Stereochemical Research on the Hydrolysis of Optically Pure Spirosulfuranes: Efficient Synthesis of Chiral Sulfoxides with Completely Opposite Stereochemistry

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The synthesis of optically pure alkoxy(acyloxy)spirosulfuranes **5a**−**e**, using the 2-*exo*-hydroxy-10-bornyl group as a chiral ligand, has been developed in high yield and with excellent diastereoselectivity. The X-ray analyses of **5a** and **5b** indicated that the spirosulfuranes have the trigonal bipyramidal (TBP) structures around the sulfur atom. Recrystallization of **5c**,**d** from moist solvent (95% EtOH aq) gave sulfoxides **7c**,**d**, respectively, as single products with an S_S absolute configuration at the sulfur atom. In contrast, hydrolysis of sulfuranes **5b**,**c**,**d** under the basic conditions afforded the sulfoxides **8b**,**c**,**d**, with an R_S absolute configuration at the sulfur atom, in high yield and with excellent diastereoselectivity. The stereochemical and mechanistic study of the hydrolysis of spirosulfuranes was performed by using spirosulfurane **5a**. Hydrolysis of **5a** under acidic and basic conditions gave, diastereoselectively, the corresponding sulfoxides **7a** and **8a** with the opposite absolute configuration at the sulfur atom. The structures of the sulfoxides **7a**,**c** and **8a**,**b** were confirmed by X-ray crystallographic analyses. The mass spectral and ^{17}O NMR studies of the sulfoxides **7a-$^{18(17)}$O** and **8a-$^{18(17)}$O**, which were prepared by the hydrolysis of **5a** with isotopically labeled water, revealed definitely that the oxygen atom bound to the sulfur atom in these compounds derives from water. The possible mechanisms of the reactions which account for the observed stereochemical results have been suggested.

Introduction

Although the stereochemical and mechanistic research on the nucleophilic reaction of compounds at a tetracoordinated atom, such as carbon, has been widely studied and an S_N1 or S_N2 pathway has been accepted as the general concept of organic reactions, the research on that of the pentacoordinated atom is quite limited to some silicon and phosphorus compounds.[1] Chalcogenuranes, are a kind of pentacoordinated (including the equatorial lone pair electrons) hypervalent compounds, usually with a trigonal bipyramidal (TBP) geometry.[2] Thus, a stereochemical study of the reaction of chalcogenuranes would lead to a general comprehension of the reactions that occur at the pentacoordinated or the multicoordinated heteroatom-containing compounds. On the other hand, chalcogenuranes have been proposed as the intermediates or transition states in various reactions involving chalcogenium compounds, such as Swern oxidation and Pummerer rearrangement.[3] Recently, some groups have proposed that the formation of chalcogenurane species is the key step in the biomimic reactions of some enzymes.[4] Therefore, the synthesis and isolation of chiral chalcogenuranes are apparently important to investigate the stereochemistry of their reactions as well as the roles in the biomimic reactions.

Since the first synthesis of the chiral chlorosulfurane **1** reported by Martin 20 years ago,[5] a number of chiral spirosulfuranes have been synthesized or isolated (Scheme 1).[6] Kapovits et al. have reported the synthesis of both (+)- and (−)-sulfuranes **2a** via the reaction of corresponding optically active (+)- and (−)-sulfoxides with acetyl chloride in the presence of triethylamine.[6a,e] Isolation of

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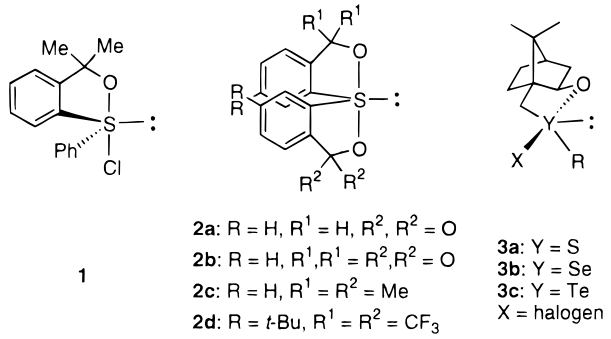
Scheme 1



1

2a: R = H, R^1 = H, R^2, R^2 = O
2b: R = H, R^1,R^1 = R^2,R^2 = O
2c: R = H, R^1 = R^2 = Me
2d: R = *t*-Bu, R^1 = R^2 = CF_3

3a: Y = S
3b: Y = Se
3c: Y = Te
X = halogen

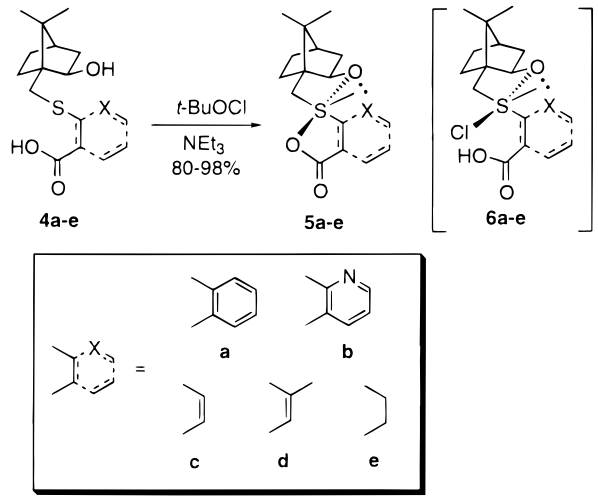
optically pure spirosulfurane **2b** has been successfully carried out by Allenmark et al. by using chiral HPLC.[6b] Recently, Martin and co-workers have reported their synthesis of optically active spirosulfuranes **2c**,**d** via the reaction of sulfoxides with chiral acid.[6c,d] However, there is only one report on the synthesis of optically active spirosulfuranes with definite determination of the structure.[6e] And, to the best of our knowledge, up to now there is no example of the stereochemical aspects of the nucleophilic reaction of a chiral spirosulfurane.

Our group has carried out the synthesis, reaction, and stereochemical research on chiral hypervalent chalcogenium compounds by using the 2-*exo*-hydroxy-10-bornyl group as a chiral auxiliary.[7] We found it is a good ligand for the stereoselective synthesis of optically pure chalcogenuranes **3**. Using this ligand, we have synthesized the chiral halooxasulfuranes **3a**,[7e] selenuranes **3b**,[7a] and telluranes **3c**[7d] in very high yields and with excellent diastereoselectivities (Scheme 1). The bornyl group has proved to be an excellent group for the diastereoselective synthesis of these compounds; its bulky protective factor as well as the five-numbered ring effect have been considered as the main reasons for the stability of these compounds and the diastereoselectivity of their synthesis. Hydrolysis of chiral chlorosulfuranes **3a** (X = Cl) as well as other nucleophilic reactions of halooxachalcogenuranes **3** afforded a good method to prepare the optically pure chalcogenonium(IV) compounds.[7] On the other hand, our laboratory, as well as some other groups, have confirmed that these optically pure chalcogenonium(IV) compounds are very useful chiral blocks in the synthesis of some optically active natural products through the asymmetric Diels−Alder reaction,[8a−c] [2,3]sigmatropic rearrangement,[7c,f,g] etc.[8d,e] To gain insight into the stereochemistry of the reaction of hypervalent chalcogenium compounds and to seek efficient methods to synthesize the chiral chalcogenonium(IV) compounds, we designed and prepared the chiral spirosulfuranes **5a**−**e**, using the 2-*exo*-hydroxy-10-bornyl group as a chiral ligand, with two different kinds of oxygen atoms (alkoxy and acyloxy) bound to the central sulfur atom. We hoped the difference of these two oxygen groups at the apical positions of the trigonal bipyramidal (TBP) structure of spirosulfuranes **5** would display a difference of reactivity under various conditions and, therefore, affect the stereochemical process of the nucleophilic reactions of the spirosulfuranes which might in turn afford products with different stereochemistry around the central sulfur atom. Herein we report our results on the synthesis, structure, and mechanistic research on the hydrolysis of these chiral spirosulfuranes.[9]

Results and Discussion

Synthesis and Stereochemistry of Optically Pure Spirosulfuranes 5a−e. Synthesis of optically pure spirosulfuranes **5a**−**e** with 2-*exo*-hydroxy-10-bornyl group as a chiral ligand is shown in Scheme 2. Reaction of chiral sulfides **4a**−**e**, which were readily prepared from (1*S*)-(−)-10-iodo-2-*exo*-bornanol[7j] or (−)-10-mercaptoisoborneol, with *t*-BuOCl (1.1 equiv) at 0 °C for 30 min in anhydrous dichloromethane under nitrogen followed by treatment with Et_3N (1.2 equiv) for 1.5 h gave optically pure spirosulfuranes **5a**−**e** in high yield and as single diastereomers; no any other epimeric compounds could be detected.[10] The reactions are believed to proceed through the diastereoselective generation of intermediates of chlorosulfuranes **6**, which had been proposed previously, followed by intramolecular cyclization.

Scheme 2



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(10) See Experimental Section for detailed procedures. Sulfurane **5e** is not stable to moisture, and only the sulfoxide was obtained after extraction with EtOAc from water. The structure of sulfurane **5e** was determined by the ^1H NMR analysis of the crude product which was directly evaporated without extraction.

The formation of the five-membered spirosulfurane structure was detected by spectroscopic means. In the ^{1}H NMR spectra of spirosulfuranes, the chemical shifts of protons on the methylene bound to the sulfur atom are considerably downfield as compared with those of the analogous sulfides and sulfoxides. In the ^{13}C NMR spectra, the chemical shift of the carbon bound to the alkoxy oxygen in spirosulfuranes **5a**−**d** is at about 95 ppm whereas shifts of the corresponding carbon atom of sulfides and sulfoxides are at about 77 ppm. These spectral characteristic could be considered as the features of compounds with TBP structure.[7] On the other hand, sulfuranes **5a**−**d** have their carbonyl stretching frequencies at 1657−1664 cm^{-1}, which are considerably lower as compared with those of general carbonyl groups. Previous study on the relationship between the structures and the carbonyl stretching frequencies of spirosulfuranes indicated that the lower carbonyl stretching frequency could been considered as an indication of a high degree of carboxylate anion character in carbonyl-containing spirosulfuranes.[11,12c,13c] The acyloxy ligand is effectively more electronegative than the alkoxy ligand, and electron density is expected to be removed from the alkoxy ligand toward the acyloxy ligand. Thus, these two S−O bonds at the apical positions of the sulfuranes were expected to show different structural and reactive properties.

