chemical chameleons[19] endowed with a chiral carbanion-stabilizing nucleofuge whose chirality, however, is retained when acting as a nucleofuge and which apparently do not racemize thermally as shown in the case of **1** and **18**.[13] We felt, therefore, that allylic sulfoximines, the chiral aza analogs of allylic sulfones, warrant investigation. Here we report on the synthesis of enantiomerically pure endocyclic allylic sulfoximines from cycloalkanones and on a study of their regio- and enantioselective substitution with organocopper and organocuprate reagents[20] as well as on the role of halide and BF_3 in such substitutions.

Results and Discussion

Synthesis and Properties of Allylic Sulfoximines. There are three routes conceivable for the synthesis of optically active allylic sulfoximines: (1) from an enantiomerically pure (lithioalkyl)sulfoximine and a carbonyl compound via addition,[21] elimination[22-27] and isomerization,[13,28] (2) from an enantiomerically pure sulfonimidate and an allylic lithium(magnesium) organyl,[12,15,29] and (3) through the imination of an enantiomerically pure allylic sulfoxide.[17] We have chosen the first route for the synthesis of (*S*)-configurated allylic *N*-methylsulfoximines **17**-**20** and **26**-**29** on a preparative scale mainly because of the ready availability of cycloalkanones and both enantiomers of the *S*-methylsulfoximine **7**[30a,b] in enantiomerically pure form[30] on a preparative scale (Scheme 2). Whereas route 2 has been utilized recently for the synthesis of optically active acyclic allylic sulfoximines bearing a chiral substituent at the N atom,[29] route 3 has thus far not been followed to achieve this goal.[17]

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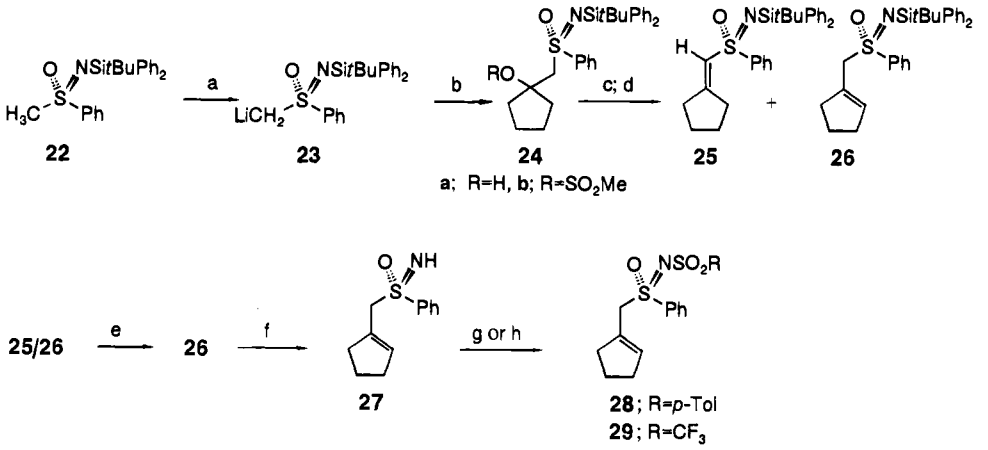
Scheme 3[a]



[a] Reagents: (a) *n*-BuLi; (b) cyclopentanone; (c) $MeSO_2Cl$; (d) DBU; (e) KOMe; (f) Bu_4NF; (g) *p*-$TolSO_2Cl$; (h) $(CF_3SO_2)_2O$.

Addition of the lithiomethyl *N*-methylsulfoximine **8**[30a,31] to the corresponding cycloalkanones, which is well-exemplified mainly through the work of Johnson et al.,[21] led to the isolation of the hydroxy sulfoximines **9b−12b** in yields of 94, 97, 96, and 83%, respectively. For the elimination of β-hydroxy sulfoximines to vinylic sulfoximines, there are several methods available.[22−27] In the case of *N*-methylsulfoximines, elimination of the silyl ethers with *n*-BuLi generally gives the vinylic sulfoximines in good to high yields.[13,24] Sequential treatment of the hydroxy sulfoximines **9b−12b** with *n*-BuLi, Me_3SiCl, and *n*-BuLi gave with the intermediary of the lithium alkoxides **9a−12a** and silyl ethers **9c−12c** the vinylic sulfoximines **13−16** in good to high yield. By this one-pot process, olefination of cyclobutanone gave the vinylic sulfoximine **13** in 56% yield and the allylic sulfoximine **17** in 22% yield, and olefination of cyclopentanone gave the vinylic sulfoximine **14** in 80% yield and the allylic sulfoximine **18** in 12% yield. Cyclohexanone gave exclusively the vinylic sulfoximine **15** in 88% yield. Elimination of the hydroxy sulfoximine **12b** gave rise to the formation of an inseparable mixture of the vinylic and allylic sulfoximines **16** and **20**, respectively, in a ratio of 81:19 in a combined yield of 79%. Complete isomerization of the vinylic sulfoximines **14−16** either pure or admixed with the allylic sulfoximines **18−20** was achieved upon treatment with an excess of LiOMe or KOMe in THF−toluene at room temperature for several hours.[22b] The allylic sulfoximines **18**, **19**, and **20** were isolated in 95, 88, and 89% yield, respectively. Complete isomerization of the four-membered vinylic sulfoximine **13** under these conditions was met with no success. Attempted isomerization with LiOMe gave a 52% recovery of **13** and only 14% of **17**. In addition, the adduct **21** was isolated in 27% yield. With KOMe, **21** was the major product (79% yield) besides 7% of a mixture of **13** and **17** in a ratio of 73:27 which seems to represent the equilibrium composition.

To explore the influence of the sulfonimidoyl group on the reactivity of allylic sulfoximines with copper organyls and on the asymmetric induction in the γ-substitution, the cyclopentenylsulfoximines **26−29** carrying a *tert*-butyldiphenylsilyl, a H atom, a *p*-tolylsulfonyl, and a (trifluoromethyl)sulfonyl (triflyl) group, respectively, at the N atom were synthesized (Scheme 3). The parent allylic sulfoximine **27**, which is a versatile precursor not only for the synthesis of **26**, **28**, and **29** but also for various other *N*-substituted allylic sulfoximines, was secured starting from the silylsulfoximine **22**[32] which in turn was easily prepared from (*S*)-*S*-methyl-*S*-phenylsulfoximine[30] in 81% yield. From the *S*-(lithiomethyl)-*N*-silylsulfoximine **23**[32] and cyclopentanone, the hydroxy sulfoximine **24a** whose elimination was best achieved by conversion to the mesylate **24b** and treatment of the latter without isolation with 1,8-diazabicyclo[5.4.0]undec-7-ene was obtained in 84% yield.[22a,25] Thereby, an inseparable mixture of the vinylic and allylic sulfoximines **25** and **26**, respectively, was isolated in a ratio of 12:88 in 93% yield. Treatment of this mixture with an excess of KOMe in THF gave **26** in 89% yield. For the synthesis of **27**, the mixture of **25** and **26** was both desilylated and isomerized completely in one synthetic operation with Bu_4NF in THF to give **27** in 90% yield. If only **27** is desired, (*S*)-*N*-(trimethylsilyl)-*S*-methyl-*S*-phenylsulfoximine[33] is the more economical reagent. The *N*-tosylsulfoximine **28** was prepared from **27** by treatment with tosyl chloride in 89% yield, and the *N*-triflylsulfoximine **29** was prepared in 96% yield upon reaction of the former with triflyl anhydride.[27,34]

We observed recently that acyclic allylic sulfoximines bearing a phenyl group in the γ-position suffer partial rearrangements at elevated temperatures to the isomeric allylic sulfinamides.[35] These rearrangements, which proceed presumably by an ion pair mechanism, are, however, not accompanied by a racemization of the allylic sulfoximines or the allylic sulfinamides at the S atom. A study of the thermal behavior of the endocyclic allylic sulfoximines **17−20** and **26−29** was deemed necessary in the light of these results. Heating **18**, which according to ^1H NMR spectroscopy in the presence of (*R*)-1-(9-anthryl)-2,2,2-trifluoroethanol (3 equiv) had an ee value of ≥99% ($\Delta\Delta\delta$(Me) = 0.25 ppm, $CDCl_3$), in toluene solution to reflux for 8 h led to its recovery in 95% yield with no sign of loss of optical activity or rearrangement to the corresponding sulfinamides. Similar observations were made with **17**, **19**, **20**, and **26−29**, although not in every case was thermolysis investigated in detail. However, all allylic sulfoximines prepared within this study were optically and chemically stable at room temperature, and their synthesis on a preparative scale posed no problems. *S*-Methyl-*S*-phenylsulfoximine[30a,b] used as educt for the synthesis of **17−20** and **26−29** had an ee value of ≥99% (^1H NMR, 300 MHz, $CDCl_3$, 20 mol % tris[3-((trifluoromethyl)hydroxymethylene)-*d*-camphorato]europium (Eu(tfc)$_3$), $\Delta\Delta\delta$(Me) = 0.32 ppm[30d]).[30b,c] Thus, it is safe to assume that all allylic sulfoximines synthesized had ee values of ≥99%.

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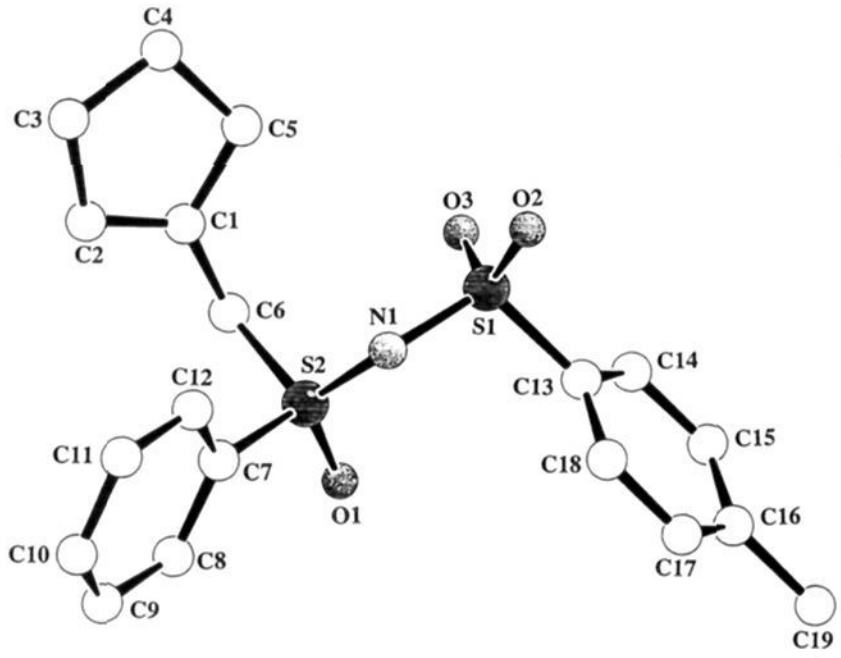

Figure 1. SCHAKAL drawing (Keller, E. *SCHAKAL-88B*. A Fortran Program for the Graphic Representation of Molecular and Crystallographic Models. Freiburg, 1988) of the solid state structure of **28** with atom-labeling scheme. Selected bond lengths (Å) and bond angles (deg): S1−N1, 1.616(3); N1−S2, 1.560(3); S2−O1, 1.432(3); S2−C7, 1.761(4); S2−C6, 1.797(5); C6−C1, 1.501(7); C1−C2, 1.344(7); S1−N1−S2, 121.3(2); N1−S2−O1, 119.7(2); N1−S2−C7, 101.7(2); N1−S2−C6, 112.4(2); O1−S2−C7, 110.4(2); O1−S2−C6, 106.0(2); S2−C6−C1, 116.0(3); C6−S2−C7, 106.0(2).

In order to probe the possibility of a complex formation between BF_3 and the allylic sulfoximines (vide infra), mixtures of the *N*-methylsulfoximine **18**, *N*-tosylsulfoximine **28**, or *N*-triflylsulfoximine **29** and BF_3 in $CDCl_3$ were investigated by ^1H NMR spectroscopy. Major shift differences were recorded only in the case of **18** ($\Delta\delta$(Me) = 0.04 ppm, $\Delta\delta(\alpha\text{-}CH_2)$ = 0.69 ppm, and $\Delta\delta$(=CH) = 0.35 ppm) and practically none in the case of **28** and **29**. Thus, BF_3 coordinates most likely to the N atom of **18** but not to the N atom of **28** and **29**. This would be in accordance with the well-documented protonation, alkylation, and complexation of *N*-alkylsulfoximines at the N atom which is not observed in the case of *N*-sulfonylsulfoximines because of the electronegative substituent at the N atom.[34] From the NMR spectroscopic results, a coordination of BF_3 to the O atoms of the sulfonyl groups of **28** and **29**, which may not manifest itself in the NMR spectra, cannot, however, be excluded. Such a complexation is more likely to occur with **28** than with **29** because of electronic reasons.

Because of the complete lack of information on the bonding parameters of allylic sulfoximines, the crystal structure of the *N*-tosylsulfoximine **28** (Figure 1) was determined. The molecule adopts conformations around the C6−S2 and the S2−N1 bond in the crystal which are characterized by antiperiplanar positions of the O atom and the cyclopentenyl ring as well as the phenyl and the sulfonyl group. The conformation around the N1−S1 bond is such that the p orbital at the N atom almost bisects the O−S−O angle and is thus quite similar to those found in the corresponding sulfoximines having a 3-isopropyloxiran-2-yl,[22a] a 3-pentyloxiran-2-yl,[22a] a 3-methyl-1-butenyl,[36] or a 3-methyl-2-butenyl[36] group instead of the cyclopentenyl group. The bond lengths and bond angles are in the expected range and show no peculiarities.

