Regio- and stereoselective 1,3-Oxathiolane formation in the reaction of Thiolactones with optically active oxiranes

Fu, Changchun; Linden, Anthony; Heimgartner, Heinz

Abstract: The reactions of 3H-isobenzofuran-1-thione (1) with (S)-2-methyl oxirane (2) and (R)-2-phenyloxirane (6) in the presence of SiO2 in anhydrous CH2Cl2 led to two pairs of diastereoisomeric spirocyclic 1,3-oxathiolanes, i.e., 3 and 4 with a Me group at C(5'), and 7 and 8 with a Ph group at C(4'), respectively (Schemes 2 and 3). In both cases, 3H-isobenzofuran-1-one (5) was formed as a main product. The analogous reactions of 3,4-dihydro-2H-[1]benzopyran-2-thione (9) and 3,4,5,6-tetrahydro-2H-pyran-2-thione (14) with 2 and 6 yielded four pairs of the corresponding diastereoisomeric spirocyclic compounds 10 and 11, 12 and 13, 15 and 16, and 18 and 19, respectively (Schemes 4 - 7). In the reaction of 14 with 6, the 1,3-oxathiolane 20 with a Ph group at C(2) was also formed. The structures of 3, 7, 8, 10, 19, and 20 were established by X-ray crystallography (Figs.1-4). In contrast to the thiolactones 1, 9, and 14, the thioesters 21a-21d did not react with (R)-2-phenyloxirane (6) either in the presence of SiO2 or under more-drastic conditions with BF3 . Et2O or SnCl4 (Scheme 8). The results show that spirocyclic 1,3-oxathiolanes can be prepared from thiolactones with oxiranes. The nucleophilic attack of the thiocarbonyl S-atom at the SiO2-activated oxirane ring proceeds with high regio- and stereoselectivity via an SN2-type mechanism.

DOI: https://doi.org/10.1002/hlca.200490205

Posted at the Zurich Open Repository and Archive, University of Zurich
ZORA URL: https://doi.org/10.5167/uzh-79816
Accepted Version

Originally published at:
DOI: https://doi.org/10.1002/hlca.200490205
Regio- and Stereoselective 1,3-Oxathiolane Formation in the Reaction of Thiolactones with Optically Active Oxiranes

by Changchun Fu1, Anthony Linden, and Heinz Heimgartner*

Organisch-chemisches Institut der Universität Zürich

Winterthurerstr. 190, CH-8057 Zürich

1) Part IV of the projected Ph.D. thesis of C. F., University of Zurich. Part I: see [1], Part II: see [2], Part III: see [3].
The reactions of 3H-isobenzofuran-1-thione (1) with (S)-2-methyloxirane (2) and (R)-2-phenyloxirane (6) in the presence of SiO$_2$ in anhydrous CH$_2$Cl$_2$ led to two pairs of diastereoisomeric spirocyclic 1,3-oxathiolanes, i.e., 3 and 4 with Me at C(5)\(\ddot{}\), and 7 and 8 with Ph at C(4)\(\ddot{}\), respectively (Schemes 2 – 3). In both cases, 3H-isobenzofuran-1-one (5) was formed as a main product. The analogous reactions of chroman-2-thione (9) and tetrahydropyran-2-thione (14) with 2 and 6 yielded four pairs of the corresponding diastereoisomeric spirocyclic compounds 10 and 11, 12 and 13, 15 and 16, and 18 and 19, respectively (Schemes 4 – 7). In the reaction of 14 with 6, the 1,3-oxathiolane 20 with Ph at C(2) was also formed. The structures of 3, 7, 8, 10, 19, and 20 were confirmed by X-ray crystallography (Figs. 1 – 4). In contrast to the thiolactones 1, 9, and 14, the thioesters 21a – d did not react with (R)-2-phenyloxirane (6) either in the presence of SiO$_2$ or under more drastic conditions with BF$_3$·Et$_2$O or SnCl$_4$ (Scheme 8). The results show that spirocyclic 1,3-oxathiolanes can be prepared from thiolactones with oxiranes. The nucleophilic attack of the thiocarbonyl S-atom at the SiO$_2$-activated oxirane ring proceeds with high regio- and stereoselectivity via an S$_N$2-type mechanism.
1. Introduction. – The formation of 1,3-oxathiolanes via the Lewis acid-catalyzed reaction of thiketones with oxiranes has been investigated thoroughly in recent years [1–6]. The reported results for this novel synthetic approach indicate that the reactions proceed with high regio- and stereoselectivity via an S_{N}2-type mechanism (Scheme 1). In the case of 2-alkyl-substituted oxiranes, the nucleophilic thiocarbonyl S-atom attacks preferentially at C(3) to give the 5-substituted 1,3-oxathiolanes with retention of the configuration at C(2) of the oxirane. On the other hand, 2-phenyloxirane is attacked mainly at C(2) under inversion of the configuration to yield the 4-phenyl-substituted products. Similar reactions have been observed with 1,3-thiazole-5(4H)-thiones [7][8], with cyclic trithiocarbonates [9], and with a rhodanine derivative [10].

Scheme 1

So far, the reaction of thioesters with oxiranes to afford 1,3-oxathiolanes, i.e., monothioorthoesters, has not been reported. With the aim of further extending the scope of the formation of 1,3-oxathiolanes, reactions of thiolactones such as 3H-isobenzofuran-1-thione (1), chroman-2-thione (9), tetrahydropyran-2-thione (14), as well as of thioesters, i.e., O-ethyl 2,2-dimethylthiopropanoate (21a), O-methyl thiooctanoate (21b), O-methyl thiobrezoate (21c), and O-phenyl thiobrezoate (21d), with optically active oxiranes were carried out. In the present paper, the results of the reactions of 1, 9, and 14 with (S)-2-methyloxirane (2) and (R)-2-phenyloxirane (6), and those of 21a–d with 6 are described.

2. Results. – 2.1. Reaction of 3H-Isobenzofuran-1-thione (1) with (S)-2-Methyloxirane (2). The reaction of 1 with 2 in a molar ratio of 1:2 was carried out in anhydrous CH_2Cl_2 at room temperature under an N_2 atmosphere in the presence of SiO_2. After stirring for 10 h, filtration and the usual workup by means of
column chromatography (CC) and HPLC on a chiral solid phase gave two diastereoisomeric spirocyclic 1,3-oxathiolanes 3 and 4 in 16 and 8% yield, respectively. The reaction was repeated under the same conditions, and the analysis of the reaction mixture by $^1$H-NMR spectroscopy showed 26% of 3, 10% of 4, as well as 54% of 3H-isobenzofuran-1-one (5) and 9% of 1, referenced to a weighed amount of 1,1,2,2-tetrachloroethane as a standard (Scheme 2). The enantiomeric excess (ee) of the products (> 99%) was determined by analytical HPLC (Chiralcel OD-H, hexane/i-PrOH 25:1).

Scheme 2

The structures of 3 and 4 were assigned on the basis of the elemental analyses, MS, IR, $^1$H- and $^{13}$C-NMR (2D-NOESY, HSQC, HSQC-TOCSY, and HMBC) spectra, which clearly indicated the relative configurations of the products. The 2D-NOESY spectrum of 3 showed one cross-signal between H–C(7) at 7.51–7.50 ppm and Me at 1.48 ppm, and that of 4 gave one cross-signal between H–C(7) at 7.49–7.48 ppm and H–C(5) at 4.70–4.67 ppm. The formation of 3 and 4 proceeded by nucleophilic attack of the thiocarbonyl S-atom at C(3) and, for this reason, the configuration at C(2) of the oxirane 2 is retained. Therefore, the configuration at C(1) in 3 and 4 should be 1R and 1S, respectively, relative to the known 5S-configuration$^2$). Finally, the structure of 3 was established by X-ray crystallography (Fig. 1).

