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Asymmetric Decarboxylative Claisen Rearrangement Reactions of Sulfoximine-Substituted Allylic Tosylacetic Esters

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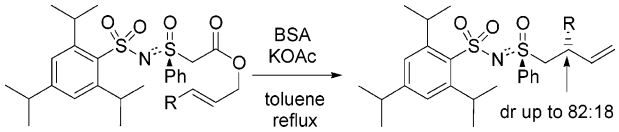
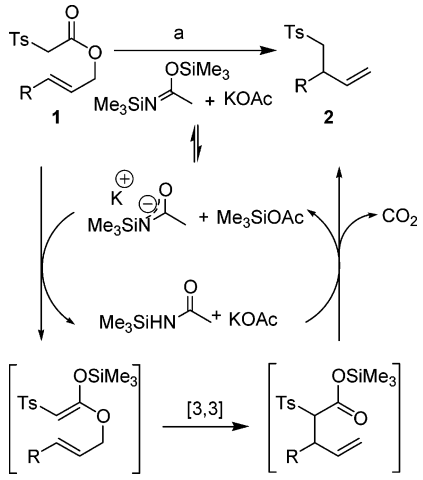


Allylic acetate esters containing a variety of *N*-arylsulfonyl sulfoximines on the acetyl residue have been prepared and submitted to the decarboxylative Claisen rearrangement reaction. Rearranged products were isolated in generally good yields, and diastereoselectivities up to 82:18 have been obtained. The *N*-(2,4,6-triisopropylphenylsulfonyl)-*S*-phenyl sulfoximine moiety gave the best selectivity. The stereochemistry of the major isomer was established by X-ray crystallography. A model to explain the stereochemical course of the rearrangement is proposed.

Introduction

Since its discovery nearly a century ago the Claisen rearrangement[1] has become a mainstay of organic synthesis. The power and versatility of this strategy-level transformation has prompted considerable efforts to develop variants of this [3,3]-sigmatropic rearrangement, and several of these are now widely used to generate regio- and stereochemically defined carbon−carbon and carbon−heteroatom bonds.[2] We recently introduced a novel variant of the classical process, the decarboxylative Claisen rearrangement (dCr) reaction.[3] In this modified transformation α-tosyl silylketene acetals formed in situ from allylic tosylacetates **1** in the presence of stoichiometric or substoichiometric *N*,*O*-bis(trimethylsilyl)acetamide (BSA) and substoichiometric potassium acetate undergo [3,3]-sigmatropic rearrangement followed by acetate-induced desilylation−decarboxylation in situ to provide homoallylic sulfones **2** (Scheme 1). The loss of CO_2 in these reactions gives the products of formal transfer with allylic transposition of a carbon atom substituted with a heteroatom, such that the dCr reaction may be regarded as analogous to the 2,3-Wittig rearrangement.

SCHEME 1. Synthesis of Homoallylic Sulfones by the Decarboxylative Claisen Rearrangement Reaction and Proposed Mechanism[3,a]



[a] Reagents and conditions: (a) BSA (0.1 or 1 equiv), KOAc (0.1 equiv), toluene, 110 °C, 15 h or microwave irradiation, 150 °C, 3 min.

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(1) Claisen, L. *Chem. Ber.* **1912**, *45*, 3157−3166.
(2) For reviews on Claisen and related rearrangements, see: (a) Pereira, S.; Srebnik, M. *Aldrichim. Acta* **1993**, *26*, 17−29. (b) Enders, D.; Knopp, M.; Schiffers, R. *Tetrahedron*: *Asymmetry* **1996**, *7*, 1847−1882. (c) Ito, H.; Taguchi, T. *Chem. Soc. Rev*. **1999**, *28*, 43−50. (d) Chai, Y.; Hong, S. P.; Lindsay, H. A.; McFarland, C.; McIntosh, M. C. *Tetrahedron* **2002**, *58*, 2905−2928. (e) Nubbemeyer, U. *Synthesis* **2003**, *7*, 961−1008. (f) Martin Castro, A. M. *Chem. Rev.* **2004**, *104*, 2939−3002. (g) For transition metal-catalyzed, nonregiospecific allylation of α-arylsulfinyl esters through O → C allyl transfer, see: Hiroi, K.; Suzuki, Y.; Kato, F.; Kyo, Y. *Tetrahedron*: *Asymmetry* **2001**, *12*, 37−40. (h) For highly diastereoselective thio-Claisen rearrangement reactions of ketene aminothioacetals, and leading references, see: Nowaczyk, S.; Alayrac, C.; Reboul, V.; Metzner, P.; Averbuch-Pouchot, M.-T. *J. Org. Chem.* **2001**, *66*, 7841−7848.
(3) Bourgeois, D.; Craig, D.; King, N. P.; Mountford, D. M. *Angew. Chem.*, *Int. Ed.* **2005**, *44*, 618−621.

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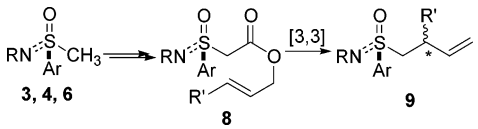
SCHEME 2. Decarboxylative Claisen Rearrangement Reaction of Sulfoximine-Containing Substrates



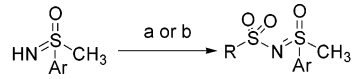
As part of our program devoted to the study of this new [3,3]-sigmatropic rearrangement−fragmentation reaction mode, we were keen to devise an asymmetric version. Most of the published research on asymmetric variants of Claisen and Ireland−Claisen rearrangements has until now focused on reactions characterized by high diastereoselectivity arising from the presence of chiral substituents positioned outside but adjacent to the pericyclic array,[2e−h] usually in the α-position with respect to the vinylic moiety. In light of the effectiveness of the tolylsulfonyl substituent in facilitating decarboxylation post-rearrangement, we selected the *N*-arylsulfonylsulfoximine group as a chiral sulfone surrogate in the dCr reaction (Scheme 2). Chiral, nonracemic sulfoximines may readily be accessed[4] by resolution of racemates[5] or by oxidative imination of enantiomerically pure sulfoxides.[6] They are optically stable under normal reaction conditions, and combine similar or greater steric bulk and enhanced electron-withdrawing capabilities with respect to the analogous sulfones. In addition, we were attracted by the prospect of being able to fine-tune diastereoselectivity by varying the nitrogen substituent.

