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# Catalytic Asymmetric [2,3]-Sigmatropic Rearrangement of Sulfur Ylides Generated from Copper(I) Carbenoids and Allyl Sulfides

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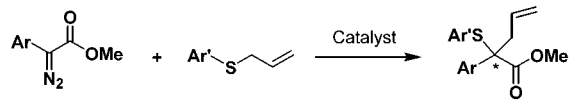
Catalytic asymmetric sulfur ylide [2,3]-sigmatropic rearrangement of carbenoids generated from aryldiazoacetates has been investigated with a number of chiral Rh(II) and Cu(I) catalysts, and moderately high enantioselectivity (52−78% ee) can be achieved with $Cu(MeCN)_4PF_6$/2,2′-isopropylidenebis[(4*S*)-4-*tert*-butyl-2-oxazoline].

## Introduction

Rh(II)−carbene and Cu(I)−carbene can efficiently react with allylic sulfides to generate sulfur ylides, which can subsequently undergo [2,3]-sigmatropic rearrangement.[1] [2,3]-Sigmatropic rearrangement is a synthetically useful reaction. It can generate tertiary sulfides, which are not easily available. Recently a catalytic asymmetric system was developed that could introduce chirality into the newly formed tertiary carbon center. Although the [2,3]-sigmatropic rearrangement reaction of the ylide generated by transition metal catalyzed diazo decomposition in the presence of sulfide is generally believed to occur from free ylide rather than metal-associated ylide,[2] recent developments of asymmetric induction in similar oxygen and iodine ylide reactions strongly suggest that the metal complex may still be attached to the ylide intermediate during the subsequent reaction.[3] If a chiral metal complex is associated with the ylide, it will be likely that it transfers chirality to the final product. Inter- and intramolecular [2,3]-sigmatropic rearrangement through oxonium ylide has been studied with chiral Rh(II) and Cu(I) catalysts,[3,4] but the corresponding reaction through sulfur ylide has not been fully investigated. Uemura et al. in 1995 published first work on sulfur ylide [2,3]-sigmatropic rearrangement in chiral Cu(OTf)/bis(oxazoline)-catalyzed reaction of *trans*-cinnamyl phenyl sulfide with ethyl diazoacetate, although the enantioselectivity was low (highest 22% ee).[4] Later Katsuki et al. improved the enantioselectivity in similar reaction with chiral cobalt(III)−salen (up to 64% ee).[5] McMillen et al. reported a detailed investigation on the effect of the sulfide structure on the enantioselectivity in Cu(OTf)/bis(oxazoline)-catalyzed reaction.[6] More recently, Hashimoto et al. investigated the similar system with chiral Rh(II) complexes.[7] In these previous investigations, ethyl diazoacetate or its derivatives were employed as carbenoids source. On the other hand, Davies and co-workers have recently published a series of papers on the exceptionally high enantioselectivity in C−H insertion and cyclopropanation of carbenoids derived from aryldiazoacetate.[8] Herein we report our study on asymmetric [2,3]-sigmatropic rearrangement with aryldiazoacetates (Scheme 1).

**SCHEME 1**

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## Results and Discussion

First, the phenyldiazoacetate was employed as the substrate to optimize the reaction conditions. We have

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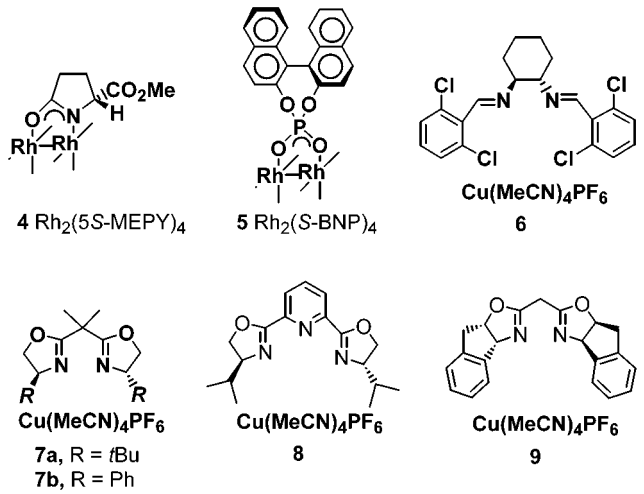
**CHART 1**




**4** $Rh_2$(5*S*-MEPY)$_4$ **5** $Rh_2$(*S*-BNP)$_4$ **6**

**7a**, R = *t*Bu
**7b**, R = Ph

**8** **9**

examined two Rh(II) catalysts, $Rh_2$(5*S*-MEPY)$_4$, **4**,[9] and $Rh_2$(*S*-BNP)$_4$, **5**,[10] and five Cu(I) catalysts, **6**,[11] **7a**,[12] **7b**,[12] **8**,[13] and **9**[14] (Chart 1). These chiral catalysts have been demonstrated to be highly effective in asymmetric cyclopropanations or C−H insertions of carbenoids.[1c,15] From the results summarized in Table 1, it is obvious that Rh(II) catalysts are less effective in the sulfur ylide [2,3]-sigmatropic rearrangement compared with Cu(I) catalyst. $Cu(MeCN)_4PF_6$/bis(oxazoline) **7a,b** or **9** gave the highest enantioselectivity, although the reaction was generally slower compared to the reaction with catalyst **6**.

