Stereoselective Intramolecular Hetero Diels–Alder Reactions of Cyclic Benzylidenesulfoxides and DFT Calculations on the Transition Structures

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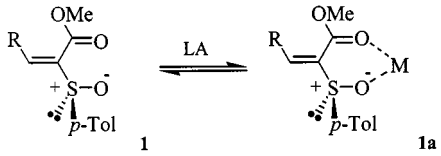
The 4-benzylidene-3-oxo[1,3]oxathiolan-5-ones **13**–**15**, which were derived from the 3-oxo[1,3]oxathiolan-5-ones **9**–**11** by Knoevenagel condensation with the aldehydes **12**, cyclize in an intramolecular hetero Diels–Alder reaction with high yield and excellent *endo/exo* as well as induced diastereoselectivity to give the hetero Diels–Alder adducts **16**–**18**. The preferred formation of the Knoevenagel products **13**–**15** with a (*Z*) configuration was predicted with DFT calculations (B3LYP/6-311+G*) using the model systems **28** and **29**. In addition B3LYP/6-31G*//B3LYP/3-21G(*) calculations on transition structures for the hetero Diels–Alder reaction of **29** and **30** allowed a good correlation with the experimental results, which show that an *endo* attack of the dienophile *syn* to the S–O group in **13**–**15** leads to the main products.

Introduction and Experimental Results

The hetero Diels−Alder reaction of 1-oxa-1,3-dienes is a highly useful method for the synthesis of dihydropyrans.[1] Especially efficient are those cycloadditions where the oxabutadienes are formed in situ. This can easily be achieved by a Knoevenagel condensation[2] of 1,3-dicarbonyl compounds. Thus, two, three, and four component domino Knoevenagel hetero Diels−Alder reactions have been developed with 1,3-dicarbonyl compounds and aldehydes containing a dienophile moiety or 1,3-dicarbonyl compounds, aldehydes, and enol ethers.[3] The transformations can be performed in solution or on solid phase and may be used in combinatorial chemistry for the preparation of substance libraries.[4] In these domino reactions enantioenriched and enantiopure cycloadducts have been obtained with either chiral Lewis acids, chiral aldehydes or chiral 1,3-dicarbonyl compounds in enantiopure form. Here we describe the Knoevenagel hetero Diels−Alder reactions of the chiral cyclic sulfoxides **9**−**11** and the aldehydes **12a**−**e**, which lead to the cycloadducts **16**−**18** in excellent diastereoselectivity with up to > 99:1. In the described transformations the intermediately formed Knoevenagel products have been isolated to allow a structure determination. The cyclic structure of the employed sulfoxides is of importance, since alkylidenene sulfoxides of type **1** (Scheme 1) in the presence of a Lewis acid only lead to ene products,[5] as it is also observed for simple alkylidene malonates.[6] The results can be explained by assuming that **1** forms a chelate complex **1a** with the Lewis acid,[7] in which the carbonyl group is orientated *s-trans* and thus prohibits a Diels−Alder reaction. In contrast, the 1,3-oxabutadiene moiety in **13**−**15** is preserved in the *s-cis* conformation, which is required for a Diels−Alder reaction.

Scheme 1



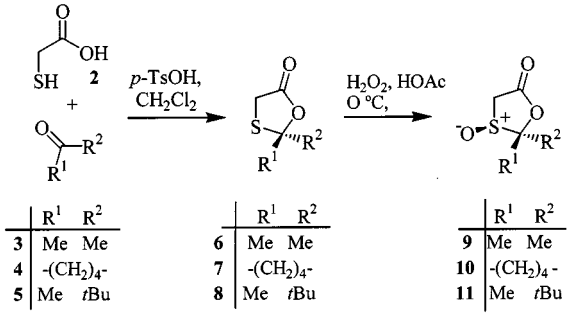
1 **1a**

The synthesis of the [1,3]oxathiolan-5-one-oxides **9**−**11** was performed by condensation of mercaptoacetic acid **2** and the ketones **3**−**5** in the presence of a catalytic amount of *p*-toulenesulfonic acid with azeotropic removal of water followed by oxidation of the purified intermediates **6**−**8** (Scheme 2). For the synthesis of racemic [1,3]oxathiolan-5-one oxides *rac*-**9**−**11**, which were primarily applied in the investigations, hydrogen peroxide in acetic acid at room temperature was used. For the synthesis of enantioenriched sulfoxide **9**, which allows the preparation of enanatioenriched cycloadducts, two methods were employed: First the asymmetric oxidation of **6** and second the enzymatic resolution of **9**. The best results were obtained using the procedure developed by Kagan.[8] Oxidation of **6** with 1,1-diphenylethyl hydroperoxide in the presence of the titanium complex of diisopropyl tartrate and 1 eqiv. of water led to the sulfoxide **9** with an enantiomeric excess of 73% in 41% yield. For this reaction it is assumed that the titanium coordinates to the sulfur atom;[9] however, this is only true for unfunctionalized sulfoxides. In the case of the cyclic sulfoxide **6** with a carbonyl group an even stronger coordination to the oxygen due to the well-known strength of titanium

  1434−193X/98/1212−2733 $ 17.50+.50/0

oxygen bonds can be expected. This may explain the lower enantioselectivity found for the oxidation of **6** relative to simple aryl alkyl sulfides. However, it cannot be excluded that the cyclic structure of the sulfide causes the decrease of enantioselectivity. We have also used the manganese(III) salen catalyst developed by Jacobsen;[10] however, no oxidation product could be obtained. Finally, the enantiomer differentiating enzymatic saponification[11] of racemic **9** with chymotrypsin was investigated. Here, only complete decomposition of the substrate was observed. In **11** a second stereogenic center exists. In this case only one diastereomer is obtained with the *tert*-butyl group *trans* to the oxygen at the sulfur.

Scheme 2



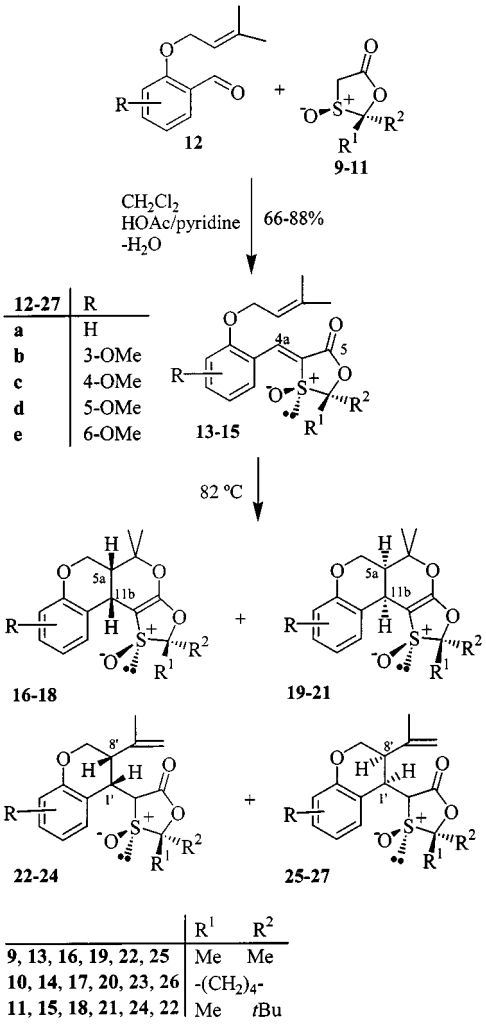
	R^1	R^2
3	Me	Me
4	-$(CH_2)_4$-	
5	Me	*t*Bu

