One-Pot, Asymmetric and Diastereoselective Four-Component Synthesis of Polyfunctional (*Z*)-Alkenyl Methyl Sulfones with Three Stereogenic Centers

by **Vera Narkevitch**[1]) and **Pierre Vogel***

Institut des Sciences Moléculaires de l'Ecole Polytechnique Fédérale de Lausanne, BCH, CH-1015 Lausanne-Ecublens

and **Kurt Schenk**

Institut de Cristallographie, BSP, Université de Lausanne, CH-1015 Lausanne-Dorigny

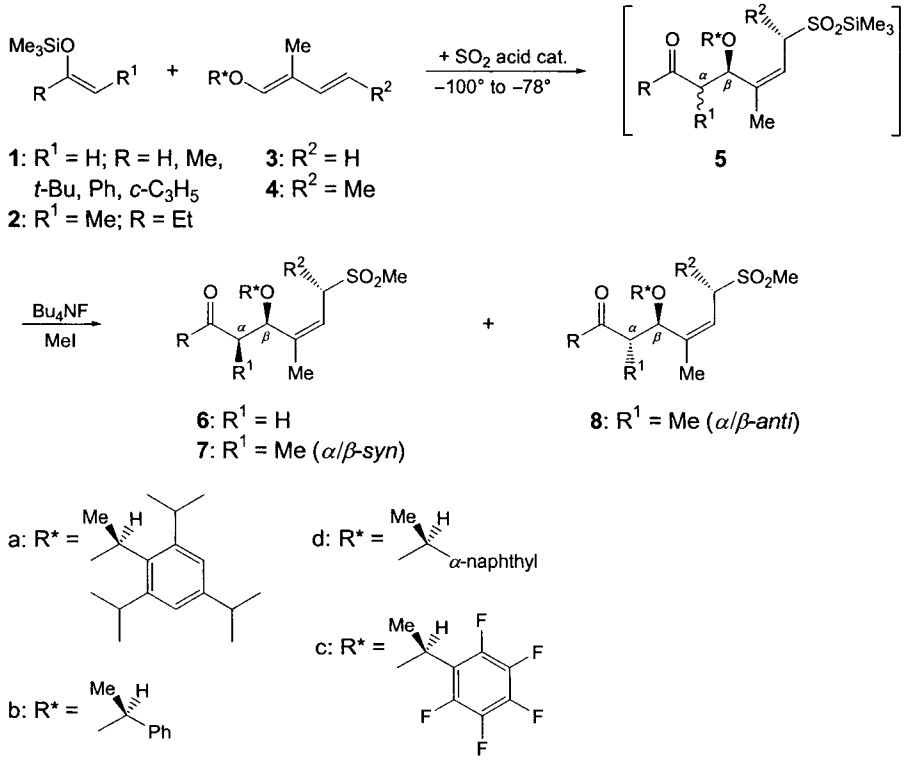
The reaction of 1-(trimethylsilyloxy)cyclopentene (**9**) with (±)-1,3,5-triisopropyl-2-(1-(*RS*)-{[(1*E*)-2-methylpenta-1,3-dienyl]oxy}ethyl)benzene ((±)-**4a**) in SO_2/CH_2Cl_2 containing $(CF_3SO_2)_2NH$, followed by treatment with Bu_4NF and MeI gave a 3.0:1 mixture of (±)-(2*RS*)-2{(1*RS*,2*Z*,4*SR*)-2-methyl-4-(methylsulfonyl)-1-[(*RS*)-1-(2,4,6-triisopropylphenyl)ethoxy]pent-2-en-1-yl}cyclopentanone ((±)-**10**) and (±)-(2*RS*)-2-{(1*RS*,2*Z*)-2-methyl-4-[(*SR*)-methylsulfonyl]-1-[(*SR*)-1-(2,4,6-triisopropylphenyl)ethoxy]pent-2-en-1-yl}cyclopentanone ((±)-**11**). Similarly, enantiomerically pure dienyl ether (−)-(1*S*)-**4a** reacted with 1-(trimethylsilyloxy)-cyclohexene (**12**) to give a 14.1:1 mixture of (−)-(2*S*)-2-{(1*S*,2*Z*,4*R*)-2-methyl-4-(methylsulfonyl)-1-[(*S*)-1-(2,4,6-triisopropylphenyl)ethoxy]pent-2-enyl}cyclohexanone ((−)-**13a**) and its diastereoisomer **14a** with (1*S*,2*R*,4*R*) or (1*R*,2*S*,4*S*) configuration. Structures of (±)-**10**, (±)-**11**, and (−)-**13a** were established by single-crystal X-ray crystallography. Poor diastereoselectivities were observed with the (*E*,*E*)-2-methylpenta-1,3-diene-1-ylethers (+)-**4b** and (−)-**4c** bearing (**1*S***)-1-phenylethyl and (1*S*)-1-(pentafluorophenyl)ethyl groups instead of the *Greene*'s auxiliary ((1*S*)-(2,4,6-triisopropylphenyl)ethyl group). The results demonstrate that high *α*/*β*-*syn* and asymmetric induction (due to the chiral auxiliary) can be obtained in the four-component syntheses of the *β*-alkoxy ketones. The method generates enantiomerically pure polyfunctional methyl sulfones bearing three chiral centers on C-atoms and one (*Z*)-alkene moiety.

