Cyclopropanation Reactions of Enones with Lithiated Sulfoximines: Application to the Asymmetric Synthesis of Chiral Cyclopropanes

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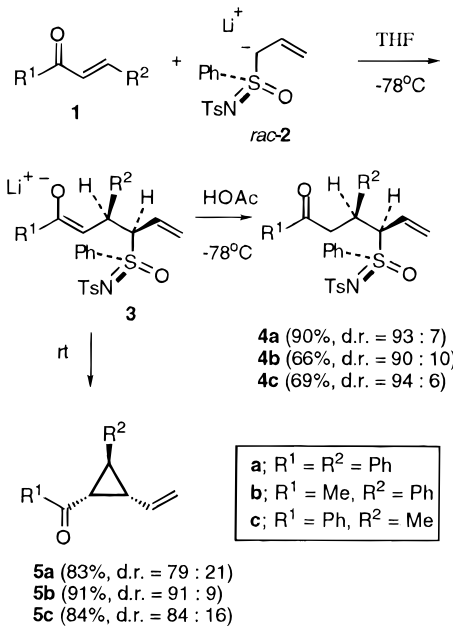
Stabilized lithiated sulfoximines **2** and **9** undergo highly diastereoselective Michael reactions with acyclic enones under kinetically controlled conditions. At rt the initially formed anionic Michael adducts undergo intramolecular displacement of the sulfonimidoyl group, with inversion of stereochemistry at the carbon bearing the nucleofuge, to give cyclopropanes. Lithiated sulfoximines derived from *S*-alkyl sulfoximines give mixtures of 1,2- and 1,4-adducts with enones under kinetically controlled conditions. However, at rt the 1,2-adducts are in equilibrium with their corresponding 1,4-adducts. The 1,4-adducts are formed in a highly diastereoselective manner and are rapidly converted to diastereomerically pure cyclopropanes in good to excellent yields. Optically active versions of these sulfoximines give cyclopropanes in high enantiomeric purities.

Introduction

We recently reported that enones undergo regioselective conjugate addition reactions with lithiated *N*-tosyl-*S*-allyl-*S*-phenylsulfoximine at −78 °C to give exclusively 1,4-α adducts.[1] Cyclic enones gave mixtures of diastereomeric 1,4-α adducts while the reactions that involved acyclic enones were highly diastereoselective.[2] Furthermore, we have demonstrated that the products from the latter reactions can be converted, by further highly diastereoselective reactions, to acyclic molecules having three, well-defined stereogenic centers.[3] With the current interest in the asymmetric synthesis of cyclopropanes[4] we became interested in developing the method of Johnson who first described the cyclopropanation of chalcone using lithiated *N*-tosyl-*S*-alkyl-*S*-phenyl sulfoximines in 1973.[5] In one example, an optically active (ee 49%) cyclopropane ((1*S*,2*S*) 2-phenylcyclopropyl phenyl ketone) was prepared from the reaction of chalcone and lithiated (*R*)-*N*-tosyl-*S*-methyl-*S*-phenylsulfoximine (ee 84%) at rt for 12 h. We report here a study of the reactions of enones with lithiated *S*-allyl-, *S*-benzyl-, and *S*-alkyl-*N*-tosylsulfoximines under kinetically controlled conditions at −78 °C and under reversible conditions at rt that give rise to cyclopropanes. Furthermore, the stereochemistry and mechanism of these reactions is described, and the application of this methodology to give cyclopropanes in high enantiomeric purities is reported.

Scheme 1



Results and Discussion

***S*-Allyl- and *S*-Benzyl-*N*-tosylsulfoximines.** Treatment of a solution of racemic lithiated *N*-tosyl-*S*-allyl-*S*-phenylsulfoximine (*rac*-**2**)[1] at −78 °C with the acyclic enones **1a**−**c** (1.2 equiv) for 3 min gave, after quenching at −78 °C with acetic acid, the racemic 1,4-α adducts **4a**−**c** in modest to excellent yields (Scheme 1). The product diastereoselection ranged from 90:10 to 94:6 as determined by ^{1}H NMR analysis of the crude reaction mixtures.[6] The relative (3*R**,4*R**,S*S**) stereochemistry of **4a** has been determined by X-ray structural analysis and has been rationalized as occurring via the transition

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(1) Pyne, S. G.; Dong, Z.; Skelton, B. W.; White, A. H. *J. Chem. Soc., Chem. Commun.* **1994**, 751.

(2) For previous studies on metalated allylic sulfoximines see: (a) Harmata, M.; Claassen, R. J., II. *Tetrahedron Lett.* **1991**, *32*, 6497. (b) Pyne, S. G.; Boche, G. *Tetrahedron* **1993**, *49*, 8449. (c) Reggelin M.; Weinberger, H.; Gerlach, M.; Welcker, R. *J. Am. Chem. Soc.* **1996**, *118*, 4765 and references cited therein. (d) Hainz, R.; Gais, H. J.; Raabe, G. *Tetrahedron: Asymmetry* **1996**, *7*, 2505 and references cited therein.

(3) Pyne, S. G.; Dong, Z.; Skelton, B. W.; White, A. H. *J. Chem. Soc., Chem. Commun.* **1995**, 445.

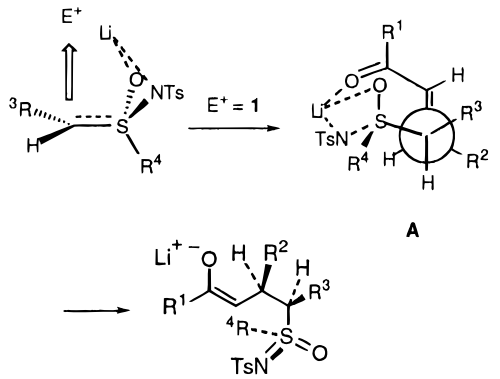
(4) For some recent examples see: Yeh, S.-M.; Huang, L. H.; Luh, T.-Y. *J. Org. Chem.* **1996**, *61*, 3906. Doyle, M. P.; Peterson, C. S.; Parker, D. L. *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 13349. Mash, E. A.; Gregg, T. M.; Stahl, M. T. Walters, W. P. *J. Org. Chem.* **1996**, *61*, 2738 and references cited therein. Hanessian, S.; Andreotti, D.; Gomtsyan, A. *J. Am. Chem. Soc.* **1995**, *117*, 10393. Pique, C.; Fahndrich, B.; Pfaltz, A. *Synlett* **1995**, 491. Charette, A. B.; Prescott, S.; Brochu, C. *J. Org. Chem.* **1995**, *60*, 1081 and references cited therein.

(5) Johnson, C. R.; Kirchhoff, R. A.; Reischer, R. J.; Katekar, G. F. *J. Am. Chem. Soc.* **1973**, *95*, 4287.