Substitution of *N*-Methylsulfoximines. Reaction of the five-membered sulfoximine *rac*-**18** with the organocuprate reagent **2**/LiI[37a,b] gave with a high α-selectivity the endocyclic alkene **39a** (Table 1, entry 1). In the presence of BF_3, the reaction was significantly faster but proceeded with a greatly reduced regioselectivity (entry 2). Reaction of **18** with the organocopper reagent **5**/LiI[37b] in the presence of BF_3 led with a high γ-selectivity to the exocyclic alkene **38a** (entry 3). The substitution did proceed with asymmetric induction through the sulfonimidoyl group as the ee value of 71% for **38a** revealed. The influence of the protecting group in **5** on the asymmetric induction was investigated with **30**. Treatment of **18** with **30**/LiI in the presence of BF_3 gave **38b** with equal high γ-selectivity but with a higher ee value of 90% (entry 4). The use of THF instead of ether resulted in a lower enantioselectivity (80% ee). Reaction of **18** with the functionalized organocopper reagents **5**/LiI, **30**/LiI, and **31**/LiI[37c] showed that the functional group in the γ- and δ-position has only a small influence on the regioselectivity but a more pronounced one on the enantioselectivity. In order to get a somewhat broader basis, reaction of **18** with the alkylcopper reagents **32**/LiI and **33**/LiI bearing no heteroatom substituent in the γ- or δ-position was studied. Sulfoximine **18** and **32**/LiI gave **38d** with a high γ-selectivity (entry 6). The enantioselectivity was almost the same as with **5**/LiI. Similarly, **18** and **33**/LiI gave, with a high γ-selectivity and a similar moderate enantioselectivity, **38e** (entry 7). Since *n*-Bu_3P is frequently used instead of Me_2S for the solubilization of CuI and copper organyls,[1] the influence of this additive upon the selectivities of the substitution was investigated. Surprisingly, reaction of **18** with **33**/LiI in THF in the presence of BF_3 and *n*-Bu_3P led with a low α-selectivity to the preferential formation of **39e** (entry 8). In order to gain more information on the influence of the nature of the copper organyl on the regio- and enantioselectivity of the substitution, alkylorganocopper reagents with noncoordinating substituents in the α- and β-position such as the [(trimethylsilyl)methyl]copper reagent **34**/LiI,[37d] the benzylcopper reagent **36**/LiI, and the phenethylcopper reagent **37**/LiI were also included in the present study. Reaction of **18** with **34**/LiI in the presence of BF_3 gave with moderate regio- and enantioselectivities **38f** (entry 9). A surprising result was found with **18** and **34**/LiI if ether was used instead of THF (entry 10). Within a few minutes after the addition of **18** to a solution of **34**/LiI and BF_3 in ether, a white solid deposited which, according to atom absorption spectroscopy and titration with silver nitrate, was CuI contaminated with approximately 5% LiI. Its amount corresponded to two-thirds of the copper initially present, and the isolation of **39f** revealed that a highly α-selective substitution reaction typical for the [(trimethylsilyl)-methyl]cuprate reagent **35**/Li[37e,f] had occurred. In a control experiment, **35** (1 equiv) and Me_3SiCH_2Li (1 equiv) in ether were treated with BF_3 and **18** (entry 11), and the mixture, which remained *homogeneous*, was quenched after 4 h with CF_3-COOD. Besides **18**, which contained 25% deuterium in the α-position, the α-substitution product **39f** was isolated. These results suggest the existence of an equilibrium, according to eq 1, which is shifted to the right by the deposition of CuI and the consumption of **35**. NMR spectroscopic investigations[37f,g]

$$3Me_3SiCH_2Cu + 2LiI \rightleftharpoons (Me_3SiCH_2)_2CuLi + Me_3SiCH_2Li + 2CuI\downarrow \quad (1)$$

revealed that **35** and Me_3SiCH_2Li do not react with formation of the higher order organocuprate $[(Me_3SiCH_2)_3Cu]Li_2$.[37h] Of further importance for the above equilibrium could be a complexation of the lithium organyl by BF_3 and the formation of a heterocuprate from **34** and LiI (vide infra).

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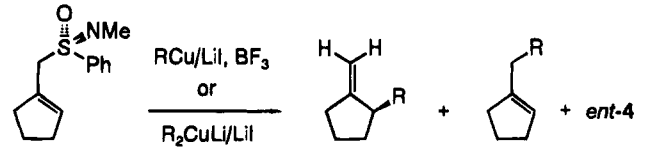
(37) (a) Tufariello, J. J.; Trybulski, E. J. *J. Org. Chem.* **1974**, *39*, 3378. (b) Gardette, M.; Alexakis, A.; Normant, J. F. *Tetrahedron* **1985**, *41*, 5887. (c) Eaton, P. E.; Cooper, G. F.; Johnson, R. C. *J. Org. Chem.* **1972**, *37*, 1947. (d) Jarvis, J. A. J.; Pearce, R.; Lappert, M. F. *J. Chem. Soc., Dalton Trans.* **1977**, 999. (e) Olmstead, M. M.; Power, P. P. *Organometallics* **1990**, *9*, 1720. (f) Kieft, R. L.; Brown, T. L. *J. Organomet. Chem.* **1974**, *77*, 289. (g) Gais, H.-J.; Brandt, J. Unpublished results. (h) Lipshutz, B. H.; Kozlowski, J. A.; Breneman, C. M. *J. Am. Chem. Soc.* **1985**, *107*, 3197. (i) Sommer, L. H.; Murch, R. M.; Mitch, F. A. *J. Am. Chem. Soc.* **1954**, *76*, 1619.

Table 1. Substitution of the Allylic Sulfoximine **18** with Organocopper and Organocuprate Reagents

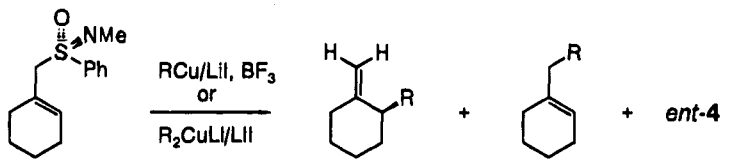


18 **38** **39**

entry	reagent[a]	solvents/additives[a]	product 38/39	yield (%)	γ/α[b]	ee (%)
1	[EtO(Me)C(H)O(CH$_2$)$_4$]$_2$CuLi (**2**)/LiI[c]	Et$_2$O,[d] Me$_2$S	**a**	90	2:98	–
2	[EtO(Me)C(H)O(CH$_2$)$_4$]$_2$CuLi (**2**)/LiI[c]	Et$_2$O,[d] Me$_2$S/BF$_3$[c]	**a**	93	38:62	–
3	EtO(Me)C(H)O(CH$_2$)$_4$Cu (**5**)/LiI[c]	THF,[d] Me$_2$S/BF$_3$[c]	**a**	90	98:2	71[e]
4	*t*BuPh$_2$SiO(CH$_2$)$_4$Cu (**30**)/LiI[f]	Et$_2$O,[d] Me$_2$S/BF$_3$[g]	**b**	88	97.5:2.5	90[e]
5	EtO(Me)C(H)O(CH$_2$)$_3$Cu (**31**)/LiI[f]	THF,[d] Me$_2$S/BF$_3$[f]	**c**	87	87:13	63[h]
6	*n*-C$_4$H$_9$Cu (**32**)/LiI[f]	THF,[d] Me$_2$S/BF$_3$[f]	**d**	89	99:1	72[i]
7	*n*-C$_{11}$H$_{23}$Cu (**33**)/LiI[c]	THF,[d] Me$_2$S/BF$_3$[c]	**e**	95	99.5:0.5	67[j]
8	*n*-C$_{11}$H$_{23}$Cu (**33**)/LiI[c]	THF,[d] Me$_2$S/BF$_3$,[c] *n*-Bu$_3$P[c]	**e**	96	38:62	–
9	Me$_3$SiCH$_2$Cu (**34**)/LiI[f]	THF,[d] Me$_2$S/BF$_3$[f]	**f**	60–70	85:15 to 66:34	60–66[i]
10	Me$_3$SiCH$_2$Cu (**34**)/LiI[f]	Et$_2$O,[k] Me$_2$S/BF$_3$[f]	**f**	60	8:92 to 1:99	–
11	(Me$_3$SiCH$_2$)$_2$CuLi (**35**)/LiI,[l] Me$_3$SiCH$_2$Li[l]	Et$_2$O,[d] Me$_2$S/BF$_3$[f]	**f**	62	1.5:98.5	–
12	PhCH$_2$Cu (**36**)/MgClI[f]	THF,[m] Me$_2$S/BF$_3$[f]	**g**	95	2:98	–
13	PhCH$_2$Cu (**36**)/MgClI[f]	Et$_2$O,[m] Me$_2$S/BF$_3$[g]	**g**	97	45:55	36[n]
14	Ph(CH$_2$)$_2$Cu (**37**)/LiI[f]	THF,[d] Me$_2$S/BF$_3$[g]	**h**	93	95:5	76[o]

[a] Equivalent based on **18**. [b] γ/α-Ratios were determined by capillary GC analysis and by integration of the olefinic signals in the ^{1}H NMR spectra. [c] 4 equiv. [d] Homogeneous solution. [e] Determined by capillary GC analysis of **38j** (R = (CH$_2$)$_4$OCOCF$_3$) obtained from **38i** (R = (CH$_2$)$_4$OH) on a 2,3-di-*O*-pentyl-6-*O*-methyl-γ-cyclodextrin column. [f] 3 equiv. [g] 6 equiv. [h] Determined by capillary GC analysis of **38l** (R = (CH$_2$)$_3$OCOCF$_3$) obtained from **38k** (R = (CH$_2$)$_3$OH) on a 2,3-di-*O*-pentyl-6-*O*-methyl-γ-cyclodextrin column. [i] Determined by capillary GC analysis on a 2,3-di-*O*-pentyl-6-*O*-methyl-γ-cyclodextrin column (König, W. A. *Gas Chromatographic Enantiomer Separation with Modified Cyclodextrins*; Hüthig Verlag: Heidelberg, 1992). [j] Determined by optical rotation after ozonization to **48c** and oxidation to **49c**. [k] Heterogeneous solution containing a white precipitate. [l] 1 equiv. [m] Dark brown, heterogeneous solution. [n] Determined by ^{1}H NMR spectroscopy in the presence of (*R*)-1-(9-anthryl)-2,2,2-trifluoroethanol (3 equiv) (Pirkle, W. H.; Sikkenja, D. L.; Pavlin, M. S. *J. Org. Chem.* **1977**, *42*, 384) after ozonization to **48e**. [o] Determined by ^{1}H NMR spectroscopy in the presence of Ag(fod) (1 equiv) and Pr(tfc)$_3$ (1 equiv) (Wenzel, T. J.; Bettes, T. C.; Sadlowski, J. E.; Sievers, R. E. *J. Am. Chem. Soc.* **1980**, *102*, 5904).

Table 2. Substitution of the Allylic Sulfoximine **19** with Organocopper Reagents



19 **41** **42**

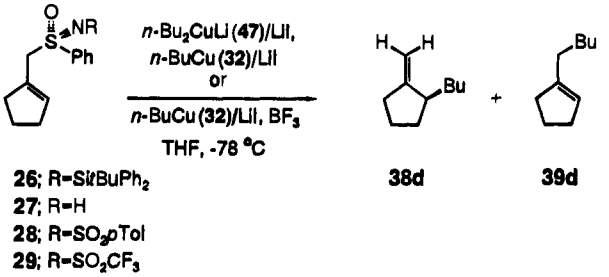
entry	reagent[a]	solvents/additives[a]	product 41/42	yield (%)	γ/α[b]	ee (%)
1	EtO(Me)C(H)O(CH$_2$)$_4$Cu (**5**)/LiI[c]	THF,[d] Me$_2$S/BF$_3$[c]	**a**	91	91:9	60[e]
2	*t*BuPh$_2$SiO(CH$_2$)$_4$Cu (**30**)/LiI[c]	THF,[d] Me$_2$S/BF$_3$[c]	**b**	81	96:4	63[f]
3[g]	EtO(Me)C(H)O(CH$_2$)$_3$Cu (**31**)/LiI[c]	THF,[d] Me$_2$S/BF$_3$[c]	**c**	95	96:4	73[h]
4[g]	*n*-C$_3$H$_7$Cu (**40**)/LiI[c]	THF,[d] Me$_2$S/BF$_3$[c]	**d**	68	99:1	72[i]
5	*n*-C$_4$H$_9$Cu (**32**)/LiI[c]	THF,[d] Me$_2$S/BF$_3$[c]	**e**	83	99:1	60[i]
6	PhCH$_2$Cu (**36**)/MgClI[c]	Et$_2$O,[j] Me$_2$S/BF$_3$[c]	**f**	93	5:95	–
7	Ph(CH$_2$)$_2$Cu (**37**)/LiI[c]	THF,[d] Me$_2$S/BF$_3$[k]	**g**	91	97:3	61[l]

[a] Equivalent based on **19**. [b] γ/α-Ratios were determined by capillary GC analysis and by integration of the olefinic signals in the ^{1}H NMR spectra. [c] 3 equiv. [d] Homogeneous solution. [e] Determined by optical rotation after conversion to **41h** (R = (CH$_2$)$_4$OH). [f] Determined by capillary GC analysis on a permethyl-α-cyclodextrin column after conversion to **41e** via **41h** (R = (CH$_2$)$_4$OH) and **41i** (R = (CH$_2$)$_4$OTs). [g] In this substitution, *ent*-**19** was used and *ent*-**41** was isolated. [h] Determined by capillary GC analysis on a permethyl-α-cyclodextrin column after conversion to *ent*-**41d** via *ent*-**41j** (R = (CH$_2$)$_3$OH) and *ent*-**41k** (R = (CH$_2$)$_3$OTs). [i] Determined by capillary GC analysis on a permethyl-α-cyclodextrin column. [j] Dark brown, heterogeneous solution. [k] 6 equiv. [l] Determined by ^{1}H NMR spectroscopy in the presence of Ag(fod) (1 equiv) and Pr(tfc)$_3$ (1 equiv).