Introduction. – We have found a new C−C bond-forming reaction that condenses enyl silyl ethers (*e.g.*, **1** and **2**) with butadien-1-yl ethers (*e.g.*, **3** and **4**), SO_2, and C-electrophiles (*e.g.*, MeI) to generate polyfunctional sulfones (*e.g.,* **6**–**8**, *Scheme 1*) in a one-pot reaction [1–3]. The process is believed to involve a cascade of reactions starting with the hetero-*Diels-Alder* addition of SO_2 to the 1,3-dienyl ether, giving the corresponding 3,6-dihydro-1,2-oxathiin-2-oxides (sultines) [4] in a reversible fashion. In the presence of *Lewis* or protic acid catalysts, the intermediate sultines are ionized to zwitterionic intermediates containing (*Z*)-allylic cation moieties, which add to the enyl silyl ethers (oxyallylation) to give silyl sulfonates of type **5** that can be alkylated or allylated *in situ* [3], providing the corresponding sulfones. An asymmetric version of this reaction based on enantiomerically pure 1,3-dien-1-yl ethers such as **3** and **4** (*Scheme 1*) has been presented [5][6]. With dienyl ethers of type **4**, the reaction is highly *β*/*ε*-unlike stereoselective. The reactions of enyl silyl ether **2** with dienyl ethers of type **4** generate sulfones containing three stereogenic centers, the *α*/*β*-diastereoselec-

[1]) Current address: Scripps Research Institute, 10550 N. Torrey Pines Road, La Jolla, CA 92037, USA.

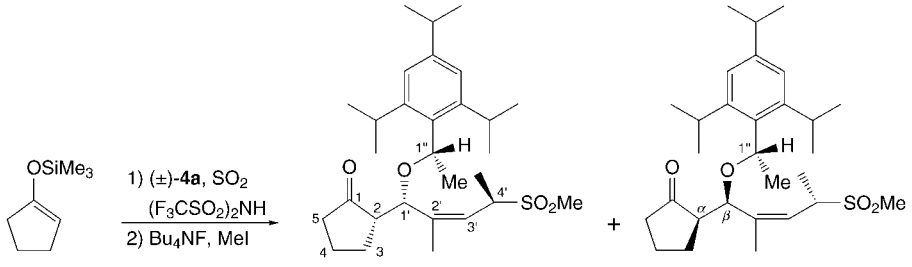
tivity being modest [6]. The best asymmetric inductions were observed with reactions involving dienyl ethers **3** and **4** bearing *Greene*'s chiral auxiliary [7]. With the goal to improve the α/β-diastereoselectivity of our one-pot, four-component synthesis of β-alkoxyketones we have now explored the reactions of cyclic enyl silyl ethers with dienyl ethers of type **4**. We report our preliminary results for the enyl trimethylsilyl ethers derived from cyclopentanone and cyclohexanone and show that high *α/β-syn* diastereoselectivity can be realized. It depends on the nature of the enyl silyl ethers and of the chiral benzyloxy group in dienyl ethers **4**. After acidic cleavage of the chiral auxiliaries, enantiomerically pure β-hydroxy ketones can be obtained.