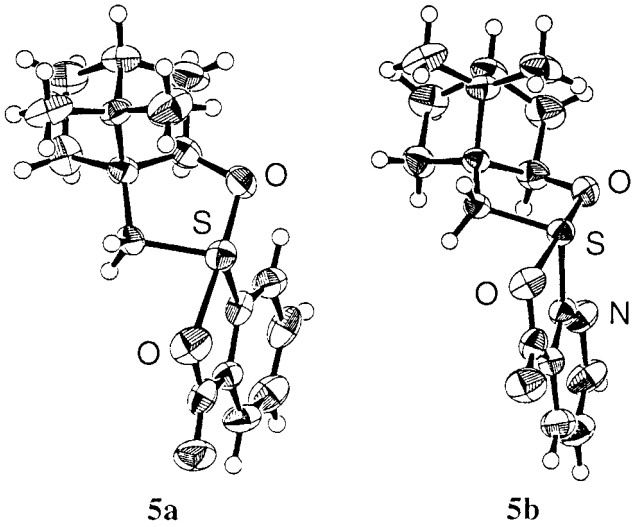

Figure 1. ORTEP drawing of the compounds **5a** and **5b** with 50% thermal ellipsoids.

The X-ray crystallographic analyses of **5a** and **5b** indicate that the spirosulfuranes have slightly distorted trigonal bipyramidal (TBP) structures as shown in Figure 1. As expected, two carbon atoms and a lone pair occupy equatorial positions, while the two electronegative oxygen atoms bound to the sulfur atom occupy apical positions. The O−S−O moieties with the angle of 177.1° and 178.9° in **5a** and **5b**, respectively, are almost linear. Systemic investigation on the crystallographic structures of some achiral spirosulfuranes has indicated that there is some characteristic relationship between the sum of the O−S−O distances, as well as the S−O distances, and the structure of the spirosulfuranes.[12] Thus, the sum of the S−O−S distances in bis(acyloxy)spirosulfuranes are longer than those in dialkoxy analogues but shorter than in the mixed alkoxy(acyloxy) derivatives, and the length of S−O(alkoxy) is usually shorter than that of the S−O(acyloxy) in the alkoxy(acyloxy)spirosulfurane. Our X-ray analyses gave a similar result: the sum of the O−S−O bond distances in **5a** and **5b** [3.759(3) and 3.765(6) Å, respectively] is consistent with those of racemic alkoxy(acyloxy)spirosulfuranes, the bond length of the S−O (alkoxy) [1.686(6) and 1.650(3) Å for **5a** and **5b**, respectively] is shorter than that of the S−O (acyloxy) [2.072(7) and 2.115(3) Å for **5a** and **5b**, respectively], which shows a "alkoxy-sulfonium-carboxylate zwitterion characteristic" as do the racemic spirosulfuranes.[12] The different structural properties of the two oxygen groups at the apical positions were expected to lead to a difference in the reactivity of spirosulfuranes under various conditions.

Stereochemical and Mechanistic Research on the Hydrolysis of Spirosulfuranes. Spirosulfuranes **5a** and **5b** are stable, and no hydrolysis or isomerizations were observed at room temperature for several days. Refluxing a solution of spirosulfuranes **5a** in anhydrous EtOH or in EtOH−H_2O (95:5) for 5 h gave only the recovery of the starting material (Table 1). Compared to **5a**, the sulfuranes **5c**,**d** are not too stable to moisture. Recrystallization of **5c**,**d** from moist solvent (EtOH, 95% aq) gave the products of the hydrolysis, sulfoxides **7c**,**d**, as single diastereomers in high yields. The stereochemistry of **7c**,**d** has been determined by an X-ray analysis of **7c** which indicated that the absolute configuration of the sulfur atom is S_S as shown in Figure 2.

Table 1. The Hydrolysis of 5a under Basic or Acidic Conditions

entry	substrate	condition	product	yield (%)
1	**5a**	EtOH, reflux, 5 h	**5a**	99
2	**5a**	EtOH−H_2O, reflux, 5 h	**5a**	99
3	**5a**	1 N HCl, rt, 48 h	**7a**	98
4	**5a**	1 N NaOH, 0 °C, 0.5 h	**8a**	88
5	**5a**	1 N HCl, reflux, 5 h	**7a** + **8a**	87 (2:1)[a]
6	**5a**	1 N NaOH, reflux, 5 h	**8a**	90

[a] Ratio in parentheses refers to **7a**:**8a**.

Previous study of the hydrolysis of racemic spirosulfuranes showed that these compounds are readily hydrolyzed to their parent sulfoxides and that their stability decreased with increasing electron density at the sulfur atom and with enlarging the size of the spiro rings from five- to six-membered.[13] However, since these spirosulfuranes are achiral or racemic, the stereochemistry of the reactions was unclear. On the other hand, oxidation of the 2-*exo*-hydroxy-10-bornyl sulfides with *t*-BuOCl[7e] or MCPBA[14] has been extensively studied. The hydroxyl group has been known to play a key role in the control of the diastereoselectivity through the formation of intermediate chlorosulfuranes, or through hydrogen bonding with the oxidative reagent (MCPBA). Thus, hydroly-

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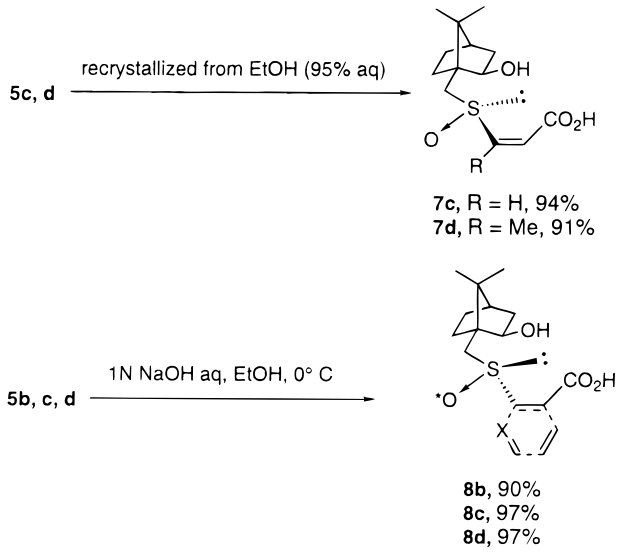
sis of chlorosulfuranes or the oxidation of the sulfides with MCPBA has been known to give sulfoxides with a predictable absolute configuration at sulfur atom. Interestingly, the sulfoxides **7c**,**d** are of the opposite absolute configuration at the sulfur atom as compared with that of sulfoxides obtained by the usual oxidation.

Scheme 3



These fascinating results prompted us to investigate the basic hydrolysis of spirosulfuranes **5c**,**d**. Hydrolysis of **5c**,**d** with 1 N aq NaOH at 0 °C for 0.5 h afforded the sulfoxides **8c**,**d** in high yield and with excellent diastereoselectivity. Since the spectral characteristics of the sulfoxides **7c**,**d** and the corresponding **8c**,**d**, obtained through the basic hydrolysis, were quite different, the latter appeared to be the diastereomers of the former at the sulfur atom, respectively.[15] An X-ray analysis of the sulfoxide **8b**, obtained by a similar basic hydrolysis of spirosulfurane **5b**, proved that the above suggestion of the stereochemistry of the sulfoxides **8c**,**d** is correct (Figure 2). Our initial results mentioned above indicated that the structure of the spirosulfuranes, especially the two apical S−O bonds, might play an important role in the control of the stereochemistry of the hydrolysis of these hypervalent sulfur compounds depending the conditions used.

To gain a deeper understanding of the reactions of these spirosulfuranes, we carried out the hydrolysis of the spirosulfurane **5a**, which is comparatively stable, under various conditions to see how the conditions affect the diastereoselectivity of the reactions (Scheme 4, Table 1). As mentioned above, even by refluxing an EtOH−H_2O solution, **5a** recovered without an appreciable change; however, hydrolysis of spirosulfuranes **5a** in a solution of EtOH with 1 N aq HCl at room temperature for 48 h gave sulfoxide **7a** in high yield as a single diastereomer. The S_S absolute configuration of the sulfur atom in sulfoxide **7a** has been determined by an X-ray analysis as shown in Figure 3. On the contrary, stirring an EtOH

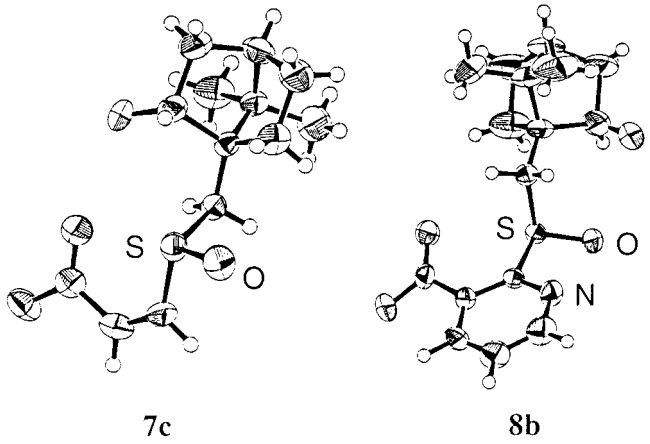
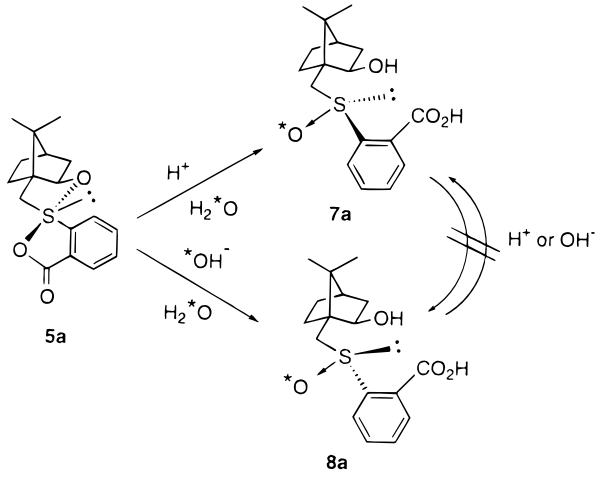


Figure 2. ORTEP drawing of the compounds **7c** and **8b** with 50% thermal ellipsoids.

Scheme 4



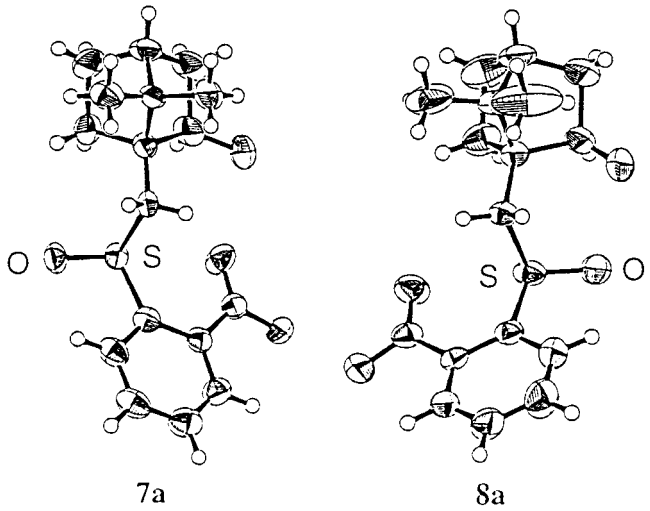


Figure 3. ORTEP drawing of the compounds **7a** and **8a** with 50% thermal ellipsoids.