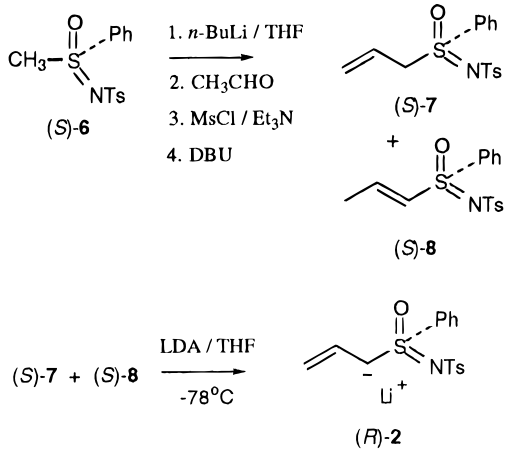
(6) The stereochemistry of the minor diastereoisomers in Schemes 1, 5−7, and 10 and eq 1 have not been determined.

S0022-3263(96)02216-5 CCC: $14.00

Scheme 2



Scheme 3

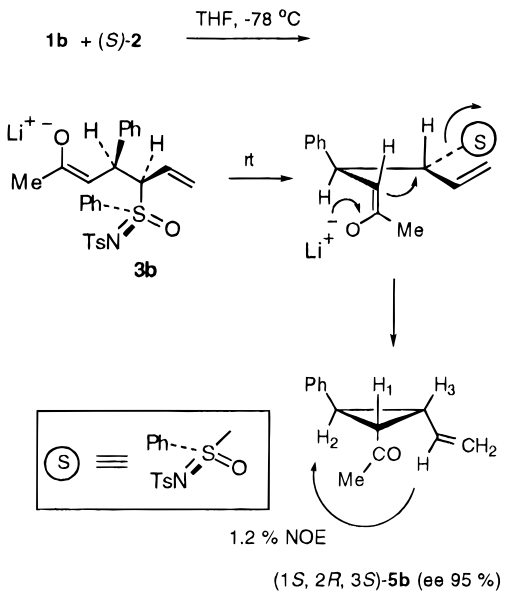


state structure **A** in which the largest groups on the two reacting partners (R^2 and the sulfonimidoyl group) are *anti* in order to minimize steric interactions (Scheme 2).[1]

Warming a solution of the anionic adducts **3a**−**c** to rt for 1 h gave the racemic vinylcyclopropanes **5a**−**c** in good yields (83−91% after column chromatography) and, in the case of the cyclopropyl phenyl ketones **5a** and **5c**, in lower diastereoselectivity than their respective Michael adducts **4a** and **4c** (Scheme 1). In contrast, the diastereoselctivity observed for the cyclopropyl methyl ketone **5b** was essentially identical to that found in its related Michael product **4b**. Cyclopropane **5b** was easily obtained diastereomerically pure by column chromatography. Enantiomerically enriched (1*S*,2*R*,3*S*)-**5b** was prepared from the reaction of enantiomerically enriched (*R*)-**2**[7] (prepared according to Scheme 3 from (*S*)-**6**[5] (ee 94%)) and **1b** under identical reaction conditions and procedures as described above. ^{1}H NMR studies using the chiral shift agent europium tris[3-[(heptafluoropropyl)-hydroxymethylene]-(+)-camphorate] indicated that the enantiomeric purity of **5b** was 95% after correction for the enantiomeric purity of (*S*)-**2** (ee 94%). These studies resulted in well-resolved separate signals for the methyl ketone group of **5b** for the two enantiomers of these compounds in both racemic and optically active samples. The stereochemistry of **5b** was established by NMR studies. NOE difference experiments on **5b** showed a 1.2% enhancement of the signal due to H2 upon selective irradiation of the alkene methine proton that established their *syn* stereochemical relationship (Scheme 4). Furthermore, an analysis of the proton vicinal coupling

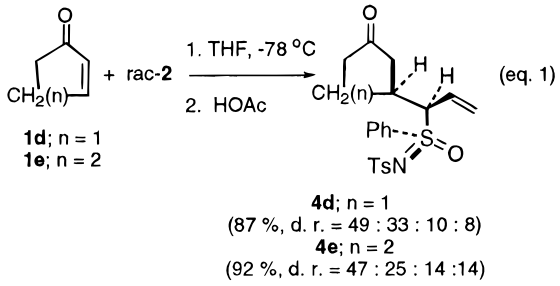
(7) Upon deprotonation with BuLi, (*S*)-sulfoximines become (*R*)-lithiated sulfoximines.

Scheme 4



constants between H1, H2, and H3 in the ^{1}H NMR spectrum of **5b** showed two *trans* couplings ($J_{1,2} = J_{2,3} =$ 6 Hz) and one *cis* coupling ($J_{1,3} = 9.2$ Hz).[8] On the basis of this information, and knowing the relative stereochemistry of **4b**, we assigned the absolute stereochemisty of **5b** as (1*S*,2*R*,3*S*). This stereochemisty is expected for an intramolecular nucleophilic displacement reaction of the sulfoximidoyl group from the intermediate **3b**, with inversion of stereochemistry at the carbon bearing the sulfonimidoyl group (Scheme 4).

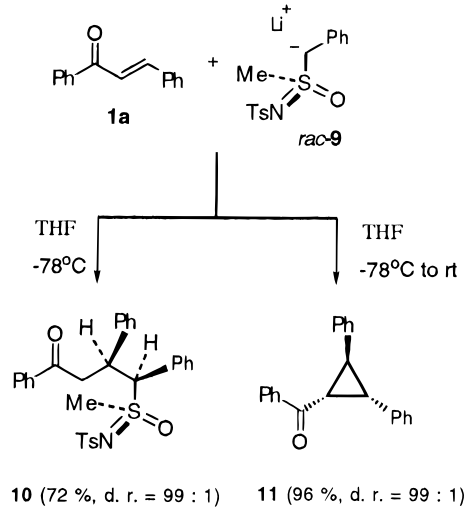
In contrast, the reactions of *rac*-**2** with the cyclic enones **1d** and **1e** at −78 °C were poorly diastereoselective and gave mixtures of the four possible diastereoisomers (eq 1). The major diastereoisomer **4d** from these reaction of *rac*-**2** with 2-cyclopentenone had the relative (3*S**,1′*R**,S*S**) stereochemistry from a single crystal



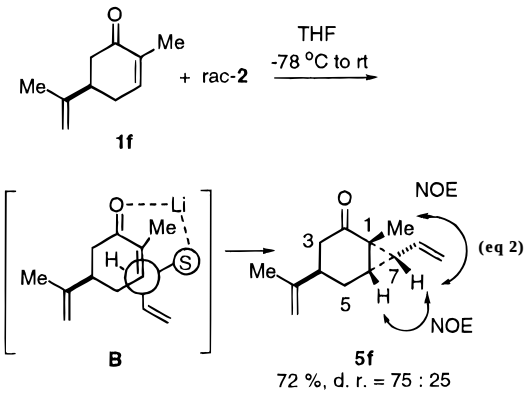
X-ray analysis.[1] The assignment of the same relative stereochemistry to the major diastereoisomer of **4e**, however, is tenuous as this could not be unequivocally determined. The reaction of *rac*-**2** with (*R*)-carvone **1f**, intially at −78 °C followed by warming to rt for 1 h, gave the vinylcyclopropane **5f** in 72% yield and moderate diastereoselectivity (dr = 75:25).[6] The stereochemistry of the major diastereoisomer is that shown in structure **5f** from ^{1}H NMR studies. NOESY experiments on **5f** showed cross peaks between the allylic cyclopropyl proton and the angular methyl group and the other cyclopropane methine. The stereochemistry at C6 is that expected from the known stereochemical outcome of nucleophilic

(8) Jackman, L. M.; Sternhell, S. In *Applications of Nuclear Magnetic Resonance Spectroscopy in Organic Chemistry*, 2nd ed.; Pergamon: Sydney, 1969; p 286.