In this paper we describe in detail the synthesis of small libraries of various esters **8**, sulfoximine analogues of **1**, and the evaluation of their stereochemical behavior in the dCr reaction.

Results and Discussion

A. Synthesis and [3,3]-Sigmatropic Rearrangement of Racemic Sulfoximine-Containing Substrates. With the aim of screening rapidly various *N*- and *S*-substituted sulfoximines which could serve as chiral auxiliaries in our study, initial efforts were focused on the use of racemic α-sulfoximine-substituted acetate allylic esters. On the basis of the proposed mechanism of the dCr reaction of the analogous sulfone-containing substrates,[3] it was postulated that the desired rearrangement−decarboxylation sequence would be feasible only in sulfoximines in which the nitrogen atom was substituted with an electron-withdrawing sulfonyl group. In particular, we were keen to study the influence of the electronic and steric characteristics of the sulfonyl *N*-substituent on the stereochemical course of the reaction. We wished also to probe the effect of differing sulfur aryl substituents, not least because this structural motif has rarely been modified in sulfoximine chemistry.[4,6i]

SCHEME 3. Sulfonylation of Sulfoximines 3a and 4a[a]

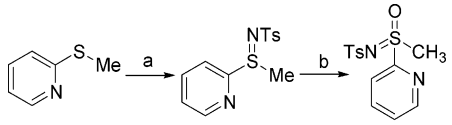


3a Ar = Ph
4a Ar = Mes

3b Ar = Ph R = tolyl
3c Ar = Ph R = 2,4,6-triisopropylphenyl
3d Ar = Ph R = 1-naphthyl
3e Ar = Ph R = CF_3
3f Ar = Ph R = 2-$CF_3OC_6H_4$
3g Ar = Ph R = 2,5-$(CF_3CH_2O)_2C_6H_3$
4b Ar = Mes R = tolyl

[a] Reagents and conditions: (a) (for **3b**−**d**, **3f**, **3g**, **4b**) RSO_2Cl (1 equiv), pyridine, 71−85%; (b) (for **3e**) $(CF_3SO_2)_2O$ (1.2 equiv), pyridine (2 equiv), CH_2Cl_2, 51%.[11]

SCHEME 4. Preparation of Sulfoximine 6[a]



[a] Reagents and conditions: (a) chloramine-T hydrate (1.4 equiv), *n*-Bu_4NBr (0.05 equiv), CH_2Cl_2, 23%; (b) $RuO_2{\cdot}xH_2O$ (0.02 equiv), $NaIO_4$ (2 equiv), CCl_4−MeCN−H_2O, rt, 89%.

N-Sulfonyl derivatives **3b**−**g** and **4b** were simply prepared by reaction of the known *N*-unsubstituted parent sulfoximines **3a**[7] and **4a**[8] with the corresponding sulfonylating reagent (Scheme 3).[9] The previously unreported *N*-(4-tolylsulfonyl)sulfoximine **6**[10] was prepared by oxidative imination of 2-methylsulfanyl pyridine to give the corresponding sulfilimine **5**, which was then oxidized (Scheme 4).

(i) Preparation of Racemic Sulfoximine-Substituted Acetate Esters. Carboxylation of sulfoximines[12] **3b**−**g**, **4b**, and **6** was carried out by metalation with *n*-BuLi[13] at −78 °C in anhydrous THF followed by addition of gaseous CO_2;[14] acidic workup gave the corresponding substituted acetic acids **7a**−**h** (Scheme 5, Table

(4) For a review on sulfoximines, see: Reggelin, M.; Zur, C. *Synthesis* **2000**, 1−64.

(5) For an efficient, improved resolution of *S*-methyl-*S*-phenyl sulfoximine with (+)-10-camphorsulfonic acid, see: Brandt, J.; Gais, H.-J. *Tetrahedron*: *Asymmetry* **1997**, *8*, 909−912.

(6) (a) Rayner, D. R.; Von Schriltz, D. M.; Day, J.; Cram, D. J. *J. Am. Chem. Soc.* **1968**, *90*, 2721−2723. (b) Johnson, C. R.; Schroeck, C. W. *J. Am. Chem. Soc.* **1973**, *95*, 7418−7423. (c) Jones, M. R.; Cram, D. J. *J. Am. Chem. Soc.* **1974**, *96*, 2183-2190. (d) Johnson, C. R.; Kirchhoff, R. A.; Corkins, H. G. *J. Org. Chem.* **1974**, *39*, 2458−2459. (e) Müller, J. F. K.; Vogt, P. *Tetrahedron Lett.* **1998**, *39*, 4805−4806. (f) Bach, T.; Körber, C. *Eur. J. Org. Chem.* **1999**, 1033−1039. (g) Lacôte, E. K.; Amtore, M.; Fensterbank, L.; Malacria, M. *Synlett* **2002**, 116−118. (h) Okamura, H.; Bolm, C. *Org. Lett.* **2004**, *6*, 1305−1307. (i) Cho, G. Y.; Okamura, H.; Bolm, C. *J. Org. Chem.* **2005**, *70*, 2346−2349.