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(15) To confirm the stereochemistry of **8c**,**d**, hydrolysis of chlorosulfuranes **6c**,**d** under basic condition has been performed to give sulfoxides in high yield and diastereoselectivity. The spectral data of the products are identical with that of sulfoxides **8c**,**d**, which indicated definitely that the stereochemistry of the sulfoxides are as shown in Scheme 3.

solution of **5a** in a 1 N aq NaOH at 0 °C for 0.5 h gave optically pure sulfoxide **8a** in 88% yield, also as a single diastereomer but with an opposite absolute configuration at the sulfur atom. The stereochemistry of sulfoxide **8a** has also been clearly determined by an X-ray analysis as shown in Figure 3.

Although we believe that the stereochemical outcome results from the diastereoselective hydrolysis of the sulfurane **5a**, the isomerization of the products should be investigated to verify the optically stability of the sulfoxides. The chiral chalcogenonium(IV) compounds have been known to isomerize through the pyramidal inversion or the formation of pentacoordinated intermediates.[16] Isomerization of sulfoxides **7a** and **8a** under various conditions has been, therefore, studied to clarify the optically stability of them. As shown in Table 2, no isomerization could been observed after stirring **7a** and **8a** in 1 N NaOH−EtOH solution at room temperature or under reflux for a considerably long time. Stirring **7a** and **8a** in 1 N HCl−EtOH solution at room temperature for 48 h resulted in only their recovery. Only a slight isomerization was really observed even after refluxing **7a** and **8a** in 1 N HCl−EtOH solution for 5 h, respectively. However, since the hydrolytic reactions of spirosulfurane **5a** were all performed under mild conditions, the possibility of the isomerization of their products during the hydrolysis could be ruled out. Therefore, we can conclude that the excellent diastereoselectivity of these reactions is induced from the difference of the reactivity of the two S−O bonds of the spirosulfuranes.

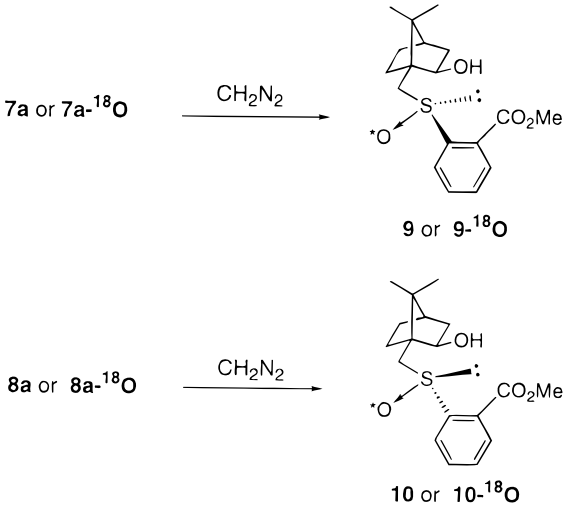
Table 2. The Isomerization of 7a and 8a under Various Conditions

entry	substrate	condition[a]	product	yield (%)
1	**7a**	1 N HCl, rt, 48 h	**7a**	98
2	**7a**	1 N NaOH, rt, 48 h	**7a**	96
3	**7a**	1 N HCl, reflux, 5 h	**7a** + **8a**	96 (2.04:1)[b]
4	**7a**	1 N NaOH, reflux, 5 h	**7a**	93
5	**8a**	1 N HCl, rt, 48 h	**8a**	98
6	**8a**	1 N NaOH, rt, 48 h	**8a**	92
7	**8a**	1 N HCl, reflux, 5 h	**7a** + **8a**	92 (1:8.35)[b]
8	**8a**	1 N NaOH, reflux, 5 h	**8a**	97

[a] All reactions were carried out in the solution of EtOH. [b] Ratio in parentheses refers to **7a**:**8a**.

To make the reaction mechanism clear, the mass and ^{17}O NMR spectral studies of the products were performed to see where H_2O attacked and whether the oxygen bound to the sulfur in the sulfoxides came from H_2O or not. Thus, the hydrolytic reactions of **5a** under acidic and basic conditions were carried out with $H_2{}^{18}O$ and $H_2{}^{17}O$, respectively (Scheme 4). Since no molecular peak could be observed in the mass spectra of **7a** and **8a**, esterification was necessary in order to observe the mass spectra (Scheme 5). Hydrolysis of sulfurane **5a** with $H_2{}^{18}O$ under acidic and basic condition followed by esterification with diazomethane gave the corresponding esters **9-^{18}O** and **10-^{18}O** in 98 and 91% yield, of which both mass spectra have peaks at 339 ($M^+ + 1$) (Scheme 5). The mass spectroscopic analyses revealed that **9-^{18}O** and **10-^{18}O** are enriched with ^{18}O to a significant extent [91% and 70% incorporation, respectively, which were obtained by comparison of the mass spectrum of **9-^{18}O** (or **10-^{18}O**) with that of **9-^{16}O** (or **10-^{16}O**)].[17] The position of the oxygen atom from H_2O was studied by use of ^{17}O NMR.[18] Since there should be a quite different chemical shift for the oxygen bound to sulfur and the oxygen of the carbonyl in the sulfoxides **7a** and **8a**, the ^{17}O NMR spectra of these compounds could provide important information on the position of the oxygen from H_2O. The products obtained by hydrolysis of **5a** with $H_2{}^{17}O$ under acidic and basic conditions showed signals with chemical shift of −8.103 and −9.184 ppm in their ^{17}O NMR spectra, respectively, which indicated that the oxygen atoms from H_2O were definitely bound to the sulfur atoms of the products (Scheme 4).

Scheme 5



Possible Mechanisms: Association versus Dissociation. As compared with that of the tetracoordinated atom, the stereochemistry of nucleophilic reactions occurring at a pentacoordinated atom is more complex. Two kinds of mechanisms, namely associative (analogous to S_N2-type reactions) and dissociative (analogous to S_N1-type reactions) mechanisms, have been suggested to account for the nucleophilic reactions of the hypervalent chalcogenium compounds.[13,19] We have proposed an associative mechanism for the reaction of **5a** as shown in Scheme 6:[9] hydrolysis under acidic and basic conditions may proceed through the formation of the hexacoordinated sulfur species **B** and **D**, which is generated, respectively, from the attack of H_2O onto the protonated spirosulfurane **A**[20] or the reaction of hydroxide anion with **5a**. Since the protonated alkoxy group in **B** could be considered a better leaving group as compared with the acyloxy group bound to the same sulfur atom, the cleavage of the S−O (alkoxy) bond followed by the isomerization around the sulfur center generates the pentacoordinated intermediate **C** with the hydroxy group at the apical position.[21] On the other hand, the S−O (acyloxy) bond in **D** is easily broken as compared with

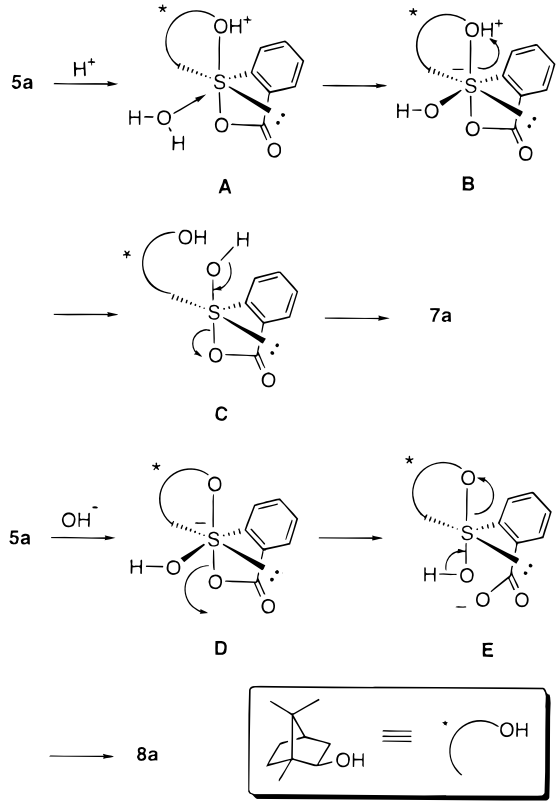
(16) (a) Shimizu, T.; Yoshida, M.; Kobayashi, M. *Bull. Chem. Soc., Jpn.* **1987**, *60*, 1555−1557. (b) Shimizu, T.; Kobayashi, M.; Kamigata, N. *Bull. Chem. Soc., Jpn.* **1988**, *61*, 3761−3763. (c) Shimizu, T.; Kamigata, N. *J. Synth. Org. Chem., Jpn.* **1997**, *55*, 35−43.

(17) The isotopic purity is calculated by comparing the height of peaks at $m/z = 186$ with that of peaks at $m/z = 184$ in the mass spectra of sulfoxides (**7-^{18}O** or **8-^{18}O**), while in the mass spectra of sulfoxides (**7-^{16}O** or **8-^{16}O**) there are no peaks at $m/z = 186$.

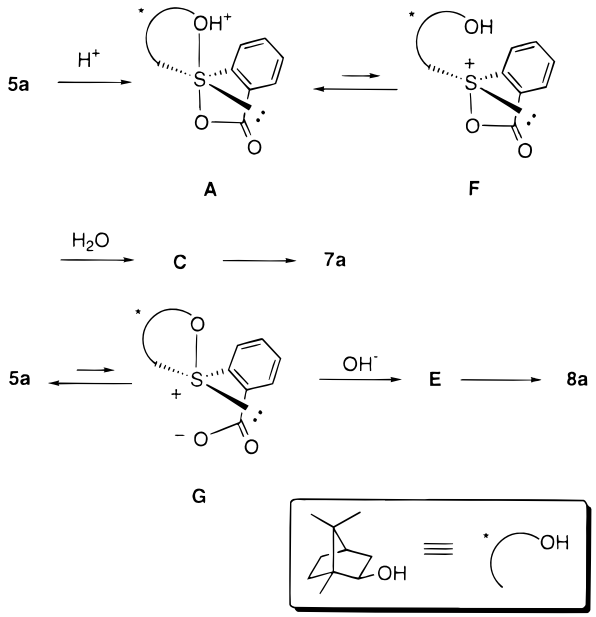
(18) Review on the ^{17}O NMR: (a) Boykin, D. W.; Baumstark, A. L. *Tetrahedron* **1989**, *45*, 3613−3651. On the chemical shift of sulfoxides in ^{17}O NMR spectroscope, see: (b) Dyer, J. C.; Harris, D. C.; Evans, J. S. A. *J. Org. Chem.* **1982**, *47*, 3660−3664.