Reaction of **18** with **36**/MgClI in ether or THF in the presence of BF$_3$, where the reaction mixture was also heterogeneous, occurred also selectively at the α-position with formation of **39g**. The regioselectivity, however, was greatly dependent on the amount of BF$_3$ used (entries 12 and 13). Heterogeneous reaction conditions can obviously be deleterious for the attainment of a high γ-selectivity in the substitution of allylic sulfoximines with organocopper reagents perhaps because of the formation of the corresponding organocuprate. A normal pattern was observed with **18** and **37**/LiI where the reaction mixture remained homogeneous (entry 14).

In the case of the six-membered *N*-methylsulfoximine **19**, reaction with the organocopper reagents **5**/LiI, **30**/LiI, **31**/LiI, **32**/LiI, **36**/MgClI, **37**/LiI, and **40**/LiI was investigated (Table 2). The regio- and enantioselectivities observed are quite similar to those found in the substitution of the five-membered *N*-methylsulfoximine **18**. The reaction of the four- and seven-membered *N*-methylsulfoximines **17** and **20**, respectively, was studied with **32**/LiI in order to see if they exhibit a reactivity similar to those of **18** and **19**, respectively. Reaction of **17** with **32**/LiI in THF in the presence of BF$_3$ proceeded with a high γ-selectivity and gave the exocyclic alkene **43** (Scheme 4). The

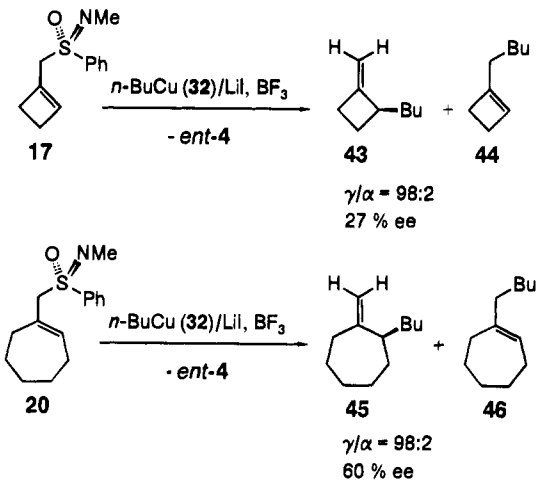
Table 3. Substitution of the Allylic Sulfoximines **26**–**29** with Organocopper and Organocuprate Reagents



entry	sulfoximine	reagent[a]	additive[a]	t (h)	educt (%)	product **38d**/**39d** (%)	γ/α	ee (%)
1	**26**	**47**/LiI	–	*b*	91	–	–	–
2	**27**	**47**/LiI	–	*b*	90	–	–	–
3	**28**	**47**/LiI	–	1.5	–	89	8:92	–
4	**29**	**47**/LiI	–	0.5	–	87	2:98	–
5	**18**	**47**/LiI	–	2	–	86	6:94	–
6	**26**	**32**/LiI	BF_3	*b*	73	–	–	–
7	**27**	**32**/LiI	BF_3	*b*	77	–	–	–
8	**28**	**32**/LiI	BF_3	8	22	70	99:1	27
9	**29**	**32**/LiI	BF_3	2	–	84	98:2	33
10	**18**	**32**/LiI	BF_3	1	–	86	99:1	65
11	**26**	**32**/LiI	–	*b*	89	–	–	–
12	**27**	**32**/LiI	–	*b*	86	–	–	–
13	**28**	**32**/LiI	–	*b*	91	–	–	–
14	**29**	**32**/LiI	–	2	–	87	98:2	32
15	**18**	**32**/LiI	–	*b*	88	–	–	–

[a] 3 equiv. [b] Workup after a reaction time of 8 h.

Scheme 4



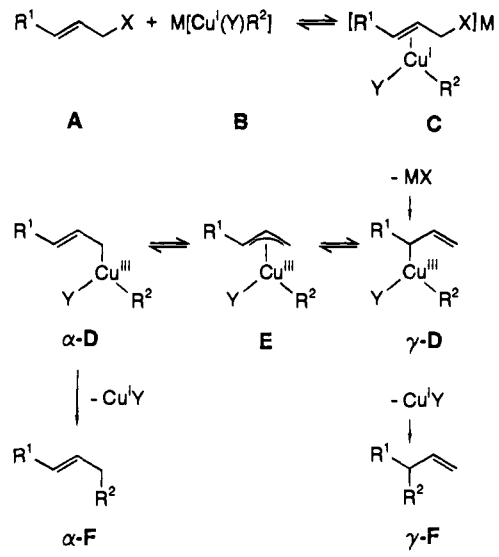
enantioselectivity is, with an ee value of 27% for **43**, the lowest in the series of the *N*-methylsulfoximines. Reaction of **20** with **32**/LiI in either ether or THF in the presence of BF_3 gave with an equal high γ-selectivity the exocyclic alkene **45** in 90% yield. The ee value of **45** was 52% if the reaction was run in THF and 60% if the substitution was run in ether.

Substitution of *N*-*tert*-Butyldiphenylsilyl-, *N*-H-, *N*-Tosyl-, and *N*-Triflylsulfoximines. The influence of the substituent at the N atom of the sulfonimidoyl group on the regio- and enantioselectivity of the substitution reaction was investigated with the five-membered sulfoximines **26**–**29** bearing a H atom, a silyl group, a tosyl group, and a triflyl group, respectively, at the N atom (Table 3). As copper organyls, the butylcopper reagent **32**/LiI and butylcuprate reagent **47**/LiI were chosen. Surprisingly, the *N*-silylsulfoximine **26** and *N*-H sulfoximine **27** did not react under these conditions with the cuprate reagent **47**/LiI (entries 1 and 2). Reaction of the *N*-tosylsulfoximine **28**, *N*-triflylsulfoximine **29**, and *N*-methylsulfoximine **18** with **47**/LiI proceeded readily with high α-selectivity and formation of **39d** in high yield in each case (entries 3–5). The *N*-triflylsulfoximine **29** has the highest reactivity and the *N*-methylsulfoximine **18** the lowest. With **26** or **27** and the organocopper reagent **32**/LiI in the presence or absence of BF_3, no reaction was observed (entries 6, 7, 11, and 12), whereas **28**, **29**, and **18** reacted in the presence of BF_3 readily and gave with high γ-selectivity in each case **38d** (entries 8–10). Interestingly, in reactions with **32**/LiI in the presence of BF_3, the *N*-methylsulfoximine **18** showed the highest reactivity and the *N*-tosylsulfoximine **28** the lowest while that of the *N*-triflylsulfoximine **29** was intermediate. The enantioselectivity of the γ-substitution was considerably lower for the *N*-sulfonylsulfoximines **28** and **29**. In order to probe the role of the Lewis acid, **18** and **26**–**29** were treated with **32**/LiI in THF under identical reaction conditions except that BF_3 was omitted. Here, only the *N*-triflylsulfoximine **29** reacted (entries 11–15), and **38d** was formed with a low enantioselectivity and a high γ-selectivity similar to those with BF_3, which, however, had no influence upon the rate of the reaction (entries 9 and 14).

Mechanistic Considerations: Probing the Role of Halide and BF_3 through Reaction with Pure Me_3SiCH_2Cu. The mechanistic scheme put forward by Rudler et al.,[38] Goering et al.,[39] and Bäckvall et al.[40] for the reaction of primary (and other) biased allylic substrates with copper organyls is based on homoleptic cuprates **B** (Y = R^2) and heteroleptic cuprates **B** (Y = Hal) and features the following steps (Scheme 5): (1) reaction of substrate **A** with cuprate **B** with formation of π-alkene complex **C**, (2) conversion of **C** through an oxidative addition–substitution to σ-allyl complex **D**, and (3) reductive elimination of **D** to substitution product **F**. In the case of γ-**D** (Y = R^2), reductive elimination is thought to be relatively slow because of the two C-bonded organic ligands, thus allowing for an equilibration via π-allyl complex **E** (Y = R^2) to isomeric α-**D** (Y = R^2), followed by the reductive elimination of the latter to α-**F**. Reductive elimination of α-**D** is anticipated to

(38) Levisalles, J.; Rudler-Chauvin, M.; Rudler, H. *J. Organomet. Chem.* **1977**, *136*, 103.
(39) Goering, H. L.; Kantner, S. S. *J. Org. Chem.* **1981**, *46*, 2144.
(40) Bäckvall, J.-E.; Sellén, M.; Grant, B. *J. Am. Chem. Soc.* **1990**, *112*, 6615.

Scheme 5[a]



[a] X = Hal, OR (R = H, COR', SO_2R', $PO(OR')_2$), SR, SeR, SOR, SO_2R, SO(NR')R".[1,2] Y = R^2, Hal.

be faster than that of γ-**D** perhaps because of steric reasons. In the case of γ-**D** (Y = Hal), reductive elimination is assumed to be faster than its isomerization to α-**D** (Y = Hal) because of the electronegative halide and thus γ-**F** would be formed preferentially. In keeping with this scheme is the finding that the isomeric secondary substrate is converted by both cuprates **B** (Y = Hal, R^2) preferentially to α-**F**.[1,2] In general, the oxidative addition−substitution is regarded as rate-determining, and the products reflecting anti stereochemistry are favored, but a syn stereochemistry is also possible depending on the nucleofuge, the substrate, and the organocopper species.[1] Although this mechanistic scheme correlates many experimental observations with the various copper organyls and allylic substrates including allylic sulfoximines, one must recognize that the experimental evidence for the proposed intermediates **C**−**E** is very scarce.[1,2,38-43] This holds especially true for the Cu(III) species **D** and **E** which have so far escaped detection[41-43] and whose reactivity pattern can thus only be anticipated to be analogous to that of related transition metal compounds.[44] The picture is further complicated by the lack of sufficient information on the structure of the reacting organocopper species which is most likely only one entity in an equilibrium mixture of several entities.[41,42] The existence and structure of homoleptic organocuprates **B** (Y = R^2) has been demonstrated beyond any doubt by chemical and spectroscopic means as well as by X-ray structure analysis.[41,42,45] On the other hand, direct experimental evidence for the existence of heteroleptic organocuprates **B** (Y = Hal) and for their formation from a copper halide and a lithium(magnesium) organyl or from an organocopper compound and a lithium(magnesium) halide is much less abundant.[41,42] The heteroleptic organocuprate $[(Me_3Si)_2CHCuBr]$-$[Li(12\text{-crown-}4)_2]$ is the only known example of such a compound.[47,48] Whereas its solid state structure could be revealed by X-ray analysis, its stability and structure in solution, however, remain unknown. Synthetically highly useful but mechanistically even less well-understood is the reaction of allylic substrates with organocopper compounds in the presence of BF_3[3,4,50] which is characterized in general by a high γ-selectivity. Very little is known about the role of the Lewis acid in such substitutions.[3,4,50] Initially,[3,50] a reaction of the organocopper compound with BF_3 to give an organocopper−borane complex, $RCu{\cdot}BF_3$,[3] as reactive species was proposed. Such an organocopper−borane complex has so far not been detected,[4] which, however, does not disprove its existence. In the case of the substitution of allylic alcohols, formation of the well-known alcohol−BF_3 complexes as reactive intermediates has been suggested.[1,2] In nearly all reactions of allylic substrates with Yamamoto reagents,[1,2] the organocopper compounds did contain a halide as an additive because of their mode of preparation. Formation of the heteroleptic organocuprate **B** (Y = Hal) could have been possible therefore. With this assumption, the reactivity of Yamamoto reagents could be explained as well within Scheme 5 except for the role of the Lewis acid. However, to the best of our knowledge, no systematic investigation of the influence of halides and BF_3 upon the reaction of allylic substrates with organocopper compounds based on a *halide-free and soluble copper organyl* has been reported.[1-4,41,42] We decided, therefore, to study the reaction of the *N*-methylsulfoximine **18** and *N*-triflylsulfoximine **29** with an aliphatic organocopper compound which can be prepared free of halide and ligands, has a sufficient thermal stability, and is readily soluble in appropriate solvents at low temperatures (Table 4). We chose Me_3SiCH_2Cu (**34**)[37d] which can easily be prepared from Me_3SiCH_2Li[37i] and CuI and which meets all of the above criteria. The LiI-free copper organyl **34** is not capable of substituting **18**. From the yellow solution of **18** and **34** in THF, which was kept for several hours either at −78 °C or at 0 °C, **18** was recovered, and formation of **38f** and **39f** could not be detected (entry 1). Equally incapable, however, of reacting with **18** is **34** in combination with LiI (entry 2). Addition of LiI to **34** in THF at −78 °C resulted in a yellow-green solution which was treated with **18**. After 7 h first at −78 °C and then at 0 °C, alkene formation could not be detected, and **18** was recovered in high yield. In a parallel experiment, after 6 h at −78 °C, BF_3 was added to the mixture containing **34**, **18**, and LiI. Here, after 2 h, the reaction was complete, and **38f** and **39f** were isolated in 69% yield (entry 3). In order to verify the results further, **34** was treated with BF_3 in THF at −78 °C to produce an orange-red solution to which **18** was added. After 15 min, **34** deposited partially as a colorless solid. Even after 6 h at −78 °C, formation of alkenes **38f** and **39f** could not be detected and **18** was recovered (entry 4). In a parallel experiment, after 6 h at −78 °C, LiI was added to the heterogeneous reaction mixture of **34**, **18**, and BF_3. During the addition of LiI, the mixture became homogeneous and its colour changed from red to yellow-green. After 2 h, **18** had completely reacted and **38f** and **39f** were isolated in 68% yield (entry 5). In a final experiment, **34** was combined with LiI and BF_3 in THF at −78 °C to give a yellow-green solution to which **18**