	R^1	R^2
6	Me	Me
7	-$(CH_2)_4$-	
8	Me	*t*Bu

	R^1	R^2
9	Me	Me
10	-$(CH_2)_4$-	
11	Me	*t*Bu

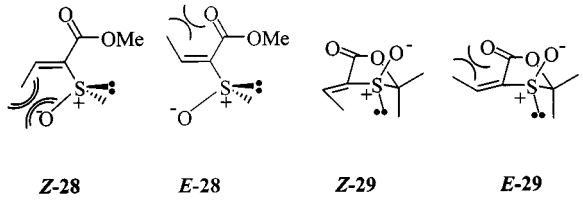
The Knoevenagel condensation of the **9**−**11** with **12** was performed in the presence of catalytic amounts of pyridinium acetate in dichloromethane with azeotropic removal of water to give the benzylidene compounds **13**−**15** in good yields and high (*Z*) selectivity (Scheme 3). The configuration of the double bond was assigned by analysis of the NMR coupling constants of C-5 and 4a-H, which were found to be in the range of $J = 6-7$ Hz. This is generally consistent with a trisubstituted (*Z*) double bond, whereas for an (*E*) double bond $J = 10-12$ Hz would have been observed.[12] The formation of the (*Z*) Knoevenagel product stays in contrast to the formation of **1** with an (*E*) double bond.[5] Knoevenagel reactions usually proceed under thermodynamic control.[2][13] Thus, one can assume that (*E*)-**1** and (*Z*)-**13**−**15** are the more stable diastereomers. To confirm this assumption, we performed B3LYP/6-311+G* calculations on the model systems (*Z*)-**28**, (*E*)-**28**, (*Z*)-**29**, and (*E*)-**29** (Scheme 4). In the preferred conformation of **28** the ester and the S−O group are in plane with the vinylic double bond.[7] Since the S−O bond is longer than the C=O bond, (*Z*)-**28** should be sterically more hindered than (*E*)-**28**. This is confirmed by the calculations showing that (*Z*)-**28** is disfavored by 8.8 kJ mol^{-1}. In compound **29** however, the S−O bond cannot occupy the stereoelectronically favored planar orientation to the C−C double bond since the tetragonal sulfur is part of a ring system. Thus, in (*Z*)-**29** there is only little steric interaction between the (*Z*)-substituent and the sulfur oxygen, whereas in (*E*)-**29** a steric interaction of the substituent at the double bond and the carbonyl group is effective. This again is confirmed by the calculations showing that (*E*)-**29** is disfavored by 3.3 kJ mol^{-1}.

Scheme 3



	R^1	R^2
9, 13, 16, 19, 22, 25	Me	Me
10, 14, 17, 20, 23, 26	-$(CH_2)_4$-	
11, 15, 18, 21, 24, 22	Me	*t*Bu

Scheme 4



***Z*-28** ***E*-28** ***Z*-29** ***E*-29**

The Diels−Alder reactions of **13**−**15** was either performed in 1,2-dichloroethane at 82°C or under the mediation of $ZnBr_2$ in CH_2Cl_2 at room temperature. In the $ZnBr_2$-mediated reaction of **13a** a single product **16a** with *cis* annulation of the ring systems and *syn* orientation of the aryl moiety to the oxygen of the sulfoxide moiety was obtained in 78% yield. Thus, only one out of four possible diastereomers was formed. The reaction was also performed in the presence of $AlCl_3$, Et_2AlCl, $TiCl_4$, $FeCl_3$, and TMS-triflate (TMSOTf). However, under these reaction conditions a fast decomposition of the substrates and possible products was observed. Thus, treatment of **13a** with TMSOTf at −78°C leads to a cleavage of the ether moiety within minutes. Under thermal conditions the reaction of

13a is slightly less selective and small amounts of an additional diastereomer **19a** and the ene products **22a** and **25a** were found (Table 1). For the reaction of **15a**, the addition of $ZnBr_2$ nearly doubles the yield and allows a reduction of the reaction time to a tenth.

The reactivity of the benzylidene oxathiolane derivatives strongly depends on the substituents R, R^1, and R^2. The substrates **13** containing a methyl group as R^1 and R^2 are most suitable. Within these series, **13e** with a methoxy group at C-6 at the arene moiety shows the highest and **13c** with the methoxy group at C-4 the lowest reactivity. These can be explained by assuming that in **13e** the arene moiety is not in plane with the 1-oxa-1,3-butadiene moiety. Therefore the LUMO energy of the 1-oxa-1,3-butadiene system is only little affected by the electron-donating arene moiety. On the other hand in **13c** a strong donating effect of the aryl moiety exists, which leads to an increase of the LUMO energy of the 1,3-butadiene. Since in this Diels–Alder reaction with inverse electron demand the interaction of the LUMO and the HOMO of the dienophile is most important, **13c** should show a lower reactivity than **13a**, **b**, **d**, **e**. It should be noted that for the subsituted substrates **13b–e** the amount of the ene products **22** and **25** is generally higher than found for **13a**. As observed for the cycloadducts the *cis*-annulated ene products are usually found preferentially.

The cycloadducts could be purified by chromatography on silicagel, they are usually crystalline and can be stored at 4°C. However, at higher temperature they decompose. The ^{1}H- and ^{13}C-NMR data did not allow an assignment of the relative configuration of the cycloadducts. But we succeeded in getting a X-ray analysis of **16a** which, in combination with the NMR data, enabled us to determine the structure of all products. From the coupling constants of $J_{5a,11b}$ = 5.0–5.5 Hz for the major and minor cycloadducts **16–18** and **19–21** it follows that both are *cis*-annulated. However, there is a clear difference between the resonances of the hydrogens at C-6, which allows to distinguish the major and the minor products. 6-H_{ax} and 6-H_{eq} of the major products resonate at δ = 3.97–4.06 and 4.37–4.50, respectively, and of the minor products at δ = 3.66–3.74 and δ = 3.81–4.37.

Discussion and Calculation of the Diels–Alder Reaction

The intramolecular Diels–Alder reaction of the benzylidene oxathiolane derivatives **13–15** leads mainly to the *cis*-fused adducts **16–18**. Since the starting material contains a (*Z*) double bond which corresponds to an (*E*)-1-oxo-1,3-butadiene moiety one can assume that the reaction takes place via an *endo*-(*E**) transition structure. But, the products could also be formed via an *exo*-(*Z*) transition structure if an isomerization of the double bond takes place intermediately and the formed isomeric 1-oxo-1,3-butadienes have the higher reactivity. However, this seems to be rather unlikely since a (*E*)-benzylidene oxathiolanone [contains a (*Z*)-1-oxa-1,3-butadiene] was never observed and the reactivity of (*Z*)-1-oxa-1,3-butadienes is usually decreased. An isomerization of the products can be excluded since they are stable under the reaction conditions.

It has to be assumed that the main product is formed by an attack of the dienophile moiety *syn* to the sulfoxide oxygen. This was not expected, since it was believed that the cycloaddition takes place *anti* to the sulfoxide oxygen to minimize steric interaction in the transition structure. To rationalize the findings we performed calculations on the cycloaddition of **29** and **30** as a model system. There are two kinds of stereoselectivity to be considered: First the *endo/exo* selectivity (simple diastereoselectivity) and secondly the induced diastereoselectivity (attack *syn* or *anti* to S–O). Thus, the four possible products **31–34** must be considered (Scheme 5). We calculated the transition structures (TS) leading to these products with B3LYP/6-31G*// B3LYP/3-21G(*) (Figure 1, Table 2). This level of theory has proven to be a good compromise for vinylsufoxides[7] with respect to the required accuracy and the computational effort.

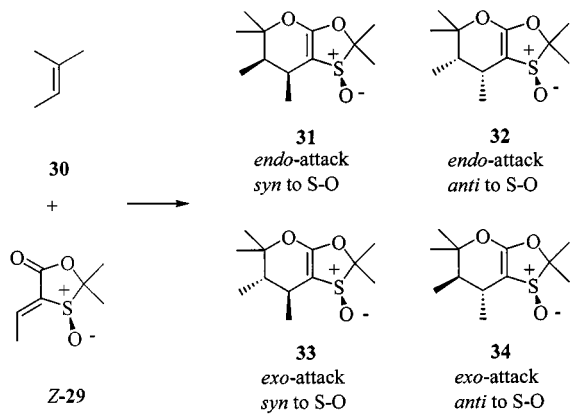
The calculations show that the cycloaddition in an *endo* mode *syn* to the S–O group to give **31** is kinetically favored.