(7) Sulfoximine **3a** was prepared by oxidation of the *S*-methyl-*S*-phenyl-*N*-(4-tolylsulfonyl)sulfilimine followed by desulfonylation of the imine nitrogen; see: (a) Johnson, C. R.; Katekar, G. F. *J. Am. Chem. Soc.* **1970**, *92*, 5753−5754. (b) For preparation of the sulfilimine by oxidative imination of thioanisole with chloramine-T hydrate, see: Johnson, C. R.; Mori, K.; Nakanishi, A. *J. Org. Chem.* **1979**, *44*, 2065−2067. (c) For oxidation of sulfilimines to the corresponding sulfoximines with $RuO_2/NaIO_4$ as oxidant, see: Veale, H. S.; Levin, J.; Swern, D. *Tetrahedron Lett.* **1978**, 503−506. (d) For the detosylation of *S*-methyl-*S*-phenyl-*N*-(4-tolylsulfonyl)sulfoximine with H_2SO_4, see: Cram, D. J.; Day, J.; Rayner, D. R.; Von Schriltz, D. M.; Duchamp, D. J.; Garwood, D. C. *J. Am. Chem. Soc.* **1970**, *92*, 7369−7384.

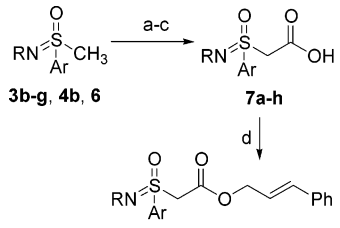
(8) Sulfoximine **4b** was prepared by oxidative imination of the corresponding sulfoxide with hydrazoic acid; see: Johnson, C. R.; Schroeck, C. W. *J. Am. Chem. Soc.* **1973**, *95*, 7418−7423.

(9) For arylsulfonylation of sulfoximines, see: Craig, D.; Geach, N. J.; Pearson, C. J.; Slawin, A. M. Z., White, A. J. P.; Williams, D. J. *Tetrahedron* **1995**, *51*, 6071−6098.

(10) Sulfoximine **5b** was prepared by oxidation of the corresponding sulfilimine. (a) For the preparation of pyridylsulfilimines, see: Furukawa, N.; Takahashi, F.; Kawai, T.; Kishimoto, K.; Ogawa, S.; Oae, S. *Phosphorus Sulfur Relat. Elem.* **1983**, *16*, 167−180. (b) For a general method for the conversion of sulfilimines into sulfoximines with $RuO_2/NaIO_4$ as oxidant, see ref 7c.

(11) For details see the Supporting Information.

SCHEME 5. Carboxylation and Esterification of Sulfoximines 3b−g, 4b, and 6[a]



8a Ar = Ph R = tolyl
8b Ar = Ph R = 2,4,6-triisopropylphenyl
8c Ar = Ph R = 1-naphthyl
8d Ar = Ph R = CF_3
8e Ar = Ph R = 2-$CF_3OC_6H_4$
8f Ar = Ph R = 2,5-$(CF_3CH_2O)_2C_6H_3$
8g Ar = Mes R = tolyl
8h Ar = pyridyl R = tolyl

[a] Reagents and conditions: (a) *n*-BuLi (1.1 equiv), THF, −78 °C; (b) gaseous CO_2; (c) acidic workup; (d) cinnamyl alcohol (1 equiv), EDCI (1 equiv), CH_2Cl_2, 0 °C.

TABLE 1. Synthesis of Esters 8a−h

entry	sulfoximine	acid	yield[a] (%)	ester	yield[b] (%)
1	**3b**	**7a**	79	**8a**	79
2	**3c**	**7b**	80	**8b**	84
3	**3d**	**7c**	52	**8c**	58
4	**3e**	**7d**	24[c]	**8d**	50
5	**3f**	**7e**	42	**8e**	57
6	**3g**	**7f**	10[c]	**8f**	50
7	**4b**	**7g**	42	**8g**	49
8	**6**	**7h**	61	**8h**	42

[a] Yield after simple extractive workup. [b] Isolated yield. [c] Unoptimized yield.

1).[15] Esterification of **7a**−**h** with cinnamyl alcohol in the presence of coupling reagent EDCI[16] provided the esters **8a**−**h**[17] (Scheme 5, Table 1).

(ii) Decarboxylative Claisen Rearrangement Reactions. The dCr reaction of substrate **8a** (Ar Ph, R Tol) was evaluated first. While the use of 0.25 equiv of BSA in the presence of 0.1 equiv of KOAc in toluene under reflux was identified as optimal (Table 2, entry 1),[3] the dCr reactions took place also under reflux in THF, reflecting the more electron-withdrawing nature of the sulfoximine functions with respect to the analogous sulfones.[18] However, these milder conditions required the use of larger quantities of BSA because of significant catalyst death during the increased reaction times necessary for complete conversion.[19] Direct formation of the decarboxylated rearranged product **9a** was observed in all cases, with no traces of the intermediate rearranged acid being detectable. As discussed previously,[3,19] [3,3]-sigmatropic rearrangement appears to be the rate-determining step, followed by relatively fast decarboxylation. In all cases the (R_S*,*R**) diastereoisomer predominated (for assignment of stereochemistry, see below); no variation of the diastereoisomeric ratio versus time or temperature was observed.

Next, the optimized conditions (0.25 equiv of BSA, 0.1 equiv of KOAc, toluene, reflux) were applied to sulfoximine-containing esters **8b**−**h**; the results of these experiments are collected in Table 2.

Several trends emerge from the data collected in Table 2. For substrates containing an *S*-phenyl sulfoximine group (Ar Ph, entries 1 to 6), selectivity in favor of the (S_S*,*S**) diastereoisomer increases from 70:30 to 78:22 to 82:18 as the sulfoximine nitrogen substituent becomes increasingly bulky (entries 1, 3, and 2). The presence of an electron-withdrawing residue within the *N*-sulfonyl group apparently exerts little or no effect on the diastereoselectivity (entries 4−6), though substrates **8d**−**f** appeared to be slightly less reactive and **8d** underwent significant decomposition under the reaction conditions. Replacement of the *S*-phenyl group with the more electron-withdrawing 2-pyridyl moiety (substrate **8h**) resulted in a decrease in rate with no significant change in diastereoselectivity (entry 8). In contrast, substrate **8g** possessing a sterically highly demanding *S*-mesityl group did not undergo dCr reaction after 10 h of exposure to the standard reaction conditions (entry 7).