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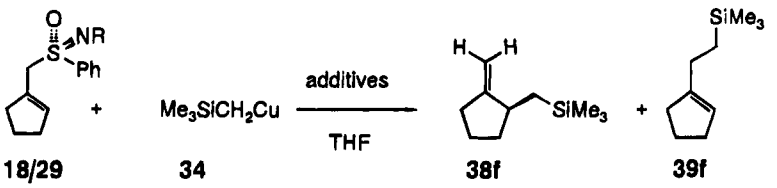
Table 4 Substitution of the Allylic Sulfoximines **26**–**29** with Organocopper and Organocuprate Reagents



18/29 34 38f 39f

entry[a]	sulfoximine	additives[b]	t (h)	educt (%)	product 38f/39f (%)	γ/α	ee (%)
1	**18**; R = Me	–	8	93	–	–	–
2	**18**; R = Me	LiI[c]	7	96	–	–	–
3	**18**; R = Me	LiI[c] + BF_3[c]	6 + 2	–	69	72:28	60
4	**18**; R = Me	BF_3[c]	6	89	–	–	–
5	**18**; R = Me	BF_3[c] + LiI[c]	6 + 2	–	68	85:15	60
6	**18**; R = Me	LiI,[c] BF_3[c]	2	–	66	66:34	66
7	**29**; R = SO_2CF_3	–	13	94	–	–	–
8	**29**; R = SO_2CF_3	LiI[c]	13	67	33	80:20	28
9	**29**; R = SO_2CF_3	n-Bu_4NI[c]	13	–	98	89:11	17

[a] 3 equiv of **34**. [b] Equivalent based on **18** and **29**, respectively. [c] 3 equiv.

was added. After 2 h, **18** was completely consumed, and a mixture of **38f** and **39f** could be isolated in 66% yield (entry 6). The order of the combination of the sulfoximine, the organocopper compound, the Lewis acid, and LiI had no significant bearing on the regio- and enantioselectivity or on the reaction rate. To corroborate the results of the reaction of the *N*-triflylsulfoximine **29** with the butylcopper reagent **32**/LiI, the reaction of **29** with **34** was studied also. LiI-free **34** does react with **29** in THF at −78 °C only very slowly. After 13 h at −78 °C, not more than 2% of a mixture of **38f** and **39f** in a ratio of 92:8 could by isolated and **29** was recovered in 94% yield (entry 7). In the presence of LiI under the same conditions, the reaction was significantly faster. Here, after 13 h, a mixture of **38f** and **39f** was isolated in a ratio of 80:20 in 33% yield and 67% of **29** was recovered (entry 8). In a last experiment, Bu_4NI was used as the halide source. Here, under the same conditions, after 13 h, **29** had *completely reacted*, and **38f** and **39f** were isolated in a ratio of 89:11 in 98% yield (entry 9). From these results, it is quite clear that iodide is a promotor in such reactions and its role in the substitution of allylic sulfoximines and perhaps in that of other allylic substrates with organocopper compounds also may be indeed the formation of heteroleptic organocuprates[38–41,51,52] of the composition $(RCu{\cdot}MHal)_n$ or $(RCu)_m{\cdot}(MHal)_n$. From the ready synthesis of organocopper compounds from lithium organyls and copper iodide,[41,42] it appears as if heteroleptic cuprates containing halide are rather labile compounds which partake in solution only in a perhaps fast equilibrium with the organocopper compound and the halide. Aggregate formation with themselves or with the organocopper compound is conceivable. The essential role of halide in another synthetically important reaction of organocopper compounds, the 1,4-addition to enones, is well-documented.[1b,51,52] In 1968, House et al. showed that a 1,4-addition to 5-methyl-2-cyclohexenone with MeCu occurs only in the presence of LiI (but not Bu_4NI!) and proposed the formation of the heteroleptic organocuprate MeCu(I)Li as the reactive species.[51a] Recently, Lipshutz et al. studied the reaction of MeCu with 4-isopropylcyclohexenone in the presence of BF_3 and concluded that both LiI and BF_3 are essential for a 1,4-addition to take place.[1b,51d] They proposed, on the basis of chemical and NMR spectroscopic experiments, the existence of the cuprate $[MeCu(I)Li]_2$ which supposedly reacts with BF_3 in an equilibrium with formation of a $MeLi{-}BF_3$ complex and I_2CuLi.[51f] This scheme, however, does not specify the nature of the reacting organocopper species and the role of the Lewis acid. Furthermore, MeCu may be a special case because of its low solubility in ethereal solvents.[41] In reactions of *N*-methyl- and *N*-tosylsulfoximines with organocopper compounds, where substitution occurs only if, besides halide, BF_3 is present also, the role of the Lewis acid is most likely confined to the activation of the substrate or an intermediate thereof through coordination to the sulfonimidoyl or sulfonyl group. The higher reactivity of *N*-methylsulfoximines toward organocuprates in the presence of BF_3, the decrease in reactivity in the series of *N*-methyl-, *N*-triflyl-, and *N*-tosylsulfoximine toward organocopper reagents in the presence of BF_3, and the failure of *N*-methyl- and *N*-tosylsulfoximines to react if BF_3 is omitted would fit into this picture. It is well-established that in cyclization reactions, the nucleofugacity of the sulfonimidoyl group is greatly increased upon replacement of the *N*-methyl group by a strongly electronegative substituent such as sulfonyl[34] or nitro.[53] The nucleofugacity of the BF_3-complexed *N*-methylsulfonimidoyl group should be close to that of the (dialkylamino)oxosulfonium group which has the highest one.[34]

Absolute Configuration of the Exocyclic Alkenes. The absolute configuration of the alkenes **38**, **41**, and **45** was determined either by chemical correlation with the corresponding lactones through ozonolysis to the corresponding cycloalkanones and oxidation of the latter with *m*-chloroperbenzoic acid or by circular dichroism (CD) measurements of the cycloalkanones or by a combination thereof (Scheme 6). Ozonolysis of (+)-**38b** cleanly delivered the cyclopentanone derivative (+)-**48a** in 89% yield. Baeyer–Villiger reaction of (+)-**48a** with *m*-chloroperbenzoic acid led to the δ-lactone (−)-**49a**. Desilylation of (−)-**49a** gave the hydroxy δ-lactone (−)-**50** of known absolute configuration.[54] Its chiroptical data showed that the sample of synthesized (−)-**50** had the (*S*)-configuration, and thus, (+)-**38b** has the (*R*)-configuration. Comparison of the ee values of **38b** and **49a** showed that ozonolysis of the former to **48a** proceeded without racemization. Deprotection of (+)-**38a** and (+)-**38b** gave in both cases the alcohol (+)-**38i** (R = $(CH_2)_4$-OH), and thus, (+)-**38a** also has the (*R*)-configuration. Deprotection of (−)-**38c** gave the alcohol (+)-**38k** (R = $(CH_2)_3OH$),

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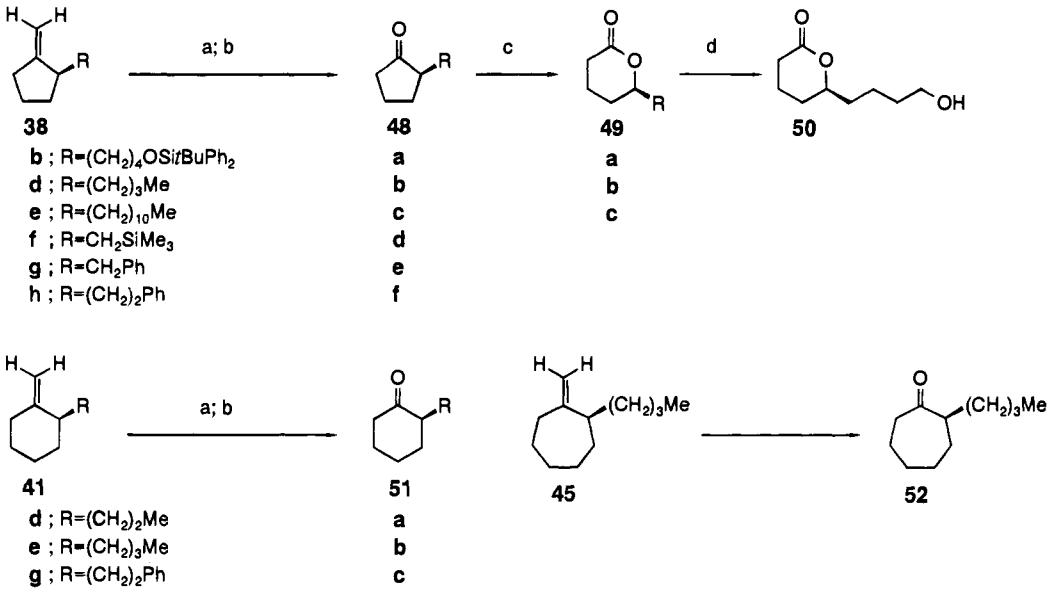
Scheme 6[a]



[a] Reagents: (a) O_3, CH_2Cl_2, MeOH, −60 °C; (b) Me_2S, −60 °C → rt; (c) *m*-ClC_6H_4COOOH; (d) *n*-Bu_4NF.

and since it differs from (+)-**38i** (R = $(CH_2)_4OH$) only by one methylene group in the side chain, it is assumed that the former also has the (*R*)-configuration. Thus, (−)-**38c** should also have the (*R*)-configuration. The absolute configuration of (+)-**38d** was determined by ozonolysis to (+)-**48b** whose ee value demonstrated that here, too, ozonolysis was not accompanied by racemization. Oxidation of (+)-**48b** with *m*-chloroperbenzoic acid gave the δ-lactone (−)-**49b** of known absolute configuration.[55] Comparison of the chiroptical data showed that (−)-**49b** and (+)-**38d** both possess the (*S*)-configuration. In a similar manner, the absolute configuration of (+)-**38e** was secured. Ozonolysis of (+)-**38e** cleanly afforded (+)-**48c** which, according to its chiroptical data,[56] had the (*S*)-configuration. Oxidation of (+)-**48c** with *m*-chloroperbenzoic acid gave (−)-**49c**, a pheromone of *Vespa orientalis*, whose chiroptical data indicated that (−)-**49c** and (+)-**38e** both possess the (*S*)-configuration.[54-58] The absolute configuration of (+)-**38f**, (+)-**38g**, and (+)-**38h** was determined by their conversion to (+)-**48d**, (+)-**48e**,[59] and (+)-**48f**, respectively, through ozonolysis and CD measurement[60] of the latter. Thereby, for (+)-**38f**, the (*S*)-configuration was established, and for (+)-**38g** and (+)-**38h**, the (*R*)-configuration was established. The absolute configuration of (−)-*ent*-**41c** derived from *ent*-**19** was determined through chemical correlation by the following sequence: deprotection to the alcohol (−)-*ent*-**41j** (R = $(CH_2)_3OH$), tosylation to the tosylate (−)-*ent*-**41k** (R = $(CH_2)_3OTs$), reduction to the cyclohexene derivative (−)-*ent*-**41d**, and ozonolysis to the cyclohexanone derivative (−)-*ent*-**51a** of known absolute configuration.[60-63] Comparison of the chiroptical data proved the (*R*)-configuration for (−)-*ent*-**51a**. Thus, (−)-*ent*-**41d** has the (*R*)-configuration, and (−)-*ent*-**41c** has the (*S*)-configuration. The absolute configuration of (+)-**41a** and (+)-**41b**, both derived from **19**, was established through chemical correlation using a similar set of transformations. Deprotection of (+)-**41a** and (+)-**41b** led in both cases to the alcohol (+)-**41h** (R = $(CH_2)_4OH$) which was converted via the tosylate (+)-**41i** (R = $(CH_2)_4OTs$) to (+)-**41e**. Ozonolysis of the latter gave the cyclohexanone derivative (+)-**51b** with the (*S*)-configuration. Thus, (+)-**41a** and (+)-**41b** have the (*R*)-configuration according to the CD measurement. The absolute configuration of the cyclohexane derivative (+)-**41g** and the cycloheptane derivative (−)-**45** established through their ozonolysis to (+)-**51c** and (+)-**52**, respectively, and CD measurement of the latter. Thus, (+)-**41g** has the (R)-configuration and (−)-**45** the (*S*)-configuration.

Stereochemical Considerations. In the γ-substitution reactions of allylic sulfoximines, the chiral nucleofuge imparts asymmetric induction in the range of 52−90% ee except for the four-membered *N*-methylsulfoximine **17** as well as the *N*-triflyl- and *N*-tosylsulfoximines **29** and **28**, respectively, where the enantioselectivity is only in the range 17−33% ee. The sense of asymmetric induction is such that with an (*S*)-configurated sulfonimidoyl group, CC bond formation occurs preferentially at the *si* side of the prochiral center regardless of the ring size and the substituent at the N atom. The important question if the substitution of the endocyclic allylic sulfoximines follows a syn or anti stereochemistry or both cannot be answered for the substrates investigated. We are currently studying the stereochemistry of the γ-substitution of the diastereomeric α-methyl derivatives of **18** with **32**/LiI in order to get some insight at least in these cases. Because of the limited knowledge available on the mechanism of the reaction of allylic sulfoximines[64] with organocopper and -cuprate reagents in general and because of the yet unsolved syn/anti stereochemistry, interpretation of the sense of asymmetric induction in the substitution of the allylic sulfoximines is not attempted. In the substitution of (*S*)-*N*-methylsulfoximines with organocopper and organocuprate reagents besides the endo- and exocyclic alkenes, the sulfinamide *ent*-**4**[12] is formed generally in higher than 90%

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(64) Acyclic primary allylic *N*-methylsulfoximines show a similar reactivity toward organocopper compounds and organocuprates (Gais, H.-J.; Scommoda, M.; Bosshammer, S. Unpublished results).

yield. Its chiroptical data[12] and ^{1}H NMR spectrum in the presence of Eu(tfc)$_3$ ($\Delta\Delta\delta$(Me) = 0.06 ppm and $\Delta\Delta\delta$(*o*-Ph) = 0.12 ppm) revealed an ee value of 97%. Because of the synthesis of enantiomerically pure sulfoximine **7** from *ent*-**4**,[12,65] the chirality of the nucleofuge is at least in principle retained.