Scheme 1



Results. – A 1:6 mixture of racemic dienyl ether (±-**4a** (derived from *Greene*'s racemic auxiliary) and enyl silyl ether **9** (derived from cyclopentanone [8]) was allowed to react with an excess of SO_2 in the presence of $(F_3CSO_2)_2NH$ (-100 to $-78°$). After SO_2 evaporation at low temperature and work-up with Bu_4NF and an excess of MeI in THF, a 3.0:1 mixture of methyl sulfones (±)-**10** and (±)-**11** was obtained. Column chromatography provided (±)-**10** and (±)-**11** in 52 and 19% yields, respectively (*Scheme 2*). Their structures were established by single-crystal X-ray crystallography (*Figs. 1* and *2*). Both β-alkoxy ketones (±)-**10** and (±)-**11** have the *α/β-syn* relative configuration (C(1′), C(2) *like*). As for the other cases of oxyallylation with dienyl

Scheme 2



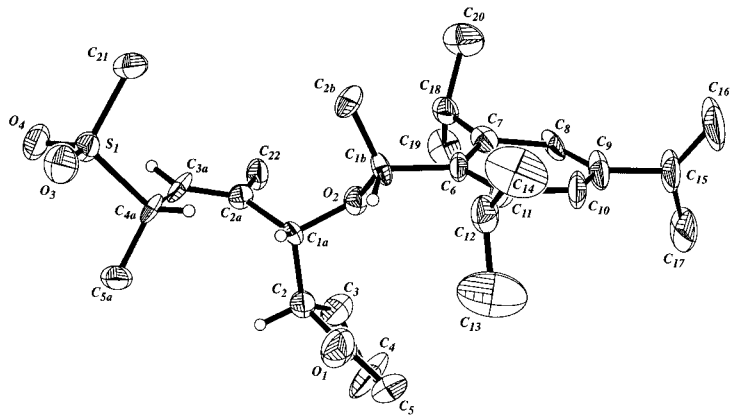


Fig. 1. *ORTEP* [9] *Representation of major β-alkoxy ketone* (±)-**10**, *showing heary atoms at the 50% probability level*[2])

ethers **3** and **4** bearing *Greene*'s chiral auxiliary, the major product (±)-**10** has a *like* relative configuration at the benzylic C-atom C(1″) and the aldol C-atom C(1′). Although only modest asymmetric induction is obtained in the oxyallylation of **9**, high *α*/*β*-*syn* diastereoselectivity is realized.

Under similar conditions a 1:3 mixture of enantiomerically pure diene (−)-**4a** (derived from *Greene*'s (*S*)-configured auxiliary [6]) and enyl silyl ether **12** (derived from cyclohexanone [8]) led to 14.1:1 mixture of *β*-alkoxy ketones (−)-**13a** and **14a** in 93% yield. The pure major ketone (−)-**13a** could be isolated by flash chromatography, and its structure was also established by single-crystal X-ray crystallography (*Fig. 3*). As for the oxyallylation of **9**, the reaction of enyl silyl ether **12** with dienyl ether (−)-**4a** is also *α*/*β*-*syn* stereoselective (*Scheme 3*). Acidic cleavage of the chiral benzylic auxiliary of a 2.4:1 mixture of (−)-**13a** and **14a** (CF_3COOH, $CDCl_3$ [10]) gave a 2.5:1 mixture of the *β*-hydroxy ketones **15** and **16**, thus demonstrating that the minor compound **14a** has a *α*/*β*-*anti* relative configuration. The absolute configurations of **14a** and **16** have not been determined.

[2]) For reasons of commodity, atom numbering does not follow the IUPAC rules.

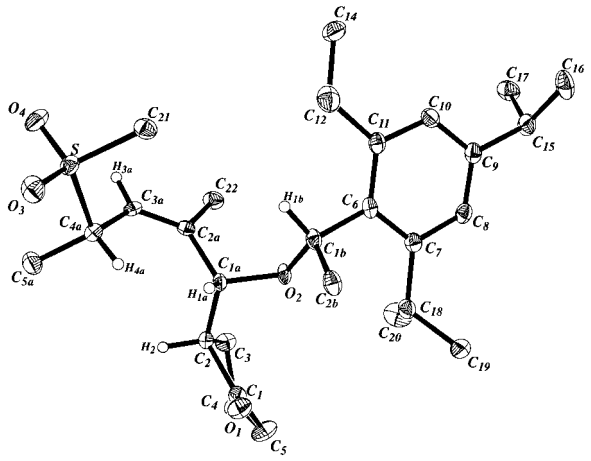


Fig. 2. *ORTEP* [9] *Representation of minor β-alkoxy ketone* (±)-**11**, *showing heary atoms at the 50% probability level*[2])