The structure of the allylic aryl sulfide also has influence over the enantioselectivity. The best result was obtained with allylic 2-methylphenyl sulfide. The $C_2$-symmetrical 2,6-dimethylphenyl sulfide, which shown highest enantioselectivity (52% ee) in McMillen's investigation,[6] was not effective in our case (entries 9 and 13). The reaction with this sulfide is slow, and enantioselectivity was not significantly improved. The combination of allylic 2-methylphenyl sulfide, ethyl diazoacetate, and **7a** in McMillen's work gave an ee value 14%.[6]

On the other hand, solvent and temperature also influence the reaction. It was observed that benzene and toluene are better solvents for the enantioselectivity. Low temperature can slightly improve the ee values in general, but the reaction is markedly slowed at low temperature.

From the above optimization experiments, we concluded that higher enantioselectivity could be obtained with chiral Cu(I) catalysts **7a** or **9** in benzene or toluene, using allylic 2-methylphenyl sulfide. Thus, a number of aryldiazoacetates were examined with this condition, and the results are summarized in Table 2. From the data collected in the table, it is seen that there is no obvious dependence of the enantioselectivity on the electronic properties of the substituent in the diazo substrate phenyl ring,[16] although the reaction of the diazo substrate bearing an electron-donating group (Ar = *p*-$MeOC_6H_4$−) is much faster.[17] Catalysts **7a** and **9** gave comparable level of enantioselectivity, and moderate to good ee values can be obtained in general. The 78% ee for methyl 1-nathyldiazoacetate is the highest selectivity reported so far for this type of reaction (entry 13).

The absolute configuration of the major product reaction with $Cu(MeCN)_4PF_6$/bis(oxazoline) **7a** as the catalyst was determined to be *R* by comparing the product **3** (Ar = Ar′ = $C_6H_5$, 41 ee %, Table 1, entry 16) with a sample prepared by diastereoselective [2,3]-sigmatropic rearrangement (Scheme 2). The [2,3]-sigmatropic rearrangement of phenyldiazoacetamide **10**[18] with $Cu(MeCN)_4PF_6$ and allylic phenyl sulfide gave a mixture of diastereomers in a ratio of 75:25. Recrystallization of the mixture gave a pure major diastereomer **11**. The stereochemistry of the newly formed chiral center was determined to be *R* by X-ray structure. The camphorsultam auxiliary was removed under basic condition, and subsequent treatment with diazomethane gave methyl ester **13**, which was compared with **3** (Ar = Ar′ = $C_6H_5$) by chiral HPLC.

A key issue in the catalytic asymmetric induction in [2,3]-sigmatropic rearrangement of sulfur ylide is whether the catalyst remains bound to the ylide during the subsequent reaction, or stereochemical outcome of the reaction is simply dictated by the stereochemistry of the initially formed ylide. Although there is evidence to show that in the reactions of oxonium[3c,g] and iodonium ylides[3a] the catalyst remains bound to the ylide during subsequent reactions, for sulfur ylide reaction the latter possibility cannot be ruled out in view of the fact that sulfonium ylides are expected to be considerably more stable, both in terms of their overall reactivity and their configurational stability. Katsuki and Hashimoto have demonstrated that the [2,3]-sigmatropic rearrangement of the sulfur ylide generated from allylic sulfides and diazoacetates in the presence of chiral Co(III) or Rh(II) catalysts gives the products in which the diastereoselectivities are independent of the nature of the catalyst. They thus conclude that the reaction proceeds through nonracemic free sulfur ylides detached from the chiral catalyst.[5,7] However, Aggarwal reported the opposite observation in the reaction of allylic sulfur ylides derived from (trimethylsilyl)diazomethane, in which the diastereoselectivity was markedly influenced by the metal catalyst used, thus suggesting that a metal-associated ylide was involved in product-forming step.[19]

To gain some insights into the detailed mechanism of the reaction in this investigation, several experiments were carried out. First, a symmetrical diallyl sulfide **14** was employed in the reaction instead of allylic aryl sulfide. In this case, the initially formed ylide is achiral, as in the case of iodonium ylides;[3a] thus, any asymmetric

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**TABLE 1. Effects of the Catalyst, Structure of Allyl Sulfide, Solvent, and Temperature on the Enantioselectivity**