Fig. 1

---

$^2$) This proposal was proven by the X-ray crystal-structure analysis of 10 (see Sect. 2.3).
The crystals of 3 were enantiomerically pure, but due to the quality of the crystals, the absolute configuration of the molecule could not be confirmed unequivocally by refinement of the absolute structure parameter. The enantiomer used in the refinement was therefore chosen to correspond with the known 5$\text{S}$-configuration. Based on this assumption, the stereogenic centre at C(1) has the R-configuration.

2.2. Reaction of 3H-Isobenzofuran-1-thione (1) with (R)-2-Phenyloxirane (6).

The analogous reaction of 1 with 6 (molar ratio 1:1.5) in anhydrous CH$_2$Cl$_2$ at room temperature for 10 h under an N$_2$ atmosphere in the presence of SiO$_2$ gave two diastereoisomeric spiroheterocycles 7 and 8 in 29 and 10% yield, respectively. The repetition of the reaction led to 7, 8, 5, and 1 in 29, 16, 29, and 26% yield, respectively, based on the $^1$H-NMR spectrum of the reaction mixture and 1,1,2,2-tetrachloroethane as an internal standard (Scheme 3). The ee values of the products (> 99%) were determined by analytical HPLC (Chiralcel OD-H, hexane/i-PrOH 25:1). It was to be expected that 7 and 8 were formed via the nucleophilic attack of the S-atom at C(2) of 6 with inversion of the configuration, leading to the S-configuration at C(4$\text{S}$) of the products.

Scheme 3

The structures of 7 and 8 were assigned on the basis of their elemental analyses and spectroscopic data, particularly 2D-NOESY, HSQC, HSQC-TOCSY, and HMBC NMR spectra, and they were confirmed by X-ray crystallography (Fig. 2). The 2D-NOESY spectrum of 7 showed no significant cross-signals which could be used for the determination of the relative configuration, but that of 8 gave one weak cross-signal between two ortho-H atoms of Ph at 7.59–7.58 ppm and two H–C(3) at 5.23–5.17 ppm, which indicated that 8 has the cis-configuration, i.e., the 1$R$,4$S$-configuration. Therefore, the diastereoisomer 7 should have the
1S,4\text{S}-configuration, which is in accordance with the X-ray crystal-structure analysis.

Fig. 2

The crystals of 7 and 8 were enantiomerically pure and the absolute configurations of the molecules have been determined independently by the diffraction experiment and found to have the 1S,4\text{S}- and 1R,4\text{S}-configuration, respectively.

2.3. Reaction of Chroman-2-thione (9) with (S)-2-Methyloxirane (2). The reaction of 9 with 2 in a molar ratio of 1:2 was carried out in anhydrous CH₂Cl₂ at room temperature under an N₂ atmosphere in the presence of SiO₂. After stirring for 3 d, filtration and the usual workup by means of column chromatography (CC) gave a 4:1 mixture (¹H-NMR) of two diastereoisomeric spirocyclic 1,3-oxathiolanes 10 and 11 in 40% total yield (Scheme 4). Separation of the mixture by HPLC led to 10 in 29% yield, but 11 could not be obtained in pure form because of its partial epimerization to 10. The ee of 10 (> 99%) was determined by analytical HPLC (Chiralcel OD-H, hexane/i-PrOH 50:1).

Scheme 4

The structure of 10 was again assigned on the basis of the elemental analysis and the spectroscopic data, particularly those obtained from NMR experiments. The 2D-NOESY spectrum of 10 showed one cross-signal between H–C(8) at 6.83 ppm and H–C(5\text{S}) at 4.83–4.78 ppm, which clearly indicated the S-configuration at C(2) relative to the known 5\text{S}-configuration. Therefore, the diastereoisomer 11, should have the 2R,5\text{S}-configuration. Finally, the structure of 10 was established by X-ray crystallography (Fig. 3).
The crystals of 10 were enantiomerically pure and the absolute configuration of the molecule has been determined independently by the diffraction experiment: the molecule has the expected 2S,5S configuration.

2.4. Reaction of Chroman-2-thione (9) with (R)-2-Phenylloxirane (6). The analogous reaction of 9 with 6 (molar ratio 1:1.5) in anhydrous CH₂Cl₂ at room temperature for 3 d under an N₂ atmosphere in the presence of SiO₂ gave two diastereoisomeric spirocyclic compounds 12 and 13 in 35 and 7% yield, respectively. The ee values of the products, determined by analytical HPLC (Chiralcel OD-H, hexane/i-PrOH 50:1), showed that 12 and 13 were formed with lower stereoselectivity, and partial racemization of ca. 10% was observed (Scheme 5).

The structures of 12 and 13 were assigned in the same way as that of 10. According to previous reactions of thiocarbonyl compounds with 6, the formation of 12 and 13 was expected to take place mainly via inversion of the configuration at C(2) of 6, which leads to the 4[R]-configuration of the products. The 2D-NOESY spectrum of 12 showed two cross-signals between two ortho-H atoms of Ph at 7.40–7.39 ppm and two H–C(3) at 2.60–2.55 and 2.51–2.46 ppm, respectively, which indicated the 2R,4[R]-configuration. On the other hand, the 2D-NOESY spectrum of 13 showed one cross-signal between two ortho-H atoms of Ph at 7.53 ppm and H–C(8) at 6.95–6.93 ppm, and another one between H–C(4[R]) at 4.94 ppm and two H–C(3) at 2.51–2.40 ppm indicating the 2S,4S-configuration.
2.5. Reaction of Tetrahydropyran-2-thione (14) with (S)-2-Methyloxirane (2).

The reaction of 14 with 2 (molar ratio 1:2) in anhydrous CH₂Cl₂ at 0°C for 2 d under an N₂ atmosphere in the presence of SiO₂ gave two diastereoisomeric spirocyclic 1,3-oxathiolanes 15, 16, together with lactone 17 in 63, 22, and 15% yield, respectively, based on the ¹H-NMR spectrum of the reaction mixture and 1,1,2,2-tetrachloroethane as a standard (Scheme 6). Separation of the two diastereoisomers by MPLC and HPLC gave 15 as a pure compound in 38% yield, but 16 was obtained only in 90% purity because of its partial epimerization to 15. The ee value of 15 was determined by analytical HPLC as > 99% (Chiralcel OB, hexane/EtOH 80:1).

![Scheme 6](image)

As in the previous cases, the structures of 15 and 16 were assigned on the basis of their elemental analysis and spectroscopic data. The 2D-NOESY spectrum of 15 showed one cross-signal between H–C(2) at 4.65–4.59 ppm and one H–C(7) at 3.94–3.90 ppm, which indicated the trans-configuration, i.e., the R-configuration at C(5) relative to the known 2S-configuration. On the other hand, the spectrum of 16 showed one cross-signal between H–C(2) at 4.33–4.28 ppm and two H–C(10) at 2.11–2.01 ppm, which implies the 2S,5S-configuration.

2.6. Reaction of Tetrahydropyran-2-thione (14) with (R)-2-Phenyloxirane (6).

The analogous reaction of 14 with 6 (molar ratio 1:1.5) in anhydrous CH₂Cl₂ at room temperature for 11 h under an N₂ atmosphere in the presence of SiO₂ gave three spirocyclic 1,3-oxathiolanes 18, 19, and 20 in 54, 11, and 8% yield, respectively. The ee values of the products, determined by analytical HPLC (Chiralcel OB, hexane/EtOH 80:1), showed that the reaction proceeded with lower stereoselectivity and partial racemization (10% in the case of 19) (Scheme 7).
The structures of 18, 19, and 20 were assigned as usual. The 2D-NOESY spectrum of 18 showed one cross-signal between two \textit{ortho}-H atoms at 7.38–7.36 ppm and two H–C(10) at 2.27–2.16 ppm, indicating the \textit{trans} (3S,5S)-configuration. The 1D-NOESY spectrum of 19, on irradiation of H–C(3) at 4.8 ppm, gave one NOE-signal for two H–C(10) at 2.17–2.05 ppm, corresponding to the \textit{cis} (3S,5R)-configuration. Finally, the 2D-NOESY spectrum of 20 showed one cross-signal between two \textit{ortho}-H atoms of Ph at 7.47–7.45 ppm and one H–C(7) at 4.06–4.02 ppm, and another one between H–C(2) at 5.30 ppm and two H–C(10) at 2.17–2.08 ppm, indicating the 2R,5R-configuration. The structures and absolute configurations of 19 and 20 were established by X-ray crystallography (Fig. 4).