Scheme 5



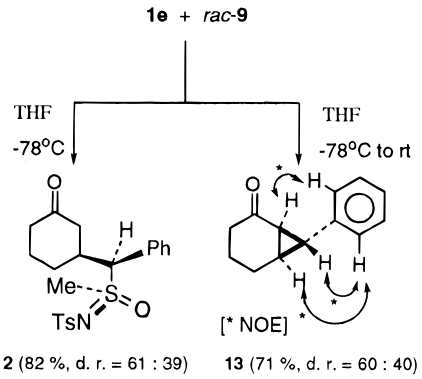
conjugate addition to **1f**, that usually arises from addition *anti* to the *β*′-2-propenyl group.[9] The relative stereochemistry at C1, C6, and C7 in **5f** was that expected based upon the stereochemical outcome of the reaction of *rac*-**2** with the achiral cyclic enone **1d** and consistent with our previously proposed chelated transition state[1] for cyclic enones (compare with the transition state **B** (eq 2)).



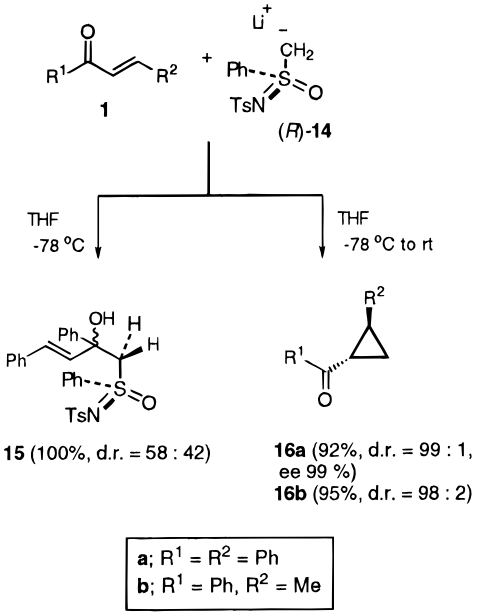
Under conditions similar to those described above, the reactions of lithiated racemic *N*-tosyl-*S*-benzyl-*S*-methylsulfoximine *rac*-**9** and chalcone **1a** gave the diastereomerically pure and racemic Michael adduct **10** at −78 °C and the diastereomerically pure cyclopropane **11** at rt (Scheme 5). The relative (3*R**,4*R**,S*S**) stereochemistry of **10** was established by X-ray diffraction (see Supporting Information) and was identical to that obtained from the reaction of **1a** and *rac*-**2**, and consistent with the transition state structure **A** (Scheme 2). The relative stereochemistry of **11** was evident from ^{1}H NMR spectroscopy and was that expected from an intramolecular S_N2 displacement reaction *via* the enolate anion derived from **10**. Not unexpectedly, the reaction of *rac*-**9** and cyclohexenone gave a mixture of racemic and diastereomeric Michael adducts **12** at −78 °C and a mixture of racemic diastereomeric cyclopropanes **13** at rt. The stereochemistry of the major diastereoisomer of **13** is that shown in Scheme 6 from NOESY experiments that showed cross peaks between the *ortho* aromatic protons of the phenyl group and the three cyclopropane methines.

(9) Srikrishna, A.; Jagadeeswar Reddy, T. *J. Org. Chem.* **1996**, *61*, 6422.

Scheme 6

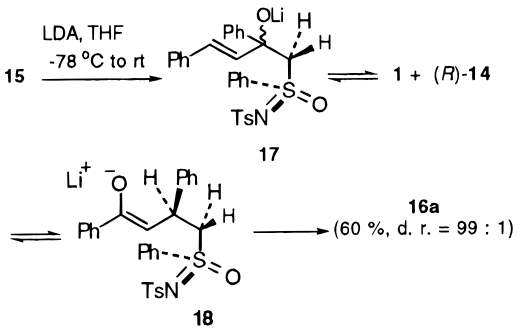


Scheme 7

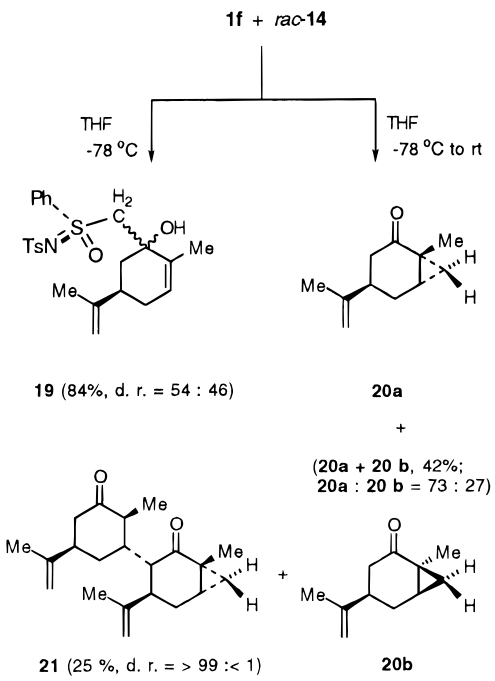


***S*-Alkyl-*S*-phenyl-*N*-tosylsulfoximines.** The reaction of optically active lithiated (*S*)-*N*-tosyl-*S*-methyl-*S*-phenylsulfoximine ((*R*)-**14** (ee 99%)[5,7] with enone **1a** at −78 °C gave exclusively the 1,2-adduct **15** as a 58:42 diastereomeric mixture in quantitative yield (Scheme 7). When this reaction was performed at rt the optically active and diastereomerically pure cyclopropane **16a** was isolated in 88% yield (Scheme 7). The enantiomeric purity of **16a** ([α]$^{27}_D$ −388° (*c* 0.05, acetone) was judged to be 99% based on the reported specific rotation of enantiomerically pure **16a** (lit.[5] [α]$^{25}_D$ +390.5° (*c* 1.0, acetone)). Treatment of **15** with LDA at −78 °C followed by warming the reaction mixture to rt for 1 h gave the diastereomerically pure cyclopropane **16a** in 60% yield (Scheme 8). Surprisingly, oxirane products, that could potentially arise from nucleophilic displacement of the sulfonimidoyl group by the alkoxide in **17**,[5] could not be detected in the crude reaction mixture. This experiment indicated that at rt the kinetically favored anionic 1,2-adduct **15** is in equilibrium with the anionic 1,4-adduct **18** and that the latter undergoes intramolecular displacement of the sulfonimidoyl group at a much faster rate than the former anion that could give rise to an oxirane. The reaction of *rac*-**14** with enone **1c** gave the cyclopropane **16b** in high diastereomeric purity (dr = 98:2 from GC analysis) in 95% yield. Treatment of (*R*)-carvone **1f** with *rac*-**14** gave a mixture of the diastereomeric 1,2-adducts **19** at −78 °C, the diastereomeric cyclopropanes