| entry | catal[a] | sulfide: Ar′ [b] | solvent | temp (°C) | reacn time (h) | ee (%)[c] | yield (%) |
|---|---|---|---|---|---|---|---|
| 1 | **4** | $C_6H_5$ | $C_6H_6$ | 25 | 38 | 7 | 79 |
| 2 | **5** | $C_6H_5$ | $C_6H_6$ | 25 | 36 | 7 | 64 |
| 3 | **6** | $C_6H_5$ | $C_6H_6$ | 25 | 24 | 24 | 79 |
| 4 | **6** | 2-$CH_3C_6H_4$ | $C_6H_6$ | 25 | 24 | 41 | 80 |
| 5 | **6** | 2-$CH_3C_6H_4$ | $CH_2Cl_2$ | 25 | 16 | 12 | 56 |
| 6 | **6** | 2-$CH_3C_6H_4$ | THF | 25 | 36 | 27 | 70 |
| 7 | **6** | $C_6H_5$ | $PhCH_3$ | 25 | 24 | 21 | 62 |
| 8 | **6** | 2-$ClC_6H_4$ | $C_6H_6$ | 25 | 24 | 26 | 67 |
| 9 | **6** | 2,6-$(CH_3)_2C_6H_3$ | $C_6H_6$ | 25 | 47 | 30 | 50 |
| 10 | **6** | 2-$CH_3C_6H_4$ | $PhCH_3$ | 0 | 120 | 30 | <10 |
| 11 | **6** | $C_6H_5$ | $PhCH_3$ | 0 | 120 | 25 | <10 |
| 12 | **7a** | 2-$ClC_6H_4$ | $C_6H_6$ | 25 | 24 | 34 | 77 |
| 13 | **7a** | 2,6-$(CH_3)_2C_6H_3$ | $C_6H_6$ | 25 | 48 | 37 | 74 |
| 14 | **7a** | 2-$CH_3C_6H_4$ | $C_6H_6$ | 25 | 36 | 62 | 92 |
| 15 | **7a** | 2-$CH_3C_6H_4$ | $PhCH_3$ | −41 | 72 | 67 | <10[d] |
| 16 | **7a** | $C_6H_5$ | $C_6H_6$ | 25 | 24 | 41 | 89 |
| 17 | **7b** | 2-$CH_3C_6H_4$ | $C_6H_6$ | 25 | 24 | 48 | 92 |
| 18 | **8** | 2-$CH_3C_6H_4$ | $C_6H_6$ | 25 | 36 | 8 | 57 |
| 19 | **9** | 2-$CH_3C_6H_4$ | $C_6H_6$ | 25 | 17 | 56 | 86 |

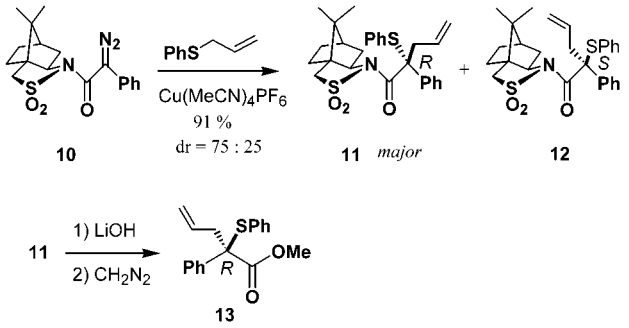
[a] Catalysts **4** and **5**, 1 mol %; catalysts **6**, **7a,b**, **8**, and **9**, 10 mol % $Cu(MeCN)_4PF_6$ and 11 mol % of the ligand. [b] A 1 equiv amount of sulfide was employed. [c] Ee's determined by chiral HPLC; Chiracel OJ; hexane/2-propanol. [d] Methyl *p*-methoxydiazoacetate was the substrate.

**TABLE 2. Enantioselectivity of the Reaction of Aryldiazoacetate and Allyl 2-Methylphenyl Sulfide with Chiral Cu(I) Catalyst 7a or 9**

| entry | diazo compd: Ar | catal[a] | reacn time (h)[b] | ee (%)[c] | $[\alpha]_D$ (*c*, $CHCl_3$) | yield (%) |
|---|---|---|---|---|---|---|
| 1 | $C_6H_5$ | **7a** | 36 | 62 | −31.8 (0.75) | 92 |
| 2 | $C_6H_5$ | **9** | 25 | 56 | +28.7 (0.83) | 86 |
| 3 | *p*-$MeOC_6H_4$ | **7a**[d] | 24 | 56 | −44.3 (1.59) | 86 |
| 4 | *m*-$MeOC_6H_4$ | **7a** | 17 | 56 | −24.6 (1.11) | 81 |
| 5 | *m*-$MeOC_6H_4$ | **9** | 17 | 52 | +23.3 (1.11) | 87 |
| 6 | *p*-$BrC_6H_4$ | **7a** | 36 | 59 | −34.3 (0.65) | 70 |
| 7 | *p*-$BrC_6H_4$ | **9** | 36 | 48 | +27.9 (1.04) | 85 |
| 8 | *p*-$PhC_6H_4$ | **7a** | 24 | 55 | −61.1 (0.52) | 74 |
| 9 | *m*-$CH_3C_6H_4$ | **7a** | 36 | 62 | −36.1 (0.6) | 83 |
| 10 | *m*-$CH_3C_6H_4$ | **9** | 36 | 55 | +31.0 (0.54) | 74 |
| 11 | *m*-$ClC_6H_4$ | **7a** | 36 | 52 | −10.5 (1.08) | 93 |
| 12 | *m*-$ClC_6H_4$ | **9** | 24 | 48 | +9.72 (1.07) | 91 |
| 13 | 1-naphthyl | **7a** | 24 | 78 | −185.5 (0.49) | 66 |
| 14 | 1-naphthyl | **9** | 24 | 65 | +149 (1.41) | 72 |

[a] Bis(oxazoline) ligand (11 mol %) was mixed with $Cu(MeCN)_4PF_6$ (10 mol %). [b] All reactions were run at room temperature. [c] Ee's determined by chiral HPLC using the condition given in Table 1. [d] 2% mol catalyst is used.