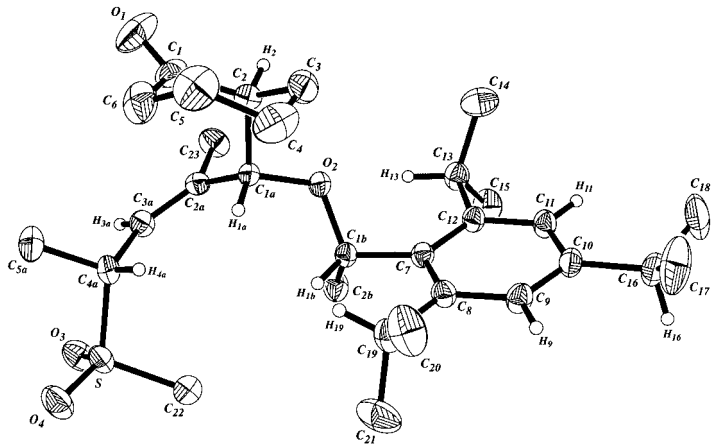
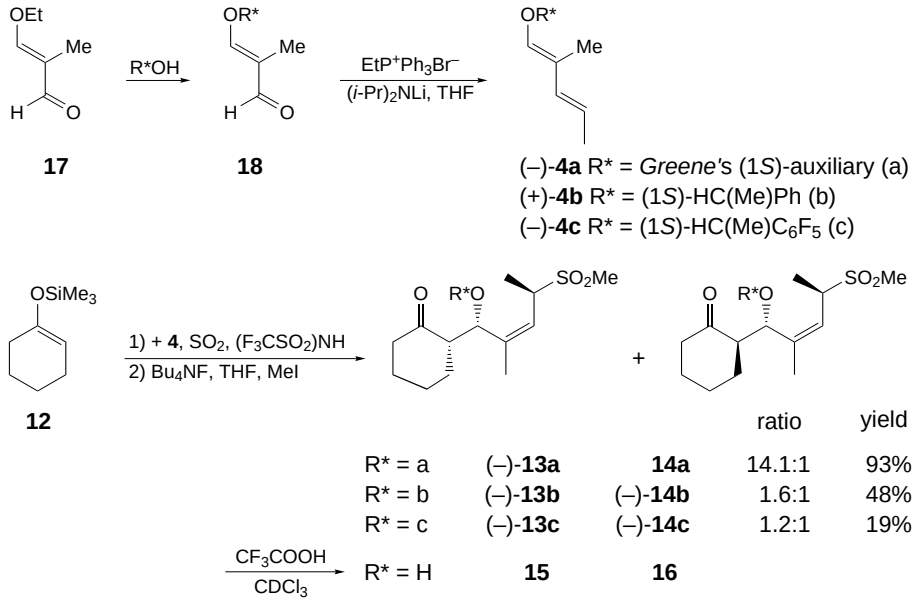


Fig. 3. *ORTEP* [9] *Representation of major β-alkoxy ketone* (±)-**13a**, *showing heavy atoms at the 50% probability level*[2])

Although satisfactory diastereoselectivity was observed for the oxyallylation **12** + (−)-**4a** + SO_2 + MeI → (−)-**13a**, we explored whether it could be improved or modified by exchange of the *Greene*'s chiral auxiliary by other benzylic (1*S*)-configured auxiliaries. We prepared dienyl ethers (+)-**4b** and (−)-**4c** as shown in *Scheme 3* [11]. Substitution of the EtO group of (*E*)-3-ethoxy-2-methylprop-2-enal (**17**) with (−)-(*S*)-1-phenylethoxy and (−)-(*S*)-1-(pentafluorophenyl)ethoxy groups [6] gave aldehydes (+)-**18b** and (−)-**18c**, respectively. *Wittig* olefination with ($EtPPh_3$)Br and (i-Pr)$_2$NLi in THF provided (+)-**4b** and (−)-**4c**, respectively, in good yield.

The oxyallylation of enyl silyl ether **12** with dienyl ether (+)-**4b**, SO_2, and MeI provided a 1.6:1 mixture of (−)-**13b** and (−)-**14b** in 48% yield (considering the