Conclusion

Primary endocyclic allylic sulfoximines carrying various substituents at the N atom are readily available in enantiomerically pure form from cycloalkanones and (*R*)- or (*S*)-*S*-methyl-*S*-phenylsulfoximines. They do not racemize thermally or rearrange easily to the corresponding allylic sulfinamides. In substitution reactions with copper organyls, the sulfonimidoyl group is an excellent nucleofuge whose nucleofugacity strongly depends on the substituent at the N atom. Like other biased primary allylic substrates, the allylic sulfoximines generally react with organocuprate reagents with high selectivity at the α-position and with organocopper reagents in the presence or absence of BF_3 depending on the nature of the sulfonimidoyl group at the γ-position with equal high selectivity. In the reactions of allylic sulfoximines with organocopper compounds, iodide plays a pivotal role and heteroleptic organocuprates may be the reacting species. BF_3 is not generally necessary for the substitution to occur. Thus, formation of a complex with the organocopper compound or heteroleptic cuprate can be excluded as a necessary mode of action of the Lewis acid. The role of the Lewis acid is most probably that of an activation of the nucleofuge at the stage of the educt or some intermediate thereof through coordination. The *N*-methylsulfonimidoyl group imparts a moderate to good asymmetric induction to the γ-substitution with the same sense in all cases investigated whereby the (*S*)-configurated nucleofuge preferentially leads to a *si* side attack. In the substitutions of *N*-methyl allylic sulfoximines, *N*-methylsulfinamide is formed with complete retention of configuration at the S atom. Through the steps of carbonyl olefination with a *N*-substituted *S*-methyl-*S*-phenylsulfoximine, isomerization of the vinyl sulfoximine to the allylic sulfoximine, and substitution of the latter with a copper organyl, a cycloalkanone can be converted in good overall yield with good to high regioselectivity and in modest to good enantioselectivity to α-substituted exocyclic alkenes.[66]

Experimental Section

All manipulations except workup and chromatographic purification were performed in an atmosphere of dry, oxygen-free argon, with Schlenk and syringe techniques in oven-dried glassware. Solvents were purified and dried prior to use by distillation from an appropriate drying agent. Diethyl ether and *n*-pentane were distilled from sodium benzophenone ketyl, and tetrahydrofuran (THF) was distilled from potassium benzophenone ketyl. Dichloromethane, pyridine, dimethyl sulfide, and triethylamine were distilled from calcium hydride, methanol was distilled from magnesium turnings, and toluene was distilled from sodium. Bulk solvents for chromatography were distilled through glass prior to use. Starting materials were obtained from commercial sources and used without further purification unless otherwise stated. Cu^{I}I was purified by the method described by Kauffman and Teter.[67] BF_3·OEt_2 was distilled under reduced pressure, and Me_3SiCl was distilled from calcium hydride. The organolithium compounds EtO(Me)C(H)O-$(CH_2)_4$Li,[37a,b] *t*-Bu$Ph_2SiO(CH_2)_4$Li, EtO(Me)C(H)O$(CH_2)_3$Li,[37c] Ph-$(CH_2)_2$Li, *n*-PrLi, *n*-$C_{11}H_{23}$Li, and Me_3SiCH_2Li[37i] were prepared from the corresponding chlorides and lithium powder under standard conditions in Et_2O[68a] and standardized by titration with diphenylacetic acid.[68b] $PhCH_2MgCl$ was prepared in the usual manner and standardized by titration with benzylic alcohol in toluene in the presence of 1,10-phenanthroline.[68a] LiI and Bu_4NI were purchased water-free and were heated in vacuo for 0.5 h at 50−60 °C prior to use. Analytical thin-layer chromatography (TLC) was performed on E. Merck precoated TLC plates (silica gel 60 F_{254}, layer thickness 0.2 mm). Gravitation column chromatography (denoted as chromatography) was performed with E. Merck silica gel 60 (230−400 mesh) and flash chromatography (FC) following the method of Still et al.[69] with E. Merck silica gel 60 (70−230 mesh). Medium-pressure chromatography (MPLC) was done on columns with E. Merck LiChroprep Si 60 silica gel (15−25 μm, 50 × 4 cm) on a Kronwald instrument. Melting points were determined using a Büchi 535 apparatus and are uncorrected. ^{1}H and ^{13}C NMR spectra were recorded on a Bruker AM 400, a Varian VRX 300, or a Varian Unity 500 instrument. ^{1}H NMR chemical shifts are reported in ppm relative to Me_4Si: δ 0.00 as the internal standard. Splitting patterns are designated as s, singlet; d, doublet; dd, double doublet; t, triplet; qua, quartet; qui, quintet; sep, septet; m, multiplet; and br, broadened. ^{13}C NMR chemical shifts are reported in ppm relative to Me_4Si: δ 0.00 as the internal standard. Peaks in ^{13}C NMR spectra are denoted as "u" for carbons with zero or two attached protons or as "d" for carbons with one or three attached protons, as determined from the APT puls sequence. Low-resolution mass spectra were recorded on a Varian MAT 212 mass spectrometer, and high-resolution mass spectra were recorded on a Varian MAT 95 mass spectrometer. Capillary GC analysis for the determination of γ/α-selectivities were carried out on a Chrompack CP 9000 gas chromatograph coupled with PC-recording software MOSAIC (Chrompack) using a commercially available DB5 column (J&W Scientific). Determination of ee by capillary GC analysis was performed on a Carlo-Erba HRGC 5300 Mega-Series coupled with PC-recording software MOSAIC (Chrompack) using a commercially available Cyclodex αI (CS Chromatography Service, 50 m × 0.25 mm i.d., 0.25 μm film) or a glass capillary column filled with 2,3-di-*O*-pentyl-6-*O*-methyl-γ-cyclodextrin (25 m × 0.32 mm i.d., 0.25 μm film). The injector temperature was 250 °C, and the detector temperature was 300 °C. Optical rotations were measured with a Perkin-Elmer 241 polarimeter at room temperature. CD spectra were recorded on a JASCO Spectropolarimeter J 41. Elemental analyses were performed by the Institut für Organische Chemie Microanalytical Laboratory.

(−)-(*S*)-*S*-(Cyclopentylidenemethyl)-*N*-methyl-*S*-phenylsulfoximine (14). To a solution of **7** (8.5 g, 50 mmol) in THF (60 mL) was added *n*-BuLi (50 mmol, 32.3 mL of 1.55 M in *n*-hexane) at −30 °C. The resulting orange solution was warmed up to room temperature, stirred for 10 min, and cooled to −78 °C, and then cyclopentanone (4.2 g, 50 mmol) in THF (20 mL) was added. The solution was stirred for 1 h at −78 °C before Me_3SiCl (10.2 mL, 80 mmol) was added dropwise. After being stirred for 10 min at this temperature, the pale yellow solution was allowed to warm to room temperature and was stirred for another 2 h. The mixture was cooled to −78 °C, and *n*-BuLi (50 mmol, 32.3 mL of 1.55 M in *n*-hexane) was added. After the resulting yellow solution was stirred for 30 min, saturated aqueous NH_4Cl (100 mL) was added. The mixture was extracted with EtOAc (4 × 100 mL). The combined organic extracts were dried ($MgSO_4$) and concentrated in vacuo. Purification of the residue by chromatography (20% *n*-hexane−EtOAc) gave **14** (9.6 g, 80%) and **18** (1.8 g, 12%) as colorless oils: $[\alpha]_D$ −53.4° (*c* 0.89, acetone); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.93−7.84 (m, 2 H), 7.59−7.46 (m, 3 H), 6.33 (qui, *J* = 2.3 Hz, 1 H), 2.93−2.79 (m, 1 H), 2.66 (s, 3 H), 2.48−2.18 (m, 3 H), 1.76−1.46 (m, 4 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 164.40 (u), 140.44 (u), 132.16 (d), 129.03 (d), 128.74 (d), 121.66 (d), 36.11 (u), 30.30 (u), 29.19 (d), 26.44 (u), 25.21 (u); MS (EI) *m/z* (relative intensity) 235 (M^+, 3), 187 (37), 157 (28), 156 (51), 155 (100), 129 (50), 125 (44), 109 (40), 107 (52), 91 (35), 81 (50), 79 (92), 78 (65), 77 (91), 67 (34), 53 (44), 51 (58), 42 (47), 41 (54), 39 (33). Anal. Calcd for $C_{13}H_{17}NOS$: C, 66.35; H, 7.28; N, 5.95. Found: C, 66.25; H, 7.31; N, 5.86.

(+)-(*S*)-*S*-(1-Cyclopenten-1-ylmethyl)-*N*-methyl-*S*-phenylsulfoximine (18). To a solution of 1,10-phenanthroline (1 mg) in THF (10

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(69) Still, W. C.; Hahn, M.; Mitra, A. *J. Org. Chem.* **1978**, *43*, 2923.

mL) was added *n*-BuLi (77 mmol, 50 mL of 1.55 M in *n*-hexane). The resulting dark red solution was cooled to −50 °C, and MeOH was added dropwise until the suspension turned yellow. The thus-formed suspension of LiOMe was treated with **14** (9.0 g, 38 mmol) in THF (10 mL) and toluene (20 mL) at −50 °C. After the suspension was stirred for 1 h, the cooling bath was removed, and stirring was continued for 72 h at room temperature. After the addition of saturated aqueous NH_4Cl (100 mL), the mixture was extracted with EtOAc (4 × 100 mL). The combined organic extracts were dried ($MgSO_4$) and concentrated in vacuo. Purification of the residue by chromatography (20% *n*-hexane−EtOAc) gave **18** (8.5 g, 95%) as a colorless oil: $[\alpha]_D$ +62.3° (*c* 1.37, acetone); ^1H NMR (300 MHz, $CDCl_3$) δ 7.85−7.79 (m, 2 H), 7.64−7.48 (m, 3 H), 5.51−5.47 (m, 1 H), 3.97 (s, 2 H), 2.72 (s, 3 H), 2.45−2.29 (m, 1 H), 2.29−2.16 (m, 3 H), 1.81 (qui, *J* = 7.4 Hz, 2 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 137.27 (u), 135.536 (d), 132.56 (d), 131.75 (u), 129.55 (d), 129.02 (d), 58.75 (u), 35.03 (u), 32.73 (u), 29.79 (d), 23.62 (u); MS (EI) *m/z* (relative intensity) 235 (M^+, 3), 157 (62), 156 (32), 154 (35), 126 (31), 125 (85), 110 (100), 107 (75), 106 (55), 81 (100), 80 (32), 79 (98), 78 (100), 77 (86), 53 (50), 51 (50), 43 (34), 41 (59). Anal. Calcd for $C_{13}H_{17}NOS$: C, 65.35; H, 7.28; N, 5.95. Found: C, 66.31; H, 7.12; N, 5.87.

(+)-(*S*)-1-[[*N*-(*tert*-Butyldiphenylsilyl)-*S*-phenylsulfonimidoyl]-methyl]cyclopentanol (24a). To a solution of **22** (19.5 g, 50 mmol) in THF (60 mL) was added *n*-BuLi (50 mmol, 33.4 mL of 1.55 M in *n*-hexane) at −30 °C. The resulting orange solution was stirred for 15 min at room temperature and cooled to −78 °C, and cyclopentanone (4.2 g, 50 mmol) in THF (15 mL) was added. After this solution was stirred for 1 h, saturated aqueous NH_4Cl (100 mL) was added, and the resulting mixture was extracted with EtOAc (5 × 100 mL). The combined organic extracts were dried ($MgSO_4$) and concentrated in vacuo. Purification of the oily residue by chromatography (20% *n*-hexane−EtOAc) gave **24a** (20.2 g, 84%) as a colorless solid: mp 104 °C; $[\alpha]_D$ +46.8° (*c* 1.11, MeOH); ^1H NMR (300 MHz, $CDCl_3$) δ 7.78−7.69 (m, 4 H), 7.53−7.50 (m, 2 H), 7.35−7.10 (m, 9 H), 5.34 (sbr, 1 H), 3.57 (d, *J* = 14 Hz, 1 H), 3.23 (d, *J* = 14 Hz, 1 H), 2.10−2.04 (m, 1 H), 1.90−1.76 (m, 4 H), 1.69−1.62 (m, 1 H), 1.58−1.50 (m, 1 H), 1.46−1.40 (m, 1 H), 1.08 (s, 9 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 143.73 (u), 135.76 (d), 135.66 (d), 135.25 (u), 134.84 (u), 132.12 (d), 129.09 (d), 128.95 (d), 128.65 (d), 127.44 (d), 127.25 (d), 127.16 (d), 80.02 (u), 67.70 (u), 41.14 (u), 39.16 (u), 27.24 (d), 23.85 (u), 22.93 (u), 19.33 (u); MS (EI) *m/z* (relative intensity) 420 (M^+ − *t*-Bu, 10), 340 (30), 338 (100), 262 (31), 200 (46), 199 (77). Anal. Calcd for $C_{28}H_{35}NO_2SSi$: C, 70.40; H, 7.28; N, 2.93. Found: C, 70.31; H, 7.30; N, 3.11.