**SCHEME 2**

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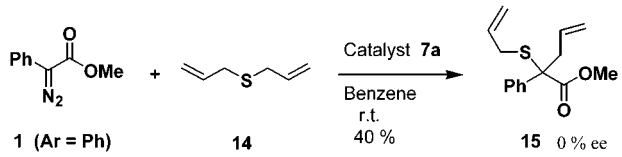


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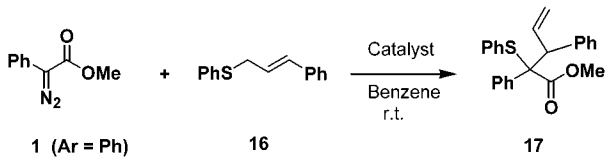


induction must be due to the catalyst-bound species. However, [2,3]-sigmatropic rearrangement of this sulfide with catalyst **7a** did not show any enantioselectivity (Scheme 3). Although this result does not provide conclusive evidence, it is in favor of the mechanism by which the stereochemical outcome is controlled by initial sulfur ylide formation.

Next we investigated the dependence of the diastereoselectivity on the catalyts when cinnamylic phenyl sulfide **16** was employed in the reaction (Scheme 4). If the catalyst is still attached to the sulfur ylide, change in diastereomeric ratio will be expected when different catalyst is used. However, the experiments show that there is no obvious dependence of the diastereomeric ratio on the catalyst (Table 3). This result is again in favor of the mechanism with free ylide as the intermediate, as previously proposed by Katsuki and Hashimoto.[5,7]

In summary, catalytic asymmetric [2,3]-sigmatropic rearrangement has been investigated with aryldiazoacetates. Moderate to good enantioselectivity has been achieved for a number of diazo substrates.

**TABLE 3. Dependence of the Diastereoselectivity on the Catalyts**

| entry | catal | diastereomeric ratio of **17**[a] |
|---|---|---|
| 1 | $Rh_2(OAc)_4$ | 31:69 |
| 2 | **4** | 36:64 |
| 3 | $Cu(MeCN)_4PF_6$ | 36:64 |
| 4 | **6** | 39:61 |
| 5 | **7a** | 37:63 |

[a] Product ratio was determined by $^1$H NMR (400 MHz) of the crude product.

## Experimental Section

**General Methods.** All reactions were performed under a nitrogen atmosphere in a flame-dried reaction flask, and the components were added via syringe. All solvents were distilled prior to use. $CH_2Cl_2$, THF, and benzene were freshly distilled from $CaH_2$ before use. For the preparation of aryldiazoacetates, see ref 17 and the references therein.

**Typical Procedure for the Reaction of Aryldiazoacetate with Sulfide Catalyzed by Cu(I) Complex.** In a nitrogen atmosphere, $Cu(MeCN)_4PF_6$ ($7.5 \times 10^{-3}$ mmol, 2.7 mg) and ligand **7a** ($7.9 \times 10^{-3}$ mmol, 2.3 mg) were added to a 25 mL round-bottom flask. Dry benzene (4.0 mL) was introduced, and the solution was stirred for 1 h. To the slightly blue solution was then added aryl sulfide **2** (Ar′ = 2-$CH_3C_6H_4$, 0.375 mmol, 61.5 mg) in benzene (2 mL). Methyl (*p*-methoxyphenyl)diazoacetate (**1**, Ar = *p*-$MeOC_6H_4$) (0.375 mmol, 77 mg) in dry benzene (6 mL) was added via a syringe over 30 min. The solution was stirred for additional 22 h. Solvent was removed by evaporation, and the green oily residue was purified by column chromatography (60:1 petroleum ether/ethyl acetate) to give a colorless solid of **3** (Ar = *p*-$MeOC_6H_4$, Ar′ = 2-$CH_3C_6H_4$) (110 mg, 86%).

**Methyl 2-(1-naphthyl)-2-((2-methylphenyl)thio)-4-pentenoate (3, Ar = 1-naphthyl, Ar′ = 2-$CH_3C_6H_4$):** HPLC (254 nm), 95:5 hexane/2-propanol, $t_R$ = 26.819 min, $t_R$ = 34.157 min; mp 100−101 °C; IR (KBr) 3050 (m), 1722 (s); $^1$H NMR (200 MHz, $CDCl_3$) $\delta$ 1.99 (s, 3H), 2.94−3.05 (s, 3H), 5.04−5.14 (m, 2H), 6.06−6.26 (m, 1H), 6.87−8.18 (m, 13H); $^{13}$C NMR (50 MHz, $CDCl_3$) $\delta$ 20.63, 41.59, 52.43, 64.22, 118.44, 124.166, 124.22, 125.28, 125.38, 126.00, 128.97, 129.16, 129.25, 129.89, 130.16, 131.16, 133.28, 134.10, 135.16, 138.47, 144.51, 173.36; MS (*m*/*z*, relative intensity) 362 ($M^+$, 14), 321 (15), 303 (3), 261 (4), 239 (77), 211 (7), 207 (31), 179 (100), 165 (45), 152 (28), 127 (10), 115 (5), 91 (13), 71 (20), 59 (13), 45 (25), 27 (3). Anal. Calcd for $C_{23}H_{22}O_2S$: C, 76.21; H, 6.12. Found: C, 75.92; H, 6.45.