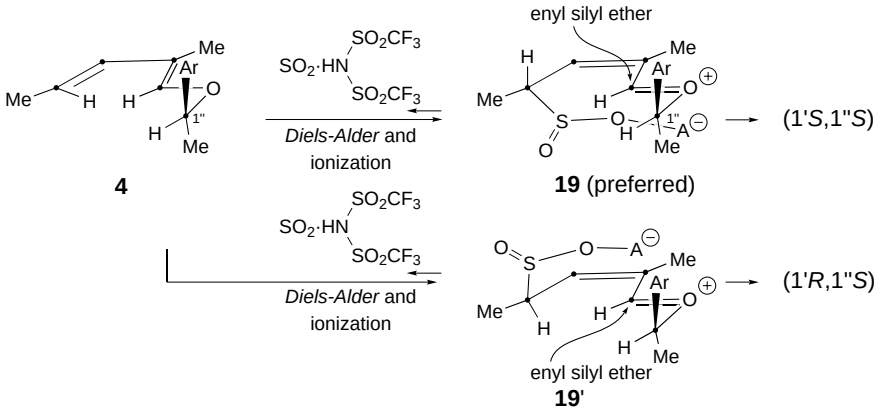
Scheme 3



recovery of the starting dienyl ether). These products could be separated by column chromatography. Under similar conditions, reaction **12** + (−)-**4c** + SO_2 + MeI was even less satisfactory, as it led to a 1.2:1 mixture of (−)-**13c** and (−)-**14c** in mediocre yield (19%). Acidic cleavage of the chiral benzylic moieties of (−)-**13b** and (−)-**13c** provided *β*-hydroxy ketone **15**, whereas (−)-**14b** and (−)-**14c** gave its *α*/*β*-*anti* isomer **16** (absolute configurations not known).

Discussion. – The diastereoselectivity (1′*S*,1″*S*) *vs.* (1′*R*,1″*S*) induced by the benzylic chiral auxiliary arises from the facial stereoselectivity of the hetero-*Diels-Alder* addition of SO_2 activated by the acid promotor $(F_3CSO_2)_2NH$ as shown in *Scheme 4*. The intermediate sultine equilibrates with dienyl ether + SO_2 and with the corresponding zwitterions **19**. If the latter is not quenched rapidly by reaction with the enyl silyl ether, both modes of hetero-*Diels-Alder* reaction compete and lead to a decrease in (1′,1″)-diastereoselectivity, as zwitterions **19′** form also and react with the enyl silyl ether [6]. The *α*/*β*-*syn vs.* *α*/*β*-*anti* diastereoselectivity of the oxyallylation is governed by the orientation of the attacking enyl silyl ether. In the case of reactions of **12** with dienyl ethers (−)-**4a**, (+)-**4b**, and (−)-**4c**, reaction paths involving orientations of type **20** are preferred for steric reasons (*Fig. 4*), as for *Mukaiyama* cross-aldol reactions [12] (open transition state [13]). The preference for the orientation of type **21** or **21′** depends also on the nature of the enyl silyl ether: it is higher for the five-membered-ring than for the six-membered-ring enyl silyl ether. Very important is the nature of the substituents at C(2) and C(6) of the phenyl ring of the chiral benzyl auxiliary. For small substituents (H, F) as with dienyl ethers (+)-**4b** and (−)-**4c**, orientations of type **21** or **21′** compete with reaction paths involving orientations of type **20**. With large

Scheme 4



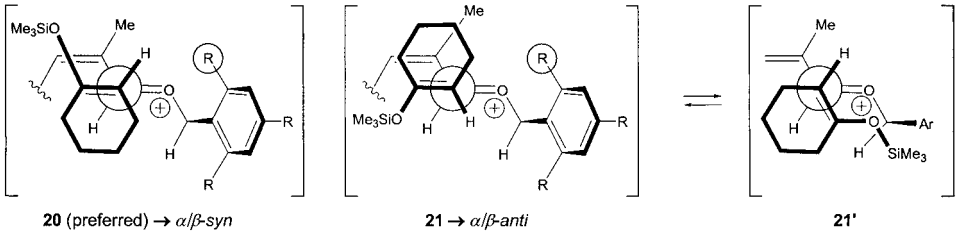


Fig. 4. *Orientations involved in different reaction paths*

substituents at C(2) and C(6), such as the i-Pr groups of *Greene*'s auxiliary (dienyl ether (−)-**4a**), orientations **21** or **21**′ are more hindered than **20** for steric reasons. Thus, this explains the difference in *α*/*β-syn vs. α*/*β-anti* diastereoselectivity of the reaction of enyl silyl ether **12** with enantiomerically pure dienyl ethers (−)-**4a**, (+)-**4b**, and (−)-**4c**.

Conclusions. – The four-component synthesis of *β*-alkoxy ketones that condenses enyl silyl ethers, 1,3-dien-1-yl ethers, SO_2, and MeI can be highly *α*/*β-syn* diastereoselective for cyclic enyl silyl ethers such as those derived from cyclopentanone and cyclohexanone. With the 1-arylethyl (*E*,*E*)-2-methylpenta-1,3-dienyl ether bearing *Greene*'s chiral auxiliary (**4a**), good diastereoselectivity induced by the chiral auxiliary is observed. The results can be interpreted in terms of steric factors, as for the *Mukaiyama* cross-aldol reaction. Better yield and diastereoselectivity can be reached by tuning the domino game that involves the chiral auxiliary attached as an 1-oxy-group to the 1,3-diene and the shape of the enyl silyl ether.