(+)-(*S*)-*N*-(*tert*-Butyldiphenylsilyl)-*S*-(1-cyclopenten-1-ylmethyl)-*S*-phenylsulfoximine (26). To a solution of **24a** (6.3 g, 13 mmol) in CH_2Cl_2 (100 mL) and NEt_3 (9 mL, 65 mmol) was added $MeSO_2Cl$ (3.15 mL, 39 mmol) at 0 °C. The solution was stirred for 1 h, and DBU (12 mL, 78 mmol) was added. After the reaction mixture was stirred for 12 h, it was diluted with Et_2O (500 mL). The solution was washed with water, saturated aqueous NH_4Cl, and 10% aqueous Na_2CO_3 (in this order), dried ($MgSO_4$), and concentrated in vacuo. Purification of the residue by chromatography (20% EtOAc−*n*-hexane) gave an inseparable mixture of **25** and **26** (5.53 g, 93%) in a ratio of 12:88. To a suspension of KOMe [preparation: To potassium (0.97 g, 25 mmol) in THF (20 mL) was added dropwise MeOH (5 mL) at −70 °C; the reaction mixture was allowed to warm to room temperature until the metal had completely disappeared; the volatiles were removed in vacuo, and the white solid was suspended in 20 mL of THF] was added the mixture of **25** and **26** (1.70 g, 3.7 mmol) in THF (10 mL) at room temperature. After the suspension was stirred for 72 h, saturated aqueous NH_4Cl (50 mL) was added and the mixture extracted with EtOAc (4 × 50 mL). The combined organic extracts were dried ($MgSO_4$) and concentrated in vacuo. Purification of the residue by chromatography (20% EtOAc−*n*-hexane) gave **26** (1.51 g, 89%) as a colorless oil which crystallized in the freezer as a colorless solid: mp 54 °C; $[\alpha]_D$ +3.2° (*c* 1.08, MeOH); ^1H NMR (300 MHz, $CDCl_3$) δ 7.85−7.68 (m, 6 H), 7.50−7.24 (m, 9 H), 5.28−5.24 (m, 1 H), 3.78 (d, J_{AB} = 13.5 Hz, 1 H), 3.74 (d, J_{AB} = 13.5 Hz, 1 H), 2.24−2.06 (m, 4 H), 1.75−1.65 (m, 2 H), 1.06 (s, 9 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 142.67 (u), 136.49 (u), 136.39 (u), 135.61 (d), 134.66 (d), 132.65 (u), 132.02 (d), 128.85 (d), 128.81 (d), 128.37 (d), 127.94 (d), 127.25 (d), 127.20 (d), 63.18 (u), 35.02 (u), 32.67 (u), 27.18 (d), 23.55 (u), 19.44 (u); MS (EI) *m/z* (relative intensity) 403 (M^+ − *t*-Bu, 32), 402 (100), 199 (48). Anal. Calcd for $C_{28}H_{33}NOSSi$: C, 73.15; H, 7.23; N, 3.05. Found: C, 73.26; H, 7.42; N, 2.91.

(−)-(*S*)-*S*-(1-Cyclopenten-1-ylmethyl)-*N*-hydrido-*S*-phenylsulfoximine (27). To a solution of **25** and **26** (5.5 g, 12 mmol) in THF (100 mL) was added $Bu_4NF{\cdot}3H_2O$ (7.6 g, 24 mmol) in THF (20 mL) at 0 °C. The ice bath was removed, and the mixture was stirred for 6 h at room temperature. Concentration of the mixture in vacuo and purification of the oily residue by chromatography (33% *n*-hexane−EtOAc) gave **27** (2.38 g, 90%) as a colorless solid: mp 65 °C; $[\alpha]_D$ −8.0° (*c* 0.89, MeOH); ^1H NMR (300 MHz, $CDCl_3$) δ 7.99−7.92 (m, 2 H), 7.64−7.49 (m, 3 H), 5.56−5.52 (m, 1 H), 4.02−3.90 (m, 2 H), 2.83 (sbr, 1 H), 2.41−2.27 (m, 4 H), 1.85 (qui, *J* = 7 Hz, 2 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 141.12 (u), 135.52 (d), 132.94 (d), 128.81 (u), 128.66 (d), 128.58 (d), 60.65 (u), 35.11 (u), 32.79 (u), 23.63 (u); MS (EI) *m/z* (relative intensity) 221 (M^+, 3), 157 (32), 142 (94), 125 (100), 96 (72), 81 (93), 80 (40), 79 (89), 78 (36), 77 (51), 41 (26). Anal. Calcd for $C_{12}H_{15}NOS$: C, 65.12; H, 6.83; N, 6.33. Found: C, 65.16; H, 6.97; N, 6.55.

(+)-(*S*)-*S*-(1-Cyclopenten-1-ylmethyl)-*N*-(*p*-tolylsulfonyl)-*S*-phenylsulfoximine (28). To a solution of **27** (5.5 g, 25 mmol) in pyridine (50 mL) was added *p*-TsCl (5.2 g, 28 mmol) in pyridine (50 mL) at 0 °C. The ice bath was removed, and the mixture was stirred for 12 h at room temperature. Concentration of the mixture in vacuo and purification of the residue by chromatography (20% EtOAc−*n*-hexane) gave **28** (8.3 g, 89%) as a colorless solid from which single crystals were obtained by a slow evaporation of a solution in $CHCl_3$: mp 118 °C; $[\alpha]_D$ +68.8° (*c* 0.99, MeOH); ^1H NMR (300 MHz, $CDCl_3$) δ 7.91−7.82 (m, 4 H), 7.69−7.62 (m, 1 H), 7.59−7.50 (m, 2 H), 7.28−7.21 (m, 2 H), 5.51−5.47 (m, 1 H), 4.39 (d, J_{AB} = 14.5 Hz, 1 H), 4.35 (d, J_{AB} = 14.5 Hz, 1 H), 2.38 (s, 3 H), 2.31−2.10 (m, 4 H), 1.76 (qui, *J* = 7.6 Hz, 2 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 142.61 (u), 141.07 (u), 138.20 (d), 135.93 (u), 134.29 (d), 129.91 (u), 129.25 (d), 129.21(d), 128.62 (d), 126.68 (d), 60.69 (u), 34.90 (u), 32.93 (u), 23.65 (u), 21.57 (d); MS (EI) *m/z* (relative intensity) 298 (M^+ − Ph, 3), 296 (23), 278 (27), 155 (56), 140 (32), 139 (41), 125 (57), 91 (88), 81 (100), 79 (52), 78 (34), 77 (35). Anal. Calcd for $C_{19}H_{21}NO_3S_2$: C, 60.77; H, 5.64; N, 3.73. Found: C, 60.86; H, 5.69; N, 3.86.

(+)-(*S*)-*S*-(1-Cyclopenten-1-ylmethyl)-*S*-phenyl-*N*-[(trifluoromethanyl)sulfonyl]sulfoximine (29). To a solution of **27** (1.0 g, 4.5 mmol) in CH_2Cl_2 (10 mL) was added NEt_3 (1 mL) and $(CF_3SO_2)_2O$ (1.48 mL, 9 mmol) at −78 °C. After the mixture was stirred for 2 h, saturated aqueous $NaHCO_3$ (50 mL) was added. The resulting mixture was extracted with EtOAc (4 × 50 mL). The combined organic extracts were dried ($MgSO_4$) and concentrated in vacuo. The crude product was dissolved in EtOAc and the solution filtered through a pad of silica gel (EtOAc). Concentration of the solution gave **29** (1.53 g, 96%) as a colorless solid: mp 105 °C; $[\alpha]_D$ +21.1° (*c* 0.85, MeOH); ^1H NMR (300 MHz, $CDCl_3$) δ 7.99−7.90 (m, 2 H), 7.81−7.74 (m, 1 H), 7.69−7.61 (m, 2 H), 5.66−5.60 (m, 1 H), 4.45 (d, J_{AB} = 14.5 Hz, 1 H), 4.34 (d, J_{AB} = 14.5 Hz, 1 Hz), 2.40−2.12 (m, 4 H), 1.83 (qui, *J* = 7 Hz, 2 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 139.70 (d), 135.22 (d), 135.11 (u), 129.67 (d), 128.59 (u), 128.39 (d), 61.36 (u), 34.85 (u), 32.99 (u), 23.60 (u); MS (EI) *m/z* (relative intensity) 220 (M^+ − SO_2CF_3, 1), 81 (100), 80 (44), 79 (39). Anal. Calcd for $C_{13}H_{14}F_3NO_3S_2$: C, 44.19; H, 3.99; N, 3.96. Found: C, 44.11; H, 4.14; N, 3.95.

1-[5-(1-Ethoxyethoxy)pentyl]cyclopentene (39a). To a solution of Cu^II (381 mg, 2.0 mmol) in Et_2O (15 mL) and Me_2S (3 mL) was added $EtO(Me)C(H)O(CH_2)_4Li$ (4.0 mmol, 3.1 mL of 1.29 M in Et_2O) at −60 °C. The solution was warmed to −45 °C and stirred for 45 min. To the resulting brown-green, homogeneous solution of **2**/LiI was added *rac*-**18** (148 mg, 0.63 mmol) in Et_2O (10 mL). The solution was stirred for 3 h at −45 °C, and then a 10:1 mixture of saturated aqueous NH_4Cl and concentrated aqueous NH_3 was added. The resulting mixture was extracted with Et_2O (4 × 20 mL). The combined organic extracts were dried ($MgSO_4$) and concentrated in vacuo. Purification of the residue by chromatography (9% EtOAc−*n*-hexane) gave a mixture of **39a** and **38a** (128 mg, 90%) in a ratio of 98:2 as a colorless oil: ^1H NMR (400 MHz, $CDCl_3$) δ 5.30 (sep, *J* = 1.9 Hz, 1 H), 4.68 (qua, *J* = 5.5 Hz, 1 H), 3.70−3.32 (m, 4 H), 2.34−2.23 (m, 2 H), 2.20 (tbr, *J* = 7.5 Hz, 2 H), 2.05 (tbr, *J* = 7.3 Hz, 2 H), 1.90−1.77 (m, 2 H), 1.63−1.40 (m, 4 H), 1.40−1.26 (m, 2 H), 1.30 (d, *J* = 5.5 Hz, 3 H), 1.20 (t, *J* = 7.2 Hz, 3 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 144.88 (u),

123.18 (d), 99.58 (d), 65.29 (u), 60.71 (u), 35.09 (u), 32.47 (u), 31.18 (u), 29.84 (u), 27.71 (u), 26.20 (u), 22.49 (u), 19.94 (d), 15.38 (d); MS (EI) *m/z* (relative intensity) 180 (M^+ − OHEt, 2), 95 (17), 81 (30), 73 (100), 45 (42). Anal. Calcd for $C_{14}H_{26}O_2$: C, 74.28; H, 11.57. Found: C, 74.09; H, 11.53.

(+)-(*R*)-1-[4-(1-Ethoxyethoxy)butyl]-2-methylenecyclopentane (38a). To a solution of Cu(I) (381 mg, 2.0 mmol) in THF (15 mL) and Me_2S (3 mL) was added $EtO(Me)C(H)O(CH_2)_4Li$ (2.0 mmol, 1.5 mL of 1.33 M in Et_2O) at −50 °C. The solution was stirred for 45 min and then cooled to −78 °C. The resulting brown, homogeneous solution of **5**/LiI was treated with $BF_3{\cdot}OEt_2$ (246 μL, 2.0 mmol) and stirred for 10 min. Then the solution was cooled to −100 °C, and **18** (117 mg, 0.5 mmol) in THF (15 mL) was added. The reaction mixture was allowed to warm to −78 °C during 4 h. Aqueous workup and purification of the crude product by chromatography (9% EtOAc−*n*-hexane) gave a mixture of **38a** and **39a** (103 mg, 91%) in a ratio of 98:2 as a colorless oil with an ee value of 71% for **38a**: $[\alpha]_D$ +38.0° (*c* 0.88, THF); ^1H NMR (400 MHz, $CDCl_3$) δ 4.86−4.84 (m, 1 H), 4.75−4.73 (m, 1 H), 4.68 (qua, *J* = 5.5 Hz, 1 H), 3.70−3.30 (m, 4 H), 2.40−2.13 (m, 3 H), 1.98−1.80 (m, 1 H), 1.29 (d, *J* = 5.5 Hz, 3 H), 1.18 (t, *J* = 7.0 Hz, 3 H), 1.75−1.10 (m, 9 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 157.17 (u), 104.07 (u), 99.62 (d), 65.30 (u), 60.78 (u), 44.04 (d), 34.42 (u), 33.28 (u), 30.21 (u), 24.64 (u), 24.30 (u), 19.98 (d), 15.42 (d); MS (EI) *m/z* (relative intensity) 211 (M^+ − Me, 18), 180 (27), 163 (25), 121 (32), 95 (90), 93 (30), 82 (58), 81 (100), 79 (64), 73 (100), 67 (83), 55 (58), 53 (29), 45 (100), 41 (60), 39 (26). Anal. Calcd for $C_{14}H_{26}O_2$: C, 74.28; H, 11.57. Found: C, 74.19; H, 11.63.