**Methyl 2-(*p*-methoxylphenyl)-2-((2-methylphenyl)thio)-4-pentenoate (3, Ar = *p*-$MeOC_6H_4$, Ar′ = 2-$CH_3C_6H_4$):** HPLC (254 nm), 90:10 hexane/2-propanol, $t_R$ = 27.518 min, $t_R$ = 31.9 min; mp 76−78 °C; IR (KBr) 3084 (m), 1728 (s); $^1$H NMR (200 MHz,$CDCl_3$) $\delta$ 2.21 (s, 3H), 2.87−2.91 (m, 2H), 3.68 (s, 3H), 3.80 (s, 3H), 5.00−5.09 (m, 2H), 5.80−5.89 (m, 1H), 6.77−7.26 (m, 8H); $^{13}$C NMR (50 MHz, $CDCl_3$) $\delta$ 20.73, 41.43, 52.29, 55.12, 63.95, 113.26, 118.44, 125.69, 128.72, 129.01, 130.25, 130.56, 131.65, 133.37, 137.32, 158.72, 172.37; MS (*m*/*z*, relative intensity) 342 ($M^+$, 4), 301 (5), 283 (2), 219.2 (100), 191 (5), 187 (5), 159 (64), 151 (50), 129 (9.5), 115 (12), 91 (11.5), 71 (16), 59 (58.5), 45 (16.5), 27 (12). Anal. Calcd for $C_{20}H_{22}O_3S$: C, 70.15; H, 6.48. Found: C, 70.14; H, 6.51.

**Methyl 2-(*m*-methylphenyl)-2-((2-methylphenyl)thio)-4-pentenoate (3, Ar = *m*-$MeC_6H_4$, Ar′ = 2-$CH_3C_6H_4$):** HPLC (254 nm), 99:1 hexane/2-propanol, $t_R$ = 19.808 min, $t_R$ = 25.019 min; mp 82−83 °C; IR (KBr) 3058 (m), 1725 (s); $^1$H NMR (200 MHz, $CDCl_3$) $\delta$ 2.16 (s, 3H), 2.27 (s, 3H), 2.89−2.94 (m, 2H), 3.68 (s, 3H), 5.00−5.09 (m, 2H), 5.91−6.0 (m, 1H), 7.00−7.25 (m, 8H); $^{13}$C NMR (50 MHz, $CDCl_3$) $\delta$ 20.73, 21.44, 30.82, 41.23, 52.42, 64.63, 118.52, 124.40, 125.72, 127.85, 128.12, 129.14, 130.275, 130.43, 133.38, 137.53, 137.59, 139.57, 144.05, 172.45; MS (*m*/*z*, relative intensity) 326 ($M^+$, 15), 285 (3), 267 (4), 225 (5), 203 (71), 175 (5), 171 (30), 143 (100), 135 (66), 115 (15), 91 (23), 71 (51), 59 (16), 45 (25), 27 (4). Anal. Calcd for $C_{20}H_{22}O_2S$: C, 73.59; H, 6.79. Found: C, 73.45; H, 6.91.

**Methyl 2-(*p*-phenylphenyl)-2-((2-methylphenyl)thio)-4-pentenoate (3, Ar = *p*-$PhC_6H_4$, Ar′ = 2-$CH_3C_6H_4$):** HPLC (254 nm), 90:10 hexane/2-propanol, $t_R$ = 16.233 min, $t_R$ = 22.340 min; mp 73−75 °C; IR (KBr) 3065 (m), 1727 (s); $^1$H NMR (200 MHz, $CDCl_3$) $\delta$ 2.19 (s, 3H), 2.94−3.00 (m, 2H), 3.71 (s, 3H), 5.01−5.12 (m, 2H), 5.91−6.0 (m, 1H), 7.15−7.62 (m, 13H); $^{13}$C NMR (50 MHz, $CDCl_3$) $\delta$ 20.73, 41.21, 52.47, 64.32, 118.76, 125.77, 126.52, 126.90, 127.33, 127.87, 128.69, 129.21, 130.19, 130.32, 133.15, 137.56, 138.63, 140.09, 140.27, 143.99, 172.21; MS (*m*/*z*, relative intensity) 388 ($M^+$, 3), 329 (1.5), 287 (1), 266 (26), 265.2 (100), 233 (24), 225 (2), 205 (91), 197 (62), 179 (16), 165 (14), 152 (10), 123 (11), 115 (4.5), 84 (33), 71 (30), 59 (39), 49 (32), 35 (4). Anal. Calcd for $C_{25}H_{24}O_2S$: C, 77.29; H, 6.23. Found: C, 77.18; H, 6.14.

**Methyl 2-(*p*-bromophenyl)-2-((2-methylphenyl)thio)-4-pentenoate (3, Ar = *p*-$BrC_6H_4$, Ar′ = 2-$CH_3C_6H_4$):** HPLC (254 nm), 99:1 hexane/2-propanol, $t_R$ = 18.533 min, $t_R$ = 24.216 min; mp 70−72 °C; IR (KBr) 1731 (s); $^1$H NMR (200 MHz, $CDCl_3$) $\delta$ 2.20 (s, 3H), 2.86−2.93 (m, 2H), 3.66 (s, 3H), 5.04−5.09 (m, 2H), 5.85−5.96 (m, 1H), 7.12−7.41 (m, 8H); $^{13}$C NMR (50 MHz, $CDCl_3$) $\delta$ 20.80, 41.55, 52.48, 63.89, 119.02, 121.44, 125.91, 129.38, 129.41, 129.45, 130.07, 130.45, 130.99, 132.78, 137.42, 138.76, 143.84, 171.75; MS (*m*/*z*, relative intensity) 392 [$(M + 1)^+$, 11]], 351 (3), 333 (3), 289 (3), 269 (64), 267 (62), 241 (2), 235 (16), 210 (6), 199 (43), 183 (6), 169 (3), 155 (3), 144 (8), 128.2 (100), 115 (7), 91 (16), 77 (22), 71 (78), 59 (41), 39 (12), 27 (5). Anal. Calcd for $C_{19}H_{19}O_2SBr$: C, 58.32; H, 4.89. Found: C, 58.32; H, 5.07.