B. Synthesis and [3,3]-Sigmatropic Rearrangement of Enantiomerically Pure *N*-(2,4,6-Triisopropylphenylsulfonyl)-*S*-phenylsulfoximine Derivatives. Following the identification of the *N*-(2,4,6-triisopropylphenylsulfonyl)-*S*-phenylsulfoximine group as the optimal chiral auxiliary in the dCr reaction, attention was turned toward the synthesis and rearrangement reactions of enantiomerically pure substrates possessing a variety of allylic residues.

(i) Preparation of (+)-(S_S)-*S*-Phenyl-*N*-(2,4,6-triisopropylphenylsulfonyl)sulfoximinoyl Acetate Allylic Esters. Esters (S_S)-**8b**,**i**−**n** were readily prepared as described for the racemic derivatives in two steps from (+)-(S_S)-*S*-methyl-*S*-phenyl-*N*-(2,4,6-triisopropylphenylsulfonyl)sulfoximine (S_S)-**3c**,[20] which was obtained by resolution of *S*-methyl-*S*-phenylsulfoximine with (+)-10-camphorsulfonic acid[5] followed by *N*-sulfonylation. The syntheses of sulfoximines (S_S)-**8b**,**i**−**n** are summarized in Scheme 6 and Table 3.

(ii) Decarboxylative Claisen Rearrangement Reactions. The [3,3]-sigmatropic rearrangement of sulfoximines (S_S)-**8b**,**i**−**n** was carried out with use of the standard conditions (0.25 equiv of BSA, 0.1 equiv of

(12) For the *C*-carboxylation of sulfoximines containing *N*-alkoxycarbonyl substituents, see: (a) Schaffner-Sabba, K.; Tomaselli, H.; Henrici, B.; Renfroe, H. B. *J. Org. Chem.* **1977**, *42*, 952−958. (b) Bolm, C.; Kahmann, J. D.; Moll, G. *Tetrahedron Lett.* **1997**, *38*, 1169−1172. (c) Bolm, C.; Moll, B.; Kahmann, J. D. *Chem. Eur. J.* **2001**, *7*, 1118−1128. (d) See ref 6i.

(13) For the metalation of *N*-sulfonylsulfoximines with *n*-BuLi and their reaction with other electrophiles, see for example: (a) Reference 9. (b) Pyne, S. G.; Dong, Z. *J. Org. Chem.* **1996**, *61*, 5517−5522.

(14) As previously noticed by Bolm and co-workers, moisture should be avoided; see refs 11b,c.

(15) Due to their instability, acids **7a**−**h** were isolated by simple extractive workup and were used rapidly without further purification.

(16) Use of EDCI in combination of DMAP or HOBt gave the esters in lower yields. For example, esterification of **7a** under these conditions gave **8a** in 62−64% yield.

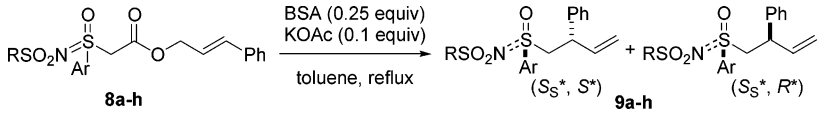
(17) Esters **8a**−**h** were stored in a freezer due to their instability toward decarboxylation, regenerating the starting sulfoximines **3b**−**g**, **4b**, or **6**.

(18) (a) Matthews, W. S.; Bares, J. E.; Bartmess, J. E.; Bordwell, F. G.; Cornforth, F. J.; Drucker, G. E.; Margolin, Z.; McCallum, R. J.; McCollum, G. J.; Vanier, N. R. *J. Am. Chem. Soc.* **1975**, *97*, 7006−7014. (b) Bordwell, F. G.; Branca, J. C.; Johnson, C. R.; Vanier, N. R. *J. Org. Chem.* **1980**, *45*, 3884−3889.

(19) For ambient-temperature decarboxylative Claisen rearrangement reactions of sulfone derivatives containing an additional electron-withdrawing group on the α-position, see: Craig, D.; Grellepois, F. *Org. Lett.* **2005**, *7*, 463−465.

(20) Trost, B. M.; Matsuoka, R. T. *Synlett* **1992**, 27−30.

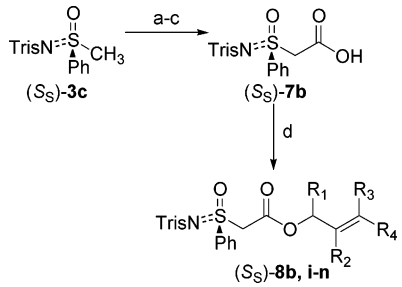
TABLE 2. Decarboxylative Claisen Rearrangement Reaction of Racemic Sulfoximine-Substituted Esters 8a–h



entry	sulfoximine ester 8			rearranged product 9	time	yield[a] (%)	dr[b,c] (S_S*,S*):(S_S*,R*)[d]
		Ar	R				
1	8a	Ph	tolyl	9a	2 h	85	70:30
2	8b	Ph	2,4,6-triisopropylphenyl	9b	1 h 30 min	91	82:18
3	8c	Ph	1-naphthyl	9c	8 h	83	75:25
4	8d	Ph	CF_3	9d	7 h	~30[e]	66:34
5	8e	Ph	2-$CF_3OC_6H_4$	9e	8 h	64	75:25
6	8f	Ph	2,5-$(CF_3CH_2O)_2C_6H_3$	9f	15 h	83	78:22
7	8g	Mes	tolyl	9g	10 h	0	
8	8h	2-pyridyl	tolyl	9h	18 h	~50[e]	68:32

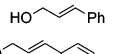
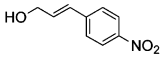
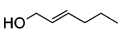
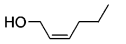
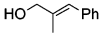
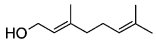
[a] Isolated yield. [b] dr diastereoisomeric ratio. [c] dr determined by ^1H or ^{19}F NMR. [d] For determination of stereochemistry, see below. [e] Product contained traces of starting material or impurities; see the Supporting Information.