Table 1. Formation and cycloaddition of **13–15**

	Sulfoxide		Aldehyde		Knoevenagel condensation product	yield [%]	Cyclization Product ratio Diels–Alder products *syn*		Diels–Alder products *anti*		Ene products *syn*		Ene products *anti*		Total yield [%]
	R^1	R^2		R											
9	CH_3	CH_3	**12a**	H	**13a**	88	**16a**	100	**19a**	–	**22a**	–	**25a**	–	78[a]
							16a	92	**10a**	4	**22a**	2	**25a**	2	85
9	CH_3	CH_3	**12b**	3-OMe	**13b**	66	**16b**	73	**19b**	5	**22b**	22	**25b**	–	82
9	CH_3	CH_3	**12c**	4-OMe	**13c**	70	**16c**	80	**19c**	6	**22c**	8	**25c**	6	50[b]
9	CH_3	CH_3	**12d**	5-OMe	**13d**	87	**16d**	74	**19d**	8	**22d**	9	**25d**	9	76[c]
9	CH_3	CH_3	**12e**	6-OMe	**13e**	69	**16e**	74	**19e**	–	**22e**	26	**25e**	–	96
10	CH_2–CH_2		**12a**	H	**14a**	68	**17a**	91	**20a**	9	**23a**	–	**26a**	–	53[d]
							17a	91	**20a**	9	**23a**	–	**26a**	–	32
11	CH_3	*t*Bu[e]	**12a**	H	**15a**	78	**18a**	56	**21a**	15	**24a**	27	**27a**	2	84

[a] Reaction in CH_2Cl_2 in presence of equimolar amounts of $ZnBr_2$ at 20°C. – [b] In addition 41% of **13c** were reisolated. – [c] In addition 6% of **13d** were reisolated. – [d] Reaction in $CHCl_3$ in presence of equimolar amounts of $ZnBr_2$. – [e] The *tert*-butyl group is *trans* to the S–O group.

Scheme 5



This nicely fits with the experimental results of the cycloaddition of **13** to give **16**. The quantitative values of the selectivity predicted by B3LYP/3-21G(*) differ slightly from the experimental values. Whereas in the experiment the *endo* selectivity is higher than the induced selectivity, the calculations give a higher induced selectivity. The underestimation of the *endo* selectivity was not unexpected since the calculations were performed for an intermolecular reaction, whereas the experiments were done in an intramolecular mode. However, by calculating the energies of the TS with B3LYP/6-31G*, a higher *endo* selectivity is obtained, although the predicted induced diastereoselectivity is still higher than the *endo* selectivity. Finally, we calculated the energies of the TS using the self consistent isodensity polarized continuum model (SCIPCM) to include the effect of a solvent. In this case a lower induced diastereoselectivity of 92:6 is found, which compares well with the induced diastereoselectivity obtained in the cyclizations of **13** under thermal conditions. The obtained *endo* selectivity is higher than the induced diastereoselectivity. The calculations clearly show that a change of the method leads to different quantitative results. However, in all cases the product obtained by an *endo* attack *syn* to the S−O group is highly favored.

To explain the preference of the attack *syn* to the S−O group (*syn* mode) the calculated transition structures were inspected (Figures 1 and 2, Table 2). Since the *syn* mode attack should be disfavored due to steric interaction with the S−O group, this must be overcompensated by severe interaction in the *anti* mode. The rings system of the heterodiene displays an envelope conformation, in which the methyl group at C-6 *syn* to the S−O group is orientated in a pseudo-equatorial orientation to minimize steric interaction. From this it follows that the methyl group at C-6 *anti* to the S−O group must occupy a pseudo-axial orientation which very strongly shields the face *anti* to the S−O group. This is confirmed by the calculations, which show that the distance between the axially orientated methyl group at C6 of (*Z*)-**29** and the dienophile in the *anti* mode (**TS 32**: $r_{C2'a\text{-}C6a}$ = 464 pm and $r_{C1'a\text{-}C6a}$ = 456 pm; **TS 34**: $r_{C2'a\text{-}C6a}$ = 433 pm, numeration of the atoms in the calculated structures follows Figure 1) is shorter than the distance between the pseudo-equatorial methyl group and the dienophile in the *syn* mode (**TS 31**: $r_{C2'a\text{-}C6a}$ = 478 pm and $r_{C1'a\text{-}C6a}$ = 582 pm; **TS 33**: $r_{C2'a\text{-}C6a}$ = 459 pm). One might argue, that these distances are too long to explain the high selectivity; however, it should be noted that in the *anti* mode **TS 32** and **TS 34** the distances $r_{C2'a\text{-}C6a}$ and $r_{C1'a\text{-}C6a}$ would be shorter, if the oxathiolanone ring were not bent in a more planar form to minimize the steric interaction between the dienophile and the pseudo-axial methyl group at C6. This deformation of the ring system destabilizes the *anti* mode TS. In the transition structure for the *syn* attack however, the envelope form of the ring is maintained. The methyl group C1′a in the intermolecular model system represents the tether of the experimentally investigated intramolecular systems **13**−**15**. Since the tether is bulkier than the methyl group of the dienophile **30** an even stronger steric interaction in the anti-mode **TS 13** should exist compared to the model system.

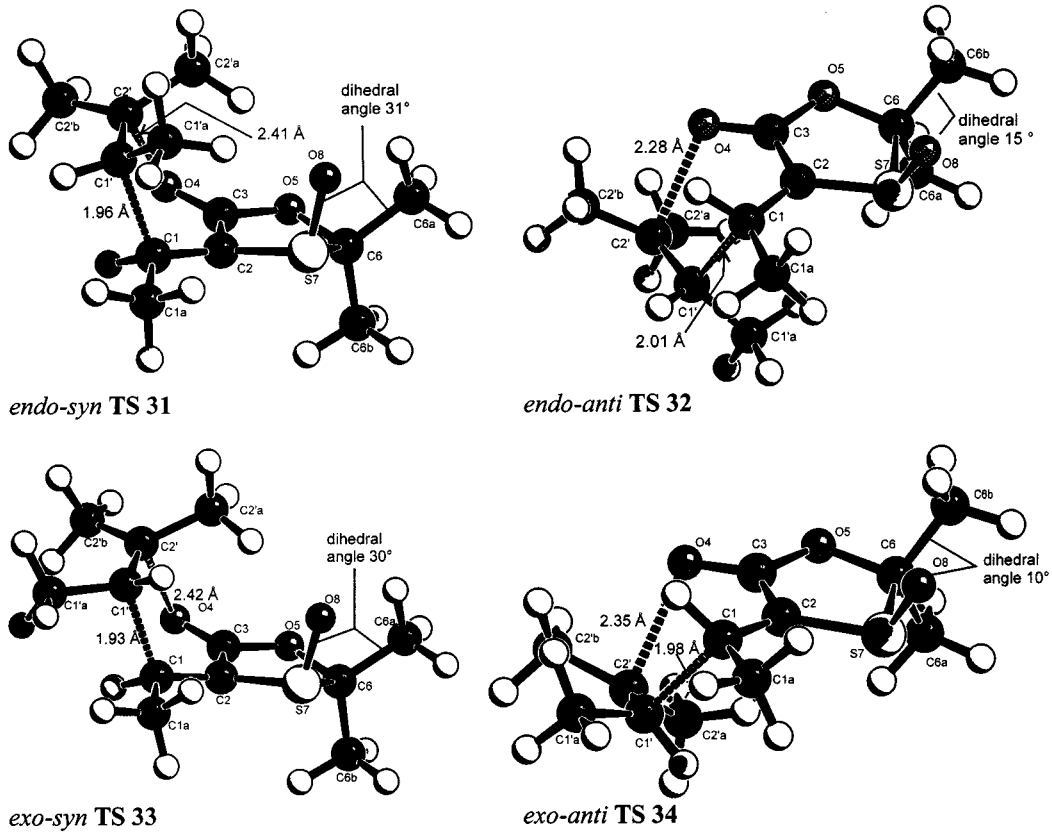
The usage of the SCIPCM model lowers the predicted induced selectivity. Thus, the steric interactions in the *anti* mode TS must be partially compensated by solvation. In

Table 2. Transitions structures of the Diels−Alder reaction between (*Z*)-**29** and **30**

Transition structure		*endo-syn* **TS 31**	*endo-anti* **TS 32**	*exo-syn* **TS 33**	*exo-anti* **TS 34**
B3LYP/3-21G*	energy [au]	−1087.45799	−1087.44635	−1087.45433	−1087.44430
	relative energy [kJ mol^{-1}]	0	30.6	9.6	35.9
	product distribution[b]	96%	< 1%	4%	< 1%
	$r_{C1\text{-}C1'}$ [pm]	196	201	193	198
	$r_{O4\text{-}C2'}$ [pm]	241	228	242	235
	$r_{C2'a\text{-}C6a}$ [pm]	478	464	459	433
	$r_{C1'a\text{-}C6a}$ [pm]	582	456	–	–
B3LYP/6-31G*//	energy [au]	−1093.07612	−1093.07033	−1093.07117	−1093.06788
B3LYP/3-21G*	relative energy [kJ mol^{-1}]	0	15.2	13.0	21.6
	product distribution[b]	99%	< 1%	1%	< 1%
B3LYP/6-31G*//	energy [au]	−1093.08486	−1093.08182	−1093.08071	−1093.07899
B3LYP/3-21G* SCIPCM[a]	relative energy [kJ mol^{-1}]	0	8.0	10.9	15.4
	product distribution[b]	92%	6%	2%	< 1%

[a] With a cavity boundary at the electron density of 0.0004 and the relative dielectricity constant of 10.6 for $ClCH_2CH_2Cl$. − [b] Calculated for a reaction temperature of 82°C.