**Methyl 2-phenyl-2-((2-methylphenyl)thio)-1-pentenoate (3, Ar = $C_6H_5$, Ar′ = 2-$CH_3C_6H_4$):** HPLC (254 nm), 90:10 hexane/2-propanol, $t_R$ = 15.218 min, $t_R$ = 19.570 min; mp 66−67 °C; IR (KBr) 3059 (m), 1731 (s); $^1$H NMR (200 MHz, $CDCl_3$) $\delta$ 2.17 (s, 3H), 2.93−2.95 (m, 2H), 3.67 (s, 3H), 4.97−5.06 (m, 2H), 5.89−5.99 (m, 1H), 6.99−7.25 (m, 9H); $^{13}$C NMR (50 MHz, $CDCl_3$) $\delta$ 20.65, 41.16, 52.21, 64.47, 118.62, 125.68, 127.33, 127.88, 129.12, 130.23, 133.14, 137.48, 139.61, 143.93, 172.22; MS (*m*/*z*, relative intensity) 312 ($M^+$, 15), 271 (5), 253 (4), 211 (7), 189 (56), 178 (3), 157 (28), 149 (3), 129.1 (100), 121 (61), 115 (16.5), 103 (10), 91 (26), 71 (52), 59 (19), 51 (11), 45 (17), 27 (5). Anal. Calcd for $C_{19}H_{20}O_2S$: C, 73.04; H, 6.45. Found: C, 73.00; H, 6.62.

**Methyl 2-phenyl-2-((2,6-dimethylphenyl)thio)-1-pentenoate (3, Ar = $C_6H_5$, Ar′ = 2,6-$(CH_3)_2C_6H_3$):** HPLC (254 nm), 90:10 hexane/2-propanol, $t_R$ = 7.553 min, $t_R$ = 8.253 min; mp 66−68 °C; IR (KBr) 3059 (m), 1730 (s); $^1$H NMR (200 MHz, $CDCl_3$) $\delta$ 2.35 (s, 6H), 2.87−3.05 (m, 2H), 3.45 (s, 3H), 4.9−5.00 (m, 2H), 5.58−5.72 (m, 1H), 7.02−7.39 (m, 8H); $^{13}$C NMR (50 MHz, $CDCl_3$) $\delta$ 22.268, 30.358, 43.912, 51.501, 64.235, 118.345, 126.83, 127.232, 127.581, 127.763, 129.069, 130.344, 132.810, 139.329, 145.848, 171.363; MS (*m*/*z*, relative intensity) 326 ($M^+$, 10), 285 (11), 189.1 (100), 129 (96), 121 (97), 71 (79), 45 (32), 27 (8). Anal. Calcd for $C_{20}H_{22}O_2S$: C, 73.59; H, 6.79. Found: C, 73.55; H, 6.77.

**Methyl 2-phenyl-2-((2-chlorophenyl)thio)-1-pentenoate (3, Ar = $C_6H_5$, Ar′ = 2-$ClC_6H_4$):** HPLC (254 nm), 90:10 hexane/2-propanol, $t_R$ = 20.086 min, $t_R$ = 22.626 min; mp 49−51 °C; IR (KBr) 3072 (m), 1730 (s); $^1$H NMR (200 MHz, $CDCl_3$) $\delta$ 2.92−2.96 (m, 2H), 3.72 (s, 3H), 4.95−5.08 (m, 2H), 5.92−6.01 (m, 1H), 7.05−7.36 (m, 9H); $^{13}$CNMR (50 MHz, $CDCl_3$) $\delta$ 41.48, 52.48, 64.90, 118.69, 126.32, 127.45, 127.52, 127.89, 129.67, 129.97, 130.30, 132.97, 137.86, 138.84, 139.80, 171.67; MS (*m*/*z*, relative intensity) 332 ($M^+$, 8), 291 (9), 273 (5), 231 (4), 189 (70), 157 (25), 143 (10), 129.1 (100), 121 (52), 103 (10), 71 (50), 59 (18), 41 (8), 27 (3). Anal. Calcd for $C_{18}H_{17}O_2SCl$: C, 64.96; H, 5.15. Found: C, 64.98; H, 5.19.