(19) Twenty years ago, Martin et al. studied the mechanism of the basic hydrolysis of chlorosulfuranes and proposed an associative mechanism involving a hexacoordinated sulfur species with a negative charge on sulfur, see: ref 5.

Scheme 6



Scheme 7



S−O (alkoxy) bond, and the selective cleavage of the S−O (acyloxy) bond and the isomerization around the sulfur center produce the pentacoordinated intermediate **E** with the hydroxy group at the opposite apical position.[21] Then, deprotonation and tandem breaking of another S−O bond in **C**, **E** take place to give the highly diastereoselective formation of the corresponding sulfoxides **7a** and **8a** with S_S and R_S absolute configurations at sulfur, respectively.

However, recent research on the kinetic study of the hydrolysis of the achiral spirosulfuranes indicates that the dissociative mechanism might be an alternative pathway to account for the stereochemical results of the hydrolysis of spirosulfurane **5a**.[13b−d] The stereochemical outcome can be explained readily using the dissociative mechanism by considering the diastereoselective formation of the sulfonium cation as the key intermediate in hydrolysis of the spirosulfurane **5a** (Scheme 7). Thus, under the acidic condition, the initial protonation of **5a** takes place at the oxygen of S−O(alkoxy) which leads to the easier cleavage of the S−O(alkoxy) bond to form the intermediate sulfonium cation **F**; then attack of H_2O from the β-side of the pseudoaxial direction onto the sulfonium cation **F** affords sulfoxide with a S_S absolute configuration at the sulfur atom. While under a basic condition, "alkoxy-sulfonium-carboxylate zwitterion character" of the unsynmmetric spirosulfurane would lead the equilibrium preferentially to the sulfonium cation **G** through the cleavage of the S−O(acyloxy) bond,[22] which then induces the hydroxide ion to attack the sulfur atom from the α-side to produce the sulfoxide with an R_S configurations at the sulfur atom. Therefore, the different stereochemistry of the chiral sulfonium cation leads to the diastereoselective generation of the sulfoxides with the opposite absolute configuration at the sulfur atom. Considering the numerous possible stereoisomers of a hexacoordinated sulfur species in the associative pathway (Scheme 6), it might be difficult to explain the high diastereoselectivity of these reactions. Therefore, at present, we consider the dissociative pathway more reasonable.

Conclusions

In conclusion, we have accomplished the synthesis of a series of optically pure spirosulfuranes **5a**−**e**, using the 2-*exo*-hydroxy-10-bornyl group as a chiral ligand, in high yield and with excellent diastereoselectivity. The defined structures were determined by X-ray analyses. The stereochemistry of the hydrolysis of the spirosulfuranes is dramatically affected by the reactivity of the apical S−O bonds and the reaction conditions. Both of the diastereomers of the optically pure sulfoxides could be obtained by the hydrolysis of the spirosulfurane under different conditions. These results are helpful for the understanding of the stereochemistry of nuclophilic reactions concerning multicoordinated heteroatom compounds. The role of the apical ligands on the stereochemistry of nucleophilic reactions of the spirosulfuranes is

(20) The basicity of ethers ($pK_{BH}+ = -3.5$) is generally stronger than that of esters ($pK_{BH}+ = -6.5$). March, J. *Advanced Organic Chemistry: Reactions, Mechanisms, and Structure;* Wiley-Interscience: New York, 1992; p 250. Since the lack of the precise data of the basicity of the two S−O groups in the alkoxy(acyloxy)spirosulfuranes, we think data cited herein is reasonable to support the order of the protonation of the two S−O groups proposed. Considering the central sulfur as a carbon atom, the basicity of the two oxygens in the structure of C−O−S−O−C(=O) should have similar order as that of C−O−C−O−C(=O). However, the two oxygen atoms might influence each other through the hypervalent O−S−O bond system, which might be different from that of the O−C−O system. Further investigation of the reactions using the computer calculation is ongoing, and the results will be reported elsewhere.

(21) The pentacoordinated intermediates (**C** and **E**) can be reasonably considered as with the TBP geometry, and the most electronegative groups in **C** and **E** are expected to occupy axial positions.

(22) The S−O (acyloxy) bond is expected to hydrolyze easier compared with the S−O (alkoxy) bond in alkoxy(acyloxy)spirosulfuranes since the S−O (acyloxy) bond is longer and more negative charge is distributed on the S−O (acyloxy) bond than S−O (alkoxy), see: ref 13a.

(23) Yamakoshi, Y. N.; Ge, W. Y.; Okayama, K.; Takahashi, T.; Koizumi, T. *Heterocycles* **1996**, *42*, 129−133.

expected to be utilized in the design of novel methods for the synthesis of optically active chalcogenonium compounds with a given stereochemistry on the central chlcogen atom.

Experimental Section

General Methods. Common experimental procedures and instrumentation have been described previously.[7j] Spectroscopic measurements were carried out with the following instruments: ^{17}O NMR, Varian Unity 500 (67.8 MHz) for solutions in $CDCl_3$ with $H_2{}^{17}O$ (0 ppm) as an external standard. Coupling constants (J) are given in hertz. $H_2{}^{17}O$ and $H_2{}^{18}O$ were purchased from Matheson Co.

2-({(1*S*,2*R*,4*R*)-2-Hydroxy-7,7-dimethylbicyclo[2.2.1]-heptan-1-yl}methylthio)benzoic acid (4a). To a stirred suspension of NaH (60%, 336 mg, 8.4 mmol) in dry benzene (16 mL) was added thiosalicyclic acid (616 mg, 4.0 mmol) at 0 °C under N_2 atmosphere. After completion of addition (5 min), DMF (8 mL) was added to the mixture at 0 °C, and the solution was stirred until a clear solution was obtained (ca. 20 min). Then (1*S*)-(−)-10-iodo-2-*exo*-bornanol (1.12 g, 4.0 mmol) in dry benzene (2 mL) was added dropwise to the mixture at 0 °C, and the whole mixture was stirred at 95 °C for 6 h. The reaction was quenched with H_2O (6 mL) followed by acidification with 1 N HCl, and the mixture was extracted with AcOEt (70 mL × 3). The combined extracts were washed with water (15 mL × 3) followed by brine (10 mL × 1) and dried over $MgSO_4$. After removal of the solvent, the residual oil was purified by column chromatography (hexane/AcOEt = 1/1) to give pure product **4a** (718 mg, 59%) as colorless crystals: mp 193−195 °C; $[\alpha]^{26}_D$ −8.08° (*c* 0.967, EtOH); IR (KBr) 2952, 1682 cm^{-1}; ^1H NMR δ: 0.91 (s, 3H), 1.12 (s, 3H), 1.24−1.41 (m, 3H), 1.58−1.84 (m, 6H), 2.89 (d, J = 9.9, 1H),3.21 (d, J = 10.4, 1H), 4.08 (dd, J = 3.9, 7.7, 1H), 7.24−7.29 (m, 1H), 7.50−7.52 (m 2H), 8.08 (d, J = 7.1, 1H); ^{13}C NMR δ: 20.3, 21.1, 27.5, 31.1, 33.4, 39.6, 45.3, 48.5, 52.0, 76.7, 124.9, 131.1, 132.3, 132.7, 133.2, 133.3, 164.7; MS *m*/*z*: 306 (M^+), 288 (M^+ − 18). Anal. Calcd for $C_{17}H_{22}O_3S$: C, 66.64; H, 7.24. Found: C, 66.67; H, 7.07.

2-({(1*S*,2*R*,4*R*)-2-Hydroxy-7,7-dimethylbicyclo[2.2.1]-heptan-1-yl}methylthio)nicotinic acid (4b). To a stirred suspension of NaH (60%, 84 mg, 2.1 mmol) in dry benzene (4 mL) was added 2-mercaptonicotinic acid (155 mg, 1 mmol) at 0 °C under N_2 atmosphere. After completion of addition (5 min), DMF (2 mL) was added to the mixture at 0 °C, and the solution was stirred until a clear solution was obtained (ca. 20 min). Then (1*S*)-(−)-10-iodo-2-*exo*-bornanol (280 mg, 1.0 mmol) in dry benzene (1 mL) was added dropwise to the mixture at 0 °C, and the whole mixture was stirred at 120 °C for 5.5 h. The reaction was quenched with H_2O (4 mL) followed by acidification with 1 N HCl to pH = 6, and the mixture was extracted with AcOEt (60 mL × 3). The combined extracts were washed with water (10 mL × 3) followed by brine (10 mL) and dried over $MgSO_4$. After removal of the solvent, the residual oil was purified by column chromatography (hexane/AcOEt = 1/1) to give pure product **4b** (161 mg, 52%) as colorless crystals: mp 152−154 °C; $[\alpha]^{26}_D$ +73.33° (*c* 1.03, EtOH); IR (KBr) 2955, 1712 cm^{-1}; ^1H NMR δ: 0.92 (s, 3H), 1.0−1.05 (m, 1H), 1.20 (s, 3H), 1.29−1.40 (m, 1H), 1.60−1.82 (m, 5H), 2.85 (d, J = 14.8, 1H), 3.78 (dd, J = 3.3, 7.7, 1H), 3.85 (d, J = 14.8, 1H), 7.13 (dd, J = 4.9, 7.7, 1H), 8.33 (dd, J = 2.2, 7.7, 1H), 8.56 (dd, J = 2.2, 4.9, 1H); ^{13}C NMR δ: 20.5, 21.1, 27.4, 29.8, 31.7, 38.9, 45.8, 48.2, 53.2, 75.9, 118.8, 123.2, 140.6, 152.0, 163.8, 168.7; MS *m*/*z*: 307 (M^+), 289 (M^+ − 18). Anal. Calcd for $C_{16}H_{21}NO_3S$: C, 62.51; H, 6.89; N, 4.56. Found: C, 62.26; H, 6.89; N, 4.28.