(+)-(*R*)-1-[4-[(*tert*-Butyldiphenylsilyl)oxy]butyl]-2-methylenecyclopentane (38b). To a solution of Cu^II (485 mg, 2.6 mmol) in Et_2O (20 mL) and Me_2S (5 mL) was added *t*-$BuPh_2SiO(CH_2)_4Li$ (2.6 mmol, 5.3 mL of 0.49 M in Et_2O) at −50 °C. The resulting dark red, homogeneous solution of **30**/LiI was stirred for 45 min at this temperature and cooled to −78 °C, and $BF_3{\cdot}OEt_2$ (640 μL, 5.2 mmol) was added dropwise. After the mixture was stirred for 10 min, it was cooled to −100 °C, and **18** (200 mg, 0.85 mmol) in Et_2O (10 mL) was added. The reaction mixture was stirred for 2 h at −100 °C. Aqueous workup and purification of the residue by chromatography (9% EtOAc-*n*-hexane) and MPLC (0.0005% EtOAc−*n*-hexane) gave **38b** (297 mg, 88%) as a colorless oil with an ee value of 90%: $[\alpha]_D$ +40.7° (*c* 1.08, THF); ^1H NMR (400 MHz, $CDCl_3$) δ 7.73−7.54 (m, 4 H) 7.48−7.27 (m, 6 H), 4.86−4.84 (m, 1 H), 4.75−4.73 (m, 1 H), 3.66 (t, *J* = 6.7 Hz, 2 H), 2.40−2.15 (m, 3 H), 1.94−1.81 (m, 1 H), 1.75−1.29 (m, 7 H), 1.29−1.13 (m, 2 H), 1.04, (s, 9 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 157.22 (u), 135.68 (u), 134.29 (d), 129.57 (d), 127.66 (d), 104.04 (u), 64.03 (u), 44.04 (d), 34.33 (u), 33.32 (u), 32.89 (u), 32.79 (u), 26.98 (d), 24.31 (u), 24.15 (u), 19.32 (u); MS (CI, NH_3) *m/z* (relative intensity) 393 (M^+, 7), 256 (46), 154 (100); HRMS (EI) calcd for $C_{22}H_{27}OSi$ (M^+ − *t*-Bu) 335.1831, found 335.1834.

(+)-(*S*)-1-Butyl-2-methylenecyclopentane (38d). To a solution of **32**/LiI, which was prepared from Cu^II (2.6 mmol) and *n*-BuLi (2.6 mmol) in THF (20 mL) and Me_2S (5 mL) as described for the preparation of **5**, was added $BF_3{\cdot}OEt_2$ (320 μL, 2.6 mmol) at −78 °C. After stirring for 10 min at this temperature, the solution was cooled to −100 °C, and **18** (200 mg, 0.85 mmol) in THF (10 mL) was added. The solution was stirred for 3 h at −100 °C. Aqueous workup of the reaction mixture and purification of the crude product by chromatography (*n*-hexane) gave a mixture of **38d** and **39d** (120 mg, 89%) in a ratio of 99:1 as a colorless liquid with an ee value of 72% for **38d**: $[\alpha]_D$ +61.8° (*c* 2.00, THF); ^1H NMR (300 MHz, $CDCl_3$) δ 4.87−4.84 (m, 1 H), 4.79−4.75 (m, 1 H), 2.42−2.20 (m, 3 H), 1.95−1.83 (m, 1 H), 1.78−1.42 (m, 3 H), 1.42−1.14 (m, 6 H), 0.90 (t, *J* = 6.7 Hz, 3 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 157.32 (u), 103.87 (u), 44.05 (d), 34.29 (u), 33.30 (u), 32.82 (u), 30.19 (u), 24.28 (u), 23.01 (u), 14.18 (d); MS (EI) *m/z* (relative intensity) 138 (M^+, 2), 82 (90), 81 (100), 67 (90), 41 (44). Anal. Calcd for $C_{10}H_{18}$: C, 86.88; H, 13.12. Found: C, 86.54; H, 13.26.

(+)-(*S*)-1-Undecyl-2-methylenecyclopentane (38e). To a solution of **33**/LiI, which was prepared from Cu^II (8 mmol) and *n*-$C_{11}H_{23}Li$ (8 mmol) in THF (50 mL) as described for the preparation of **5**, was added $BF_3{\cdot}OEt_2$ (0.92 mL, 7.5 mmol) at −78 °C. The solution was stirred for 10 min and cooled to −100 °C, and then **18** (470 mg, 2.0 mmol) in THF (30 mL) was added. The resulting mixture was stirred for 3 h at −100 °C, and it was then allowed to warm to −78 °C over a period of 3 h. Aqueous workup of the reaction mixture and purification of the residue by chromatography (*n*-hexane) gave **38e** (440 mg, 93%) as a colorless oil with an ee value of 67% containing only traces (<0.5%) of **39e**: $[\alpha]_D$ +41.2° (*c* 0.86, THF); ^1H NMR (400 MHz, $CDCl_3$) δ 4.85−4.82 (m, 1 H), 4.79−4.76 (m, 1 H), 2.40−2.19 (m, 3 H), 1.95−1.81 (m, 1 H), 1.76−1.62 (m, 1 H), 1.60−1.40 (m, 2 H), 1.40−1.10 (m, 20 H), 0.88 (t, *J* = 7.0 Hz, 3 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 157.42 (u), 103.91 (u), 44.11 (d), 34.65 (u), 33.34 (u), 32.86 (u), 32.04 (u), 30.02 (u), 29.78 (u), 29.77 (u), 29.47 (u), 28.01 (u), 24.32 (u), 22.80 (u), 14.21 (d); MS (EI) *m/z* (relative intensity) 236 (M^+, 8), 96 (58), 95 (49), 83 (39), 82 (100), 81 (100), 67 (94), 55 (43), 43 (31), 41 (48). Anal. Calcd for $C_{17}H_{32}$: C, 86.40; H, 13.64. Found: C, 86.50; H, 13.85.

(+)-(*R*)-1-[(Trimethylsilyl)methyl]-2-methylenecyclopentane (38f). To a solution of **34**/LiI, which was prepared from Cu^II (2.6 mmol) and Me_3SiCH_2Li (2.6 mmol, 2.6 mL of 1.0 M in *n*-pentane) in THF (20 mL) and Me_2S (5 mL) as described for the preparation of **5**, was added $BF_3{\cdot}OEt_2$ (320 μL, 2.6 mmol) at −78 °C. The resulting orange, homogeneous solution was stirred for 10 min and cooled to −100 °C, and then **18** (200 mg, 2.6 mmol) in THF (10 mL) was added. The solution was stirred for 4 h at this temperature. Aqueous workup of the reaction mixture and purification of the crude product by chromatography (*n*-pentane) gave a mixture of **38f** and **39f** (102 mg, 71%) as a colorless oil in a ratio of 85:15 and an ee value of 60% for **38f**: $[\alpha]_D$ +18.8° (*c* 1.64, THF); ^1H NMR (300 MHz, $CDCl_3$) δ 4.86−4.81 (m, 1 H), 4.80−4.75 (m, 1 H), 2.44−2.18 (m, 3 H), 2.00−1.64 (m, 2 H), 1.59−1.42 (m, 1 H), 1.36−1.08 (m, 1 H), 0.97 (dd, *J* = 14.6, and 3.7 Hz, 1 H), 0.48 (dd, *J* = 14.6, and 10.9 Hz, 1 H), 0.02 (s, 9 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 159.70 (u), 103.29 (u), 40.58 (d), 35.36 (u), 32.30 (u), 23.96 (u), 21.68 (u), −0.67 (d); MS (EI) *m/z* 168 (M^+, 8), 94 (17), 73 (100); HRMS calcd for $C_{10}H_{20}Si$ 168.1334, found 168.1342.

1-[2-(Trimethylsilyl)ethyl]cyclopentene (39f). To a solution of **34**/LiI, which was prepared from Cu^II (2.6 mmol) and Me_3SiCH_2Li (2.6 mmol, 2.6 mL of 1.0 M in *n*-pentane) in Et_2O (20 mL) and Me_2S (5 mL), was added $BF_3{\cdot}OEt_2$ (320 μL, 2.6 mmol) at −78 °C. The resulting orange, homogeneous solution was cooled to −100 °C, and **18** (200 mg, 0.85 mmol) in 10 mL of Et_2O was added. During the next 15 min, a white solid precipitated. The mixture was stirred for 3 h at −100 to −78 °C. Aqueous workup of the reaction mixture and purification of the crude product by chromatography (*n*-pentane) gave a mixture of **39f** and **38f** (97 mg, 68%) in a ratio of 99:1. **39f**: ^1H NMR (300 MHz, $CDCl_3$) δ 5.37−5.35 (m, 1 H), 2.37−2.22 (m, 4 H), 2.13−2.02 (m, 2 H), 1.94−1.83 (m, 2 H), 1.40−1.25 (m, 1 H), 0.95−0.86 (m, 1 H), 0.71−0.65 (m, 2 H), 0.00 (s, 9 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 147.60 (u), 122.08 (d), 34.92 (u), 32.40 (u), 25.40 (u), 23.34 (u), 14.96 (u), −1.70 (d); MS (EI) *m/z* 168 (M^+, 8), 125 (15), 94 (16), 73 (100), 59 (15); HRMS calcd for $C_{10}H_{20}Si$ 168.1334, found 168.1342.

Isolation of the Precipitate. The suspension was filtered, and the precipitate was washed with Et_2O (4 × 10 mL) to give CuI (321 mg, 1.7 mmol) as a colorless solid. Cation analysis by quantitative AAS gave a ratio of Cu:Li = 20:1. The iodide content was determined through reduction with zinc and titration with $AgNO_3$.

Substitution of the Allylic Sulfoximine 18 with the Cuprate Reagent 35/LiI in the Presence of Me_3SiCH_2Li and BF_3. To a solution of Cu^II (162 mg, 0.85 mmol) in Et_2O (20 mL) and Me_2S (5 mL) was added Me_3SiCH_2Li (2.6 mmol, 2.6 mL of 1.0 M in *n*-pentane) at −40 °C. The resulting colorless solution was cooled to −78 °C, and $BF_3{\cdot}OEt_2$ (320 μL, 2.6 mmol) was added. The solution was stirred for 10 min and cooled to −100 °C, and **18** (200 mg, 0.85 mmol) in Et_2O (10 mL) was added. The solution was stirred for 4 h, and then CF_3CO_2D (1 mL) was added. Aqueous workup of the reaction mixture and purification of the crude product by chromatography (*n*-pentane) gave a mixture of **39f** and **38f** (96 mg, 62%) in a ratio of 98.5:1.5. Besides the alkenes, **18** (54 mg, 27%) containing 25% deuterium in the α-position was isolated.

(+)-(*R*)-[2-(2-Methylenecyclopentyl)ethyl]benzene (38h). To a solution of **37**/LiI, which was prepared from Cu^II (2.6 mmol) and $Ph(CH_2)_2Li$ (2.6 mmol) in THF (20 mL) and Me_2S (5 mL), was added $BF_3{\cdot}OEt_2$ (640 μL, 2.6 mmol) at −78 °C. The solution was stirred for 10 min and cooled to −100 °C, and **18** (200 mg, 0.85 mmol) in THF (10 mL) was added. The solution was stirred for a further 4 h at this temperature. Aqueous workup of the reaction mixture and purification of the residue by chromatography (*n*-hexane) gave a mixture of **38h**

and **39h** (150 mg, 93%) in a ratio of 95:5 as a colorless liquid with an ee value of 76% for **38h**: $[\alpha]_D$ +59.1° (*c* 1.24, THF); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.34−7.17 (m, 5 H), 4.93−4.88 (m, 1 H), 4.84−4.80 (m, 1 H), 2.80−2.57 (m, 2 H), 2.46−2.24 (m, 3 H), 2.06−1.85 (m, 2 H), 1.85−1.70 (m, 1 H), 1.65−1.49 (m, 2 H), 1.44−1.28 (m, 1 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 156.76 (u), 142.85 (u), 128.43 (d), 128.35 (d), 125.70 (d), 104.34 (u), 43.67 (d), 36.42 (u), 33.30 (u), 32.80 (u), 24.30 (u); MS (EI) *m/z* (relative intensity) 186 (M^+, 2), 194 (100), 95 (57), 91 (50), 82 (44), 81 (40), 80 (29), 67 (63); HRMS calcd for $C_{14}H_{18}$ 186.1409, found 186.1406.

(+)-(*R*)-1-[4-(1-Ethoxyethoxy)butyl]-2-methylenecyclohexane (41a). To a solution of **5**/LiI (3.9 mmol) in THF (20 mL), Me_2S (5 mL), and Et_2O (3.9 mL) was added BF_3·OEt_2 (480 μL, 3.9 mmol) at −78 °C. The solution was stirred for 10 min and cooled to −100 °C, and **19** (324 mg, 1.3 mmol) was added in THF (10 mL). The solution was stirred for 4 h. Aqueous workup of the reaction mixture and purification of the residue by chromatography (9% EtOAc−*n*-hexane) gave a mixture of **41a** and **42a** (287 mg, 91%) in a ratio of 91:9 as a colorless oil with an ee value of 60% for **41a**: $[\alpha]_D$ +13.3° (*c* 0.70, MeOH); ^{1}H NMR (300 MHz, $CDCl_3$) δ 4.68 (qua, *J* = 5.4 Hz, 1 H), 4.65−4.62 (m, 1 H), 4.58−4.54 (m, 1 H), 3.72−3.35 (m, 4 H), 2.28−2.15 (m, 1 H), 2.07−1.85 (m, 2 H), 1.80−1.23 (m, 16 H), 1.20 (t, *J* = 7.3 Hz, 3 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 152.96 (u), 105.43 (u), 99.52 (d), 65.32 (u), 60.71 (u), 43.10 (d), 34.75 (u), 33.81 (u), 32.00 (u), 30.12 (u), 28.87 (u), 24.24 (u), 24.16 (u), 19.81 (d), 15.34 (d); MS (CI, *i*-C_4H_9) *m/z* (relative intensity) 240 (M^+, 16), 239 (100), 195 (45), 167 (87). Anal. Calcd for $C_{15}H_{28}O_2$: C, 74.95; H, 11.74. Found: C, 74.90; H, 11.85.