**Methyl 2-phenyl-2-(phenylthio)-1-pentenoate (3, Ar = $C_6H_5$, Ar′ = $C_6H_5$):** HPLC (254 nm), 85:15 hexane/2-propanol, $t_R$ = 19.453 min, $t_R$ = 24.723 min; mp 72−73 °C; IR (KBr) 3063 (m), 1728 (s); $^1$H NMR (200 MHz, $CDCl_3$) $\delta$ 2.84−2.89 (m, 2H), 3.69 (s, 3H), 5.02−5.14 (m, 2H), 5.91−6.01 (m, 1H), 7.16−7.31

(m, 10H); $^{13}$C NMR (50 MHz, $CDCl_3$) $\delta$ 40.34, 52.27, 64.22, 118.54, 127.17, 127.77, 127.81, 128.19, 129.00, 130.43, 132.92, 136.567, 139.47, 171.95; MS (*m*/*z*, relative intensity) 298 ($M^+$, 26), 257 (18), 239 (8), 189 (92), 157 (35), 149 (3), 129.1 (100), 121 (80), 105 (91), 77 (31), 71 (74), 59 (28), 39 (18), 27 (5). Anal. Calcd for $C_{18}H_{18}O_2S$: C, 72.45; H, 6.08. Found: C, 72.59; H, 5.85.

**Methyl 2-(*m*-methoxylphenyl)-2-((2-methylphenyl)-thio)-4-pentenoate (3, Ar = *m*-MeOC$_6$H$_4$, Ar′ = 2-CH$_3$C$_6$H$_4$):** HPLC (254 nm), 99:1 hexane/2-propanol, $t_R$ = 36.033 min, $t_R$ = 45.797 min; mp 63−66 °C; IR (KBr) 3072 (w), 1724 (s); $^1$H NMR (200 MHz, $CDCl_3$) $\delta$ 2.15 (s, 3H), 2.86−2.93 (m, 2H), 3.67 (s, 3H), 3.74(s, 3H), 4.95−5.09 (m, 2H), 5.79−5.96 (m, 1H), 6.73−7.24 (m, 8H); $^{13}$C NMR (50 MHz, $CDCl_3$) $\delta$ 20.74, 30.82, 41.23, 52.45, 55.14, 64.46, 112.84, 113.47, 118.63, 119.81, 125.77, 125.80, 128.92, 129.18, 130.30, 133.21, 137.50, 141.17, 144.01, 159.13, 172.21; MS (*m*/*z*, relative intensity) 343 ($M^+$ + 1, 8), 342 ($M^+$, 23), 219 (48), 187 (38), 159.1 (100), 151 (47), 129 (22), 128 (19), 91 (23), 77 (7), 71 (43), 43 (28). Anal. Calcd for $C_{20}H_{22}O_3S$: C, 70.15; H, 6.48. Found: C, 70.07; H, 6.51.

**Methyl 2-(*m*-chlorophenyl)-2-((2-methylphenyl)thio)-4-pentenoate (3, Ar = *m*-ClC$_6$H$_4$, Ar′ = 2-CH$_3$C$_6$H$_4$):** HPLC (254 nm), 90:10 hexane/2-propanol, $t_R$ = 9.492 min, $t_R$ = 11.733 min; mp 78−80 °C; IR (KBr) 1736 (s); $^1$H NMR (200 MHz, $CDCl_3$) $\delta$ 2.18 (s, 3H), 2.80−3.00 (m, 2H), 3.64 (s, 3H), 4.97−5.09 (m, 2H), 5.74−5.91(m, 1H), 6.97−7.23 (m, 8H); $^{13}$C NMR (50 MHz, $CDCl_3$) $\delta$ 20.65, 41.32, 52.45, 63.92, 119.02, 125.73, 125.81, 127.40, 127.75, 129.03, 129.40, 129.74, 130.35, 132.61, 133.75, 137.46, 141.60, 143.83, 171.51; MS (*m*/*z*, relative intensity) 346 ($M^+$, 32), 305 (17), 287 (9), 245 (11), 223 (46), 191 (34), 163 (70), 155 (61), 129 (51), 124 (96), 101 (8), 91 (24), 77 (20), 71 (100), 45 (39), 41 (12). Anal. Calcd for $C_{19}H_{19}O_2SCl$: C, 65.79; H, 5.52. Found: C, 65.58; H, 5.47.

***N*-[(2*R*)-2-(Phenylthio)-2-allyl-2-phenylacetyl]-(1*S*)-camphorsultam (11).** Under a nitrogen atmosphere, Cu(MeCN)$_4$PF$_6$ (37 mg, 0.1 mmol) and phenyl allyl sulfide (300 mg, 2 mmol) were dissolved in anhydrous $CH_2Cl_2$ (10 mL). The solution was cooled to 0 °C, and the diazo compound **10** (359 mg, 1 mmol) in anhydrous $CH_2Cl_2$ (10 mL) was added slowly. The mixture was stirred at 0 °C for an additional 12 h. Solvent was removed, and the catalyst and the excessive sulfide were removed by flash chromatography (1:6 petroleum ether/EtOAc) to give the product (438 mg, 91%). The diastereomeric ratio was analyzed with the $^1$H NMR spectrum of the crude product ($\delta$ 3.81 for major isomer, $\delta$ 4.30 for minor isomer). The crude product was recrystallized several times to give the major isomer **11** as a pure diastereoisomer, which was subjected to X-ray diffraction for determining the configuration of the newly generated chiral center: mp 199−201 °C; IR (KBr) 2966 (m), 1664 (s); $^1$H NMR (400 MHz, $CDCl_3$) $\delta$ 0.85 (s, 3H), 0.87 (s, 3H), 1.25−1.34 (m, 2H), 1.76−1.81 (m, 3H), 1.93−1.97 (m, 1H), 2.13−2.17 (m, 1H), 2.59−2.66 (m, 1H), 3.23 (s, 2H), 3.26−3.31 (m, 1H), 3.81 (brs, 1H), 5.03−5.14 (m, 2H), 5.95−5.97 (m, 1H), 7.08−7.09 (m, 2H), 7.15−7.19 (m, 2H), 7.26−7.31 (m, 6H); $^{13}$C NMR (50 MHz, $CDCl_3$) $\delta$ 19.93, 20.49, 26.43, 33.02, 38.52, 39.12, 44.28, 47.65, 48.05, 52.89, 66.92, 67.48, 118.55, 127.52, 127.91, 128.38, 128.98, 129.34, 130.05, 132.83, 136.55, 137.43, 171.57; MS (*m*/*z*, relative intensity) 481 ($M^+$, 2), 440 (5), 372 (78), 308 (5), 238 (28), 199 (13), 174 (18), 157 (43), 135 (92), 129 (100), 93 (31), 79 (22), 55 (17), 41 (32). Anal. Calcd for $C_{27}H_{31}O_3S_2N$: C, 67.33; H, 6.49; N, 2.91. Found: C, 67.00; H, 6.45; N, 2.91.