The crystals of 19 and 20 were enantiomerically pure and the absolute configurations of the molecules have been determined independently by the diffraction experiment. The molecules of 19 and 20 have the 3S,5R- and 2R,5R-configuration, respectively.

2.7. \textit{Reactions of Thioesters} 21a–d with (R)-2-Phenyloloxirane (6). In analogy to the reactions with thiolactones (Sect. 2.1–2.6), the reactions of 21a–d with 6 were carried out in anhydrous CH$_2$Cl$_2$ at room temperature for 2–6 d under an N$_2$ atmosphere in the presence of SiO$_2$. Surprisingly, none of the expected 1,3-oxathiolanes was formed. Therefore, the reactions of 21a–b with 6 were repeated in anhydrous CH$_2$Cl$_2$ at −78°C for 20–30 min under an N$_2$ atmosphere in the presence of the stronger \textit{Lewis} acids BF$_3$·Et$_2$O or SnCl$_4$, but they did not lead to any of the expected product, either (Scheme 8).
3. Discussion and Conclusions. – The presented results show that thiolactones 1, 9, and 14 react with the monosubstituted oxiranes 2 and 6 to yield the spirocyclic 1,3-oxathiolanes with high regio- and stereoselectivity. On the other hand, no reactions occur between the thioesters 21a – d with 6. An S_N2-type mechanism for the 1,3-oxathiolane formation is proposed in Scheme 9, whereby the nucleophilic thiocarbonyl S-atom favorably attacks the C(3)-atom (O–C(3) cleavage) of the activated (S)-2-methyloxirane (2) to give the thiocarbonylium ion A with retention of the configuration. The latter undergoes ring closure by nucleophilic addition of the O-atom from the si- and re-face of the thiocarbonylum group to yield the spirocyclic 1,3-oxathiolanes 15 and 16, respectively. On the other hand, the addition to (R)-2-phenyloxirane (6) occurs selectively at the C(2)-atom (O–C(2) cleavage) with inversion of the configuration leading to intermediate B. Cyclization of B by addition of the O-atom from the re- and si-face gives 18 and 19, respectively. The partial loss of the stereochemical integrity of the phenyloxirane moiety in the formation of 19 may be interpreted by a competing reaction in which the oxirane ring-opening take place prior to the nucleophilic attack (S_N1-type). The formation of lactones in the cases of 1 and 14 can be explained by the hydrolysis of intermediates of type A and B.

Although thiolactones 9 and 14 are enolizable, their reactions with oxiranes 2 and 6 do not yield the open-chain enesulfanyl alcohols apart from the spirocyclic 1,3-oxathiolanes, in contrast to the reactions of thiocamphor with oxiranes [2].

The observed epimerizations of 11 and 16 to the thermodynamically more stable epimers 10 and 15, respectively, proceed smoothly during column
chromatography on SiO$_2$. This isomerization can be explained via acid-catalyzed ring opening of 1,3-oxathiolanes, as has been described in Scheme 9 of [2].

We thank the analytical services of our institute for NMR and mass spectra and elemental analyses, Mr B. Bürgi for his assistance with the determination of the crystal structures, and the Swiss National Science Foundation and F. Hoffmann-La Roche AG, Basel, for financial support.

**Experimental Part**

1. **General.** See [12]. Optical rotations: Perkin-Elmer-241 polarimeter (c = 1, in THF). IR spectra: film or KBr, cm$^{-1}$. NMR spectra at 600 (1H) and 150.9 MHz (13C) in CDCl$_3$. Enantiomeric excesses were determined by analytical HPLC on a Chiralcel OD-H or Chiralcel OB column. The thiolactones 1 [13], 9 [14], and 14 [15] have been prepared by thionation of the corresponding lactones following described procedures. Similarly, the thioesters 21a–d were obtained from the esters by treatment with Lawesson's reagent [16].

2. **General Procedure for the Reactions of 3H-Isobenzofuran-1-thione (1), Chroman-2-thione (9), and Tetrahydropyran-2-thione (14) with (S)-Methyl- and (R)-Phenylxirane (2 and 6).** To the soln. of 1, 9, or 14 (ca. 1 mmol) and oxirane 2 or 6 (ca. 2 mmol) in anh. CH$_2$Cl$_2$ (15 ml) under an N$_2$ atmosphere, 4.5 g of silica gel (SiO$_2$, Uetikon-Chemie Chromatographiegel C-560) were added at r.t. or 0$^\circ$. After stirring the suspension for 10 h – 3 d at r.t. or 0$^\circ$, the mixture was filtered and the residue was washed with Et$_2$O (4[l]). Then, the combined filtrate was evaporated *in vacuo*. and the products were separated by chromatography (SiO$_2$ or Alox; hexane/Et$_2$O, or hexane/AcOEt; CC, MPLC or HPLC).

3. **Reactions of 1. 3.1. With (S)-2-Methyloxirane (2).** Reaction of 1 (300 mg, 2 mmol) with 2 (232 mg, 4 mmol) and 4.5 g of SiO$_2$ at r.t., 34 h, and CC (Alox,
hexane/Et₂O 10:1) yielded 115 mg (28%) of a mixture of \((IR,5\[\ddagger\])\-5\[\ddagger\] methylspiro[1,3-dihydroisobenzofuran-1,2\[\ddagger\]1,3]oxathiolane (3) and \((IS,5\[\ddagger\])\-5\[\ddagger\] methylspiro[1,3-dihydroisobenzofuran-1,2\[\ddagger\]1,3]oxathiolane (4). Separation of the two diastereoisomers by HPLC (Chiralcel OD column, hexane/i-PrOH 25:1) gave 68 mg (16%) of 3 and 35 mg (8%) of 4. Repetition of the reaction of 1 (150 mg, 1 mmol) with 2 (116 mg, 2 mmol) for 10 h yielded 26% of 3, 10% of 4, and 54% of 3H-isobenzofuran-1-one (5) based on \(^1\)H-NMR analysis of the reaction mixture and a weighed amount of 1,1,2,2-tetrachloroethane as a standard. In addition, 9% of 1 remained (Scheme 2).

Data of 3: Colorless crystals. M.p. 64.4 – 65.1°C. \([\alpha]_D^{23} = +136.4\) (> 99% ee). IR (KBr): 3081w, 3049w, 3022w, 2975m, 2936m, 2915m, 2904m, 2864m, 1643w, 1476w, 1461m, 1450w, 1385w, 1358w, 1349m, 1281m, 1253s, 1227w, 1193w, 1182w, 1170w, 1140m, 1110m, 1088m, 1037s, 1009s, 998s, 962m, 951s, 937s, 912m, 852m, 768s, 732w, 713w. \(^1\)H-NMR: 7.51–7.50 (m, H–C(7)); 7.38–7.36 (m, H–C(5), H–C(6)); 7.23–7.21 (m, H–C(4)); 5.15 (d, J = 12.6, 1 H–C(3)); 5.09 (d, J = 12.6, 1 H–C(3)); 4.67–4.64 (m, H–C(5)); 3.36 (dd, J = 10.0, 4.7, 1 H–C(4)); 3.03 (t, J = 10.1, 1 H–C(4)); 1.48 (d, J = 6.1, Me). \(^{13}\)C-NMR: 139.4 (s, C(3a)); 138.1 (s, C(7a)); 128.8 (d, C(5)); 128.3 (d, C(6)); 124.1 (d, C(7)); 124.0 (s, C(1)); 121.0 (d, C(4)); 78.9 (d, C(5)); 72.0 (t, C(3)); 41.6 (t, C(4)); 19.1 (q, Me). ESI-MS (MeOH + Na): 439 (5, [2M+Na]⁺), 231 (100, [M + Na]⁺), 157 (45). Anal. calc. for C₁₁H₁₂O₅S (208.28): C 63.43, H 5.81, S 15.40; found: C 63.35, H 5.86, S 15.40.