Scheme 8



Scheme 9

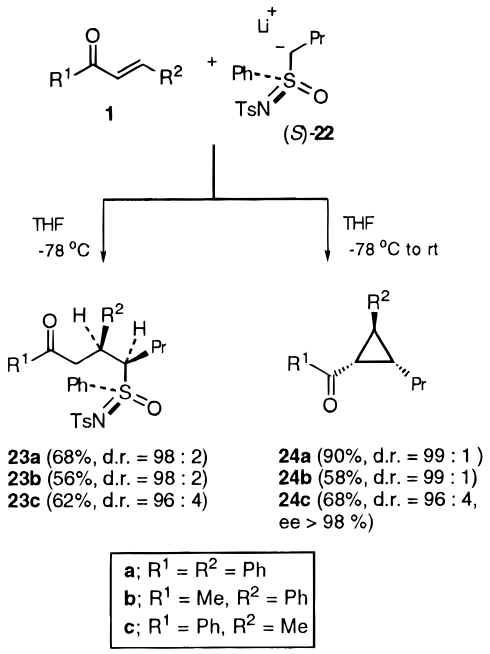


20a,b, and the double addition product **21** as a single diastereoisomer at rt (Scheme 9). The diastereoselectivity in the case of **20** was similar to that obtained when (*R*)-**14** was employed. Compound **20** has been prepared as a single diastereoisomer by Corey and Chaykovsky.[10]

Racemic and optically active (*S*)-*N*-tosyl-*S*-butyl-*S*-phenylsulfoximine were prepared by alkylation of lithiated *rac*-**14** or (*R*)-**14**[5,7] (ee 97%) with bromopropane, respectively. Treatment of lithiated racemic *N*-tosyl-S-butyl-*S*-phenylsulfoximine (*rac*-**22**) with the acyclic enones **1a**−**c** at −78 °C gave mixtures of 1,2 and 1,4-adducts (Scheme 10). The latter were formed in high diastereomeric purities (dr = 98−96:2−4) while the former were formed as diastereoisomeric mixtures. The relative stereochemistry of **23a** was the same as that of **4a** and **10** as determined by X-ray diffraction.[15] When these reactions were performed at rt, the cyclopropanes **24a**−**c** could be isolated in high diastereomeric purities. Optically active **24a** and **24c** were obtained from the reaction of (*R*)-**21** with **1a** and **1c**, respectively. The enantiomeric purity of **24c** was determined to be 98% from ^{1}H NMR studies using chiral shift reagents, while that of **24a** could not be determined in this manner. However the ee of **24a** was expected to be high based upon its diastereomeric purity and the magnitude of its specific rotation when compared to that of **24c**.

(10) Corey, E. J.; Chaykovsky, M. *J. Am. Chem. Soc.* **1965**, *87*, 1353.

Scheme 10



In conclusion, we have shown that stabilized lithiated sulfoximines (**2** and **9**) undergo highly diastereoselective Michael reactions with acyclic enones under kinetically controlled conditions. At rt the initially formed anionic Michael adducts undergo intramolecular displacement of the sulfonimidoyl group, with inversion of stereochemistry at the carbon bearing the nucleofuge, to give cyclopropanes. Lithiated sulfoximines derived from *S*-alkyl sulfoximines give mixtures of 1,2- and 1,4-adducts with enones under kinetically controlled conditions. However, at rt the 1,2-adducts are in equilibrium with their corresponding 1,4-adducts. The 1,4-adducts are formed in a highly diastereoselective manner and are rapidly converted to diastereomerically pure cyclopropanes in good to excellent yields. The absolute stereochemistry of the Michael adducts has been unequivocally determined from single crystal X-ray analysis and the stereochemical outcomes of all these reactions is consistent with the general transition state **A** (Scheme 2). Optically active versions of these sulfoximines give cyclopropanes in high enantiomeric purities.

Experimental Section

General procedures were as described previously.[11] All NMR spectra were recorded in $CDCl_3$ solution at 400 MHz (^{1}H NMR) or 100 MHz (^{13}C NMR) unless otherwise noted. Preparative HPLC was carried out using a Waters pump Model 510 and a Waters μ Porasil column (particle size 10 μm, pore size 125, dimensions 25 mm × 100 mm). The UV detector was a Waters Series 450 variable wavelength detector operating at 254 nm. Full lists of spectral and characterization data are included in the Supporting Information.

(*S*)-(+)-*N*-Tosyl-*S*-butyl-*S*-phenylsulfoximine. To a solution of (*S*)-(+)-*N*-tosyl-*S*-methyl-*S*-phenylsulfoximine[5] (464 mg, 1.5 mmol, $[\alpha]^{23}_D$ +35, c 1.06, in acetone, 97% ee) in dry THF (6 mL) at −78 °C was added n-BuLi (1.1 equiv, 1.4 mL, 1.2 M in hexane). The reaction mixture was stirred for 40 min and was treated with bromopropane (0.3 mL, 2.2 mmol) at −78 °C. The solution was then warmed to rt and stirred overnight. A saturated solution of aqueous NH_4Cl (0.2 mL) was added followed by water (15 mL), and the mixture was extracted with CH_2Cl_2 (2 × 30 mL). The combined extracts were dried ($MgSO_4$) and evaporated, and the crude product was purified

by column chromatography on silica gel. Elution with 25% EtOAc/hexane gave the title compound (335 mg, 67%): $[\alpha]^{23}_D$ +95.5 (*c* 1.7, acetone); mp 96−97 °C; ^{1}H NMR δ 7.98−7.96 (2H, m), 7.85−7.83 (2H, m), 7.72−7.68 (1H, m), 7.62−7.58 (2H, m), 7.24 (2H, d, J = 8.0 Hz), 3.55−3.38 (2H, m), 2.38 (3H, s), 1.68−1.56 (2H, m), 1.34 (2H, dq, J = 7.6, 7.2 Hz), 0.85 (3H, t, J = 7.2 Hz); MS (ES + ve): m/z 352 (M + H$^+$, 100%), 288 (10). Anal. Calcd for $C_{17}H_{21}NO_3S_2$: C, 58.09; H, 6.02; N, 3.98. Found: C, 57.89; H, 6.15; N, 3.84.