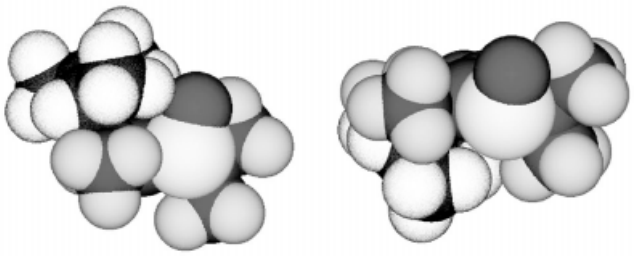
Figure 1. Calculated transition structures of the Diels−Alder reaction of (*Z*)-**29** and **30** to give the cycloadducts **31**−**34**



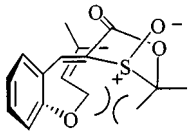
endo-syn **TS 31** *endo-anti* **TS 32**

exo-syn **TS 33** *exo-anti* **TS 34**

Figure 2. Space filling models of transition structures **TS 31** and **TS 32**



Scheme 6



TS-13 *anti*

the TS of the *anti* mode the polar S−O group (NBO charge of the sulfoxide oxygen in **TS 32** = −0.98) is located at the outer sphere of the transition structure and is freely accessible for solvents, whereas in the TS of the *syn* mode the S−O group is located inside the structure and is shielded by the attacking dienophile. Thus, the *anti* mode can be stabilized to a higher extent by interaction with a polar solvent.

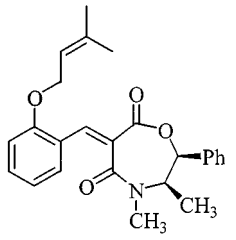
Conclusions

The intramolecular hetero Diels−Alder reaction of **13**−**15** to give the tetracyclic heterocycles **16**−**18** is a highly useful and efficient method for the synthesis of novel and unusual heterocycles. It shows an excellent induced and simple diastereoselectivity and is also adaptable for the synthesis of enantiopure compounds. However, the enantioselective oxidation of the oxathiolane **6** to give the chiral sulfoxide **9** has not exceeded 73% ee so far. The unexpected high facial selectivity caused by the stereogenic sulfur center could nicely be explained using DFT calculations of the transition structures of a model system. The calculations clearly show that the facial selectivity in the intramolecular Diels−Alder reaction is not controlled by the S−O group directly but by the methyl group at C-6 *anti* to the S−O group. A comparable result was observed by us some time ago in the hetero Diels−Alder reaction of **35** in which the attack of the dienophile moiety takes place *syn* to the bulkier groups at the stereogenic centers.[14] This also is caused by the conformational orientation of the molecule as shown in the X-ray of **36** in which the lower face is shielded by a hydrogen.

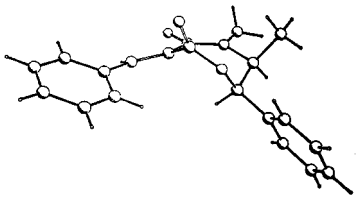
Calculation Methods

All starting geometries for the DFT calculations were generated with PC Model, using the MMX force field[15]

Scheme 7



35



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and were preoptimized with the semiempirical PM3[16] method, using the VAMP[17] program on a IBM RS/6000 workstation. As starting values for the newly formed C−O and C−C bonds in the transition structures 2.01 Å and 1.99 Å, respectively, were used; these values are the C−O and C−C distances calculated for the cyclization of acrolein and ethene.[18] For the DFT calculations Becke's three-parameter hybrid functional (B3)[19] together with the correlation functional of Lee, Yang, and Parr (LYP)[20] were employed as implemented in Gaussian 94.[21] For the interpretation of wavefunctions we utilized the natural bond population analysis (NBO).[22][23] Standardized 3-21G,[24] 6-31G,[25] and 6-311G[26] basis sets were used together with polarization (*)[27] and diffuse (+)[28] functions. The transition structures were characterized by frequency analysis and were found to have exact one imaginary vibration frequency. For the calculation of solvent effects the SCI-PCM[29] model, a polarized continuum model included in Gaussian 94, was employed. All calculations were carried out on an IBM RS/6000 Workstation and an SGI Power-Challenge.

Experimental Section

General Methods: Column chromatography was performed with silicagel 60 (0.063−0.200 mesh) from Macherey & Nagel. Solvents were dried before use, all other commercial available compounds were used without purification. Compound **6** and racemic **9** were prepared following the literature.[30] The aldehydes **12** were prepared from the corresponding salicylic aldehydes according to the literature.[31][32] − IR: Bruker IFS. − NMR: Varian XL200, VXR 200, UNITY 300, INOVA 500, and Bruker AMX-300 solvent $CDCl_3$ and TMS as internal standard. − MS: Varian MAT 311A and MAT 731.

Synthesis of the [1,3]Oxathiolanon-5-ones. − General Procedure: A solution of the ketones **3**−**5** (1.4 mol) and mercapto acetic acid **2** (63.5 g, 0.7 mol) in toluene (300 ml) was refluxed in presence of 0.6 g of *p*-toulene sulfonic acid for 24 h with azeotropic removal of water. The mixture was washed with saturated aqueous $NaHCO_3$ solution (100 ml) and brine, and dried over Na_2SO_4. The solvent was removed in vacuo and the products **6**−**8** purified by destillation.

1-Oxa-4-thiaspiro[4.4]nonan-2-one (**7**): Yield 48%, b. p. 110°C (5 mbar). − ^{1}H NMR ($CDCl_3$): δ = 1.5−2.5 (m, 8 H), 3.78 (s, 2 H). − ^{13}C-NMR ($CDCl_3$): δ = 23.54, 33.21, 41.14, 97.27, 172.1 − $C_7H_{10}O_2S$ (158.22): calcd. C 53.13, H 6.37, S 20.27, found C 53.33, H 6.30, S 20.07.

2-tert-Butyl-2 Methyl-1,3-oxathiolan-5-one (**8**): Yield: 77%, b. p. 101°C (20 mbar). − ^{1}H NMR ($CDCl_3$): δ = 1.09 (s, 9 H), 1.75 (s, 3 H), 3.60 (d, *J* = 16 Hz, 1 H), 3.85 (d, *J* = 16 Hz, 1 H). − ^{13}C NMR ($CDCl_3$): δ = 25.17, 25.99, 33.08, 40.09, 98.95, 172.2. − $C_8H_{14}O_2S$ (174.27): calcd. C 55.14, H 8.10, S 18.40, found C 55.26, H 7.97, S 18.30.

Oxidation of the [1,3]Oxathiolan-5-ones. − General Procedure: To a mixture of the [1,3]oxathiolan-5-one **6**−**8** (0.10 mol) and acetic acid (50 ml) was added H_2O_2 (1.5 equiv.) dropwise at 0°C with stirring. Stirring was continued for 1 h at 0°C and 16 h at r.t. The workup was performed according to the literature[30] and the 3-oxo[1,3]oxathiolan-5-ones were purified by column chromatography.