3-({(1*S*,2*R*,4*R*)-2-Hydroxy-7,7-dimethylbicyclo[2.2.1]-heptan-1-yl}methylthio)acrylic Acid (4c). To a solution of methyl-3-({(1*S*,2*R*,4*R*)-2-hydroxy-7,7-dimethylbicyclo[2.2.1]-heptan-1-yl}methylthio)acrylate[23] (600 mg, *Z*/*E* = ca. 4/1, 2.22 mmol) in THF−H_2O−EtOH (1/1/1, 15 mL) was added a solution of 1 N aqueous NaOH (8 mL, 8 mmol), and then the reaction mixture was stirred under N_2 atmosphere at room temperature overnight. After acidification with 2 N HCl (ca. 5 mL), the reaction mixture was extracted with CH_2Cl_2 (75 mL × 3). The combined organic layer was then washed with H_2O (15 mL × 2) followed by brine (15 mL × 1) and dried over $MgSO_4$. Evaporation of the solvent under reduced pressure afforded the product **4c** (570 mg) in quantitative yield as a white solid. (*Z*/*E* = ca. 4/1). IR (neat) 2952, 1681 cm^{-1}; ^1H NMR δ: (*Z*)-**4c**: 0.87 (s, 3H), 1.0−1.2 (m, 1H), 1.08 (s, 3H), 1.2−1.8 (m, 8H), 2.78 (d, J = 12.1, 1H), 3.21 (d, J = 12.1, 1H), 3.94 (dd, J = 3.8, 8.2, 1H), 5.86 (d, J = 9.9, 1H), 7.38 (d, J = 9.9, 1H); (*E*)-**4c**: 0.90 (s, 3H), 1.0−1.2 (m, 1H), 1.10 (s, 3H), 1.2−1.8 (m, 8H), 2.7 (d, J = 12.1, 1H), 3.19 (d, J = 12.1, 1H), 3.90 (dd, J = 3.3, 8.0, 1H), 5.81 (d, J = 14.9, 1H), 7.91 (d, J = 15.4, 1H); MS *m*/*z*: 257 (M^+ + 1), 256 (M^+); HRMS calcd for $C_{13}H_{20}O_3S$: 256.1133. Found 256.1114.

Ethyl-(*Z*)-3-({(1*S*,2*R*,4*R*)-2-Hydroxy-7,7-dimethylbicyclo-[2.2.1]heptan-1-yl}methylthio)crotonate. To a solution of (−)-10-mercaptoisoborneol (168 mg, 1.0 mmol) and ethyl 2-butynoate (112 mg, 1.0 mmol) in EtOH−H_2O (9:1) (5 mL) was added Et_3N (5 drops) at room temperature under N_2 atmosphere. The mixture was then stirred at room temperature for 24 h. The solvent was evaporated, and the residue was then extracted from H_2O (10 mL) with EtOAc (50 mL × 3). The combined organic layer was washed with H_2O (10 mL × 1) followed by brine (10 mL × 1) and dried over $MgSO_4$. Removal of the solvent under reduced pressure afforded the crude products which were then purified by chromatography (hexane/EtOAc = 10/1 to 5/1) on silica gel gave product (180 mg, 44%) yield as a colorless oil; $[\alpha]^{26}_D$ = −39.9° (*c* 0.94, $CHCl_3$); IR (neat) 2953, 1698 cm^{-1}; ^1H NMR δ: 0.87 (s, 3H), 1.08 (s, 3H), 1.02−1.10 (m, 1H), 1.30−1.41 (m, 1H), 1.27 (t, J = 7.1, 3H), 1.50−1.62 (m, 2H), 1.68−1.79 (m, 4H), 2.28 (d, J = 1.1, 3H), 2.80 (d, J = 10.4, 1H), 3.21 (d, J = 10.4, 1H), 3.97−4.09 (m, 1H), 4.16 (q, J = 7.1, 2H), 5.83 (d, J = 1.1, 1H); ^{13}C NMR δ: 14.5, 20.1, 20.8, 24.4, 27.2, 29.8, 30.5, 39.8, 45.1, 48.1, 51.4, 59.6, 75.9, 112.2, 158.4, 166.1; MS *m*/*z*: 299 (M^+ + 1), 298 (M^+); HRMS calcd for $C_{16}H_{26}O_3S$: 298.1602. Found 298.1580.

***Z*-3-({(1*S*,2*R*,4*R*)-2-Hydroxy-7,7-dimethylbicyclo[2.2.1]-heptan-1-yl}methylthio)crotonic Acid (4d).** To a solution of ethyl-(*Z*)-3-({(1*S*,2*R*,4*R*)-2-hydroxy-7,7-dimethylbicyclo[2.2.1]-heptan-1-yl}methylthio)crotonate (233 mg, 0.78 mmol) in THF−H_2O−EtOH (1/1/1, 6 mL) was added a solution of 2 N aqueous NaOH (4 mL, 8 mmol), and then the reaction mixture was stirred under N_2 atmosphere at room temperature for 27 h. After acidification with 1 N HCl (ca. 10 mL), the reaction mixture was extracted with CH_2Cl_2 (50 mL × 3). The combined organic layer was then washed with H_2O (10 mL × 1) followed by brine (10 mL × 1) and dried over $MgSO_4$. Evaporation of the solvent under reduced pressure afforded the crude product which, after purification by chromatography (hexane/EtOAc = 2/1), gave pure product **4d** (97 mg, 46%) as a white solid: mp 145−147 °C; $[\alpha]^{26}_D$ −43.54° (*c* 1.05, $CHCl_3$); IR (KBr) 2953, 1672 cm^{-1}; ^1H NMR δ: 0.87 (s, 3H), 1.05−1.09 (m, 1H), 1.07 (s, 3H), 1.34−1.35 (m, 1H), 1.49−1.53 (m, 1H), 1.70−1.79 (m, 4H), 2.30 (s, 3H), 2.79 (d, J = 10.4, 1H), 3.20 (d, J = 10.4, 1H), 3.98 (dd, J = 3.8, 8.2, 1H), 5.84, (s, 1H); ^{13}C NMR δ: 20.3, 20.9, 24.9, 27.4, 30.2, 30.72, 39.9, 45.2, 48.4, 51.6, 76.2, 111.8, 161.7, 170.9; MS *m*/*z*: 272 (M^+ + 2). Anal. Calcd for $C_{14}H_{22}O_3S$: C, 62.19; H, 8.20. Found: C, 62.44; H, 8.20.

Ethyl-3-({(1*S*,2*R*,4*R*)-2-Hydroxy-7,7-dimethylbicyclo-[2.2.1]heptan-1-yl}methylthio)propionate. To a stirred suspension of NaH (60%, 84 mg, 2.1 mmol) in dry benzene (8 mL) was added ethyl 3-mercaptopropionate (268 mg, 2 mmol) at 0 °C. After completion of addition (5 min), DMF (4 mL) was added to the mixture at 0 °C, and the solution was stirred until a clear solution was obtained (ca. 20 min). Then (1*S*)-(−)-10-iodo-2-*exo*-bornanol (550 mg, 1.96 mmol) in dry benzene (1 mL) was added dropwise to the mixture at 0 °C, and the whole mixture was stirred at 0 °C to room temperature for 6.5 h under N_2 atmosphere. The reaction was quenched with H_2O (4 mL) and acidified with 1 N HCl. The mixture was then extracted with AcOEt (60 mL × 3). The combined extracts were washed with water (10 mL × 3) followed by brine (10 mL) and dried over $MgSO_4$. After removal of the solvent, the residual oil was purified by column chromatography (hexane/AcOEt =

40/1 to 10/1) to give pure product (280 mg, 61%) as a colorless oil. $[\alpha]^{26}_D$ −29.8° (c 1.17, $CHCl_3$); IR (neat) 2953, 1736 cm^{-1}; ^1H NMR δ: 0.82 (s, 3H), 1.05 (s, 3H), 1.26 (t, J = 7.2, 3H), 1.01−1.30 (m, 2H), 1.46−1.53 (m, 1H), 1.65−1.80 (m, 4H), 2.56−2.66 (m, 3H), 2.72−2.90 (m, 3H), 3.85 (dd, J = 3.8, 8.2, 1H), 4.11−4.19 (m, 3H); ^{13}C NMR δ: 14.5, 20.2, 20.9, 27.2, 27.4, 28.6, 31.2, 32.1, 35.0, 39.3, 45.3, 47.9, 52.3, 61.0, 172.1; MS m/z: 287 (M^+ + 1), 286 (M^+); HRMS calcd for $C_{15}H_{26}O_3S$: 286.1602. Found 286.1599.

3-({(1*S*,2*R*,4*R*)-2-Hydroxy-7,7-dimethylbicyclo[2.2.1]-heptan-1-yl}methylthio)propionic Acid (4e). To a solution of ethyl 3-({(1*S*,2*R*,4*R*)-2-hydroxy-7,7-dimethylbicyclo[2.2.1]-heptan-1-yl}methylthio)propionate (60 mg, 0.21 mmol) in THF−H_2O−EtOH (1:1:1, 1.5 mL) was added a solution of 1 N aqueous NaOH (0.5 mL, 0.5 mmol), and then the reaction mixture was stirred under N_2 atmosphere at room temperature overnight. After acidification with 1 N HCl (ca. 1 mL) the reaction mixture was extracted with CH_2Cl_2 (25 mL × 3). The combined organic layer was then washed with H_2O (5 mL × 1) followed by brine (5 mL × 1) and dried over $MgSO_4$. Evaporation of the solvent under reduced pressure afforded the crude product which, after purification by chromatography (hexane/EtOAc = 1/1) gave pure product **4e** (45 mg, 83%) as a yellow oil. $[\alpha]^{26}_D$ −40.39° (*c* 0.813, $CHCl_3$); IR (neat) 2952, 1712 cm^{-1}; ^1H NMR δ: 0.82 (s, 3H), 1.01−1.06 (m, 2H), 1.04 (s, 3H), 1.17−1.20 (m, 1H), 1.70−1.77 (m, 4H), 2.59 (d, J = 11.0, 1H), 2.58−2.86 (m, 7H), 3.88 (dd, J = 3.8, 8.2, 1H); ^{13}C NMR δ: 20.2, 20.9, 27.3, 28.3, 31.2, 32.2, 34.6, 39.2, 45.2, 47.9, 52.3, 76.9, 177.1; MS m/z: 259 (M^+ + 1), 258 (M^+); HRMS calcd for $C_{13}H_{22}O_3S$: 258.1290. Found: 258.1299.

General Procedure for Preparation of Spirosulfurans 5a−e. To a solution of sulfide **4a−e** (1.10 mmol) in CH_2Cl_2 (50 mL) was added *t*-BuOCl (0.14 mL, 1.16 mmol) dropwise at 0 °C under N_2 atmosphere. The mixture was stirred at 0 °C for 30 min followed by addition of Et_3N (0.17 mL, 1.21 mmol) dropwise, and then the reaction was stirred for 1.5 h at 0 °C to room temperature. The reaction mixture was worked up by removal of the solvent and excess reagents directly followed by diluting with H_2O (5 mL). The aqueous layer was extracted with EtOAc (50 mL × 3). The combined organic layer was then washed with H_2O (10 mL × 3) followed by brine (10 mL × 1) and dried over $MgSO_4$. Evaporation of the solvent under reduced pressure afforded the crude product which was purified by recrystallization to give the product **5a−d** as colorless crystals. Spirosulfurane **5e** was obtained by evaporation of the solvent directly, and the yield was caculated by the integration of the ^1H NMR of the crude products.