Crystals of 3 suitable for the X-ray crystal-structure determination were grown from hexane/i-PrOH.

Data of 4: Colorless oil. \([\alpha]_D^{23} = -63.7\) (> 99% ee). IR (film): 3078w, 3039w, 2976m, 2930m, 2868m, 1612w, 1463m, 1437w, 1378m, 1353m, 1307w, 1281m, 1251s, 1198w, 1176w, 1140w, 1113s, 1088m, 1036s, 1025s, 1012s, 955s, 941s, 924s, 757s, 720m, 711w. \(^1\)H-NMR: 7.49–7.48 (m, H–C(7)); 7.37–7.35 (m,
H–C(5), H–C(6)); 7.23–7.21 (m, H–C(4)); 5.20 (d, J = 12.6, 1 H–C(3)); 5.05 (d, J = 12.6, 1 H–C(3)); 4.70–4.67 (m, H–C(5)); 3.35 (dd, J = 10.6, 5.2, 1 H–C(4)); 3.17 (dd, J = 10.6, 8.0, 1 H–C(4)); 1.53 (d, J = 6.2, Me). 13C-NMR: 139.2 (s, C(7a)); 138.7 (s, C(3a)); 129.5 (d, C(5)); 128.1 (d, C(6)); 125.2 (s, C(1)); 123.4 (d, C(7)); 120.9 (d, C(4)); 81.2 (d, C(5)); 71.6 (t, C(3)); 40.3 (t, C(4)); 20.3 (q, Me). ESI-MS (MeOH + NaI): 439 ([M + Na]+), 231 (100, [M + Na]+), 157 (17). Anal. calc. for C11H12O2S (208.28): C 63.43, H 5.89, S 15.46; found: C 63.43, H 5.89, S 15.46.

3.2. With (R)-2-Phenylxirane (6). Reaction of 1 (150 mg, 1 mmol) with 6 (180 mg, 1.5 mmol) and 4.5 g of SiO2 at r.t., 10 h, and CC (Alox, hexane/Et2O 10:1) yielded 79 mg (29%) of (1S,4$\overline{S}$)-4[2]Phenylspiro[1,3-dihydroisobenzofuran-1,2]oxathiolane (7), 26 mg (10%) of (IR,4$\overline{S}$)-4[2]phenylspiro[1,3-dihydroisobenzofuran-1,2][1,3]oxathiolane (8). Repetition of the reaction of 1 (150 mg, 1 mmol) with 6 (180 mg, 1.5 mmol) for 10 h yielded 28% of 7, 16% of 8, and 29% of 5 based on 1H-NMR analysis of the reaction mixture and a weighed amount of 1,1,2,2-tetrachloroethane. In addition, 26% of 1 remained (Scheme 3).

Data of 7: Colorless crystals. M.p. 112.5 – 113.4°. [α]D$^{23}$ = −63.9 (> 99% ee). IR (KBr): 3050w, 3028w, 2981w, 2942m, 2886w, 2874m, 1601w, 1495m, 1475w, 1462s, 1351m, 1303w, 1283s, 1251s, 1236s, 1197m, 1147m, 1108s, 1085m, 1054vs, 1018vs, 1007vs, 984s, 962vs, 947vs, 938vs, 929vs, 874w, 795w, 766vs, 752s, 702s. 1H-NMR: 7.57 (d, J = 6.9, H–C(7)); 7.53 (d, J = 7.4, 2 arom. H of Ph); 7.41–7.36 (m, H–C(5), 2 arom. H of Ph, H–C(6)); 7.31–7.28 (m, 1 arom. H of Ph); 7.26–7.24 (m, H–C(4)); 5.19 (d, J = 12.6, 1 H–C(3)); 5.13 (d, J = 12.6, 1 H–C(3)); 4.95 (dd, J = 5.9, 2.2, H–C(4)); 4.68 (dd, J = 9.4, 5.9, 1 H–C(5)); 4.51 (dd, J = 9.3, 2.3, 1 H–C(5)). 13C-NMR: 142.5 (s, 1 arom. C of Ph); 139.6 (s, C(7a)); 137.5 (s, C(3a)); 130.0 (d, C(5)); 129.0 (d, 2 arom. CH of Ph); 128.4 (d, C(6)); 127.8 (d, 1 arom. CH of Ph); 127.4 (d, 2 arom. CH of Ph); 125.8 (s, C(1)); 124.2 (d, C(7)); 121.1 (d, C(4)); 77.0 (t, C(5)); 72.2 (t, C(3)); 54.2 (d, C(4)). CI-
MS (NH₃): 271 (1, [M + H]⁺), 153 (9), 152 (100). Anal. calc. for C₁₆H₁₄O₂S (270.35): C 71.08, H 5.22, S 11.86; found: C 70.92, H 5.03, S 11.63.

Crystals of 7 suitable for the X-ray crystal-structure determination were grown from Et₂O/hexane.

Data of 8: Colorless crystals. M.p. 120.4 – 124.0°. [α]D²⁰ = + 61.2 (> 99% ee). IR (KBr): 3079w, 3061w, 3029w, 2978w, 2940w, 2923w, 2879w, 1600w, 1492w, 1461m, 1454w, 1367w, 1354w, 1281w, 1257m, 1242m, 1200w, 1189w, 1110m, 1082w, 1061s, 1047m, 1009s, 992s, 973m, 949s, 927m, 859w, 755s, 726w, 698s. ¹H-NMR: 7.59–7.58 (m, H–C(7), 2 arom. H of Ph); 7.42–7.39 (m, H–C(5), H–C(6)); 7.37–7.35 (m, 2 arom. H of Ph); 7.31–7.28 (m, 1 arom. H of Ph); 7.27–7.24 (m, H–C(4)); 5.21 (d, J = 12.6, 1 H–C(3)); 5.19 (d, J = 12.6, 1 H–C(3)); 5.08 (dd, J = 10.4, 6.4, H–C(4]]; 4.56 (dd, J = 9.3, 6.4, 1 H–C(5)]; 4.26 (dd, J = 10.3, 9.5, 1 H–C(5)]. ¹³C-NMR: 139.5 (s, C(7a)); 137.8 (s, C(3a)); 137.1 (s, 1 arom. C of Ph); 130.0 (d, C(5)); 129.0 (d, 2 arom. CH of Ph); 128.6 (d, 2 arom. CH of Ph); 128.4 (d, C(6))); 128.2 (d, 1 arom. CH of Ph); 126.0 (s, C(1)); 124.2 (d, C(4)); 121.0 (d, C(7)); 77.0 (t, C(5]]; 72.4 (t, C(3)); 56.6 (d, C(4]]. CI-MS (NH₃): 271 (1, [M + H]⁺), 153 (9), 152 (100). Anal. calc. for C₁₆H₁₄O₂S (270.35): C 71.08, H 5.22, S 11.86; found: C 71.00, H 5.02, S 11.78.

Crystals of 8 suitable for the X-ray crystal-structure determination were grown from Et₂O/hexane.