4-Oxo-1-oxa-4-thiaspiro[4.4]nonan-2-one (**10**): Yield: 60%, m. p. 55°C, R_f = 0.32 (diethyl ether/CH_2Cl_2, 1:1) − ^{1}H NMR ($CDCl_3$): δ = 1.70−2.38 (m, 6 H), 2.38−2.76 (m, 2 H) 3.65 (d, *J* = 16 Hz, 1 H), 3.85 (d, *J* = 16 Hz, 1 H). − ^{13}C NMR ($CDCl_3$): δ = 23.35, 24.90, 30.88, 33.69, 52.40, 108.1, 170.2. − $C_7H_{10}O_3S$ (174.22): calcd. C 48.26, H 5.79, S 18.41, found C 48.11, H 5.71, S 18.15.

2-tert-Butyl-2-methyl-3-oxo[1,3]oxathiolan-5-one (**11**): Yield: 74%, m. p. 99° C, R_f = 0.20 (*tert*-butyl methyl ether/petroleum ether, 1:1). − ^{1}H-NMR ($CDCl_3$): δ = 1.11 (s, 9 H), 1.65 (s, 3 H), 3.58 (d, br., *J* = 18 Hz, 1 H) 4.05 (d, *J* = 18 Hz, 1 H). − ^{13}C NMR ($CDCl_3$): δ = 14.69, 25.54, 37.83, 53.67, 108.2, 169.2 − $C_8H_{14}O_3S$ (190.26): calcd. C 50.50, H 7.42, S 16.85, found C 50.68, 7.26, 16.96.

Knoevenagel Condensations. − General Procedure: A solution of the sulfoxides **9**−**11** (3−8 mmol) and the aldehydes **12a**−**e** (1.1 equiv.) in $CHCl_3$ (20 ml/mmol sulfoxide) was refluxed in the presence of catalytic amounts of piperidinium acetate with azeotropic removal of water. After 2−3 h the solvent was removed in vacuo and the product was purified by column chromatography.

Knoevenagel Product **13a**: Yield: 88%, R_f = 0.34 (diethyl ether/petroleum ether, 2:1). − ^{1}H NMR ($CDCl_3$): δ = 1.55 (s, 3 H), 1.77 (s, 3 H) 1.81 (s, 6 H), 4.64 (d, *J* = 7 Hz, 2 H), 5.48 (m, 1 H), 6.92−7.18 (m, 2 H), 7.55 (ddd, *J* = 8 Hz, 7.5 Hz, 1.8 Hz, 1 H), 8.17 (dd, *J* = 8 Hz, 1.8 Hz, 1 H), 8.81 (s, 1 H). − ^{13}C NMR ($CDCl_3$): δ = 18.29, 19.92, 24.28, 25.77, 65.72, 95.27, 112.5, 118.8, 121.1, 121.8, 129.1, 131.8, 135.3, 138.7, 149.7, 159.1, 167.1 − $C_{17}H_{20}O_4S$ (320.42): calcd. C 63.72, H 6.29, S 10.01, found C 63.74, H 6.20, S 10.16.

Knoevenagel Product **13b**: Yield: 66%, R_f = 0.41 (*tert*-butyl methyl ether/petroleum ether, 4:1) − ^{1}H NMR ($CDCl_3$): δ = 1.54 (s, 3 H), 1.68 (d, *J* = 1 Hz, 3 H) 1.74 (s, 3 H), 1.80 (s, 3 H), 3.94 (s, 3 H), 4.66 (d, *J* = 7 Hz, 2 H), 5.52 (m, 1 H), 7.14−7.34 (m, 2 H), 7.83 (dd, *J* = 7 Hz, 3 Hz, 1 H), 8.80 (s, 1 H). − ^{13}C NMR ($CDCl_3$): δ = 17.90, 19.90, 24.23, 25.83, 55.98, 70.22, 95.30, 117.2, 119.3, 122.3, 124.7, 127.4, 130.2, 140.6, 148.9, 150.3, 153.1, 166.8 − $C_{18}H_{22}O_5S$ (350.44): calcd. C 61.70, H 6.33, S 9.15, found C 61.66, H 6.33, C 9.18.

Knoevenagel Product **13c**: Yield: 70%, R_f = 0.38 (*tert*-butyl methyl ether/petroleum ether, 4:1) − ^{1}H NMR ($CDCl_3$): δ = 1.54 (s, 3 H), 1.78 (s, 3 H) 1.80 (s, 6 H), 3.92 (s, 3 H), 4.64 (d, *J* = 7

Hz, 2 H), 5.50 (m, 1 H), 6.51 (d, *J* = 2 Hz, 1 H), 6.66 (dd, *J* = 7 Hz, 3 Hz, 1 H), 8.25 (d, *J* = 9 Hz, 1 H), 8.80 (s, 1 H). – ^{13}C NMR ($CDCl_3$): δ = 18.31, 19.98, 24.42, 25.79, 55.76, 65.82, 94.83, 99.17, 106.7, 115.1, 118.6, 124.7, 133.7, 138.9, 149.2, 161.3, 166.2, 167.8 – $C_{18}H_{22}O_5S$ (350.44): calcd. C 61.70, H 6.33, S 9.15, found C 61.41, H 6.21, C 9.05.

Knoevenagel Product **13d**: Yield: 87%, R_f = 0.24 (*tert*-butyl methyl ether/petroleum ether, 1:1) – ^{1}H NMR ($CDCl_3$): δ = 1.56 (s, 3 H), 1.76 (s, 3 H) 1.82 (s, 6 H), 3.88 (s, 3 H), 4.61 (d, *J* = 7 Hz, 2 H), 5.48 (m, 1 H), 6.95 (d, *J* = 9 Hz, 1 H), 7.17 (dd, *J* = 9 Hz, 3 Hz, 1 H), 7.77 (d, *J* = 3 Hz, 1 H), 8.84 (s, 1 H). – ^{13}C NMR ($CDCl_3$): δ = 18.29, 19.98, 24.46, 25.78, 55.87, 66.25, 95.22, 114.1, 114.6, 119.1, 122.2, 122.7, 128.9, 138.7, 150.1, 153.7, 153.8, 167.0 – $C_{18}H_{22}O_5S$ (350.44): calcd. C 61.70, H 6.33, S 9.15, found C 61.74, H 6.39, C 9.18.

Knoevenagel Product **13e**: Yield: 69%, R_f = 0.26 (*tert*-butyl methyl ether/petroleum ether, 1:1) – ^{1}H NMR ($CDCl_3$): δ = 1.58 (s, 3 H), 1.74 (s, 6 H), 1.76 (s, 3 H) 1.79 (s, 3 H), 3.99 (s, 3 H), 4.70 (d, *J* = 7 Hz, 2 H), 5.49 (m, 1 H), 6.61 (d, *J* = 8 Hz, 2 H), 7.41 (t, *J* = 8 Hz, 1 H), 8.56 (s, 1 H). – ^{13}C NMR ($CDCl_3$): δ = 18.29, 20.43, 23.87, 25.74, 55.59, 65.90, 93.8, 103.3, 104.9, 110.3, 119.1, 129.8, 134.9, 38.2, 143.4, 159.5, 159.8, 167.9. – $C_{18}H_{22}O_5S$ (350.44): calcd. C 61.70, H 6.33, S 9.15, found C 61.51, H 6.24, C 8.87

Knoevenagel Product **14a**: Yield: 68%, R_f = 0.42 (*tert*-butyl methyl ether/petroleum ether, 4:1) – ^{1}H NMR ($CDCl_3$): δ = 1.50–2.0 (m, 1 H), 1.5-2.0 (m, 13 H), 4.66 (d, *J* = 7 Hz, 2 H), 5.51 (m, 1 H), 7.2-7.9 (m, 2 H), 7.59 (ddd, *J* = 8.5 Hz, 8 Hz, 2 Hz, 1 H), 8.21 (dd, *J* = 8 Hz, 2 Hz, 1 H), 8.83 (s, 1 H). – ^{13}C NMR ($CDCl_3$): δ = 18.30, 19.92, 23.40, 24.59, 25.77, 30.02, 35.32, 65.71, 105.4, 112.5, 118.8, 121.1, 121.8, 128.6, 131.8, 135.3, 138.8, 149.1, 159.1, 167.2 – $C_{19}H_{22}O_4S$ (346.45): calcd. C 65.87, H 6.40, S 9.26, found C 65.73, H 6.42, S 9.22.