Spiro[4*H*-3a,6-methano-3*H*-1,2-benzoxasulfole-2,2′λ^4-[5*H*-1,2]benzoxathiole]-5′-one, 5,6,7,7a-tetrahydro-8,8-dimethyl-, [2*R*-(2α,3aα,6α,7a*β*)] (5a): 96%; mp 212−213 °C (hexanes−EtOAc); $[\alpha]^{26}_D$ +88.79° (*c* 0.7667, $CHCl_3$); IR (neat) 2985, 1664 cm^{-1}; ^1H NMR δ: 0.96 (s, 3H), 1.0−1.3 (m, 2H), 1.23 (s, 3H), 1.78−2.0 (m, 4H), 2.22−2.4 (m, 1H), 3.35 (d, J = 14.3, 1H), 4.51 (d, J = 14.3, 1H), 4.56 (dd, J = 3.3, 7.7, 1H), 7.64−7.81 (m, 3H), 8.20−8.24 (m, 1H); ^{13}C NMR δ: 20.3, 20.5, 26.9, 28.2, 37.8, 45.4, 46.8, 55.1, 59.4, 94.5, 125.7, 130.4, 132.1, 132.7, 134.5, 138.6, 168.3; MS m/z: 305 (M^+ + 1), 304 (M^+). Anal. Calcd for $C_{17}H_{20}O_3S$: C, 67.07; H, 6.62. Found: C, 66.96; H, 6.46.

Recrystallization of the product from hexanes−EtOAc gave crystals which were suitable for X-ray analysis. Crystallographic data of **5a**: $C_{17}H_{20}O_3S$, MW = 304.40, orthorhombic, space group $P2_12_12_1$ (no. 19) with a = 11.206(3) Å, b = 12.282-(2) Å, c = 10.965(3) Å, V = 1509.1(5) Å^3, Z = 4, density(calcd) = 1.34 g cm^{-3}, F(000) = 648, λ = 0.71069 Å, T = 293 K, μ (Mo−Kα) = 2.22 cm^{-1}. Intensity data were collected on a Rigaku AFC7R diffractometer using a 0.15 × 0.15 × 0.20 mm^3 sized crystal; 1999 unique reflections; 766 with $I > 3.00\sigma(I)$ were used in refinement; R = 4.2%, R_w = 4.4%.

Spiro[4*H*-3a,6-methano-3*H*-1,2-benzoxasulfole-2,2′λ^4-[5*H*-1,2]-3″-picoloxathiole]-5′-one, 5,6,7,7a-tetrahydro-8,8-dimethyl-, [2*R*-(2α,3aα,6α,7a*β*)] (5b): 94%; mp 204−205 °C (hexane−CH_2Cl_2); $[\alpha]^{26}_D$ +97.17° (*c* 1.227, $CHCl_3$); IR (neat) 2955, 1665 cm^{-1}; ^1H NMR δ: 0.98 (s, 3H), 1.10−1.26 (m, 2H), 1.22 (s, 3H), 1.82−2.0 (m, 4H), 2.32−2.48 (m, 1H), 3.45 (d, J = 14.5, 1H), 4.56 (d, J = 14.3, 1H), 5.07 (dd, J = 3.3, 7.7, 1H), 7.68 (dd, J = 4.4, 7.7, 1H), 8.52 (dd, J = 1.6, 7.7, 1H), 8.82 (dd, J = 1.6, 4.5, 1H); ^{13}C NMR δ: 20.4, 20.5, 26.8, 28.0, 30.0, 37.9, 45.6, 46.9, 54.9, 58.3, 97.5, 111.5, 127.0, 139.2, 152.0, 200.4; MS m/z: 306 (M^+ + 1). Anal. Calcd for $C_{16}H_{19}NO_3S$: C, 62.93; H, 6.27; N, 4.59. Found: C, 62.61; H, 6.17; N, 4.17.

Recrystallization of the product from hexane−CH_2Cl_2 gave crystals which were suitable for X-ray analysis. Crystallographic data of **5b**: $C_{16}H_{19}NO_3S$, MW = 305.39, orthorhombic, space group $P2_12_12_1$ (no. 19) with a = 11.144(3) Å, b = 12.670(3) Å, c = 10.615(3) Å, V = 1498.8(6) Å^3, Z = 4, density-(calcd) = 1.353 g cm^{-3}, F(000) = 648, λ = 0.71069 Å, T = 293 K, μ (Mo−Kα) = 2.25 cm^{-1}. Intensity data were collected on a Rigaku AFC7R diffractometer using a 0.20 × 0.20 × 0.25 mm^3 sized crystal; 1987 unique reflections; 1264 with $I > 3.00\sigma(I)$ were used in refinement; R = 3.9%, R_w = 3.9%.

Spiro[4*H*-3a,6-methano-3*H*-1,2-benzoxasulfole-2,2′λ^4-[5*H*-1,2]oxasulfol]-5′-one, 5,6,7,7a-tetrahydro-8,8-dimethyl-, [2*R*-(2α,3aα,6α,7a*β*)]- (5c): 98%; mp 80−82 °C (hexane−CH_2Cl_2); $[\alpha]^{26}_D$ −138.81° (*c* 0.97, $CHCl_3$); IR (neat) 2957, 1657 cm^{-1}; ^1H NMR δ: 0.94 (s, 3H), 0.8−1.38 (m, 2H), 1.07 (s, 3H), 1.65−2.0 (m, 4H), 3.19 (d, J = 14.3, 1H), 4.33 (dd, J = 3.3, 7.5, 1H), 4.40 (d, J = 14.3, 1H), 6.80 (d, J = 6.0, 1H), 6.84 (d, J = 6.0, 1H); ^{13}C NMR δ: 20.1, 20.3, 26.8, 28.4, 37.5, 45.6, 46.5, 54.2, 58.9, 95.7, 136.8, 144.6, 168.4; MS m/z: 256 (M^+ + 2), 255 (M^+ + 1), 254 (M^+); HRMS calcd for $C_{13}H_{18}O_3S$: 254.0977. Found 254.0982.

Spiro[4*H*-3a,6-methano-3*H*-1,2-benzoxasulfole-2,2′λ^4-3′-methyl-[5*H*-1,2]oxasulfol]-5′-one, 5,6,7,7a-tetrahydro-8,8-dimethyl-, [2*R*-(2α,3aα,6α,7a*β*)]- (5d): 91%; mp 91−93 °C (hexane−CH_2Cl_2); $[\alpha]^{26}_D$ −25.90° (*c* 0.96, $CHCl_3$); IR (KBr) 2952, 1662 cm^{-1}; ^1H NMR δ: 0.94 (s, 3H), 1.0−1.4 (m, 3H), 1.12 (s, 3H), 1.65−2.20 (m, 4H), 2.26 (s, 3H), 3.33 (d, J = 14.3, 1H), 4.21 (dd, J = 2.7, 7.1, 1H), 4.43 (d, J = 14.8, 1H), 6.55 (s, 1H); ^{13}C NMR δ: 16.1, 20.2, 20.4, 26.9, 28.3, 38.0, 45.3, 46.6, 53.9, 58.7, 95.6, 132.4, 155.4, 169.1; MS m/z: 269 (M^+ + 1), 268 (M^+); HRMS calcd for $C_{14}H_{20}O_3S$: 268.1133. Found: 268.1169.

Spiro[4*H*-3a,6-methano-3*H*-1,2-benzoxasulfole-2,2′λ^4-3′,4′-dihydro-[5*H*-1,2]oxasulfol]-5′-one, 5,6,7,7a-tetrahydro-8,8-dimethyl-, [2*R*-(2α,3aα,6α, 7a*β*)]- (5e): 80%; ^1H NMR δ: 0.93 (s, 3H), 1.0−1.1 (m, 1H), 1.04 (s, 3H), 1.65−2.0 (m, 4H), 2.0−2.2 (m, 2H), 2.8−3.0 (m, 2H), 3.4−3.5 (m, 2H), 3.60 (d, J = 14.3, 1H), 4.42 (dd, J = 4.4, 7.7, 1H), 4.15 (d, J = 14.8, 1H).

(*S*$_S$)-2-({(1*S*,2*R*,4*R*)-2-Hydroxy-7,7-dimethylbicyclo[2.2.1]-heptan-1-yl}methanesulfinyl)benzoic Acid (7a). To a solution of spirosulfurane **5a** (15 mg, 0.05 mmol) in EtOH (2 mL) was added 1 N HCl (0.1 mL, 0.1 mmol) at room temperature under N_2 atmosphere. The reaction mixture was then stirred at room temperature for 48 h. After diluting with H_2O (1 mL), the reaction mixture was extracted with CH_2Cl_2 (10 mL × 3). The combined organic layer was then washed with H_2O (3 mL × 1) followed by brine (3 mL × 1) and dried over $MgSO_4$. Evaporation of the solvent under reduced pressure afforded the crude product which, after purification by recrystallization from CH_2Cl_2−EtOH, gave pure product **7a** (15.5 mg, 98%) as colorless crystals: mp 202−204 °C; $[\alpha]^{26}_D$ −268.37° (*c* 1.26, EtOH); IR (KBr) 2943, 1677 cm^{-1}; ^1H NMR δ: 0.84 (s, 3H), 1.02 (s, 3H),1.20−1.30 (m, 1H), 1.50−1.62 (m, 1H), 1.71−2.07 (m, 7H), 2.50 (d, J = 13.2, 1H), 3.37 (d, J = 13.2, 1H), 4.50 (t, J = 5.5, 1H), 7.60 (t, J = 7.2, 1H), 7.87 (t, J = 7.2), 8.19 (d, J = 7.7, 1H), 8.36 (d, J = 7.7, 1H); ^{13}C NMR δ: 20.4, 20.9, 27.8, 30.7, 30.8, 44.7, 49.1, 52.1, 60.4, 124.9, 126.6, 130.3, 131.7, 134.4, 150.2, 168.5; MS m/z: 304 (M^+ − 18). Anal. Calcd for $C_{17}H_{22}O_4S$: C, 63.33; H, 6.88. Found: C,63.09; H, 6.83.

Recrystallization of the product from CH_2Cl_2−EtOH gave crystals which were suitable for X-ray analysis. Crystallographic data of **7a**: $C_{17}H_{22}O_4S$, MW = 322.42, monoclinic, space group $P2_1$ (no. 4) with a = 6.961(4) Å, b = 10.993(3) Å, c = 10.765(4) Å, β = 103.04(4)°, V = 802.6(6) Å^3, Z = 2, density-(calcd) = 1.334 g cm^{-3}, F(000) = 344.00, λ = 0.71069 Å, T = 293 K, μ (Mo−Kα) = 2.17 cm^{-1}. Intensity data were collected on a Rigaku AFC7R diffractometer using a 0.30 × 0.20 × 0.20

mm^3 sized crystal; 2084 unique reflections; 1138 with $I > 3.00\sigma(I)$ were used in refinement; $R = 4.1\%$, $R_w = 4.2\%$.