(*S*)-(+)-*N*-Tosyl-*S*-allyl-*S*-phenylsulfoximine [(*S*)-7] and (*S*)-(+)-*N*-tosyl-*S*-(1-propenyl)-*S*-phenylsulfoximine [(*S*)-8]. To a solution of (*S*)-(+)-*N*-tosyl-*S*-methyl-*S*-phenylsulfoximine (0.72 g, 2.33 mmol) in anhydrous THF (11 mL) was added n-BuLi (2.6 mL, 2.6 mmol, 1M in hexane) at −78 °C, and the reaction was stirred for 40 min. Acetaldehyde (0.17 mL, 3.03 mmol) was added at −78 °C, and stirring was continued for a further 30 min. A saturated solution of aqueous NH_4Cl (0.5 mL) was added at −78 °C and then water (20 mL), and the mixture was extracted with CH_2Cl_2 (2 × 30 mL). The combined extracts were dried ($MgSO_4$) and evaporated, and the crude product was purified by column chromatography on silica gel. Elution with 25% of EtOAc/hexane gave the desired β-hydroxyl sulfoximine (556 mg, 68%). A solution of this product (556 mg, 1.57 mmol) in CH_2Cl_2 (10 mL) was cooled to 0 °C and treated with triethylamine (1.09 mL, 5 equiv) and then methanesulfonyl chloride (0.36 mL, 3 equiv). The reaction was stirred for 3 h at 0 °C and was then treated with DBU (1.4 mL, 6 equiv) at the same temperature. After 5 min, the reaction was warmed to rt and stirred overnight. Ether (100 mL) was added, and the solution was washed with water (30 mL), a saturated solution of aqueous NH_4Cl (30 mL), and a solution of 10% Na_2CO_3 (30 mL). The ether layer was dried ($MgSO_4$) and evaporated, and the crude product was purified by column chromatography on silica gel. Elution with 25% EtOAc/hexane gave (*S*)-**7** (130 mg) and (*S*)-**8** (260 mg) in a total yield of 74%. Spectral data of **7** and **8** were identical to that of their respective racemic compounds.[2b]

***N*-Tosyl-*S*-benzyl-*S*-methylsulfoximine.** To a solution of *S*-benzyl-*S*-methylsulfoximine[12] (200 mg, 1.2 mmol) in pyridine (3 mL) was added *p*-toluenesulfonyl chloride (228 mg, 1.2 mmol) in portion at 0 °C. The reaction mixture was then warmed to rt and was stirred overnight. The mixture was treated with water (20 mL) and extracted with dichloromethane (2 × 15 mL). The combined extracts were washed with a solution of 10% HCl (2 × 10 mL) and water (2 × 10 mL), dried ($MgSO_4$), and evaporated to give the title compound (370 mg, 97%): mp 109−110 °C (lit.[14] 128−129 °C); ^{1}H NMR (300 MHz) δ 7.86−7.83 (2H, m), 7.49−7.46 (2H, m), 7.44−7.40 (3H, m), 7.27−7.24 (2H, d, J = 7.5 Hz), 4.78 (1H, d, J = 14.1 Hz), 4.71 (1H, d, J = 14.1 Hz), 3.04 (3H, s), 2.39 (3H, s).

Preparation of Cyclopropanes: A General Method. To a solution of the sulfoximine (1 mmol) in dry THF (3 mL) was added n-BuLi (1.2 equiv) at −78 °C, and the solution was stirred at −78 °C under N_2 for 40 min. The enone compound (1.3 equiv) was added, and the solution was stirred for 10 min at −78 °C. The reaction mixture was then warmed to rt, stirred for a further 1 h, and then quenched by the addition of a saturated solution of aqueous NH_4Cl (0.2 mL). Water (15 mL) was added, and the mixture was extracted with CH_2Cl_2 (2 × 20 mL). The combined extracts were dried ($MgSO_4$) and evaporated, and the crude products were purified by column chromatography on silica gel. Elution with EtOAc/hexane gave the desired cyclopropane, usually as a mixture of diastereoisomers. The yields given in the Experimental Section refer to the diastereoisomeric mixture, unless otherwise noted. The ratio of these diastereoisomers are given in the schemes of Results and Discussion. In many cases the major product was obtained diastereoisomerically pure by semi-preparative HPLC using 0.2−0.5% ethyl acetate/hexane as eluent.

(1*S,2*R**,3*S**)-(3-Ethenyl-2-phenyl)cyclopropyl phenyl ketone (5a):** oil (206 mg, 83%); ^{1}H NMR δ (major) 8.02−7.99 (2H, m), 7.58−7.55 (1H, m), 7.49−7.45 (2H, m), 7.32−7.30 (2H, m), 7.24−7.20 (3H, m), 5.90 (1H, ddd, J = 17.2, 10.4, 9.2 Hz), 5.28 (1H, ddd, J = 17.2, 1.6, 0.8 Hz), 5.07 (1H, dd, J = 10.0, 1.6 Hz), 3.26 (1H, dd, J = 9.2, 5.6 Hz), 3.15 (1H, br t, J = 6.0 Hz), 2.60 (1H, ddd, J = 9.2, 9.2, 6.4 Hz); (minor) 8.07−8.05 (2H, m), 7.63−7.59 (1H, m), 7.54−7.50 (2H, m), 7.34−7.24 (5H, m), 5.32 (1H, m), 5.31 (1H, dd, J = 8.0, 0.8 Hz), 5.05 (1H, dd, J = 8.8, 3.6 Hz), 3.24 (1H, dd, J = 9.2, 5.2 Hz), 3.22 (1H, s), 2.70−2.65 (1H, m); ^{13}C NMR (75 MHz) δ (major) 196.3, 139.7, 138.3, 133.8, 132.9, 128.6, 128.1, 126.6, 126.4, 116.7, 37.4, 35.5, 32.4; (minor) 198.1, 137.7, 136.4, 134.6, 133.0, 129.1, 128.7, 128.4, 128.1, 126.8, 117.1, 35.8, 34.7, 31.8; MS (EI + ve): m/z 248 (M$^+$, 7%), 221 (10), 105 (100), 77 (50); HRMS: calcd for $C_{18}H_{16}O$ = 248.120115; found 248.120846.

(1*S*,4*R*,6*S*,7*R*)-1-Methyl-4-(2-propenyl)-7-ethenylbicyclo-[4.1.0]heptan-2-one (5f): oil (137 mg, 72%); ^{1}H NMR (300 MHz) δ (major) 5.73 (1H, ddd, J = 16.8, 10.2, 7.5 Hz), 5.26 (1H, br, dt, J = 16.8, 1.5 Hz), 5.20 (1H, br. dt, J = 10.2, 1.5 Hz), 4.84 (1H, q, J = 1.2 Hz), 4.69 (1H, s), 2.62−2.54 (1H, m), 2.40 (1H, ddd, J = 16.8, 6.3, 1.8 Hz), 2.22 (1H, dd, J = 16.8, 4.8 Hz), 2.22−2.14 (1H, m), 1.96 (1H, ddd, J = 14.7, 5.1, 3.6 Hz), 1.86 (1H, dt, J = 7.8, 0.9 Hz), 1.75 (3H, t, J = 0.9 Hz), 1.58 (1H, ddd, J = 11.0, 9.0, 3.6 Hz), 1.26 (3H, s); (minor) 5.53 (1H, ddd, J = 17.1, 10.2, 8.1 Hz), 5.21 (1H, ddd, J = 17.1, 0.9 0.6 Hz), 5.13 (1H, ddd, J = 10.2, 0.9, 0.6 Hz), 4.78 (1H, dt, J = 0.9, 0.6 Hz), 4.73 (1H, s), 1.71 (3H, t, J = 0.9 Hz), 1.21 (3H, s); ^{13}C NMR δ 210.4, 147.1, 132.3, 119.4, 110.9, 43.8, 40.8, 36.5, 32.4, 29.3, 23.7, 21.8, 21.5; MS (ES + ve): m/z 191 (M + H$^+$, 100%), 149 (80), 125 (40), 83 (50); HRMS: calcd for $C_{13}H_{18}O$ = 190.13575; found 190.133841; $[\alpha]^{25}_D$ −229 (*c* 1.10, acetone).