SCHEME 6. Preparation of Esters (S_S)-8b,i–n[a]



[a] Reagents and conditions: (a) *n*-BuLi (1.1 equiv), THF, −78 °C; (b) gaseous CO_2; (c) acidic workup, 80% overall yield; (d) allylic alcohol (1 equiv), EDCI (1 equiv), CH_2Cl_2, 0 °C.

TABLE 3. Synthesis of Esters (S_S)-8b,i–n from Acid (S_S)-7b

entry	allylic alcohol	product	yield
1		(S_s)-**8b**	72%
2		(S_s)-**8i**	70%
3		(S_s)-**8j**	72%
4		(S_s)-**8k**	72%
5		(S_s)-**8l**	46%
6		(S_s)-**8m**	63%
7		(S_s)-**8n**[a]	64%

[a] Racemic alcohol used; product obtained as a 1:1 mixture of diastereoisomers.

KOAc, toluene, reflux) (Table 4). Rearranged products (S_S)-**9b**,**i**,**j**,**l**–**n** were isolated in good to excellent yields.

The rearrangement of compounds (S_S)-**8b**,**i** and (S_S)-**8*l*** derived from allylic esters containing a terminal aryl substituent gave the corresponding rearranged compounds (S_S)-**9b**,**i**,**l** with good diastereoselectivities (respectively 82:18, 78:22, and 75:25) (entries 1, 2, and 5). However, the alkyl-substituted *Z*-substrate (S_S)-**8k** showed the highest diastereoisomeric excess (13:87, entry 4); here, the major isomer was identical with the minor isomer obtained in the dCr reaction of the corresponding *E*-isomer (S_S)-**8j** (entry 4). Notably, the rearrangement of (S_S)-**8m** derived from geraniol led to the formation of a quaternary center with a 70:30 diastereoisomeric ratio (entry 6). Substrate (S_S)-**8n** was prepared as a mixture of enantiomerically pure diastereomers from racemic 3-penten-2-ol, and its nonselective rearrangement likely indicates the dominance of the stereochemically undefined allylic stereocenter over the sulfoximine group in determining product configuration (entry 7).

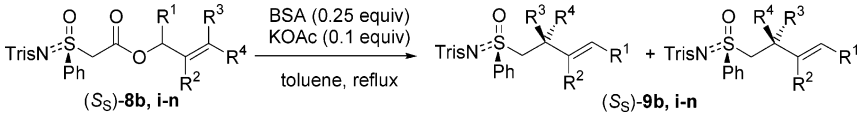
C. Assignment of Stereochemistry. The major isomer of (S_S)-**9i** obtained from the dCr reaction rearrangement of (S_S)-**8i** was unambiguously established by X-ray crystallography to have the (S_S,2*S*) configuration (Figure 1).[21] Taken together with similar trends in the ^1H chemical shifts observed for the major and minor components of the racemic rearranged products **9a**,**c**–**f**,**h** and of the enantiomerically pure products (S_S)-**9b** and (S_S)-**9i**,**l** this allowed the assignment of the same stereochemistry. Specifically, in all cases where comparison could be made, the benzylic methine signal corresponding to the newly formed stereocenter in the major products appeared between 0.12 and 0.29 ppm downfield from the corresponding signal for the minor product. However, for products (S_S)-**9j** and (S_S)-**9m**, derived from *alkyl*-substituted allylic esters (S_S)-**8j**,**k** and (S_S)-**8m**, the chemical shifts of the corresponding, nonbenzylic methine signals did not allow unequivocal assignment of configuration by simple comparison of NMR data. In the event, the structure of the major isomer (S_S)-**9m** was established by X-ray crystallography[21] to have the (S_S,3*R*)[22] configuration (Figure 2), allowing the assignment of the stereochemistry of the major isomers of (S_S)-**9j** by extrapolation.

D. Model Proposed for the Rearrangement. We rationalize the stereochemical outcome of the dCr reactions of sulfoximine-containing substrates **8** in terms of

(21) The supplementary crystallographic data for the structures of (S_S,2*S*)-**9i** and (S_S,3*R*)-**9m** have been deposited with the Cambridge Crystallographic Data Centre as CCDC 268390 and 268391, respectively. The absolute structure of (S_S,2*S*)-**9i** was unambiguously determined from the X-ray data (see the Supporting Information); for (S_S,3*R*)-**9m** only the relative stereochemistry could be determined with certainty.

(22) The (S_S,3*R*) configuration in the products of dCr reactions of substrates derived from alkyl-substituted allylic alcohols corresponds to the same sense of asymmetric induction as the (S_S,2*S*) configuration in the aryl-substituted products because of the change in priority of substituents on the stereocenter.