(S_S)-2-({(1*S*,2*R*,4*R*)-2-Hydroxy-7,7-dimethylbicyclo[2.2.1]-heptan-1-yl}methanesulfinyl)acrylic Acid (7c). Recrystallization of **5c** (131 mg, 0.51 mmol) from EtOH gave sulfoxide **7c** (122 mg, 94%) as colorless crystals: mp 140−141 °C; $[\alpha]^{26}_D$ −18.13° (*c* 0.82, $CHCl_3$) or −71.81° (*c* 1.08, EtOH); IR (KBr) 2927, 1673 cm^{-1}; ^{1}H NMR δ: 0.87 (s, 3H), 1.02 (s, 3H),1.08−1.43 (m, 3H), 1.72−2.0 (m, 6H), 2.97 (d, $J = 13.2$, 1H), 3.2 (d, $J = 13.2$, 1H), 4.33 (dd, $J = 3.8$, 7.7, 1H), 6.31 (d, $J = 9.9$, 1H), 7.14 (d, $J = 9.9$, 1H); ^{13}C NMR δ: 14.6, 20.2, 20.9, 27.2, 31.0, 39.5, 45.2, 48.2, 51.2, 59.7, 108.9, 159.1, 165.2; MS *m*/*z*: 254 ($M^+ - 18$). Anal. Calcd for $C_{13}H_{20}O_4S$: C, 57.31; H, 7.41. Found: C, 57.64; H, 7.52.

Recrystallization of the product from EtOAc−CH_2Cl_2 gave crystals which were suitable for X-ray analysis. Crystallographic data of **7c**: $C_{13}H_{20}O_4S$, MW = 272.36, orthorhombic, space group $P2_12_12_1$ (no. 19) with $a = 11.063(3)$ Å, $b = 12.150(3)$ Å, $c = 10.059(2)$ Å, $V = 1352.1(5)$ Å^3, $Z = 4$, density(calcd) = 1.338 g cm^{-3}, $F(000) = 584.00$, $\lambda = 0.71069$ Å, $T = 293$ K, μ (Mo−Kα) = 2.43 cm^{-1}. Intensity data were collected on a Rigaku AFC7R diffractometer using a $0.20 \times 0.20 \times 0.20$ mm^3 sized crystal; 1804 unique reflections; 962 with $I > 3.00\sigma(I)$ were used in refinement; $R = 4.3\%$, $R_w = 4.2\%$.

(S_S)-2-({(1*S*,2*R*,4*R*)-2-Hydroxy-7,7-dimethylbicyclo[2.2.1]-heptan-1-yl}methanesulfinyl)crotonic Acid (7d). Recrystallization of **5d** (44 mg, 0.16 mmol) from EtOH gave sulfoxide **7d** (41 mg, 91%) as colorless crystals: mp 155−157 °C; $[\alpha]^{26}_D$ −154.41° (*c* 1.05, EtOH); IR (KBr) 2955, 1687 cm^{-1}; ^{1}H NMR δ: 0.85 (s, 3H), 1.01 (s, 3H),1.06−1.58 (m, 3H), 1.7−2.0 (m, 6H), 2.28 (d, $J = 1.65$, 3H), 2.81 (d, $J = 12.6$, 1H), 3.06 (d, $J = 12.6$, 1H), 4.34 (dd, $J = 3.3$, 7.0, 1H), 6.21 (d, $J = 1.65$, 1H); ^{13}C NMR δ: 15.8, 20.2, 20.8, 27.7, 30.6, 38.9, 44.6, 49.1, 51.6, 56.6, 76.7, 120.3, 167.1, 168.4; MS *m*/*z*: 287 ($M^+ + 1$), 285 ($M^+ - 1$), 268 ($M^+ - 18$). Anal. Calcd for $C_{14}H_{22}O_4S$: C, 58.72; H, 7.75. Found: C, 58.78; H, 7.75.

(R_S)-2-({(1*S*,2*R*,4*R*)-2-Hydroxy-7,7-dimethylbicyclo[2.2.1]-heptan-1-yl}methanesulfinyl)benzoic Acid (8a). To a solution of spirosulfurane **5a** (34.5 mg, 0.11 mmol) in EtOH (2 mL) was added 1 N NaOH (0.2 mL, 0.2 mmol) at 0 °C under N_2 atmosphere. The reaction mixture was then stirred at 0 °C for 0.5 h. After acidification with 1 N HCl (ca. 0.5 mL), the reaction mixture was extracted with CH_2Cl_2 (15 mL × 3). The combined organic layer was then washed with H_2O (6 mL × 1) followed by brine (6 mL × 1) and dried over $MgSO_4$. Evaporation of the solvent under reduced pressure afforded the crude product which, after purification by recrystallization from EtOAc−CH_2Cl_2 gave pure product **8a** (31 mg, 88%) as colorless crystals: mp 208−210 °C; $[\alpha]^{26}_D$ +190.19° (*c* 0.76, EtOH); IR (KBr) 2957, 1699 cm^{-1}; ^{1}H NMR (CD_3OD) δ: 0.82 (s, 3H), 1.01 (s, 3H),1.22−1.27 (m, 1H), 1.60−1.70 (m, 1H), 1.75−1.87 (m, 5H), 2.01−2.15 (m, 1H), 3.00 (d, $J = 13.2$, 1H), 3.17 (d, $J = 12.6$, 1H), 3.30−3.32 (m, 1H), 4.14−4.92 (m, 1H), 7.68 (dt, $J = 1.1$, 7.7, 1H), 7.91 (dt, $J = 1.1$, 7.7, 1H), 8.17 (dd, $J = 1.6$, 7.7, 1H), 8.24 (dd, $J = 1.6$, 7.7, 1H); ^{13}C NMR (CD_3-OD) δ: 20.2, 20.9, 27.9, 31.4, 39.4, 46.6, 53.0, 60.1, 78.4, 124.9, 128.9, 131.7, 132.3, 134.8, 148.2, 167.9; MS *m*/*z*: 304 ($M^+ - 18$). Anal. Calcd for $C_{17}H_{22}O_4S$: C, 63.33; H, 6.88. Found: C, 63.75; H, 6.91.

Recrystallization of the product from hexanes−EtOAc−CH_2-Cl_2 gave crystals which were suitable for X-ray analysis. Crystallographic data of **8a**: $C_{17}H_{22}O_4S$, MW = 322.42, orthorhombic, space group $P2_12_12_1$ (no. 19) with $a = 13.124(3)$ Å, $b = 14.720(3)$ Å, $c = 8.659(2)$ Å, $V = 1672.8(5)$ Å^3, $Z = 4$, density-(calcd) = 1.280 g cm^{-3}, $F(000) = 688.00$, $\lambda = 0.71069$ Å, $T = 293$ K, μ (Mo−Kα) = 2.08 cm^{-1}. Intensity data were collected on a Rigaku AFC7R diffractometer using a $0.20 \times 0.20 \times 0.25$ mm^3 sized crystal; 2216 unique reflections; 1464 with $I > 3.00\sigma(I)$ were used in refinement; $R = 4.2\%$, $R_w = 4.1\%$.

(R_S)-2-({(1*S*,2*R*,4*R*)-2-Hydroxy-7,7-dimethylbicyclo[2.2.1]-heptan-1-yl}methanesulfinyl)nicotinic Acid (8b). The procedure described in the preparation of **8a** was similarly applied for **5b** (104 mg, 0.34 mmol) to prepare **8b** (93 mg, 90%) as colorless crystals: mp 239−240 °C (CH_2Cl_2−hexane); $[\alpha]^{26}_D$ +130.02° (*c* 0.50, EtOH); IR (KBr) 2949, 1699 cm^{-1}; ^{1}H NMR (CD_3OD) δ: 0.85 (s, 3H), 1.02 (s, 3H),1.2−1.29 (m, 2H), 1.61−1.69 (m, 1H), 1.76−1.89 (m, 4H), 2.0−2.13 (m, 1H), 3.13 (d, $J = 12.6$, 1H), 3.21 (d, $J = 13.2$, 1H), 3.23−3.31 (m, 1H), 4.13−4.17 (m, 1H), 7.7−7.74 (m, 1H), 8.5 (d, $J = 7.7$, 1H), 8.95−8.96 (m, 1H); ^{13}C NMR (CD_3OD) δ: 20.2, 20.9, 28.0, 31.3, 39.6, 46.5, 49.4, 53.0, 56.9, 78.3, 126.7, 128.3, 128.6, 128.9, 141.0, 164.8; MS *m*/*z*: 296. Anal. Calcd for $C_{16}H_{21}NO_4S$: C, 59.42; H, 6.54; N, 4.44. Found: C, 59.45; H, 6.55; N, 4.22.

Recrystallization of the product from hexane−CH_2Cl_2 gave crystals which were suitable for X-ray analysis. Crystallographic data of **8b**: $C_{16}H_{21}NO_4S$, MW = 323.41, monoclinic, space group $P2_1$ (no. 4) with $a = 7.235(2)$ Å, $b = 12.913(4)$ Å, $c = 8.858(2)$ Å, $\beta = 91.56(2)°$, $V = 828.4(3)$ Å^3, $Z = 2$, density (calcd) = 1.296 g cm^{-3}, $F(000) = 344.00$, $\lambda = 0.71069$ Å, $T = 293$ K, μ (Mo−Kα) = 2.12 cm^{-1}. Intensity data were collected on a Rigaku AFC7R diffractometer using a $0.25 \times 0.25 \times 0.20$ mm^3 sized crystal; 1995 unique reflections; 1709 with $I > 3.00\sigma(I)$ were used in refinement; $R = 3.7\%$, $R_w = 3.8\%$.

(R_S)-2-({(1*S*,2*R*,4*R*)-2-Hydroxy-7,7-dimethylbicyclo[2.2.1]-heptan-1-yl}methanesulfinyl)acrylic Acid (8c). The procedure described in the preparation of **8a** was similarly applied for **5c** (32 mg, 0.125 mmol) to prepare **8c** (33 mg, 97%) as colorless crystals: mp 158−160 °C; $[\alpha]^{26}_D$ +214.17° (*c* 1.20, EtOH); IR (KBr) 2954, 1684, 1613 cm^{-1}; ^{1}H NMR (CD_3OD) δ: 0.88 (s, 3H), 1.09 (s, 3H),1.15−1.33 (m, 2H), 1.49−1.56 (m, 1H), 1.72−1.91 (m, 5H), 2.93 (d, $J = 13.2$, 1H), 3.30−3.31 (m, 1H), 3.49 (d, $J = 13.2$, 1H), 4.0 (dd, $J = 3.8$, 7.7, 1H), 6.43 (d, $J = 9.9$, 1H), 7.01 (d, $J = 9.9$, 1H); ^{13}C NMR (CD_3OD) δ: 20.3, 20.9, 27.9, 31.3, 39.6, 46.5, 49.4, 52.7, 55.8, 78.2, 127.5, 156.1, 166.8; MS *m*/*z*: 273 ($M^+ + 1$). Anal. Calcd for $C_{13}H_{20}O_4S$: C, 57.33; H, 7.40. Found: C, 56.73; H, 7.29.