4. Reactions of 9. 4.1. With (S)-2-Methylxirane (2). Reaction of 9 (328 mg, 2 mmol) with 2 (232 mg, 4 mmol) and 4.5 g of SiO₂ at r.t., 3 d; CC (SiO₂, hexane/ACOEt 10:1) yielded 180 mg (40%) of a mixture of (2S,5[8])-5[8] methylspiro[chroman-2,2[1,3]oxathiolane] (10) and (2R,5[8])-5[8] methylspiro[chroman-2,2[1,3]oxathiolane] (11). The ¹H-NMR spectrum of the mixture showed 32% of 10 and 8% of 11. Separation of the two diastereoisomers by HPLC (Nucleosil 100-7 column, hexane/THF 125:1) gave 130 mg (29%) of 10, but 11 could not be purified due to its partial epimerization to 10 (Scheme 4).
Data of 10: Colorless crystals. M.p. 69.0–70.1°. \[\theta^2 = + 217.4 (> 99\% \text{ ee}).\]

IR (KBr): 3075w, 3053w, 3038w, 2989w, 2979w, 2966m, 2921m, 2851w, 1607w, 1580m, 1487s, 1457m, 1445m, 1379w, 1352w, 1345w, 1234w, 1299w, 1275w, 1234s, 1201s, 1174w, 1160m, 1138s, 1108w, 1087m, 1067s, 1049s, 1021m, 992s, 972w, 939m, 921w, 893s, 880s, 863m, 852m, 838m, 758s. \(^1\)H-NMR: 7.12–7.09 (m, H–C(7)); 7.08 (d, \(J = 7.6\), H–C(5)); 6.89 (td, \(J = 4.1\), 1H–C(6)); 6.83 (dd, \(J = 8.2\), 0.8, H–C(8)); 4.83–4.78 (m, H–C(5\[5\])); 3.29 (dd, \(J = 10.0\), 4.9, 1 H–C(4\[4\])); 3.09–3.03 (m, 1 H–C(4)); 2.91–2.86 (m, 1 H–C(4)); 2.87 (t, \(J = 10.0\), 1 H–C(4\[4\])); 2.43–2.39 (m, 1 H–C(3)); 2.35–2.30 (m, 1 H–C(3)); 1.45 (d, \(J = 6.1\), Me). \(^{13}\)C-NMR: 152.8 (s, C(8a)); 129.0 (d, C(5)); 127.4 (d, C(7)); 121.3 (s, C(4a)); 121.2 (d, C(6)); 117.3 (d, C(8)); 116.2 (s, C(2)); 79.0 (d, C(5\[5\])); 39.6 (t, C(4\[4\])); 33.3 (t, C(3)); 24.2 (t, C(4)); 18.9 (q, Me). EI-MS: 222 (21, \(M^+\)), 149 (11), 148 (100), 120 (43), 91 (12), 74 (11). Anal. calc. for C\(_{12}\)H\(_{14}\)O\(_2\)S (222.31): C 64.83, H 6.35, S 14.42; found: C 64.96, H 6.59, S 14.59.

Crystals of 10 suitable for the X-ray crystal-structure determination were grown from Et\(_2\)O/MeOH.

Data of 11: \(^1\)H-NMR (300 MHz): 4.71–4.58 (m, H–C(5\[5\])); 1.55 (d, \(J = 6.1\), Me); the other signals at 7.12–7.07, 6.90–6.80, 3.32–2.85; 2.48–2.29 overlap with those of 10.

4.2. With (R)-2-Phenyloxirane (6). Reaction of 9 (328 mg, 2 mmol) with 6 (360 mg, 3 mmol) and 4.5 g of SiO\(_2\) at r.t., 3 d, CC (SiO\(_2\), hexane/Et\(_2\)O 10:1), and HPLC (Nucleosil 100-7 column, hexane/t-BuOMe 150:1) yielded 200 mg (35%) of (2R,\(^4\)\[\$\])-4\[\[\[\[\[\$\]]\]]\]phenylspiro[chroman-2,2\[\[\[\[\[\$\]]\]]\]oxathiolane](12) and 38 mg (7%) of (2S,\(^4\)\[\$\])-4\[\[\[\[\[\$\]]\]]\]phenylspiro[chroman-2,2\[\[\[\[\[\$\]]\]]\]oxathiolane](13) (Scheme 5).

Data of 12: Colorless crystals. M.p. 63.4 – 65.8°. \([\theta^2] = -154.6 (89\% \text{ ee}).\) IR (KBr): 3081w, 3061w, 3028w, 2975w, 2942m, 2884w, 2844w, 1608w, 1600w, 1581s, 1487s, 1454s, 1440m, 1429m, 1347m, 1332w, 1303m, 1272m, 1235s, 1209s, 1145s, 1108s, 1068s, 1035s, 1013m, 987s, 938s, 911s, 895s, 880s, 861m,
EI-MS: 284 (14, C(2)); 117.6 (129.3, 2.51–2.40 H–C(6)); 4.94 (Ph); of 914 1236 2972 71.80, H 5.67, S 11.28; found: C 72.07, H 5.88, S 11.06. (45), (100), 53.2 (103, C(8a)); 142.4 (d, C(5)); 128.9 (d, 2 arom. CH of Ph); 127.8 (d, 1 arom. CH of Ph); 127.7 (d, C(7)); 127.4 (d, 2 arom. CH of Ph); 121.7 (d, C(6)); 121.4 (s, C(4a)); 118.1 (s, C(2)); 117.5 (d, C(8)); 77.6 (t, C(5)); 53.2 (d, C(4)); 33.0 (t, C(3)); 24.4 (t, C(4)).

IR (film): 2962, 2935, 1601 w, 1583 m, 1489 s, 1455 m, 1349 w, 1302 w, 1274 w, 1236 m, 1211 s, 1195 s, 1156 w, 1110 s, 1070 m, 1052 s, 1038 s, 1026 s, 988 s, 937 w, 914 m, 893 m, 880 s, 858 w, 837 m, 758 s, 700 s. 1H-NMR: 7.53 (d, J = 7.3, 2 arom. H of Ph); 7.35 (t-like, J ≈ 7.6, 2 1H of Ph); 7.28 (t-like, J ≈ 7.6, 1 arom. H of Ph); 7.16–7.14 (m, H–C(7)); 7.10 (d, J = 7.5, H–C(5)); 6.95–6.91 (m, H–C(8), H–C(6)); 4.94 (dd, J = 10.4, 6.6, H–C(4)); 4.54 (dd, J = 9.4, 6.7, 1 H–C(5)); 4.36 (dd, J = 10.3, 9.5, 1 H–C(5)); 3.10–3.07 (m, 1 H–C(4)); 2.93–2.89 (m, 1 H–C(4)); 2.51–2.40 (m, 2 H–C(3)). 13C-NMR: 152.9 (s, C(8a)); 137.3 (s, 1 arom. C of Ph); 129.3 (d, C(5)); 128.9 (d, 2 arom. CH of Ph); 128.7 (d, 2 arom. CH of Ph); 128.2 (d, 1 arom. CH of Ph); 127.7 (d, C(7)); 121.7 (d, C(6)); 121.5 (s, C(4a)); 118.2 (s, C(2)); 117.6 (d, C(8)); 77.3 (t, C(5)); 55.0 (d, C(4)); 33.2 (t, C(3)); 24.2 (t, C(4)).