Knoevenagel Product **15a**: Yield: 78%, R_f = 0.40 (*tert*-butyl methyl ether/petroleum ether, 1:1) – ^{1}H NMR ($CDCl_3$): δ = 1.08 (s, 9 H), 1.69 (s, 3 H), 1.75 (s, 3 H) 1.80 (s, 3 H), 4.65 (d, *J* = 6.5 Hz, 2 H), 5.49 (m, 1 H), 6.98 (dd, *J* = 8.8 Hz, 1 Hz, 1 H) 7.10 (m, 1 H), 7.53 (ddd, *J* = 8.5 Hz, 8 Hz, 1.7 Hz, 1 H), 8.24 (dd, *J* = 8 Hz, 1.7 Hz, 1 H), 8.78 (s, 1 H). – ^{13}C NMR ($CDCl_3$): δ = 15.50, 18.53, 25.46, 26.02, 28.59, 65.97, 104.8, 112.7, 119.2, 121.3, 121.8, 128.5, 132.8, 135.4, 138.8, 148.5, 159.4, 167.4. – $C_{20}H_{26}O_4S$ (362.48): calcd. C 66.26, H 7.23, S 8.85, found C 66.06, H 7.28, S 8.89.

Diels-Alder Reactions of the Benzylidenesulfoxides. – General Procedure: A solution of the benzylidenesulfoxides **13**–**15** (1 mmol) in 1,2-dichloroethane (40 ml) was heated to 82°C in a pressure flask for 19–64 h. Then the solvent was removed in vacuo and the products were purified by column chromatography. For yields and selectivity see Table 1.

Cyclization of **13a** (Reaction time 48 h)

Main Diels–Alder Product **16a**: R_f = 0.38 (CH_2Cl_2/diethyl ether, 1:2). – ^{1}H NMR ($CDCl_3$): δ = 1.49 (s, 3 H), 1.51 (s, 3 H), 1.58 (s, 3 H), 1.60 (s, 3 H), 2.19 (ddd, *J* = 10.5 Hz, 5 Hz, 3.5 Hz, 1 H), 4.04 (dd, *J* = 11 Hz, 10.5 Hz, 1 H), 4.20 (d, *J* = 5 Hz, 1 H), 4.37 (ddd, *J* = 11 Hz, 3.5 Hz, 1.5 Hz, 1 H), 6.82 (dd, *J* = 8 Hz, 1.3 Hz, 1 H), 6.98 (dd, *J* = 7.5 Hz, 1.3 Hz, 1 H), 7.16 (m, 1 H), 7.46 (dd, *J* = 7.5 Hz, 1.8 Hz, 1 H). – ^{13}C NMR ($CDCl_3$): δ = 18.95, 22.88, 24.85, 26.35, 30.41, 38.15, 62.04, 82.37, 88.58, 98.12, 116.8, 120.6, 121.0, 128.5, 130.3, 153.5, 162.4. – $C_{17}H_{20}O_4S$ (320.42): calcd. C 63.72, H 6.29, S 10.01, found C 63.93, H 6.34, S 10.17.

The x-ray structure of the **16a** is deposited at the CCDC under the deposit number 102074.

Minor Diels-Alder Product **19a**: R_f = 0.27 (CH_2Cl_2/diethylether, 1:2). – ^{1}H NMR ($CDCl_3$): δ = 1.42 (s, 3 H), 1.52 (s, 3 H), 1.58 (s, 3 H), 1.66 (s, 3 H), 2.26 (ddd, *J* = 11 Hz, 5.3 Hz, 3.5 Hz, 1 H), 3.72 (dd, *J* = 11 Hz, 11 Hz, 1 H), 4.18 (d, *J* = 5.3 Hz, 1 H), 4.41 (ddd, *J* = 11 Hz, 3.5 Hz, 1.5 Hz, 1 H), 6.90 (dd, *J* = 8 Hz, 1.3 Hz, 1 H), 7.02 (ddd, *J* = 7.5 Hz, 7.5 Hz, 1.3 Hz, 1 H), 7.24 (m, 1 H), 7.54 (dd, *J* = 7.5 Hz, 1.8 Hz, 1 H).

Ene Products **22a** *and* **25a**: The ene products could not be separated; they are *cis*-annulated. – ^{1}H NMR ($CDCl_3$): δ = 1.16 (s, 3 H), 1.58 (s, 3 H), 1.60 (s, 3 H), 1.73 (s, 3 H), 1.93 (m, 3 H), 2.86 (m, 1 H), 3.88 (d, *J* = 2.2 Hz, 1 H), 4.02 (d, *J* = 1.8 Hz, 1 H), 4.02-4.15 (m, 1 H), 4.24 (t, *J* = 11 Hz, 1 H), 4.4 (ddd *J* = 11 Hz, 3.5 Hz, 2.2 Hz, 1 H), 4.47 (ddd, *J* = 12 Hz, *J* = 4.5 Hz, *J* = 1.8 Hz, 1 H), 4.64 (t, *J* = 12 Hz, 1 H), 4.68 (m, 1 H), 4.79 (m, 1 H), 5.14 (m, 1 H) , 5.18 (m, 1 H), 6.78–7.40 (m, 4 H)

Cyclization of **13b** (Reaction time 19 h)

Main Diels–Alder Product **16b**: R_f = 0.12 (*tert*-butyl methyl ether/petroleum ether, 4:1). – ^{1}H NMR ($CDCl_3$): δ = 1.48 (s, 3 H), 1.52 (s, 3 H), 1.58 (s, 3 H), 1.60 (s, 3 H), 2.20 (ddd, *J* = 10.5 Hz, 5 Hz, 3.5 Hz, 1 H), 3.84 (s, 3 H), 4.06 (dd, *J* = 11 Hz, 10.5 Hz, 1 H), 4.20 (d, *J* = 5 Hz, 1 H), 4.50 (ddd, *J* = 11 Hz, 3.5 Hz, 1.3 Hz, 1 H), 6.78 (dd, *J* = 8 Hz, 1.5 Hz, 1 H), 6.95 (t, 9 Hz, 1 H), 7.10 (dd, *J* = 8 Hz, 1.5 Hz, 1 H). – ^{13}C NMR ($CDCl_3$): δ = 18.99, 22.95, 24.84, 26.37, 30.39, 38.24, 55.70, 62.49, 82.27, 88.56, 98.13, 110.2, 120.7, 121.3, 122.0, 143.0, 128.2, 162.3. $C_{18}H_{22}O_5S$ (350.44): calcd. C 61.70, H 6.33, S 9.15, found C 61.68, H 6.36, C 9.10

Minor Diels–Alder Product **19b**: R_f = 0.21 (*tert*-butyl methyl ether/petroleum ether, 4:1). – ^{1}H NMR ($CDCl_3$): δ = 1.42 (s, 3 H), 1.52 (s, 3 H), 1.59 (s, 3 H), 1.67 (s, 3 H), 2.26 (ddd, *J* = 11 Hz, 5.0 Hz, 3.5 Hz, 1 H), 3.74 (dd, *J* = 11 Hz, 11 Hz, 1 H), 3.89 (s, 3 H), 4.17 (d, *J* = 5 Hz, 1 H), 4.53 (ddd, *J* = 11 Hz, 3.5 Hz, 1.3 Hz, 1 H), 6.82 (dd, *J* = 8 Hz, 1.5 Hz, 1 H), 6.96 (t, 9 Hz, 1 H), 7.13 (dd, *J* = 8 Hz, 1.5 Hz, 1 H).

Ene Products **22b** *and* **25b**: The ene products could not be separated; they are *cis*-annulated. R_f = 0.51 (*tert*-butyl methyl ether/petroleum ether, 4:1). – ^{1}H NMR ($CDCl_3$): δ = 1.57 (s, 6 H), 1.94 (m, 3 H), 2.96 (m, 1 H), 3.90 (s, 3 H), 3.91 (m, 1 H), 4.04–4.14 (m, 1 H), 4.29 (dd, *J* = 11 Hz, 11 Hz, 1 H), 4.56 (ddd, *J* = 10.8 Hz, 3.3 Hz, 2.0 Hz, 1 H), 4.72 (m, 1 H), 5.18 (m, 1 H), 6.80–6.88 (m, 2 H), 6.96–7.04 (m, 1 H). – ^{13}C NMR ($CDCl_3$): δ = 20.15, 22.97, 24.57, 36.89, 41.00, 55.92, 65.61, 71.11, 95.09, 111.2, 114.6, 120.4, 120.5, 121.0, 141.2, 143.7, 148.9, 170.9.