TABLE 4. Decarboxylative Claisen Rearrangement Reaction of Chiral Sulfoximine-Substituted Esters (S_S)-8b,i−n



entry	ester (S_S)-**8**	rearranged product (S_S)-**9**	R_1	R_2	R_3	R_4	time[a] (h)	yield[b] (%)	dr[c−e]
1	(S_S)-**8b**	(S_S)-**9b**	H	H	H	Ph	1.5	91	82:18
2	(S_S)-**8i**	(S_S)-**9i**	H	H	H	C_6H_4-*p*-NO_2	9	65	78:22
3	(S_S)-**8j**	(S_S)-**9j**	H	H	H	*n*-Pr	6	78	75:25
4	(S_S)-**8k**	(S_S)-**9j**	H	H	*n*-Pr	H	8	67	87:13
5	(S_S)-**8l**	(S_S)-**9l**	H	Me	H	Ph	8	76	75:25
6	(S_S)-**8m**	(S_S)-**9m**	H	H	Me	$CH_2-CH_2-CH=C(CH_3)_2$	6	84	70:30
7	(S_S)-**8n**	(S_S)-**9n**	Me	H	H	Me	8	94	53:47

[a] Reaction monitored by ^{1}H NMR or TLC. [b] Isolated yield. [c] Diastereoisomeric ratio. [d] Determined by ^{1}H NMR. [e] For the determination of the stereochemistry, see below.

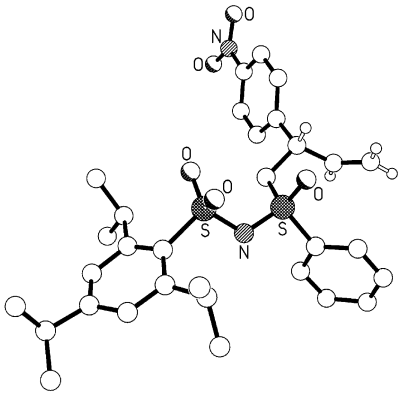


FIGURE 1. The molecular structure of (S_S,2*S*)-**9i**.

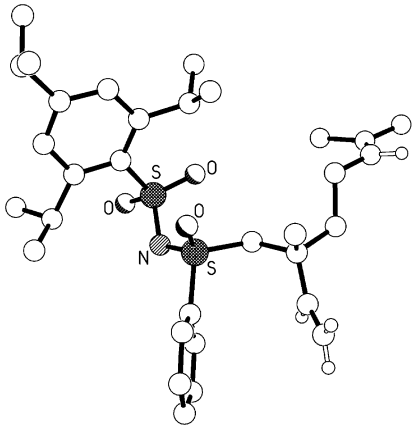
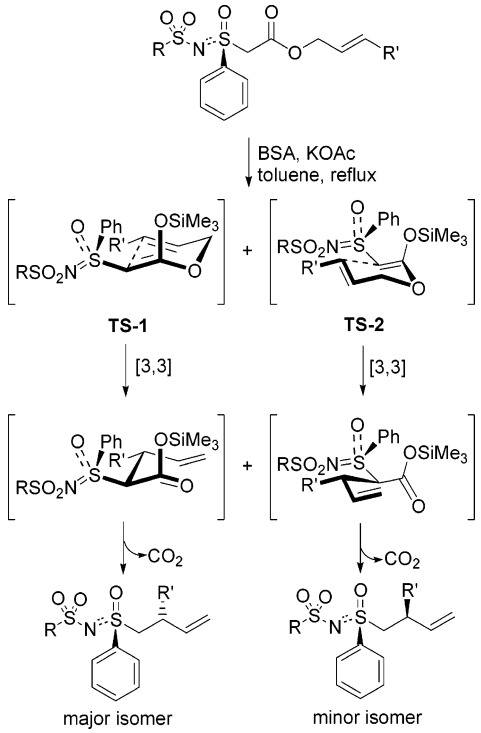


FIGURE 2. The molecular structure of one (**A**) of the two independent molecules present in the crystals of (S_S,3*R*)-**9m** (see Figure S3 in the Supporting Information for the structure of the second independent molecule, which has the same S_S,3*R* stereochemistry.)

the models depicted in Scheme 7. These depictions assume *Z*-geometry for the intermediate sulfoximine-substituted silylketene acetals formed in situ. The preferred conformation about the α-carbon−sulfur bond positions the bulky $ArSO_2N$ group antiperiplanar to the ketene acetal C−C double bond; this effect is maximized with sterically demanding Ar groups. The preferred trajectory of approach of the allylic moiety to the ketene acetal is syn with respect to the sulfoximine oxygen atom and anti to the phenyl group. This model explains the

SCHEME 7. Proposed Pseudochair Transition-State Model



maximization of selectivity with Ar 2,4,6-triisopropylphenyl (Table 2, entry 2; Table 4, entry 1), and also the enhanced selectivity for the opposite diastereoisomeric product in the reaction of (S_S)-**8k** (Table 4, entry 4), since the R′−Ph interaction is maximized when the allylic double bond has *Z*-configuration.

Conclusion

In summary, we have shown that modest to good levels of diastereoselectivity may be attained in the dCr reactions of sulfoximine-substituted allylic acetate substrates. Current studies are directed toward the development of modified systems possessing additional electron-withdrawing substituents on the α-position with a view to attaining lower reaction temperatures and enhanced selectivities. The results of these studies will be reported in due course.

Experimental Section

General Procedure for Carboxylation of Sulfoximines. A solution of sulfoximine in THF at −78 °C and under N_2 was treated with *n*-BuLi in hexanes (1.1 equiv). After the mixture was stirred for 1 h at this temperature, dried CO_2 was bubbled through the solution for 30 min. The cooling bath was then removed, the solution was diluted with CH_2Cl_2 or a solution of hexane and ether (1:1) and hydrolyzed with water, and the two layers were separated. The aqueous layer was acidified with HCl until a colorless precipitate appeared. The suspension was extracted several times with CH_2Cl_2 or a solution of hexane and ether (1:1), the organic layer was then dried ($MgSO_4$), concentrated under reduced pressure, and dried in vacuo to give the corresponding acid, which was used in the next step without further purification.