EI-MS: 284 (14, M+•), 149 (11), 148 (97), 137 (11), 136 (91), 135 (47), 120 (56), 119 (11), 105 (11), 104 (100), 103 (39), 91 (36), 78 (33), 77 (16).
5. Reactions of 14. 5.1. With (S)-2-Methyloxirane (2). Reaction of 14 (232 mg, 2 mmol) with 2 (232 mg, 4 mmol) and 4.5 g of SiO₂ at 0°, 2 d; CC (SiO₂, hexane/Et₂O/Et₃N 10:1:0.1) yielded 230 mg (66%) of a mixture of (2S,5R)-2-methyl-1,6-dioxo-4-thiaspiro[4.5]decane (15) and (2S,5S)-2-methyl-1,6-dioxo-4-thiaspiro[4.5]decane (16). Separation of the two diastereoisomers by MPLC (SiO₂, hexane/AcOEt 15:1) gave 100 mg (29%) of 15. Further purification by HPLC (Nucleosil 100-7 column, hexane/AcOEt/Et₂N 45:1:0.05) yielded 30 mg (9%) of 15, but 16 was obtained only in 90% purity because of its partial epimerization to 15. Repetition of the reaction of 14 (116 mg, 1 mmol) with 2 (116 mg, 2 mmol) at 0°, 2 d yielded 63% of 15, 22% of 16, and 15% of tetrahydropyran-2-one (17) according to the ¹H-NMR analysis of the reaction mixture and 1,1,2,2-tetrachloroethane as a standard (Scheme 6).

Data of 15: Colorless oil. [α]₂⁰° = + 202.1 (> 99% ee). IR (film): 2963s, 2937s, 2862s, 1465m, 1452m, 1440m, 1381m, 1354m, 1282m, 1256w, 1230w, 1211m, 1185s, 1165m, 1147s, 1115m, 1092m, 1075s, 1037s, 975m, 940m, 925w, 899m, 871m, 856m, 813m, 756w. ¹H-NMR: 4.65–4.59 (m, H–C(2)); 3.94–3.90 (m, 1 H–C(7)); 3.78–3.74 (m, 1 H–C(7)); 3.11 (dd, J = 9.9, 5.0, 1 H–C(3)); 2.76 (t, J = 10.0, 1 H–C(3)); 2.08–1.98 (m, 2 H–C(10)); 1.94–1.88 (m, 1 H–C(9)); 1.66–1.60 (m, 1 H–C(9)); 1.58–1.52 (m, 2 H–C(8)); 1.44 (d, J = 6.2, Me). ¹³C-NMR: 118.1 (s, C(5)); 78.3 (d, C(2)); 65.1 (t, C(7)); 39.0 (t, C(3)); 37.4 (t, C(10)); 24.7 (t, C(8)); 22.5 (t, C(9)); 19.2 (q, Me). CI-MS (NH₃): 177 (5), 176 (10), 175 (100, [M + H]⁺), 118 (39). Anal. calc. for C₈H₁₄O₂S (174.26): C 55.14, H 8.10, S 18.40; found: C 55.25, H 8.25, S 18.30.

Data of 16: Colorless oil. [α]₂⁰° = − 136.8 (> 99% ee) (containing 10% of 15). ¹H-NMR (C₆D₆): 4.33–4.28 (m, H–C(2)); 3.83–3.73 (m, 2 H–C(7)); 2.71–2.65 (m, 2 H–C(3)); 2.11–2.01 (m, 2 H–C(10)); 1.62–1.56 (m, 1 H–C(9)); 1.44–1.37 (m, 1 H–C(9)); 1.24–1.18 (m, 1 H–C(8)); 1.23 (d, J = 6.2, Me); 1.14–1.09 (m, 1 H–C(8)). ¹³C-NMR (C₆D₆): 120.5 (s, C(5)); 81.8 (d, C(2)); 66.1 (t, C(7)); 38.4 (t,
5.2. With (R)-2-Phenyloxirane (6). Reaction of 14 (232 mg, 2 mmol) with 6 (360 mg, 3 mmol) and 4.5 g of SiO2 at r.t., 11 h, CC (SiO2, hexane/Et2O/ Et3N 10:1:0.1), and MPLC (SiO2, hexane/Et2O 20:1) yielded 257 mg (54%) of (3S,5S)-3-phenyl-1,6-dioxo-4-thiaspiro[4.5]decane (18), 50 mg (11%) of (3S,5R)-3-phenyl-1,6-dioxo-4-thiaspiro[4.5]decane (19), and 36 mg (8%) of (2R,5R)-2-phenyl-1,6-dioxo-4-thiaspiro[4.5]decane (20) (Scheme 7).

Data of 18: Colorless crystals. M.p. 49.3 – 51.4°. $[\psi]_D^{23} = – 168.7$ (95% ee). IR (KBr): 3071 w, 3028 w, 3006 w, 2962 s, 2940 s, 2924 s, 2878 s, 2846 m, 1602 w, 1494 m, 1456 s, 1437 m, 1378 w, 1363 w, 1352 s, 1342 m, 1305 w, 1286 m, 1278 s, 1263 m, 1245 w, 1203 s, 1186 s, 1171 m, 1148 s, 1129 s, 1077 w, 1061 s, 1048 s, 1016 s, 959 s, 942 s, 930 s, 898 s, 868 s, 846 w, 834 m, 820 m, 802 w, 763 s, 698 s. $^1$H-NMR: 7.38 – 7.36 (m, 2 arom. H); 7.31 – 7.28 (m, 2 arom. H); 7.24 – 7.22 (m, 1 arom. H); 4.65 (dd, $J = 6.1$, 1.5, H–C(3)); 4.62 (dd, $J = 9.0$, 6.0, 1 H–C(2)); 4.33 (dd, $J = 9.0$, 1.7, 1 H–C(2)); 3.98 – 3.94 (m, 1 H–C(7)); 3.83 – 3.79 (m, 1 H–C(7)); 2.27 – 2.23 (m, 1 H–C(10)); 2.20 – 2.16 (m, 1 H–C(10)); 1.98 – 1.94 (m, 1 H–C(9)); 1.71 – 1.64 (m, 1 H–C(9)); 1.61 – 1.57 (m, 2 H–C(8)). $^{13}$C-NMR: 143.0 (s, 1 arom. C); 128.6 (d, 2 arom. CH); 127.4 (d, 1 arom. CH); 127.2 (d, 2 arom. CH); 119.6 (s, C(5)); 76.9 (t, C(2)); 65.3 (t, C(7)); 52.3 (d, C(3)); 36.7 (t, C(10)); 24.6 (t, C(8)); 22.4 (t, C(9)). Cl–MS (NH3): 238 (11), 237 (76, $[M + H]^+$), 119 (6), 118 (100). Anal. calc. for C13H16O2S (236.33): C 66.07, H 6.82, S 13.57; found: C 66.06, H 6.85, S 13.35.

Data of 19: Colorless crystals. M.p. 74.4 – 74.7°. $[\psi]_D^{23} = + 69.0$ (90% ee). IR (KBr): 3074 w, 3027 w, 2968 w, 2941 m, 2880 w, 2853 w, 1600 w, 1491 w, 1453 w, 1439 w, 1377 w, 1361 w, 1351 w, 1335 w, 1282 w, 1278 w, 1263 w, 1202 w, 1189 w, 1155 w, 1130 m, 1061 m, 1055 m, 1013 s, 969 w, 955 m, 928 m, 897 m, 868 w, 858 w, 836 w, 816 w, 760 m, 704 m, 696 m. $^1$H-NMR: 7.46 – 7.44 (m, 2 arom. H); 7.33 – 7.30 (m, 2 arom. H); 7.27 – 7.24 (m, 1 arom. H); 4.84 (dd, $J = 10.3$, 6.8, H–C(3)); 4.51
(dd, $J = 9.3, 6.7$, 1 H–C(2)); 4.20 (dd, $J = 10.3, 9.4$, 1 H–C(2)); 4.05–4.01 (m, 1 H–C(7)); 3.92–3.88 (m, 1 H–C(7)); 2.17–2.13 (m, 1 H–C(10)); 2.09–2.05 (m, 1 H–C(10)); 1.96–1.91 (m, 1 H–C(9)); 1.69–1.57 (m, 1 H–C(9), 2 H–C(8)). $^{13}$C-NMR: 138.0 (s, 1 arom. C); 128.6 (d, 2 arom. CH); 128.4 (d, 2 arom. CH); 127.8 (d, 1 arom. CH); 119.9 (s, C(5)); 76.7 (t, C(2)); 65.1 (t, C(7)); 54.1 (d, C(3)); 36.9 (t, C(10)); 24.6 (t, C(8)); 22.2 (t, C(9)). CI-MS (NH$_3$): 238 (14), 237 (100, [M + H]$^+$), 118 (70), 101 (6). Anal. calc. for C$_{13}$H$_{16}$O$_2$S (236.33): C 66.07, H 6.82, S 13.57; found: C 65.96, H 7.01, S 13.49.