Cyclization of **13c** (Reaction time 60 h)

Main Diels–Alder Product **16c**: R_f = 0.26 (*tert*-butyl methyl ether/petroleum ether, 4:1). – ^{1}H NMR ($CDCl_3$): δ = 1.48 (s, 3 H), 1.51 (s, 3 H), 1.57 (s, 3 H), 1.60 (s, 3 H), 2.17 (ddd, *J* = 11 Hz, 5 Hz, 3.5 Hz, 1 H), 3.74 (s, 3 H), 4.02 (dd, *J* = 11 Hz, 11 Hz, 1 H), 4.15 (d, *J* = 5 Hz, 1 H), 4.35 (ddd, *J* = 11 Hz, 3.5 Hz, 1.3 Hz, 1 H), 6.37 (d, *J* = 2.5 Hz, 1 H), 6.57 (dd, *J* = 8.5 Hz, 2.5 Hz, 1 H), 7.34 (d, *J* = 8.5 Hz, 1 H). – ^{13}C NMR ($CDCl_3$): δ = 19.01, 22.96, 24.95, 26.45, 29.91, 38.44, 55.20, 62.19, 82.38, 88.84, 98.17, 101.7, 108.0, 112.8, 130.8, 154.4, 159.8, 162.3. $C_{18}H_{22}O_5S$ (350.44): calcd. C 61.70, H 6.33, S 9.15, found C 61.75, H 6.30, C 9.09

Minor Diels–Alder Product **19c**: R_f = 0.16 (*tert*-butyl methyl ether/petroleum ether, 4:1). – ^{1}H NMR ($CDCl_3$): δ = 1.43 (s, 3 H), 1.52 (s, 3 H), 1.58 (s, 3 H), 1.67 (s, 3 H), 2.23 (ddd, *J* = 11 Hz, 5 Hz, 3.8 Hz, 1 H), 4.68 (dd, *J* = 11 Hz, 11 Hz, 1 H), 3.78 (s, 3

H), 4.11 (d, *J* = 5 Hz, 1 H), 4.37 (ddd, *J* = 11 Hz, 3.8 Hz, 1.3 Hz, 1 H), 6.41 (d, *J* = 2.8 Hz, 1 H), 6.59 (dd, *J* = 8.5 Hz, 2.8 Hz, 1 H), 7.34 (d, *J* = 8.5 Hz, 1 H).

Ene Product **22c**: ^{1}H NMR ($CDCl_3$): δ = 1.22 (2, 3 H), 1.61 (s, 3 H), 1.92 (m, 3 H), 2.96 (m, 1 H), 3.78 (m, 3 H), 4.03 (d, *J* = 1.5 Hz, 1 H), 4.08 (m, 1 H), 4.47 (ddd, *J* = 12 Hz, 4.5 Hz, 1.8 Hz, 1 H), 4.65 (t, *J* = 12 Hz, 1 H), 4.82 (s, 1 H), 5.20 (s, 1 H), 6.41-6.52 (m, 2 H), 6.87 (d, *J* = 9 Hz, 1 H).

Cyclization of **13d** (Reaction time 60 h)

Main Diels−Alder Product **16d**: R_f = 0.30 (*tert*-butyl methyl ether/petroleum ether, 4:1). − ^{1}H NMR ($CDCl_3$): δ = 1.50 (s, 6 H), 1.58 (s, 3 H), 1.62 (s, 3 H), 2.18 (ddd, *J* = 9.5 Hz, 5 Hz, 3.5 Hz, 1 H), 3.79 (s, 3 H), 4.04 (dd, *J* = 11 Hz, 9.5 Hz, 1 H), 4.18 (d, *J* = 5 Hz, 1 H), 4.33 (ddd, *J* = 11 Hz, 3.5 Hz, 1.3 Hz, 1 H), 6.74 (d, *J* = 1.5 Hz, 2 H), 7.05 (m, 1 H). − ^{13}C NMR ($CDCl_3$): δ = 19.03, 22.96, 24.60, 26.61, 31.12, 38.66, 55.72, 62.45, 82.70, 88.35, 98.20, 114.2, 115.2, 117.4, 121.2, 147.5, 153.9, 162.7. − $C_{18}H_{22}O_5S$ (350.44): calcd. C 61.70, H 6.33, S 9.15, found C 61.72, H 6.41, C 9.03

Minor Diels−Alder Product **19d**: R_f = 0.21 (*tert*-butyl methyl ether/petroleum ether, 4:1). - ^{1}H NMR ($CDCl_3$): δ = 1.43 (s, 6 H), 1.52 (s, 3 H), 1.58 (s, 3 H), 1.68 (s, 3 H), 2.24 (ddd, *J* = 11 Hz, 5.3 Hz, 3.5 Hz, 1 H), 3.66 (dd, *J* = 11 Hz, 11 Hz, 1 H), 3.81 (s, 3 H), 4.14 (d, *J* = 5 Hz, 1 H), 4.35 (ddd, *J* = 11 Hz, 3.5 Hz, 1.3 Hz, 1 H), 6.78−6.80 (m, 2 H).

Ene Products **22d** *and* **25d**: The ene products could not be separated; they are *cis*-annulated. − **22d**: R_f = 0.75 (*tert*-butyl methyl ether/petroleum ether, 4:1). − ^{1}H NMR ($CDCl_3$): δ = 1.60 (s, 3 H), 1.75 (s, 3 H), 1.94 (m, 3 H), 2.96 (m, 1 H), 3.74 (s, 3 H), 3.95 (d, *J* = 2.3 Hz, 1 H), 4.06 (ddd, br, *J* = 5.0 Hz, 2.3 Hz, 2.0 Hz, 1 H), 4.25 (t, *J* = 11 Hz, 1 H), 4.39 (ddd, *J* = 11 Hz, 3.5 Hz, 2 Hz, 1 H), 4.73 (m, 1 H), 5.19 (m, 1 H), 6.78-6.84 (m, 2 H), 7.02 (d, *J* = 2.8 Hz, 1 H).

25d: R_f = 0.38 (*tert*-butyl methyl ether/petroleum ether, 4:1), ^{1}H NMR ($CDCl_3$): δ = 1.20 (s, 3 H), 1.60 (s, 3 H), 1.94 (m, 3 H), 3.00 (m, 1 H), 3.92 (s, 3 H), 4.06 (d, *J* = 1.5 Hz, 1 H), 4.15 (m, 1 H), 4.58−4.74 (m, 2 H), 4.83 (m, 1 H), 5.22 (m, 1 H), 6.59 (m, 1 H), 6.80−6.90 (m, 2 H).

Cyclization of **13e** (Reaction time 24 h)

Main Diels−Alder Product **16e**: R_f = 0.25 (*tert*-butyl methyl ether/petroleum ether, 4:1). − ^{1}H NMR ($CDCl_3$): δ = 1.48 (s, 3 H), 1.54 (s, 3 H), 1.56 (s, 3 H), 1.58 (s, 3 H), 2.08 (ddd, *J* = 11 Hz, 5 Hz, 3.5 Hz, 1 H), 3.94 (s, 3 H), 3.97 (dd, *J* = 11 Hz, 11 Hz, 1 H), 4.27 (dd, *J* = 5 Hz, 1.5 Hz, 1 H), 4.36 (ddd, *J* = 11 Hz, 3.5 Hz, 1.5 Hz, 1 H), 6.44−6.52 (m, 2 H, 8-H), 7.11 (dd, *J* = 8 Hz, 8 Hz, 1 H). − ^{13}C NMR ($CDCl_3$): δ = 18.99, 23.54, 25.35, 25.63, 25.82, 38.14, 55.09, 61.74, 81.52, 88.81, 96.77, 102.1, 109.3, 109.7, 128.5, 154.3, 158.1, 161.4. − $C_{18}H_{22}O_5S$ (350.44): calcd. C 61.70, H 6.33, S 9.15, found C 61.48, H 6.27, C 9.08

Ene Product **22e**: R_f = 0.65 (*tert*-butyl methyl ether/petroleum ether, 4:1). − ^{1}H NMR ($CDCl_3$): δ = 1.52 (s, 3 H), 1.62 (s, 3 H), 1.95 (m, 3 H), 2.85 (m, 1 H), 3.77 (s, 3 H), 3.96 (d, *J* = 1.8 Hz, 1 H), 4.07 (ddd, *J* = 3.3 Hz, 2.3 Hz, 1.8 Hz, 1 H), 4.12 (t, *J* = 11.3 Hz, 1 H), 4.41 (ddd, *J* = 11.3 Hz, 3.3 Hz, 2.3 Hz), 4.69 (m, 1 H), 5.16 (m, 1 H), 6.45 (dd, *J* = 8.0 Hz, 1 Hz, 1 H), 6.64 (m, 1 H), 7.24 (dd, *J* = 8.0 Hz, 7.5 Hz, 1 H). − ^{13}C NMR ($CDCl_3$): δ = 20.32, 22.79, 25.08, 32.37, 42.28, 54.78, 65.30, 66.96, 93.03, 101.4, 110.1, 110.4, 113.67, 129.5, 143.1, 155.2, 157.4, 168.9. − $C_{18}H_{22}O_5S$ (350.44): calcd. C 61.70, H 6.33, S 9.15, found C 61.56, H 6.34, C 9.09.