2,3-Diphenylcyclopropyl phenyl ketone (11): yield 143 mg (96%) of single diastereoisomer, reaction performed on 0.5 mmol scale; mp 142−144 °C (lit.[11] 148−149 °C); ^{1}H NMR δ 7.97−7.94 (2H, m), 7.55−7.50 (1H, m), 7.46−7.41 (2H, m), 7.35−7.29 (4H, m), 7.28-7.16 (6H, m), 3.62 (1H, dd, J = 6.8, 5.6 Hz), 3.38 (1H, dd, J = 9.6, 5.6 Hz), 3.28 (1H, dd, J = 9.6, 7.2 Hz); ^{13}C NMR (75 MHz) δ 195.0, 140.0, 138.4, 135.5, 132.7, 129.1, 128.6, 128.5, 128.2, 128.1, 126.9, 126.7, 37.9, 36.5, 29.9; MS (EI + ve): m/z 298 (M$^+$, 10%), 193 (65), 115 (45), 105 (100), 77 (40); HRMS: calcd for $C_{14}H_{18}O$ = 298.13575; found 298.135605. Anal. Calcd for $C_{14}H_{18}O$: C, 88.55; H, 6.08. Found: C, 88.46; H, 6.04.

(1*R*,6*S*,7*R*)-7-Phenylbicyclo[4.1.0]heptan-2-one (13): oil (67 mg (71%), reaction performed on 0.5 mmol scale); ^{1}H NMR (300 MHz) δ 7.30−7.25 (2H, m), 7.22−7.16 (1H, m, 7.09−7.06 (2H, m), 2.66 (1H, br t, J = 4.5 Hz, 2.39 (1H, ddt, J = 9.9, 5.1, 4.8 Hz), 2.19 (1H, dd, J = 9.6, 3.5 Hz), 2.16−1.96 (4H, m), 1.84−1.77 (2H, m); ^{13}C NMR (100 MHz) δ 206.6, 139.6, 128.5, 126.5, 126.0, 37.1, 36.9, 27.9, 26.8, 21.3, 18.7; MS (EI + ve): m/z 186 (M$^+$, 45%), 130 (100), 115 (50), 77 (25); HRMS: calcd for $C_{13}H_{14}O$ = 186.10445; found 186.104922.

(1*S*,2*S*)-2-Phenylcyclopropyl phenyl ketone (16a): yield 143 mg (92%) of single diastereoisomer; mp 60−62 °C (lit.[11] 66−70 °C); ^{1}H NMR δ 8.01−7.99 (2H, m), 7.56−7.54 (1H, m), 7.48−7.44 (2H, m), 7.34−731 (2H, m), 7.25−7.23 (1H, m), 7.20−7.18 (2H, m), 2.91 (1H, ddd, J = 8.0, 5.2, 4.1 Hz), 2.71 (1H, ddd, J = 9.2, 6.8, 4.0 Hz), 1.94 (1H, ddd, J = 9.2, 5.2, 4.0 Hz), 1.57 (1H, ddd, J = 8.0, 6.8, 4.0 Hz); ^{13}C NMR (75 MHz) δ 198.5, 140.5, 137.7, 132.8, 128.6, 128.1, 126.6, 126.2, 29.9, 29.2, 19.1; MS (EI + ve): m/z 222 (M$^+$, 35%), 115 (25), 105 (100); HRMS: calcd for $C_{16}H_{14}O$ = 222.10445; found 222.103776. $[\alpha]^{27}_D$ +388 (*c* 0.55, acetone).

(1*S*,4*R*,6*S*)-1-Methyl-4-(2-propenyl)bicyclo[4.1.0]heptan-2-one (20): oil (69 mg (42%) of **20a** and **20b**); ^{1}H NMR δ (major (**20a**)) 4.76 (1H, t, J = 1.2 Hz), 4.72 (1H, s), 2.48−2.25 (1H, m), 2.42 (1H, ddd, J = 18.0, 5.2, 0.8 Hz), 2.17−1.96 (1H,

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(15) The author has deposited the atomic coordinates for the structures **10** and **23a** with the Cambridge Crystallography Data Centre. These coordinates can be obtained, on request, from the Director, Cambridge Crystallography Data Centre, 12 Union Road, Cambridge, CB2 1EZ, U.K.

m), 2.02 (1H, dd, J = 17.2, 6.0 Hz), 1.91−1.79 (1H, m), 1.70 (3H, s, 1.57 (1H, ddd, J = 8.0, 5.6, 2.8 Hz), 1.37 (1H, dd, J = 5.6, 5.2 Hz), 1.23 (3H, s), 0.86 (1H, dd, J = 8.0, 5.6 Hz); (minor) 4.88 (1H, s), 4.74 (1H, t, J = 1.6 Hz), 1.72 (3H, s), 1.25 (3H, s), 0.99 (1H, d, J = 6.8 Hz); ^{13}C NMR (75 MHz) δ 210.1, 147.1, 110.1, 41.8, 36.7, 29.2, 27.0, 25.2, 20.5, 19.7, 17.6; MS (EI + ve): m/z 164 (M^+, 95%), 149 (40), 96 (60), 68 (100), 41 (50); HRMS: calcd for $C_{11}H_{16}O$ = 164.12010; found 164.120371.

(1*S*,3*S*,4*R*,6*S*,1′*R*,2′*S*,5′*R*)-1-Methyl-3-[2′-methyl-3′-oxo-5′-(2-propenyl)cyclohexyl]-4-(2-propenyl)bicyclo[4.1.0]-heptan-2-one (21): oil (78 mg (25%) of single diastereoisomer); ^{1}H NMR δ 4.83−4.82 (2H, m), 4.77 (1H, t, J = 1.2 Hz), 4.69 (1H, s), 2.52−2.35 (4H, m), 2.30−2.15 (3H, m), 1.99−1.95 (3H, m), 1.71 (3H, s), 1.62−1.55 (1H, m), 1.50 (1H, dd, J = 6.4, 6.4 Hz), 1.19 (3H, s), 1.18 (3H, d, J = 9.2 Hz), 0.85 (1H, dd, J = 10.4, 6.4 Hz); ^{13}C NMR (75 MHz) δ 212.4, 209.7, 147.7, 145.8, 113.2, 110.3, 47.0, 44.0, 42.0, 40.7, 39.8, 30.8, 30.2, 27.3, 25.6, 20.5, 20.1, 18.5, 16.7, 12.5; MS (EI + ve) m/z 314 (M^+, 35%) 164 (75), 150 (100), 135 (80), 122 (100), 109 (70), 55 (80); HRMS: calcd for $C_{21}H_{30}O_2$ = 314.22455; found 314.224875; $[\alpha]^{26}_D$ −46 (*c* 0.48, acetone).