(+)-(*R*)-1-[4-[(*tert*-Butyldiphenylsilyl)oxy]butyl]-2-methylenecyclohexane (41b). Substitution of **19** with **30**/LiI in the presence of BF_3 in THF/Me_2S and workup as described for the synthesis of **38b** gave **41b** (273 mg, 79%) with an ee value of 63% as a colorless oil: $[\alpha]_D$ +9.9° (*c* 1.06, THF); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.75−7.62 (m, 4 H), 7.45−7.33 (m, 6 H), 4.65−4.61 (m, 1 H), 4.56−4.52 (m, 1 H), 3.66 (t, *J* = 6.3 Hz, 2 H), 2.26−2.15 (m, 1 H), 2.06−1.93 (m, 2 H), 1.78−1.18 (m, 12 H), 1.05 (s, 9 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 153.06 (u), 135.56 (d), 134.18 (u), 129.45 (d), 127.54 (d), 105.39 (u), 63.96 (u), 43.07 (d), 34.74 (u), 33.70 (u), 32.79 (u), 28.87 (u), 26.88 (d), 24.23 (u), 23.64 (u), 19.23 (u); MS (EI) *m/z* (relative intensity) 349 (M^+ − *t*-Bu, 13), 201 (24), 183 (100), 155 (40), 153 (26), 137 (51), 70 (36). Anal. Calcd for $C_{27}H_{38}OSi$: C, 79.74; H, 9.42. Found: C, 79.87; H, 9.51.

(+)-(*S*)-[2-(2-Methylenecyclohexyl)ethyl]benzene (41g). Substitution of **19** with **37**/LiI in the presence of BF_3 in THF as described for the preparation of **38h** gave a mixture of **41g** and **42g** (157 mg, 93%) in a ratio of 97:3 as a colorless oil with an ee value of 61% for **41g**: $[\alpha]_D$ +27.7° (*c* 0.88, THF); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.23−7.32 (m, 2 H), 7.22−7.14 (m, 3 H), 4.71−4.67 (m, 1 H), 4.63−4.60 (m, 1 H), 2.61 (t, *J* = 8.1 Hz, 2 H), 2.31−2.20 (m, 1 H), 2.14−1.87 (m, 3 H), 1.87−1.74 (m, 1 H), 1.74−1.37 (m, 5 H), 1.37−1.25 (m, 1 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 152.63 (u), 142.97 (u), 128.38 (d), 128.26 (d), 125.58 (d), 105.83 (u), 42.80 (d), 34.69 (u), 34.11 (u), 33.92 (u), 33.80 (u), 28.56 (u), 24.17 (u); MS (EI) *m/z* (relative intensity) 200 (M^+, 3), 104 (100), 96 (73), 95 (32), 94 (37), 91 (44), 81 (78), 67 (49). Anal. Calcd for $C_{15}H_{20}$: C, 89.94; H, 10.06. Found: C, 89.86; H, 10.22.

(+)-(*S*)-1-*n*-Butyl-2-methylenecycloheptane (45). Substitution of **20** (224 mg, 0.85 mmol) with **32**/LiI in the presence of BF_3 in Et_2O as described for the preparation of **38d** gave a mixture of **45** and **46** (127 mg, 90%) in a ratio of 98:2 as a colorless oil with an ee value of 60% for **45**: $[\alpha]_D$ +35.7° (*c* 0.85, THF); ^{1}H NMR (300 MHz, $CDCl_3$) δ 4.78−4.74 (m, 1 H), 4.66−4.63 (m, 1 H), 2.24−2.12 (m, 2 H), 2.07−1.94 (m, 1 H), 1.90−1.60 (m, 5 H), 1.39−1.06 (m, 9 H), 0.87 (t, *J* = 6.7 Hz, 3 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 155.26 (u), 111.21 (u), 46.14 (d), 36.13 (u), 34.47 (u), 33.38 (u), 31.31 (u), 30.50 (u), 29.78 (u), 26.56 (u), 22.89 (u), 14.14 (d); MS (EI) *m/z* (relative intensity) 166 (M^+, 6), 111 (30), 110 (100), 95 (58), 82 (79), 81 (95), 68 (36), 67 (97), 55 (40), 41 (54); HRMS calcd for $C_{12}H_{22}$ 166.1722, found 166.1726.

(+)-1-*n*-Butyl-2-methylenecyclobutane (43). Substitution of **17** (120 mg, 0.54 mmol) with **32**/LiI in the presence of BF_3 in Et_2O as described for the preparation of **38d** gave a mixture of **43** and **44** (27 mg, 40%) in a ratio of 98:2 as a colorless oil with an ee value of 27% for **43**: $[\alpha]$ +2.8° (*c* 0.6, $CHCl_3$); ^{1}H NMR (300 MHz, $CDCl_3$) δ 4.74−4.64 (m, 2 H), 2.95−2.81 (m, 1 H), 2.67−2.40 (m, 2 H), 2.12−1.98 (m, 1 H), 1.72−1.18 (m, 7 H), 0.89 (t, *J* = 6.8 Hz, 3 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 155.49 (u), 102.90 (u), 44.72 (d), 34.00 (u), 29.25 (u), 29.11 (u), 23.82 (u), 22.78 (u), 14.11 (d); MS (CI) *m/z* (relative intensity) 124 (M^+, 1), 81 (40), 68 (38), 67 (100), 55 (36), 54 (49), 41 (74), 39 (51).

Substitution of the *N*-Methylsulfoximine 18 with Me_3SiCH_2Cu (34). Preparation of Me_3SiCH_2Cu (34).[37d] To a suspension of CuI (10.5 g, 55 mmol) in Et_2O (25 mL) was added crystalline Me_3SiCH_2Li (5.18 g, 55 mmol) in Et_2O (95 mL) at −30 °C over a period of 3 h. The resulting suspension was stirred for another 2 h at 0 °C. The solvent was removed in vacuo, and *n*-pentane (75 mL) was added to the residue. The suspension was filtered, and the clear red-brown filtrate was cooled to −78 °C for 24 h to give **34** (6.28 g, 76%) as white needles. This material was dissolved in *n*-pentane (40 mL) at 0 °C, and the solution was cooled to −78 °C for 20 h to give **34** (4.53 g, 55%) as colorless needles which were stored at −80 °C under exclusion of light: ^{1}H NMR (500 MHz, THF-d_8) δ 0.16 (s, 9 H), −0.20 (sbr, 2 H); ^{13}C NMR (100 MHz, THF-d_8) δ 4.29 (d, ^1J(C,H) = 118.1 Hz), −8.69 (u, ^1J(C,H) = 106.8 Hz). Titration of **34** according to Fajans[70] or Vollhardt[51a] with $AgNO_3$ was negative, indicating an iodide content of less than 1%. To a yellow, homogeneous solution of **34** (390 mg, 2.6 mmol) in THF (20 mL) was added **18** (200 mg, 0.85 mmol) in THF (10 mL) at −78 °C. The solution was stirred for 6 h at −78 °C. While no alkene formation was detected by TLC, the solution was warmed to 0 °C and stirred for another 2 h. Aqueous workup and purification of the residue by chromatography (EtOAc) gave **18** (185 mg, 93%).

Attempted Reaction of 18 with 34 in the Presence of LiI. To a green-yellow, homogeneous solution of **34** (390 mg, 2.6 mmol) and LiI (350 mg, 2.6 mmol) in THF (20 mL) was added **18** (200 mg, 0.85 mmol) in THF (10 mL). The solution was stirred for 6 h at −78 °C and for 1 h at 0 °C. Aqueous workup of the reaction mixture and purification of the residue by chromatography (EtOAc) gave 193 mg (96%) of the educt **18**.

Reaction of 18 with 34 in the Presence of LiI with Subsequent Addition of BF_3. To a green-yellow, homogeneous solution of **34** (390 mg, 2.6 mmol) and LiI (350 mg, 2.6 mmol) in THF (20 mL) was added **18** (200 mg, 0.85 mmol) in THF (10 mL). The solution was stirred for 6 h at −78 °C during which time no alkene formation was detected by TLC. BF_3·OEt_2 (320 μL, 2.6 mmol) was added to the reaction mixture, which was stirred for 2 h at −78 °C. Aqueous workup of the reaction mixture and purification of the residue by chromatography (*n*-pentane) gave a mixture of **38f** and **39f** (97 mg, 69%) in a ratio of 72:28.

Attempted Reaction of 18 with 34 in the Presence of BF_3. To an orange-red, homogeneous solution of **34** (390 mg, 2.6 mmol) and BF_3·OEt_2 (320 μL, 2.6 mmol) in THF (20 mL) was added **18** (200 mg, 0.85 mmol) in THF (10 mL). After about 20 min, a white solid precipitated which was **34** according to ^{1}H NMR spectroscopy. The suspension was stirred for 6 h at −78 °C. Aqueous workup of the reaction mixture and purification of the residue gave **18** (177 mg, 89%).

Reaction of 18 with 34 in the Presence of BF_3 and Subsequent Addition of LiI. To an orange-red, homogeneous solution of **34** (390 mg, 2.6 mmol) and BF_3·OEt_2 (320 μL, 2.6 mmol) in THF (20 mL) was added **18** (200 mg, 0.85 mmol) in THF (10 mL). After about 20 min, a white solid precipitated. The suspension was stirred for 6 h at −78 °C, and LiI (350 mg, 2.6 mmol) in THF (10 mL) was added. The precipitate dissolved immediately to give a green-yellow, homogeneous solution. This solution was stirred for 2 h at −78 °C. Aqueous workup of the reaction mixture and purification of the residue by chromatography (*n*-pentane) gave a mixture of **38f** and **39f** (96 mg, 68%) in a ratio of 85:15.

Reaction of 18 with 34 in the Presence of LiI and BF_3. To a green-yellow, homogeneous solution of **34** (390 mg, 2.6 mmol) and LiI (350 mg, 2.6 mmol) in THF (20 mL) was added BF_3·OEt_2 (320 μL, 2.6 mmol) at −78 °C. After the solution was stirred for 10 min, **18** (200 mg, 0.85 mmol) in THF (10 mL) was added. The solution was stirred for 2 h. Aqueous workup of the reaction mixture and

(70) Flaschka, H. A.; Barnado, A. J., Jr.; Sturrock, P. E. *Quantitative Analytical Chemistry*; Barnes & Noble: New York, 1969; p 201.

purification of the residue by chromatography (*n*-pentane) gave a mixture of **38f** and **39f** (94 mg, 66%) in a ratio of 66:34.

Substitution of the *N*-Triflylsulfoximine 29 with Me_3SiCH_2Cu (34). Attempted Reaction of 29 with 34. To an orange, homogeneous solution of **34** (267 mg, 1.77 mmol) in THF (30 mL) was added **29** (208 mg, 0.59 mmol) in THF (10 mL) at −78 °C. The solution was stirred for 13 h at −78 °C. Aqueous workup of the reaction mixture and purification of the residue by chromatography (*n*-pentane) gave **29** (196 mg, 94%), and only a trace amount of **38f** and **39f** in a ratio of 92:8.

Reaction of 29 with 34 in the Presence of LiI. To a green-yellow, homogeneous solution of **34** (267 mg, 1.77 mmol) and LiI (237 mg, 1.77 mmol) in THF (30 mL) was added **29** (208 mg, 0.59 mmol) in THF (10 mL) at −78 °C. The solution was stirred for 13 h at −78 °C. Aqueous workup of the reaction mixture and purification of the residue by chromatography (*n*-pentane) gave a mixture of **38f** and **39f** (34 mg, 34%) in a ratio of 80:20 and **29** (141 mg, 67%).

Reaction of 29 with 34 in the Presence of Bu_4NI. To the light-yellow solution of **34** (267 mg, 1.77 mmol) and Bu_4NI (653 mg, 1.77 mmol) in THF (30 mL) was added **29** (208 mg, 0.59 mmol) in THF (10 mL) at −78 °C. The solution was stirred for 13 h at −78 °C. Aqueous workup of the reaction mixture and purification of the residue by chromatography (*n*-pentane) gave a mixture of **38f** and **39f** (98 mg, 99%) in a ratio of 89:11.

Acknowledgment. This research has been assisted by grants from the Deutsche Forschungsgemeinschaft (SFB 380) and the Fonds der Chemischen Industrie. We thank Professor Dr. W. A. König, Universität Hamburg, Professor Dr. W. Keim, RWTH Aachen, and Dr. W. Melzow, RWTH Aachen, for their help in the GC analysis on chiral columns and Professor M. F. Lappert, University of Sussex, for additional information regarding the synthesis of **34**.

Supplementary Material Available: A structure determination summary; tables of final atomic coordinates and equivalent isotropic displacement parameters; tables of hydrogen atomic coordinates, anisotropic displacement parameters, bond lengths, and bond and torsion angles; stereoviews of the molecule and its arrangement in the unit cell; details for the preparation and analytical and spectroscopic data of compounds **9**−**12**, **13**, **15**−**17**, **19**−**22**, **38c,d,i**−**l**, **39g**, **41d,h**−**k**, *ent*-**41c**, **41e**, and **42f**; the determination of absolute configuration of the exocyclic alkenes **38**, **41**, and **45** through chemical correlation and CD measurements; and experimental details for the substitutions described in Tables 1−4 and not contained in the experimental section (35 pages); a listing of observed and calculated structure factors for the X-ray structure of **28** (7 pages). This material is contained in many libraries on microfiche, immediately follows this article in the microfilm version of this journal, can be ordered from the ACS, and can be downloaded from the Internet; see any current masthead page for ordering information and Internet access instructions.

JA943013J