Cyclization of **14a** (Reaction time 40 h)

Main Diels−Alder Product **17a**: R_f = 0.36 (*tert*-butyl methyl ether/petroleum ether, 4:1). − ^{1}H NMR ($CDCl_3$): δ = 1.49 (s, 3 H), 1.52 (s, 3 H), 1.65−2.13 (m, 7 H), 2.20 (ddd, *J* = 11 Hz, 5 Hz, 3.5 Hz, 1 H), 2.42−2.60 (m, 1 H), 4.03 (dd, *J* = 11 Hz, 11 Hz, 1 H), 4.20 (d, *J* = 5 Hz, 1 H), 4.37 (ddd, *J* = 11 Hz, 3.5 Hz, 1.5 Hz, 1 H), 6.82 (dd, *J* = 7.5 Hz, 1.5 Hz, 1 H), 6.98 (ddd, *J* = 7.5 Hz, 7.5 Hz, 1.5 Hz, 1 H), 7.16 (ddd, *J* = 7.5 Hz, 7.5 Hz, 1.8 Hz, 1 H), 7.45 (dd, *J* = 7.5 Hz, 1.8 Hz, 1 H). − ^{13}C NMR ($CDCl_3$): δ = 23.74, 24.68, 24.95, 26.45, 28.96, 30.48, 34.65, 38.26, 62.05, 82.43, 88.64, 108.1, 116.9, 120.5, 121.1, 128.6, 130.3, 153.6, 162.8. − $C_{19}H_{22}O_4S$ (346.45): calcd. C 65.87, H 6.40, S 9.26, found C 65.94, H 6.38, S 9.16

Minor Diels−Alder Product **20a**: R_f = 0.19 (*tert*-butyl methyl ether/petroleum ether, 4:1). − ^{1}H NMR ($CDCl_3$): δ = 1.53 (s, 3 H), 1.59 (s, 3 H), 1.66−2.13 (m, 7 H), 2.26 (ddd, *J* = 11 Hz, 5.5 Hz, 3.5 Hz, 1 H), 2.55−2.71 (m, 1 H), 3.72 (dd, *J* = 11 Hz, 11 Hz, 1 H), 4.18 (d, *J* = 5.5 Hz, 1 H), 4.39 (ddd, *J* = 11 Hz, 3.5 Hz, 1.5 Hz, 1 H), 6.86 (dd, *J* = 7.5 Hz, 1.3 Hz, 1 H), 6.99 (ddd, *J* = 7.5 Hz, 7.5 Hz, 1.3 Hz, 1 H), 7.20 (ddd, *J* = 7.5 Hz, 7.5 Hz, 1.8 Hz, 1 H), 7.51 (dd, *J* = 7.5 Hz, 1.8 Hz, 1 H).

Cyclization of **15a** (Reaction time 52 h)

Main Diels−Alder Product **18a**: R_f = 0.14 (*tert*-butyl methyl ether/petroleum ether, 1:1). − ^{1}H NMR ($CDCl_3$): δ = 0.96 (s, 9 H), 1.53 (s, 3 H), 1.59 (s, 6 H), 2.25 (ddd, *J* = 11 Hz, 5.5 Hz, 3.5 Hz, 1 H), 3.68 (dd, *J* = 11 Hz, 10.5 Hz, 1 H), 4.18 (d, *J* = 5.5 Hz, 1 H), 4.42 (ddd, *J* = 11 Hz, 3.5 Hz, 1.5 Hz, 1 H), 6.91 (dd, *J* = 8 Hz, 1.5 Hz, 1 H), 7.06 (dd, *J* = 8 Hz, 1.5 Hz, 1 H), 7.26 (m, 1 H), 7.62 (dd, *J* = 8 Hz, 2 Hz, 1 H). − ^{13}C NMR ($CDCl_3$): δ = 14.29, 25.00, 25.11, 25.92, 39.15, 37.82, 37.98, 62.29, 82.07, 88.13, 107.9, 116.7, 120.4, 121.0, 128.5, 131.2, 153.3, 160.3. − $C_{20}H_{26}O_4S$ (362.48): calcd. C 66.26, H 7.23, S 8.85, found C 66.11, H 7.29, S 8.88.

Minor Diels−Alder Product **21a**: R_f = 0.25 (*tert*-butyl methyl ether/petroleum ether, 1:1). − ^{1}H NMR ($CDCl_3$): δ = 1.10 (s, 9 H), 1.47 (s, 3 H), 1.49 (s, 3 H), 1.52 (s, 3 H), 2.19 (ddd, *J* = 11 Hz, 5.3 Hz, 3.5 Hz, 1 H), 4.09 (dd, *J* = 11 Hz, 11 Hz, 1 H), 4.17 (d, *J* = 5.3 Hz, 1 H), 4.42 (ddd, *J* = 11 Hz, 3.5 Hz, 1.5 Hz, 1 H), 6.87 (dd, *J* = 8 Hz, 1.3 Hz, 1 H), 7.04 (dd, *J* = 8 Hz, 1.3 Hz, 1 H), 7.22 (m, 1 H), 7.55 (dd, *J* = 8 Hz, 1.8 Hz, 1 H).

Ene Product **27a**: R_f = 0.53 (*tert*-butyl methyl ether/petroleum ether, 1:1), ^{1}H NMR ($CDCl_3$): δ = 0.87 (s, 9 H), 1.60 (s, 3 H), 1.92 (s, 3 H), 2.98 (m, 1 H), 4.07 (d, *J* = 1.5 Hz, 1 H), 4.25 (m, 1 H), 4.45 (ddd, *J* = 11.5 Hz, 4.5 Hz, 2 Hz, 1 H), 4.62 (dd, *J* = 12 Hz, 11.5 Hz, 1 H), 4.78 (m, 1 H), 5.20 (m, 1 H), 6.83 (m, 1 H), 6.92-7.02 (m, 2 H), 7.23 (m, 1 H). − ^{13}C NMR ($CDCl_3$): δ = 15.07, 23.05, 24.78, 36.69, 37.58, 41.08, 65.32, 97.88, 102.8, 114.5, 117.4, 120.5, 120.6, 128.9, 129.6, 141.4, 154.1, 169.5.

Enantioselective Oxidation of **6**: To a solution of $Ti(OiPr)_4$ (1.32 g, 6 mmol), diisopropyl tartrate (2.81 g, 12 mmol), and exact 6 mmol of water (108 µl) in CH_2Cl_2 (50 ml) was added after stirring for 1.5 h at r.t. the sulfide **6** (0.79 g, 6 mmol), and stirring was continued for 1 h. Then $MePh_2COOH$ (1.93 g, 9 mmol) was added at −20°C and the mixture was stirred for 20 h. For workup the reaction mixture was washed with a saturated aqueous solution of K/Na tartrate, dried over Na_2SO_4, and the solvent was removed in vacuo. The residue was purified by column chromatography, using *tert*-butyl methyl ether to eluate the diisopropyl tartrate and then ethyl acetate to eluate **9**. 0.36 g (41%) of **9** were obtained with ee = 73% and $[\alpha]_D^{20}$ = 94.3. The enantiomeric ratio was determined by a ^{1}H-NMR shift experiment using 10 mg of **9** and 1.2 mg $Eu(hfc)_3$.

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