(+)-*S*-Carboxymethyl-*S*-phenyl-*N*-(2,4,6-triisopropylphenylsulfonyl)sulfoximine, (*S*$_S$)-7b. According to the general procedure, a solution of (+)-(*S*$_S$)-*S*-methyl-*S*-phenyl-*N*-(2,4,6-triisopropylphenylsulfonyl)sulfoximine (*S*$_S$)-**3c** (270 mg, 0.64 mmol) in THF (5 mL) reacted with *n*-BuLi (440 μL, 0.70 mmol, 1.1 equiv) and CO_2. After workup (extraction with a 1:1 mixture of diethyl ether and hexane), (+)-*S*-carboxymethyl-*S*-phenyl-*N*-(2,4,6-triisopropylphenylsulfonyl)sulfoximine (*S*$_S$)-**7b** (238 mg, 80%) was obtained as a colorless oil; $[\alpha]^{20}_D$ +46.1 (*c* 0.76, $CHCl_3$); ^{1}H NMR (270 MHz, $CDCl_3$) δ 9.22 (1H, br s, OH), 8.00 (2H, d, *J* = 7.0 Hz, 2H-*o* SOPh), 7.68 (1H, t, *J* = 7.5 Hz, H-*p* SOPh), 7.55 (2H, t, *J* = 7.0 Hz, 2H-*m* SOPh), 7.10 (2H, s, 2H-*m* triisopropylphenyl), 4.69 (1H, d, *J* = 15.0 Hz AB system, C*Ha*HbCO$_2$), 4.62 (1H, d, *J* 15.0 Hz AB system, CHa*Hb*CO$_2$), 4.32 (2H, sept, *J* = 6.5 Hz, 2 C*H*(CH$_3$)$_2$-*o*), 2.85 (1H, sept, *J* = 6.5 Hz, C*H*(CH$_3$)$_2$-*para*), 1.22 (6H, d, *J* = 6.5 Hz, CH(C*H*$_3$)$_2$-*o*), 1.21 (6H, d, *J* = 6.5 Hz, CH(C*H*$_3$)$_2$-*o*), 1.16 (6H, d, *J* = 6.5 Hz, CH(C*H*$_3$)$_2$-*p*); ^{13}C NMR (67.5 MHz, $CDCl_3$) δ 164.1, 152.2, 149.2, 135.0, 129.7, 129.6, 128.7, 127.1, 123.6, 61.9, 34.2, 29.4, 24.8, 24.6, 23.7.

General Procedure for Esterification Reactions. A solution of acid, allylic alcohol (1 equiv), and 1-(3-dimethylaminopropyl)-3-ethylcarbodiimide hydrochloride (EDCI) (1 equiv) in CH_2Cl_2 was stirred for 1 h at 0 °C and 15 h at room temperature under N_2. The solution was then diluted with CH_2Cl_2, washed with water, and dried ($MgSO_4$). Evaporation of the solvent under reduced pressure and chromatography on silica gel afforded the corresponding ester.

(+)-(*S*$_S$)-*S*-(3-Phenyl-2-propenyloxycarbonylmethyl)-*S*-phenyl-*N*-(2,4,6-triisopropylphenylsulfonyl)sulfoximine, (*S*$_S$)-8b. According to the general procedure, (+)-(*S*$_S$)-*S*-carboxymethyl-*S*-phenyl-*N*-(2,4,6-triisopropylphenylsulfonyl)sulfoximine (*S*$_S$)-**7b** (610 mg, 1.31 mmol) was esterified with cinnamyl alcohol (176 mg, 1.31 mmol, 1 equiv), and EDCI (251 mg, 1.31 mmol, 1 equiv) in CH_2Cl_2 (10 mL). Chromatography (35% EtOAc−petroleum ether) yielded (+)-(*S*$_S$)-*S*-(*3-phenyl-2-propenyloxycarbonylmethyl)-S-phenyl-N-(2,4,6-triisopropylphenylsulfonyl)sulfoximine* (*S*$_S$)-**8b** (550 mg, 72%) as a colorless oil, R_f 0.67 (33% EtOAc−petroleum ether); $[\alpha]^{20}_D$ +24.9 (*c* 1.0, acetone); IR ν_{CO} (film) 1743 cm^{-1}; ^{1}H NMR (270 MHz, $CDCl_3$) δ 7.97 (2H, d, *J* = 8.0 Hz, 2H-*o* SOPh), 7.60 (1H, t, *J* 7= .5 Hz, H-*p* SOPh), 7.47 (2H, t, *J* = 8.0 Hz, 2H-*m* SOPh), 7.32 (5H, m, Ph), 7.13 (2H, s, 2H-*m* triisopropylphenyl), 6.57 (1H, d, *J* = 16.0 Hz, CH=C*H*Ph), 6.09 (1H, td, *J* = 7.0, 16.0 Hz, CH$_2$C*H*=CH), 4.74 (1H, d, *J* = 14.5 Hz, AB system, C*Ha*HbCO$_2$), 4.67 (2H, d, *J* = 7.0 Hz. OCH$_2$), 4.64 (1H, d, *J* = 14.5 Hz AB system, CHa*Hb*CO$_2$), 4.39 (2H, sept, *J* = 6.5 Hz, 2 C*H*(CH$_3$)$_2$-*o*), 2.86 (1H, sept, *J* = 6.5 Hz, C*H*(CH$_3$)$_2$-*p*), 1.22 (6H, d, *J* = 6.5 Hz, CH(C*H*$_3$)$_2$-*o*), 1.21 (6H, d, *J* = 6.5 Hz, CH(C*H*$_3$)$_2$-*o*), 1.16 (6H, d, *J* = 6.5 Hz, CH(C*H*$_3$)$_2$-*p*); ^{13}C NMR (67.5 MHz, $CDCl_3$) δ 161.5, 152.3, 149.1, 137.5, 137.1, 136.4, 135.8, 135.7, 134.8, 129.4, 128.7, 128.5, 126.8, 123.5, 121.5, 67.0, 62.0, 34.2, 29.4, 24.8, 24.7, 23.7. Anal. Calcd for $C_{32}H_{39}NO_5S_2$: C, 66.06; H, 6.76; N, 2.34. Found: C, 65.93; H, 6.81; N, 2.34.