We thank the *Swiss National Science Foundation* (Bern) and the *Office Fédéral de l'Education et de la Science* (European COST D13/010/00) for financial support. We are grateful also to *M. Rey* and *F. Sepúlveda* for their technical help.

Experimental Part

General. See [6][14].

*(+)-{(*S*)-1-[(*E*)-2-Methylpenta-1,3-dien-1-yl)oxy]ethyl}benzene* ((+)-**4b**). (i-Pr)$_2$NH (3.3 ml, 20 mmol) in anh. THF (30 ml) was added dropwise to a stirred 1.6M soln. of BuLi in hexane (13.8 ml, 20 mmol) at $-78°$. The mixture was then allowed to warm to 0° and was stirred 1 h at this temp. (EtPPh$_3$)Br (6.75 g, 18.1 mmol) was added portionwise under stirring, and the mixture was stirred at 20° for 1 h. Crude ((+)-(*E*)-2-methyl-3-((*S*)-1-phenylethoxy)prop-2-enal) (+)-**18b**), prepared by transetherification of (*E*)-3-ethoxy-2-methylprop-2-enal (**17**) with (*S*)-1-phenylethanol (2.02 g, 16.6 mmol) [11][12], was added at 0°, and the mixture stirred at 0° for 2 h. After addition of ice-cold H_2O (100 ml), the mixture was extracted with light petroleum ether (3 × 50 ml). The combined extracts were dried ($MgSO_4$), and the solvent evaporated *in vacuo*. The residue was dissolved in light petroleum ether. The precipitate (Ph_3PO) was filtered off, and the solvent evaporated *in vacuo* to give (+)-**4b** as a yellowish oil (3.83 g, quantitative). $[\alpha]_D^{25} = +10$, $[\alpha]_{578}^{25} = +11$, $[\alpha]_{546}^{25} = +14$, $[\alpha]_{436}^{25} = +36$, ($c = 1.2$, $CHCl_3$). IR (film): 2980, 1650, 1450, 1370, 1165, 1070, 1025, 955, 840, 760, 700. ^{1}H-NMR (400 MHz, $CDCl_3$): 7.70–7.29 (*m*, 5 arom. H); 6.08 (*q*, ^4J(″,2″) = 1.2, H–C(1″)); 5.87 (*dq*, ^3J(3″,4″) = 15.4, ^4J(3″,5″) = 1.5, H–C(3″)); 5.45 (*dq*, ^3J(3″,4″) = 15.4, ^3J(4″,5″) = 6.7, H–C(4″)); 4.78 (*q*, ^3J(1′,2′) = 6.5, H–C(1′)); 1.77 (*d*, ^4J(1″,2″) = 1.2, Me–C(2″)); 1.73 (*dd*, ^3J(4″,5″) = 6.7, ^4J(3″,5″) = 1.5, H_3C(5″)); 1.57 (*d*, ^3J(1′,2′) = 6.5, Me(2′)). ^{13}C-NMR (100.6 MHz, $CDCl_3$): 144.3 (*d*, ^1J(C,H) = 177, C(1″)); 143.2 (*s*, arom. C); 130.9 (*d*, ^1J(C,H) = 149, C(3″)); 128.4 (*d*, ^1J(C,H) = 159, 2 arom. C); 125.9 (*d*, ^1J(C,H) = 162, 2 arom. C); 119.5 (*d*, ^1J(C,H) = 150, C(4″)); 114.9 (*s*, C(2″)); 79.7 (*d*, ^1J(C,H) = 147, C(1′)); 23.8 (*q*, ^1J(C,H) = 129, C(2′)); 18.3 (*q*, ^1J(C,H) = 126, C(5″)); 9.8 (*q*, ^1J(C,H) = 130, *Me*–C(2″)). CI-MS (NH_3): 220 (32, $[M+18]^+$), 203 (100, $[M+1]^+$), 202 (31, $M^{+\cdot}$), 139 (19), 122 (71), 105 (82), 98 (45), 77 (12). Anal. calc. for $C_{12}F_5H_9O_9$ (328.54): C 83.12, H 8.97; found: C 83.14, H 9.02.