**Conversion of 11 to (2*R*)-Methyl 2-Phenyl-2-(phenylthio)-1-pentenoate (13).** Compound **11** (240 mg, 0.5 mmol) was dissolved in THF/$H_2O$ (7.5 mL, 7:3), and to the solution was added LiOH (96 mg, 4 mmol). The mixture was stirred for 6 days at room temperature. The TLC analysis indicated that there was still considerable starting material left. To terminate the reaction, $H_2O$ (20 mL) was added and the pH of the solution was adjusted to 2 with aqueous HCl (1 M). The mixture was extracted with $CH_2Cl_2$ (3 × 15 mL). The combined organic layer was washed with $H_2O$ and dried over anhydrous $MgSO_4$. The drying agent was removed by filtration, and the solution was treated with an etheral solution of $CH_2N_2$ at 0 °C for 30 min. Excess $CH_2N_2$ and the organic solvent were removed, and the residue was subjected to column chromatography to afford **13**, whose $^1$H NMR spectrum was identical with the enantiomeric mixture of methyl 2-phenyl-2-(phenylthio)-1-pentenoate **3** (Ar = $C_6H_5$, Ar′ = $C_6H_5$). The samples of **3** and **13** were analyzed with chiral HPLC for determining the absolute configuration of the major enantiomer in **3**.

**Methyl 2-phenyl-2-(vinylthio)-4-pentenoate (15):** HPLC (254 nm), $t_R$ = 13.181 min, $t_R$ = 17.579 min; oil; IR ($CCl_4$) 1733 (s); $^1$H NMR (200 MHz, $CDCl_3$) $\delta$ 2.90 (dd, $J$ = 6.4, 0.9 Hz, 2H), 3.0 (ddt, $J$ = 12.6, 7.2, 1.0 Hz, 1H), 3.13 (ddt, $J$ = 12.6, 7.0, 1.0 Hz, 1H), 3.78 (s, 3H), 4.94−5.05 (m, 3H), 5.12 (dq, $J$ = 17.0, 1.4 Hz, 1H), 5.64−5.84 (m, 2H), 7.21−7.44 (m, 5H); $^{13}$C NMR (50 MHz, $CDCl_3$) $\delta$ 33.52, 43.19, 52.48, 60.79, 117.77, 118.71, 127.42, 127.70, 128.19, 132.80, 133.20, 138.97, 172.69; MS (*m*/*z*, relative intensity) 262 ($M^+$, 5), 222 (12), 221 (67), 203 (81), 190 (51), 173 (21), 161 (75), 150 (11), 131 (13), 129 (100), 115 (25), 103 (17), 91 (24), 71 (41), 59 (27), 41 (59), 39 (25). Anal. Calcd for $C_{15}H_{18}O_2S$: C, 68.67; H, 6.92. Found: C, 68.40; H, 6.98.

**Methyl 2-phenyl-2-(phenylthio)-3-phenyl-4-pentenoate (17, Ar = C$_6$H$_5$; mixture of *anti*- and *syn*-isomers):** oil; IR ($CCl_4$) 2949 (m), 1731 (s); $^1$H NMR (400 MHz, $CDCl_3$) major isomer $\delta$ 3.41 (s, 3 H), 4.61 (d, $J$ = 9.2 Hz, 1H), 5.22 (m, 2H), 6.01 (dt, $J$ = 16.7, 9.5 Hz, 1H), 6.72 (m, 2H), 7.10−7.30 (m, 11H), 7.48 (m, 2H), minor isomer $\delta$ 3.45 (s, 3H), 4.59 (d, $J$ = 9.4 Hz, 1H), 5.14 (dd, $J$ = 10.1, 1.7 Hz, 2H), 6.16 (m, 1H), 6.75 (m, 2H), 7.10−7.30 (m, 13H); MS (*m*/*z*, relative intensity) 374 ($M^+$, 13), 315 (16), 256.9 (100), 205 (66), 197 (62), 128 (19), 91 (66), 77 (37), 39 (15). Anal. Calcd for $C_{24}H_{22}O_2S$: C, 76.97; H, 5.92. Found: C, 76.75; H, 6.06.

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**Supporting Information Available:** Chiral HPLC data and X-ray structure data for **11** (CIF format). This material is available free of charge via the Internet at http://pubs.acs.org.

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