General Procedure for Decarboxylative Claisen Rearrangement Reactions. A solution of sulfoximine ester, *N*,*O*-bis(trimethylsilyl)acetamide (BSA) (0.25 equiv), and KOAc (0.1 equiv) in toluene was heated at reflux under N_2. After completion of the reaction (reaction monitored by TLC or ^{1}H NMR), the solution was cooled to room temperature. Evaporation of the solvent under reduced pressure and chromatography on silica gel afforded the corresponding rearranged products.

(*S*$_S$,2*S*)-*S*-Phenyl-*S*-(2-phenylbut-3-enyl)-*N*-(2,4,6-triisopropylphenylsulfonyl)sulfoximine and (*S*$_S$,2*R*)-*S*-Phenyl-*S*-(2-phenylbut-3-enyl)-*N*-(2,4,6-triisopropylphenylsulfonyl)sulfoximine, (*S*$_S$,2*S*)-9b and (*S*$_S$,2*R*)-9b. According to the general procedure, (+)-(*S*$_S$)-*S*-(3-phenyl-2-propenyloxycarbonylmethyl)-*S*-phenyl-*N*-(2,4,6-triisopropylphenylsulfonyl)sulfoximine (*S*$_S$)-**8b** (475 mg, 0.816 mmol) was reacted with BSA (50 μL, 0.204 mmol, 0.25 equiv) and KOAc (9 mg, 0.082 mmol, 0.1 equiv) in toluene (4 mL) for 1.5 h. Chromatography (35% EtOAc−petroleum ether) yielded *(S*$_S$*,S)-S-(2-phenylbut-3-ene)-S-phenyl-N-(2,4,6-triisopropylphenylsulfonyl)sulfoximine* (*S*$_S$,2*S*)-**9b** and *(S*$_S$*,R)-S-(2-phenylbut-3-ene)-S-phenyl-N-(2,4,6-triisopropylphenylsulfonyl)sulfoximine* (*S*$_S$,2*R*)-**9b** (420 mg, 91%, 82:18 mixture determined by ^{1}H NMR) as a colorless solid, R_f 0.68 (25% EtOAc−petroleum ether); ^{1}H NMR (400 MHz, toluene-d_8) δ 7.48 (d, *J* = 7.5 Hz, 2H-*o* SOPh major isomer), 7.41 (d, *J* = 7.5 Hz, 2H-*o* SOPh minor isomer), 6.95−6.50 (10H, m, H aromatic), 5.55 (ddd, *J* = 7.0, 10.0, 17.0 Hz, C*H*=CH$_2$ major isomer), 5.50 (ddd, *J* = 6.5, 13.5, 17.0 Hz, C*H*=CH$_2$ minor isomer), 4.86 (sept, *J* = 6.5 Hz, 2 C*H*(CH$_3$)$_2$-*o* major isomer), 4.70 (m, CH=C*H*$_2$ minor isomer), 4.68 (m, CH=C*H*aHb major isomer), 4.66 (d, *J* = 17.0 Hz, CH=CHa*H*b major isomer), 4.20 (m, 2 C*H*(CH$_3$)$_2$-*o* minor isomer), 4.08 (dd, *J* = 6.0, 15.0 Hz, SOC*H*aHb minor isomer), 4.01 (dd, *J* = 6.5, 13.5 Hz, C*H*-Ph major isomer), 3.81 (dd, *J* = 6.0, 14.5 Hz AB system, SOC*H*aHb major isomer), 3.76 (m, C*H*-Ph minor isomer), 3.66 (dd, *J* = 7.0, 14.5 Hz AB system, SOCHa*H*b major isomer), 3.54 (dd, *J* = 7.5, 14.5 Hz, SOCHa*H*b minor isomer), 2.60 (1H, m, C*H*(CH$_3$)$_2$-*p*), 1.37 (d, *J* = 6.5 Hz, CH(C*H*$_3$)$_2$-*o* major isomer), 1.36 (d, *J* = 6.5 Hz, CH(C*H*$_3$)$_2$-*o* minor isomer), 1.29 (d, *J* = 6.5 Hz, CH(C*H*$_3$)$_2$-*o* major isomer), 1.20 (d, *J* = 6.5 Hz, CH(C*H*$_3$)$_2$-*o* minor isomer), 1.06 (6H, m, CH(C*H*$_3$)$_2$-*p*); ^{13}C NMR (100 MHz, toluene-d_8) δ 151.8 (C-*p* triisopropylphenyl), 149.6 (2C-*o* triisopropylphenyl), 140.1 and 140.0, 138.8 and 138.5 (*C*H=CH$_2$), 133.3 and 133.2, 129.2, 128.8, 128.7, 128.4, 128.1, 123.5, 116.3, and 116.2 (CH=*C*H$_2$), 62.9 and 62.5 (SOCH$_2$), 45.3 and 44.8 (*C*H−Ph), 34.5 (*C*H(CH$_3$)$_2$-*p*), 29.7 and 29.4 (2*C*H(CH$_3$)$_2$-*o*), 25.1 and 25.0 and 23.8 (3CH(*C*H$_3$)$_2$); MS (CI) *m/z* 555 [M + NH$_4$]$^+$, 538 [M + H]$^+$; HMRS (CI) *m/z* calcd for [$C_{31}H_{39}NO_3S_2$ + H]$^+$ 538.2450, found 538.2451. Anal. Calcd for $C_{31}H_{39}NO_3S_2$: C, 69.24; H, 7.31; N, 2.60. Found: C, 69.32; H, 7.06; N, 2.42.

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Supporting Information Available: Experimental procedure, full characterization of all new compounds, and copies of ^{1}H, ^{13}C, and where appropriate ^{19}F NMR spectra for the products of the decarboxylative Claisen rearrangement reactions. This material is available free of charge via the Internet at http://pubs.acs.org.

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