*(–)-(*E*)-2-Methyl-3-[(*S*)-1-(pentafluorophenyl)ethoxy]prop-2-enal* ((–)-**18c**). A mixture of **17** (1.02 ml, 8.5 mmol), (–)-(*S*)-1-(pentafluorophenyl)ethanol [6] (1.75 g, 8.22 mmol), and TsOH (16 mg) was stirred at 20° for 16 h under vacuum (1 Torr) to evacuate EtOH formed in the reaction. The residue was purified by FC (SiO_2, CH_2Cl_2, R_f ((–)-**18c**) = 0.27) to give (–)-**18c** as a colorless oil (1.74 g, 75%). $[\alpha]_D^{25} = -8.2$, $[\alpha]_{578}^{25} = -8.5$, $[\alpha]_{546}^{25} = -9.5$, $[\alpha]_{436}^{25} = -12.8$ ($c = 1.1$, $CHCl_3$). IR (film): 2990, 1645, 1505, 1455, 1370, 1305, 1215, 1150, 1080, 1045, 975, 870. ^{1}H-NMR (400 MHz, $CDCl_3$): 9.23 (*s*, H–C(1)); 6.97 (*q*, ^4J(2,3) = 1.1, H–C(3)); 5.49 (*q*, ^3J(1′,2′) = 6.8, H–C(1′)); 1.82 (*d*, ^3J(1′,2′) = 6.8, Me(2′)); 1.70 (*d*, ^4J(2,3) = 1.1, Me–C(2)). ^{13}C-NMR (100.6 MHz, $CDCl_3$): 191.5 (*d*, ^1J(C,H) = 170, C(1)); 164.6 (*d*, ^1J(C,H) = 176, C(3)); 144.6 (*d*, ^1J(C,F) = 251, 2 arom. C); 141.5 (*d*, ^1J(C,F) = 255, arom. C); 137.7 (*d*, ^1J(C,F) = 251, 2 arom. C); 121.9 (*s*, C(2)); 113.8 (*s*, arom. C); 73.3 (*d*, ^1J(C,H) = 149, C(1′)); 20.4 (*q*, ^1J(C,H) = 130, C(2′)); 6.3 (*q*, ^1J(C,H) = 126, *Me*–C(2)). CI-MS (NH_3): 298 (99, $[M+18]^+$), 281 (100, $[M+1]^+$), 280 (2, $M^{+\cdot}$), 229 (2), 212 (17), 195 (30), 175 (7), 145 (12), 104 (10), 87 (25).

*(–)-1,2,3,4,5-Pentafluoro-6-{(*S*)-1-[((1*E*,*Z*,3*E*)-2-methylpenta-1,3-dien-1-yl)oxy]ethyl}benzene* ((–)-**4c**). (i-Pr)$_2$NH (1.2 ml, 7.25 mmol) in anh. THF (20 ml) was added dropwise to a stirred soln. of 1.6M BuLi in hexane (5 ml, 7.25 mmol) at $-78°$. After stirring at 0° for 2.5 h, (EtPPh$_3$)Br (2.44 g, 6.56 mmol) was added, and the mixture stirred at 20° for 1 h. Then, (–)-**18c** (1.7 g) was added to the mixture at 0°. After stirring at 0° for 2 h, ice-cold H_2O (100 ml) was added, and the mixture extracted with light petroleum ether (3 × 50 ml). The combined extracts were dried ($MgSO_4$), and the solvent was evaporated *in vacuo*. The residue was purified by FC (SiO_2, CH_2Cl_2/light petroleum ether 1:2, R_f ((–)-**4c**) = 0.59) to give (–)**4c** as a colorless oil, 5:1 mixture of (1*E*)- and (1*Z*)-isomers (0.626 g, 36%).