Crystals of 19 suitable for the X-ray crystal-structure determination were grown from Et$_2$O/hexane.

Data of 20: Colorless crystals. M.p. 55.6 – 56.9$^\circ$. $[\alpha]$_D$^{23} = -21.0$ (97% ee). IR (KBr): 3068w, 3025w, 2987w, 2968w, 2941m, 2924m, 2891m, 2857m, 1488w, 1462w, 1454m, 1441w, 1422w, 1385w, 1347w, 1325w, 1308w, 1290w, 1260w, 1215m, 1205m, 1184s, 1155m, 1126m, 1070s, 1035s, 1019vs, 1000m, 990s, 948m, 940s, 914w, 907w, 887s, 871s, 847m, 811s, 767s, 739m, 700s. $^1$H-NMR: 7.47–7.45 (m, 2 arom. H); 7.36–7.34 (m, 2 arom. H); 7.31–7.28 (m, 1 arom. H); 5.30 (dd, $J = 9.8, 6.1$, H–C(2)); 4.06–4.02 (m, 1 H–C(7)); 3.96–3.91 (m, 1 H–C(7)); 3.24–3.19 (m, 2 H–C(3)); 2.17–2.08 (m, 2 H–C(10)); 1.95–1.91 (m, 1 H–C(9)); 1.66–1.56 (m, 1 H–C(9), 2 H–C(8)). $^{13}$C-NMR: 139.9 (s, 1 arom. C); 128.7 (d, 2 arom. CH); 128.4 (d, 1 arom. CH); 126.8 (d, 2 arom. CH); 119.7 (s, C(5)); 87.6 (d, C(2)); 66.4 (t, C(7)); 39.1 (t, C(3)); 37.4 (t, C(10)); 24.9 (t, C(8)); 22.7 (t, C(9)). CI-MS (NH$_3$): 238 (8), 237 (49, [M + H]$^+$), 135 (13), 118 (100).

Crystals of 20 suitable for the X-ray crystal-structure determination were grown from Et$_2$O/MeOH.
6. X-Ray Crystal-Structure Determination of 3, 7, 8, 10, 19, and 20 (Table 1 and Figs. 1 – 4)\(^3\). All measurements were performed on a Nonius KappaCCD diffractometer [17] using graphite-monochromated Mo\(K\alpha\) radiation (\(\lambda\) 0.71073 Å) and an Oxford Cryosystems Cryostream 700 cooler. The data collection and refinement parameters are given in Table 1, and views of the molecules are shown in Figs. 1 – 4. Data reduction was performed with HKL Denzo and Scalepack [18]. The intensities were corrected for Lorentz and polarization effects, and an absorption correction based on the multi-scan method [19] was applied. The structures were solved by direct methods using SIR92 [20], which revealed the positions of all non-H-atoms. The non-H-atoms were refined anisotropically. All of the H-atoms were placed in geometrically calculated positions and refined using a riding model where each H-atom was assigned a fixed isotropic displacement parameter with a value equal to 1.2 \(U_{eq}\) of its parent C-atom (1.5 \(U_{eq}\) for the methyl group in 3 and 10). The refinement of each structure was carried out on \(F^2\) using full-matrix least-squares procedures, which minimized the function \(\sum w(F_o^2 - F_c^2)^2\). A correction for secondary extinction was applied in the cases of 10, 19, and 20. In 3, one reflection, whose intensity was considered to be an extreme outlier, was omitted from the final refinement. Refinement of the absolute structure parameter [21] yielded values of −0.1(2), −0.04(6), 0.05(8), 0.03(7), 0.05(7), and 0.01(7) for 3, 7, 8, 10, 19, and 20, respectively, which confidently confirms that the refined coordinates represent the true enantiomorph in each case except for 3, which, due to the low precision, does not give an unambiguous indication of the

\(^3\) CCDC- 235086 – 235091 contain the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/conts/retrieving.html (or from the Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, U.K. (fax: +44-(0)1223-336033; e-mail: deposit@ccdc.cam.ac.uk)).
correct absolute configuration. Neutral atom scattering factors for non-H-atoms were taken from [22a], and the scattering factors for H-atoms were taken from [23]. Anomalous dispersion effects were included in $F_c$ [24]; the values for $f'$ and $f''$ were those of [22b]. The values of the mass attenuation coefficients are those of [22c]. All calculations were performed using the SHELXL97 [25] program.

Table 1

REFERENCES


Legends:

Fig. 1. ORTEP Plot [11] of the molecular structure of 3 (arbitrary numbering of the atoms; displacement ellipsoids with 50% probability)

Fig. 2. ORTEP Plots [11] of the molecular structures of a) 7 and b) 8 (arbitrary numbering of the atoms; displacement ellipsoids with 50% probability)

Fig. 3. ORTEP Plot [11] of the molecular structure 10 (arbitrary numbering of the atoms; displacement ellipsoids with 50% probability)

Fig. 4. ORTEP Plots [11] of the molecular structures of a) 19 and b) 20 (displacement ellipsoids with 50% probability)
Table 1. Crystallographic Data of Compounds 3, 7, 8, 10, 19, and 20