(1*S,2*R**,3*S**)-2-Phenyl-3-propylcyclopropyl phenyl ketone (24a):** oil (236 mg, 90%); ^{1}H NMR δ 8.03−8.00 (2H, m), 7.57−7.53 (1H, m), 7.48−7.45 (2H, m), 7.31−7.27 (2H, m), 7.21-7.17 (3H, m), 3.00 (1H, dd, J = 9.6, 5.2 Hz), 2.88 (1H, dd, J = 6.8, 5.2 Hz), 2.04−1.96 (1H, ddt, J = 9.2, 7.2, 6.8 Hz), 1.71−1.54 (2H, m), 1.43−1.26 (2H, m), 0.88 (3H, t, J = 7.2 Hz); (minor) 0.94 (3H, t, J = 7.2 Hz); ^{13}C NMR (75 MHz) δ 197.4, 141.0, 138.7, 132.6, 128.49, 128.46, 128.0, 126.4, 126.3, 34.9, 34.1, 32.3, 28.4, 22.7, 13.8; MS (EI + ve): m/z 264 (M^+, 15%), 221 (100), 115 (30), 105 (100), 77 (60); HRMS: calcd for $C_{19}H_{20}O$ = 264.151415; found 264.151655; $[\alpha]^{23}_D$ +111.3 (*c* 1.01, acetone).

Preparation of 1,2-Adducts and Michael Adducts: A General Method. Lithiated sulfoximines **2, 9, 14,** or **22** (0.5 mmol) were prepared by the general method described above. The enone compound (0.65 mmol) was then added, and the reaction mixture was stirred for 3 min (for **4a**−**c**, **10**, and **12**) or 30 min (for **15**) or 1 h (for **23a**−**c**) and then quenched by the addition of a saturated solution of aqueous NH_4Cl (0.2 mL) at −78 °C. Water (15 mL) was added, and the mixture was extracted with CH_2Cl_2 (2 × 20 mL). The combined extracts were dried ($MgSO_4$) and evaporated, and the crude products were purified by column chromatography on silica gel using EtOAc/hexane as eluent. The yields given in the Experimental Section refer to the diastereoisomeric mixture, unless otherwise noted.

(3*R,4*R**,S*S**)-1,3-Diphenyl-4-(*N*-tosyl-*S*-phenylsulfonimidoyl)-5-hexen-1-one (4a):** yield 243 mg (90%); mp 131−132 °C; ^{1}H NMR δ (major) 7.92−7.04 (19H, m,), 5.89 (1H, dt, J = 17.2, 10.4 Hz), 5.34 (1H, dd, J = 10.0, 0.8 Hz), 4.70 (1H, d, J = 16.8 Hz), 4.69 (1H, dt, J = 11.6, 3.2 Hz), 3.92 (1H, dd, J = 10.8, 3.2 Hz), 3.62 (1H, dd, J = 9.2, 3.2 Hz), 3.48 (1H, dd, J = 17.2, 11.2 Hz), 2.16 (1H, s); (minor) 5.37 (1H, dd, J = 10, 0.8 Hz); ^{13}C NMR δ (major) 196.4, 142.5, 141.0, 139.8, 136.63, 136.57, 134.2, 133.0, 129.3, 129.2, 129.1, 128.53, 128.49, 128.4, 128.3, 127.9, 127.3, 126.5,124.3,75.8, 39.3, 38.4, 21.3. MS (CI + ve) m/z 544.2 (M + H^+, 5%), 314 (15), 314 (15), 270 (50), 226 (50), 195 (65), 142 (40), 114 (85), 101 (100). Anal. Calcd for $C_{31}H_{29}NO_4S_2$ C, 68.48; H, 5.38; N, 2.58. Found: C, 68.09; H, 5.37; N, 2.46.

3-[1′-(*N*-Tosyl-*S*-phenylsulfonimidoyl)-2′-propenyl]-cyclopentanone (4d): yield 181 mg (87%); mp 124−126 °C; ^{1}H NMR δ (major) 7.98−7.23 (9H, m), 5.56 (1H, dt, J = 16.4, 10.4 Hz), 5.41 (1H, dd, J = 10.4, 1.0 Hz), 5.16 (1H, d, J = 16.8 Hz), 4.08 (1H, dd, J = 7.2, 7.2 Hz), 2.93, (1H, m), 2.56−1.55 (6H, m), 2.39 (3H, s); ^{13}C NMR δ (major) 216, 142.8, 140.8, 135.5, 134.4, 129.24, 129.22, 127.7, 126.6, 125.6, 74.99, 43.3, 37.7, 35.3, 26.4, 21.5; MS (CI + ve) m/z 418.2 (M + H^+, 10%), 296 (100), 246 (15), 132.8 (50), 124.2 (100), 60.2 (40). Anal. Calcd for $C_{21}H_{23}NO_4S_2$: C, 60.43; H, 5.52; N, 3.36. Found: C, 60.81; H, 5.68; N, 3.27.

1,3,4-Triphenyl-4-(*N*-tosyl-*S*-methylsulfoximidoyl)-1-butanone (10): yield 191 mg (72%); mp 130−132 °C; ^{1}H NMR δ 7.73−7.71 (2H, m), 7.66−7.64 (2H, m), 7.49−7.45 (1H, m), 7.41−7.31 (8H, m), 7.20−7.15 (4H, m), 7.13 (2H, d, J = 8.0 Hz), 4.70−4.65 (2H, m), 3.38 (1H, dd, J = 17.2, 9.6 Hz), 3.26 (1H, dd, J = 17.2, 2.4 Hz), 2.81 (3H, s), 2.29 (3H, s); ^{13}C NMR (75 MHz) δ 196.6, 142.5, 140.8, 139.3, 136.7, 133.0, 130.7, 130.1, 129.5, 129.2, 129.1, 128.9, 128.7, 128.5, 127.8, 127.7, 126.5, 76.1, 43.1, 41.39, 41.35, 21.4; MS (ES + ve) m/z 570 (M + K^+, 30%), 554 (M + Na^+, 50), 530 (M + H^+, 30), 393 (20), 230 (100), 105 (70). Anal. Calcd for $C_{30}H_{29}NO_4S_2$: C, 67.72; H, 5.50; N, 2.64. Found: C, 67.18; H, 5.67; N, 2.31.

3-[*S*-Phenyl-(*N*-tosyl-*S*-methylsulfoximidoyl)-1-cyclohexanone (12): oil (171 mg, 82%); ^{1}H NMR δ (major) 7.85 (2H, d, J = 8.4 Hz), 7.46−7.41 (4H, m), 7.37−7.34 (1H, m), 7.31−7.29 (2H, m), 4.29 (1H, d, J = 5.6 Hz), 3.06−2.84 (1H, br), 2.99 (3H, s), 2.53−2.46 (1H, m), 2.44 (3H, s), 2.36−2.25 (1H, m), 2.18−2.03 (1H, m), 2.08 (1H, d, J = 13.2 Hz), 2.00−1.92 (2H, m), 1.64−1.44 (1H, m), 1.40−1.30 (1H, m); (minor) 4.40 (1H, d, J = 7.2 Hz), 2.96 (3H, s); ^{13}C NMR (75 MHz) δ (major) 208.2, 143.0, 140.7, 130.42, 130.35, 129.8, 129.6, 129.4, 126.5, 74.8, 46.1, 42.2, 40.81, 38.1, 27.8, 24.3, 21.5; (minor) 208.6, 130.4, 130.2, 129.9, 75.1, 44.5, 42.3, 40.77, 38.4, 29.8, 29.7, 24.2; MS (ES + ve): m/z 458 (M + K^+, 20%), 442 (M + Na^+, 30), 437 (M + NH_4^+, 25), 420 (M + H^+, 20), 234 (100), 187 (35).