(R_S)-2-({(1*S*,2*R*,4*R*)-2-Hydroxy-7,7-dimethylbicyclo[2.2.1]-heptan-1-yl}methanesulfinyl)crotonic Acid (8d). The procedure described in the preparation of **8a** was similarly applied for **5d** (62 mg, 0.23 mmol) to prepare **8d** (64 mg, 97%) as colorless crystals: mp 188−190 °C; $[\alpha]^{26}_D$ +228.86° (*c* 1.50, EtOH); IR (KBr) 2959, 1687, 1630 cm^{-1}; ^{1}H NMR δ: 0.82 (s, 3H), 1.08 (s, 3H),1.09−1.17 (m, 1H), 1.62−1.71 (m, 1H), 1.74−1.83 (m, 7H), 2.27 (s, 3H), 2.72 (d, $J = 12.1$, 1H), 3.37 (d, $J = 12.6$, 1H), 4.12 (dd, $J = 3.8$, 8.2, 1H), 6.24 (s, 1H); ^{13}C NMR δ: 15.8, 20.2, 20.9, 27.4, 30.4, 38.7, 45.5, 48.7, 52.0, 55.0, 78.2, 120.5, 167.0, 167.2; MS *m*/*z*: 287 ($M^+ + 1$), 268 ($M^+ - 18$). Anal. Calcd for $C_{14}H_{22}O_4S$: C, 58.72; H, 7.75. Found: C, 58.78; H, 7.75.

General Procedure of Isomerization of Sulfoxide 7a and 8a. To a solution of sulfoxide **7a** (or **8a**) (0.05 mmol) in EtOH (2 mL) was added 1 N HCl (or NaOH) at room atmosphere under nitrogen atmosphere. The reaction mixture was then stirred under the conditions shown in Table 2. Similar workup as in the case of hydrolysis of **5a** afforded the products in yields exhibited in Table 2. The diastereomeric ratio of the sulfoxides was determined by the ^{1}H NMR integration of the crude products.

(S_S)-2-({(1*S*,2*R*,4*R*)-2-Hydroxy-7,7-dimethylbicyclo[2.2.1]-heptan-1-yl}methanesulfinyl)benzoic Acid-^{18}O (7a-^{18}O). To a solution of spirosulfurane **5a** (31 mg, 0.10 mmol) in anhydrous EtOH (2 mL) and $H_2{}^{18}O$ (0.005 mL, 97 atom % ^{18}O) was added 1 N HCl (in Et_2O, 0.01 mL, 0.01 mmol) at room temperature under N_2 atmosphere. The reaction mixture was then stirred at room temperature for 48 h. Evaporation of the solvent under reduced pressure afforded the product **7a-^{18}O** (32 mg, 97%) as a white solid.

(R_S)-2-({(1*S*,2*R*,4*R*)-2-Hydroxy-7,7-dimethylbicyclo[2.2.1]-heptan-1-yl}methanesulfinyl)benzoic Acid-^{18}O (8a-^{18}O). To a solution of spirosulfurane **5a** (31 mg, 0.10 mmol) in anhydrous EtOH (2 mL) was added NaOH (0.015 mL, 0.15 mmol, prepared from 7.8 mg NaOH and 0.02 mL $H_2{}^{18}O$, 97 atom % ^{18}O) at 0 °C under N_2 atmosphere. The reaction mixture was then stirred at 0 °C for 0.5 h. After acidification with 1 N HCl (in Et_2O, 0.2 mL, 0.2 mmol), the reaction mixture was diluted with anhydrous CH_2Cl_2 (15 mL) and dried over $MgSO_4$. Evaporation of the solvent under reduced pressure afforded the product **8a-^{18}O** (33 mg, 99%) as a white solid.

(S_S)-Methyl-2-({(1*S*,2*R*,4*R*)-2-Hydroxy-7,7-dimethylbicyclo[2.2.1]heptan-1-yl}methanesulfinyl)benzonate (9).

To a solution of sulfoxide **7a** (30 mg, 0.093 mmol) in Et_2O (8 mL) was added CH_2N_2 (ca. 2 mL in Et_2O) at 0 °C under N_2 atmosphere. The reaction mixture was then stirred at 0 °C to room temperature for 3 h. Evaporation of solvent and excess reagents afforded the pure product (30 mg, 96%) as a white solid: mp 100−102 °C; $[\alpha]^{26}_D$ −284.74° (*c* 1.18, $CHCl_3$); IR (KBr) 2953, 1710 cm^{-1}; ^1H NMR δ: 0.81 (s, 3H), 1.04 (s, 3H),1.0−1.2 (m, 1H), 1.30−1.42 (m, 1H), 1.6−2.2 (m, 5H), 2.59 (d, J = 13.7, 1H), 3.39 (d, J = 13.2, 1H), 4.00 (s, 3H), 4.1−4.35 (m, 2H), 7.60 (t, J = 7.7, 1H), 7.86 (t, J = 7.7, 1H), 8.11 (t, J = 7.7, 1H), 8.70 (t, J = 7.7, 1H); ^{13}C NMR δ: 20.3, 20.8, 27.8, 30.8, 39.6, 44.7, 49.0, 52.3, 53.3, 59.7, 125.1, 126.1, 130.3, 130.9, 134.3, 150.0, 166.3; MS *m*/*z*: 337 (M^+ + 1), 318 (M^+ − 18), 184, 152, 91. Anal. Calcd for $C_{18}H_{24}O_4S$: C, 64.26; H, 7.19. Found: C, 64.22; H, 6.97.

(R_S)-Methyl 2-({(1*S*,2*R*,4*R*)-2-Hydroxy-7,7-dimethylbicyclo[2.2.1]heptan-1-yl}methanesulfinyl)benzonate (10). To a solution of sulfoxide **8a** (60 mg, 0.19 mmol) in CH_2Cl_2 (25 mL) was added CH_2N_2 (ca. 2 mL in Et_2O) at 0 °C under N_2 atmosphere. The reaction mixture was then stirred at 0 °C to room temperature for 3 h. Evaporation of solvent and excess reagents afforded the pure product (63 mg, 100%) as a white solid: mp 103−105 °C; $[\alpha]^{26}_D$ +196.11° (*c* 0.8, $CHCl_3$); IR (KBr) 2955, 1708 cm^{-1}; ^1H NMR δ: 0.80 (s, 3H), 1.03 (s, 3H),1.2−1.3 (m, 1H), 1.75−2.01 (m, 6H), 2.99 (d, J = 12.6, 1H), 3.06 (d, J = 12.6, 1H), 3.95 (s, 3H), 4.26 (dd, J = 4.4, 7.7, 1H), 4.3−4.4 (br, 1H), 7.59 (dt, J = 1.1, 7.7, 1H), 7.85 (dt, J = 1.1, 7.7, 1H), 8.11 (dd, J = 1.6, 7.7, 1H), 8.32 (dd, J = 1.6, 7.7, 1H); ^{13}C NMR δ: 20.2, 20.8, 27.4, 30.7, 38.7, 45.5, 48.5, 52.3, 52.9, 59.4, 124.7, 126.7, 130.4, 130.9, 134.1, 148.7, 165.6; MS *m*/*z*: 337 (M^+ + 1), 318 (M^+ − 18), 184, 152, 91. Anal. Calcd for $C_{18}H_{24}O_4S$: C, 64.26; H, 7.19. Found: C, 64.33; H, 7.00.

(S_S)-Methyl 2-({(1*S*,2*R*,4*R*)-2-Hydroxy-7,7-dimethylbicyclo[2.2.1]heptan-1-yl}methanesulfinyl)benzonate-^{18}O (9-^{18}O). To a solution of sulfoxide **7a-^{18}O** (32 mg, 0.1 mmol) in Et_2O (10 mL) was added CH_2N_2 (ca. 2 mL in Et_2O) at 0 °C under N_2 atmosphere. The reaction mixture was then stirred at 0 °C to room temperature for 3 h. Evaporation of solvent and excess reagents afforded the pure product (33 mg, 98%) as a white solid. MS *m*/*z*: 339 (M^+ + 1), 320, 186, 154, 91.

(R_S)-Methyl 2-({(1*S*,2*R*,4*R*)-2-Hydroxy-7,7-dimethylbicyclo[2.2.1]heptan-1-yl}methanesulfinyl)benzonate-^{18}O (10-^{18}O). To a solution of sulfoxide **8a-^{18}O** (33 mg, 0.10 mmol) in CH_2Cl_2 (25 mL) was added CH_2N_2 (ca. 2 mL in Et_2O) at 0 °C under N_2 atmosphere. The reaction mixture was then stirred at 0 °C to room temperature for 3 h. Evaporation of solvent and excess reagents afforded the pure product (31 mg, 91%) as a white solid. MS *m*/*z*: 339 (M^+ + 1), 320, 186, 154, 91.

(S_S)-2-({(1*S*,2*R*,4*R*)-2-Hydroxy-7,7-dimethylbicyclo[2.2.1]heptan-1-yl}methanesulfinyl)benzoic Acid-^{17}O (7a-^{17}O). To a solution of spirosulfurane **5a** (31 mg, 0.10 mmol) in anhydrous EtOH (2 mL) and $H_2{}^{17}O$ (0.012 mL, 20.3 atom % ^{17}O) was added 1 N HCl (in Et_2O, 0.01 mL, 0.01 mmol) at room temperature under N_2 atmosphere. The reaction mixture was then stirred at room temperature for 48 h. Evaporation of the solvent under reduced pressure afforded the product **7a-^{17}O** (31 mg, in 96%) as a white solid. ^{17}O NMR δ: −8.103.

(R_S)-2-({(1*S*,2*R*,4*R*)-2-Hydroxy-7,7-dimethylbicyclo[2.2.1]heptan-1-yl}methanesulfinyl)benzoic Acid-^{17}O (8a-^{17}O). To a solution of spirosulfurane **5a** (30.5 mg, 0.10 mmol) in anhydrous EtOH (2 mL) was added NaOH (0.015 mL, 0.17 mmol, prepared from 6.8 mg of NaOH and 0.015 mL of $H_2{}^{17}O$, 20.3 atom % ^{17}O) at 0 °C under N_2 atmosphere. The reaction mixture was then stirred at 0 °C for 0.5 h. After acidification with 1 N HCl (in Et_2O, 0.2 mL, 0.2 mmol), the reaction mixture was diluted with anhydrous CH_2Cl_2 (15 mL) and dried over $MgSO_4$. Evaporation of the solvent under reduced pressure afforded the product **8a-^{17}O** (31 mg, in 96%) as a white solid. ^{17}O NMR δ: −9.184.

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Supporting Information Available: Detailed structure determination summary and listings of final atomic coordinates, thermal parameters, bond lengths, and bond angles for compounds **5b**, **7c**, and **8b** (49 pages). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

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