<table>
<thead>
<tr>
<th></th>
<th>3</th>
<th>7</th>
<th>8</th>
<th>10</th>
<th>19</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystallized from</td>
<td>hexane/i-PrOH</td>
<td>Et₂O/hexane</td>
<td>Et₂O/hexane</td>
<td>Et₂O/MeOH</td>
<td>Et₂O/hexane</td>
<td>Et₂O/MeOH</td>
</tr>
<tr>
<td>Empirical formula</td>
<td>C₁₁H₁₄O₂S</td>
<td>C₁₁H₁₄O₂S</td>
<td>C₁₁H₁₄O₂S</td>
<td>C₁₁H₁₄O₂S</td>
<td>C₁₁H₁₄O₂S</td>
<td>C₁₁H₁₄O₂S</td>
</tr>
<tr>
<td>Formula weight [g mol⁻¹]</td>
<td>208.27</td>
<td>270.34</td>
<td>270.34</td>
<td>222.30</td>
<td>236.33</td>
<td>236.33</td>
</tr>
<tr>
<td>Crystal color, habit</td>
<td>colorless, prism</td>
<td>colorless, prism</td>
<td>colorless, tablet</td>
<td>colorless, plate</td>
<td>colorless, plate</td>
<td>colorless, plate</td>
</tr>
<tr>
<td>Crystal dimensions [mm]</td>
<td>0.05 [0.18, 20]</td>
<td>0.22 [0.22, 0.30]</td>
<td>0.07 [0.20, 0.27]</td>
<td>0.05 [0.22, 0.22]</td>
<td>0.07 [0.20, 0.25]</td>
<td>0.03 [0.20, 0.25]</td>
</tr>
<tr>
<td>Temp. [K]</td>
<td>160(1)</td>
<td>160(1)</td>
<td>160(1)</td>
<td>160(1)</td>
<td>160(1)</td>
<td>160(1)</td>
</tr>
<tr>
<td>Crystal system</td>
<td>tetragonal</td>
<td>orthorhombic</td>
<td>orthorhombic</td>
<td>orthorhombic</td>
<td>monoclinic</td>
<td>orthorhombic</td>
</tr>
<tr>
<td>Space group</td>
<td>P4₁2₁2</td>
<td>P2₁2₁₂</td>
<td>P2₁2₁₂</td>
<td>P2₁2₁₂</td>
<td>P2₁</td>
<td>P2₁</td>
</tr>
<tr>
<td>Z</td>
<td>8</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Reflections for cell determination</td>
<td>99506</td>
<td>26146</td>
<td>41579</td>
<td>17073</td>
<td>13314</td>
<td>25172</td>
</tr>
<tr>
<td>2θ range for cell determination [°]</td>
<td>4 – 50</td>
<td>4 – 60</td>
<td>4 – 60</td>
<td>4 – 60</td>
<td>4 – 55</td>
<td>4 – 60</td>
</tr>
<tr>
<td>Unit cell parameters</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a [Å]</td>
<td>7.7158(2)</td>
<td>5.6804(1)</td>
<td>5.9913(1)</td>
<td>6.1354(1)</td>
<td>5.7737(2)</td>
<td>6.3724(1)</td>
</tr>
<tr>
<td>b [Å]</td>
<td>7.7158(2)</td>
<td>8.7193(1)</td>
<td>8.5129(2)</td>
<td>9.0937(2)</td>
<td>8.0090(3)</td>
<td>8.8038(2)</td>
</tr>
<tr>
<td>V [Å³]</td>
<td>2117.6(1)</td>
<td>1319.16(3)</td>
<td>1332.22(5)</td>
<td>1070.70(4)</td>
<td>963.36(2)</td>
<td>90</td>
</tr>
<tr>
<td>D[ρ] [g cm⁻³]</td>
<td>1.306</td>
<td>1.361</td>
<td>1.348</td>
<td>1.379</td>
<td>1.321</td>
<td>1.315</td>
</tr>
<tr>
<td>D(MoKα) [mm⁻³]</td>
<td>0.276</td>
<td>0.239</td>
<td>0.237</td>
<td>0.278</td>
<td>0.254</td>
<td>0.253</td>
</tr>
<tr>
<td>Transmission factors (min; max)</td>
<td>0.736; 0.990</td>
<td>0.885; 0.956</td>
<td>0.912; 0.985</td>
<td>0.913; 0.988</td>
<td>0.888; 0.983</td>
<td>0.910; 0.994</td>
</tr>
<tr>
<td>2θmax [°]</td>
<td>50</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>55</td>
<td>60</td>
</tr>
<tr>
<td>Total reflections measured</td>
<td>18451</td>
<td>24740</td>
<td>18535</td>
<td>21972</td>
<td>13745</td>
<td>21842</td>
</tr>
<tr>
<td>Symmetry-independent reflections</td>
<td>1865</td>
<td>3841</td>
<td>3877</td>
<td>3124</td>
<td>2617</td>
<td>3487</td>
</tr>
<tr>
<td>Reflections with l &gt; 2θ(l)</td>
<td>1464</td>
<td>3236</td>
<td>2581</td>
<td>2806</td>
<td>2383</td>
<td>2832</td>
</tr>
<tr>
<td>Reflections used in refinement</td>
<td>1864</td>
<td>3841</td>
<td>3877</td>
<td>3124</td>
<td>2617</td>
<td>3487</td>
</tr>
<tr>
<td>Parameters refined</td>
<td>128</td>
<td>172</td>
<td>173</td>
<td>139</td>
<td>146</td>
<td>147</td>
</tr>
<tr>
<td>R(F) [l &gt; 2θ(l) reflections]</td>
<td>0.0538</td>
<td>0.0353</td>
<td>0.0472</td>
<td>0.0522</td>
<td>0.0340</td>
<td>0.0369</td>
</tr>
<tr>
<td>wR²(F²) (all data)</td>
<td>0.1089</td>
<td>0.0828</td>
<td>0.1064</td>
<td>0.0791</td>
<td>0.0778</td>
<td>0.0817</td>
</tr>
<tr>
<td>Weighting parameters [a; b]</td>
<td>0.0319; 2.4034</td>
<td>0.0351; 0.2187</td>
<td>0.049; 0.0</td>
<td>0.0371; 0.2533</td>
<td>0.0331; 0.183</td>
<td>0.0334; 0.2229</td>
</tr>
<tr>
<td>Goodness-of-fit</td>
<td>1.190</td>
<td>1.048</td>
<td>1.019</td>
<td>1.048</td>
<td>1.039</td>
<td>1.047</td>
</tr>
<tr>
<td>Secondary extinction coefficient</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Final D[θ]</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.002</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>D[θ] (max; min) [e Å⁻³]</td>
<td>0.28; – 0.25</td>
<td>0.19; – 0.20</td>
<td>0.26; – 0.27</td>
<td>0.26; – 0.29</td>
<td>0.17; – 0.18</td>
<td>0.22; – 0.19</td>
</tr>
</tbody>
</table>

¹) w = [D²(F) + (aP)² + bP]⁻¹, where P = (F₀² + 2F₁²)/3
Scheme 1
Scheme 2

\[
\begin{align*}
1 + 2 & \xrightarrow{\text{SiO}_2, \text{r.t.}, \text{CH}_2\text{Cl}_2 / \text{N}_2, 10 \text{ h}} 3 + 4 + 5 \\
& \quad \text{26\% (> 99\% ee)} \quad \text{10\% (> 99\% ee)} \quad \text{54\%}
\end{align*}
\]
Scheme 3

1 + 6 $\xrightarrow{\text{SiO}_2, \text{r.t.}, \text{CH}_2\text{Cl}_2 / \text{N}_2}$ 10 h

29% (> 99% ee)  16% (> 99% ee)  29%

7 + 8 + 5
Scheme 4

9 + 2 $\xrightarrow{\text{SiO}_2, \text{r.t.}} \xrightarrow{\text{CH}_2\text{Cl}_2 / N_2} 3 \text{d}$ 10 11

32% (> 99% ee) 8%
Scheme 5

9 + 6 $\xrightarrow{\text{SiO}_2, \text{r.t.}}$ CH$_2$Cl$_2$ / N$_2$

3 d

35% (89% ee) 7% (90% ee)
Scheme 6

\[
\begin{align*}
14 + 2 & \xrightarrow{\text{SiO}_2, \text{CH}_2\text{Cl}_2 / \text{N}_2, 0^\circ \text{C}} 2 \text{d} \\
& \rightarrow 15, 16, 17 \\
\end{align*}
\]

- 15: 63% (> 99% ee)
- 16: 22%
- 17: 15%
Scheme 7

\[
\text{14} + \text{6} \xrightarrow{\text{SiO}_2, \text{r.t.}} \text{CH}_2\text{Cl}_2/\text{N}_2 \xrightarrow{11 \text{ h}} \text{18} + \text{19} + \text{20}
\]

54% (95% ee) 11% (90% ee) 8% (97% ee)
Scheme 8

\[ \text{O} \quad \text{P} \quad \text{R}_1 \quad \text{O} \quad \text{R}_2 \]

21 + \( \varphi_{\text{wph}} \) →

21a  \( R_1 = \text{t-Bu}, \ R^2 = \text{Et} \)
21b  \( R_1 = \text{Heptyl}, \ R^2 = \text{Me} \)
21c  \( R_1 = \text{Ph}, \ R^2 = \text{Me} \)
21d  \( R_1 = R^2 = \text{Ph} \)
Scheme 9

14

L. A.  
14

2

L. A.  
Me

6

L. A.  
Ph

A

B

15  
16

18  
19

15

16

18

19

L. A.

re-face

si-face

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.

L. A.
Fig. 1
Fig. 2
Fig. 3
Fig. 4
Scheme Graphical Abstract

(Scheme Diagram)

1. Reaction of (S) Me with O=S
2. Reaction of (R) Ph with O=S

Products:
- (S) Me + (R) Me
- (S) Ph + (R) Ph