2,4-Diphenyl-1-(*N*-tosyl-*S*-phenylsulfoximidoyl)-3-buten-2-ol (15): oil (259 mg, 100%); ^{1}H NMR δ (major) 7.95 (2H, d, J = 8.4 Hz), 7.72 (2H, d, J = 8.4 Hz), 7.62 (1H, t, J = 7.2 Hz), 7.50 (2H, t, J = 8.0 Hz), 7.44−7.41 (2H, m,), 7.30−7.22 (6H, m), 7.16−7.14 (2H, m), 6.97 (2H, d, J = 8.0 Hz), 6.63 (1H, d, J = 16.0 Hz), 6.46 (1H, d, J = 16 Hz), 5.25 (1H, s), 4.07 (1H, d, J = 14.8 Hz), 3.75 (1H, d, J = 14.0 Hz), 2.22 (3H, s); (minor) 6.68 (1H, d, J = 16.0 Hz), 6.38 (1H, d, J = 16.0 Hz), 4.84 (1H, s), 4.33 (1H, d, J = 14.8 Hz), 3.96 (1H, dd, J = 14.8, 2.0 Hz), 2.32 (3H, s); ^{13}C NMR (75 MHz) δ (major) 143.2, 142.9, 140.2, 138.9, 136.2, 134.3, 130.9, 130.1, 129.7, 129.2, 128.7, 128.4, 128.2, 127.9, 127.8, 126.8, 126.5, 125.0, 75.4, 67.6, 21.4; (minor) 142.8, 141.9, 140.4, 138.5, 135.9, 133.9, 131.7, 129.8, 129.3, 129.1, 128.4, 128.3, 127.9, 127.5, 126.7, 126.5, 125.1, 75.5, 66.7, 21.4; MS (ES + ve) m/z 540 (M + Na^+, 15%), 518 (M + H^+, 10), 500 (30), 296 (30), 262 (25), 142 (25), 90 (40), 74 (100).

(5*R*)-5-(2-Propenyl)-2-methyl-1-[(*N*-tosyl-*S*-phenylsulfoximidoyl)methyl]-2-cyclohexen-1-ol (19): oil (193 mg, 84%); ^{1}H NMR (300 MHz) δ (major) 8.03−8.00 (2H, m), 7.81 (2H, d, J = 8.1 Hz), 7.71−7.66 (1H, m), 7.62−7.57 (2H, m), 7.23 (2H, dd, J = 8.1, 0.6 Hz), 5.48 (1H, br), 4.71−4.69 (2H, m), 4.03 (1H, d, J = 14.4 Hz), 3.52 (1H, dd, J = 14.4, 1.5 Hz), 3.15 (1H, s), 2.59 (1H, ddd, J = 12.9, 1.2, 0.9 Hz), 2.45−2.35 (1H, m), 2.40 (3H, s), 2.17−2.06 (1H, m), 1.96−1.84 (1H, m), 1.67 (3H, s), 1.63 (1H, dd, J = 12.9, 1.5 Hz), 1.59 (3H, dt, J = 1.5, 1.2 Hz); (minor) 8.02−8.00 (2H, m), 7.81 (2H, dt, J = 8.4, 1.8 Hz), 7.72−7.67 (1H, m), 7.63−7.57 (2H, m), 7.25 (2H, dd, J = 7.8, 0.9 Hz), 5.45 (1H, br), 4.60 (1H, t, J = 1.2 Hz), 4.51 (1H, s), 4.44 (1H, m), 3.88 (1H, dd, J = 14.4, 1.5 Hz), 3.44 (1H, d, J = 14.4 Hz), 2.40 (3H, s), 2.36 (1H, ddd, J = 12.9, 1.8, 1.8 Hz), 2.10−1.98 (2H, m), 1.92−1.80 (1H, m), 1.67 (3H, s), 1.58 (1H, dd, J = 12.9, 1.5 Hz), 1.53 (3H, s); ^{13}C NMR (75 MHz) δ (major) 147.6, 142.8, 140.7, 140.0, 135.4, 134.1, 129.6, 129.5, 129.2, 127.9, 126.8, 126.5, 109.8, 74.4, 63.6, 39.4, 38.7, 30.8, 21.5, 20.3, 16.4; (minor) 147.4, 143.0, 140.5, 139.4, 136.1, 134.4, 129.8, 129.3, 127.9, 126.7, 125.9, 109.2, 74.1, 62.7, 39.1, 38.6, 30.6, 21.4, 20.2, 16.6; MS (EI + ve): m/z 459 (M^+, 10%), 316 (20), 296 (90), 278 (100); HRMS: calcd for $C_{24}H_{29}NO_4S_2$ = 459.15376; found 459.152339.

1,3-Diphenyl-4-(*N*-tosyl-*S*-phenylsulfoximidoyl)heptan-1-one (23a): mp 178−180 °C; ^{1}H NMR δ 7.96−7.94 (2H, m), 7.90−7.88 (2H, m), 7.79−7.77 (2H, m), 7.70−7.66 (1H, m), 7.60-7.56 (3H, m), 7.46 (2H, t, J = 7.6 Hz), 7.21−7.16 (3H, m), 7.13−7.10 (2H, m), 7.07 (2H, d, J = 7.6 Hz), 4.51 (1H, ddd, J = 10.0, 3.2, 2.8 Hz), 3.79 (1H, dd, J = 18.0, 4.0 Hz), 3.56 (1H, dd, J = 18.0, 6.4 Hz), 3.44 (1H, ddd, J = 8.0, 5.2, 2.4 Hz), 2.21 (3H, s), 1.85−1.76 (1H, m), 1.72−1.64 (1H), 0.83−0.73 (2H, m), 0.64 (3H, t, J = 7.2 Hz); (minor) 0.51 (3H, t, J = 7.2 Hz); ^{13}C NMR (75 MHz) δ 197.2, 142.5, 141.1, 139.3, 137.6, 136.9, 134.2, 133.1, 129.6, 129.1, 128.9, 128.68, 128.61, 128.03, 128.01, 127.3, 126.6, 70.6, 38.8, 37.1, 25.8, 21.34, 21.30, 13.2; MS (ES

+ ve): *m*/*z* 598 ($M + K^+$, 20%), 582 ($M + Na^+$, 60), 560 ($M + H^+$, 20), 265 (100). Anal. Calcd for $C_{32}H_{33}NO_4S_2$: C, 68.67; H, 5.95; N, 2.50. Found: C, 68.72; H, 5.86; N, 2.41.

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Supporting Information Available: Copies of the ^1H NMR spectra for compounds **5a**−**c**,**f**, **10**, **11**−**13**, **15**, **16a,b**, **19**−**21**, **22a**−**c**, and **23a**−**c** plus the minor diastereomeric products of **5a**,**c**, **15**, and **19**, and full lists of spectral and characterization data (37 pages). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of this journal, and can be ordered from the ACS; see any current masthead page for ordering information.

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