*(±)-(2*RS*)-2-{(1*RS*,2*Z*,4*SR*)-2-Methyl-4-(methylsulfonyl)-1-[(*RS*)-1-(2,4,6-triisopropylphenyl)ethoxy]-pent-2-en-1-yl}cyclopentanone* ((±)-**10**) *and (±)-(2*RS*,2*Z*)-2-{(1*RS*,2*Z*,4*SR*)-2-Methyl-4-(methylsulfonyl)-1-[(*SR*)-1-(2,4,6-triisopropylphenyl)ethoxy]pent-2-en-1-yl}cyclopentanone* ((±)-**11**). A 0.5M soln. of $(F_3CSO_2)_2NH$ in anh. CH_2Cl_2 (60 µl, 0.03 mmol) was degassed (freeze/thaw cycles) on the *vac.* line (two necked flask). Dry SO_2 (basic alumina, *Merck*, act. I) was condensed at $-196°$ (0.32–0.64 g, 5–10 mmol). The flask was allowed to warm to $-78°$, and the mixture was stirred for 30 min. After cooling to $-100°$, (±)-1,3,5-triisopropyl-2-{(*RS*)-1-[((*E*,*E*)-2-methylpenta-1,3-dien-1-yl)oxy]ethyl}benzene ((±)-**4a** [6][7]; 0.052 g, 0.16 mmol) in anh. CH_2Cl_2 (0.5 ml) and 1-(trimethylsilyloxy)cyclopentene (**9**; 0.15 ml, 0.9 mmol) [8] were added simultaneously. After stirring at $-85°$ for 2.5 h and then at $-78°$ for 2.5 h, the solvents were evaporated *in vacuo* at $-78°$. 1M Bu_4NF in THF (1.5 ml, 1.5 mmol) and MeI (0.3 ml, 5 mmol) were added under Ar, and the mixture was allowed to warm gradually to 20° overnight. H_2O (15 ml) was added, and the mixture extracted with CH_2Cl_2 (5 × 10 ml). The combined extracts were dried ($MgSO_4$), and the solvent was evaporated *in vacuo*. The residue was purified by CC (SiO_2, AcOEt/light petroleum ether 1:3, R_f ((±)-**10**) = 0.12, R_f ((±)-**11**) = 0.07) to give (±)-**10** (39 mg, 52%) and (±)-**11** (14 mg, 19%), which were crystallized from light petroleum ether/Et_2O.

Data of (±)-**10**. Colorless crystals (see *Table 1*). M.p. 170–172°. UV (MeCN): 249 (1200), 222 (1300). IR (KBr): 2965, 2925, 1735, 1610, 1455, 1370, 1325, 1300, 1140, 1070, 1025, 1005, 960, 880, 770, 540, 505. ^{1}H-NMR (400 MHz, $CDCl_3$): 7.00–6.91 (*m*, 2 arom. H); 5.30 (*dq*, $^3J(3',4')=10.6$, $^4J(2',3')=1.1$, H–C(3′)); 5.05 (*q*, $^3J(1'',2'')=6.7$, H–C(1″)); 4.79 (*d*, $^3J(1',2)=2.8$, H–C(1′)); 4.16 (*dq*, $^3J(3',4')=10.6$, $^3J(4',5')=6.7$, H–C(4′)); 3.84, 3.11 (2 *sept.*, $^3J(Me_2CH-Ar, Me_2CH-Ar)=6.9$, 2 Me_2CH-Ar); 2.92 (*s*, $MeSO_2$); 2.84 (*sept.*, $^3J(Me_2CH-Ar, Me_2CH-Ar)=6.9$, Me_2CH-Ar); 2.07–1.66 (*m*, H–C(2), $H_2C(3)$, $H_2C(4)$, $H_2C(5)$); 1.95 (*d*, $^4J(2',3')=1.1$, Me–C(2′)); 1.46 (*d*, $^3J(4',5')=^3J(1'',2'')=6.7$, Me(5′), Me(2″)); 1.29–1.16 (*m*, 2 Me_2CH-Ar); 1.27 (*d*, $^3J(Me_2CH-Ar, Me_2CH-Ar)=6.9$, ($Me_2CH-Ar$). ^{13}C-NMR (100.6 MHz, $CDCl_3$): 218.3 (*s*, C(1)); 147.9, 147.0, 146.3, 144.5 (4*s*, 3 arom. C, C(2′)); 134.4 (*s*, arom. C); 122.7, 120.4 (2*d*, $^1J(C,H)=152$, 153, 2 arom. C); 118.2 (*d*, $^1J(C,H)=158$, C(3′)); 77.0 (*d*, C(1′)); 76.6 (*d*, C(1″)); 57.5 (*d*, $^1J(C,H)=137$, C(4′)); 55.7 (*d*, $^1J(C,H)=124$, C(2)); 38.1 (*t*, $^1J(C,H)=131$, C(5)); 37.8 (*q*, $^1J(C,H)=138$, $MeSO_2$); 33.9, 29.05, 29.00 (3*d*, $^1J(C,H)=127$, 129, 129, 3 Me_2CH-Ar); 25.4, 24.6, 24.4, 23.91, 23.86 (5*q*, $^1J(C,H)=125$, 3 Me_2CH-Ar); 24.5, 20.5 (2*t*, $^1J(C,H)=127$, C(3), C(4)); 22.0 (*q*, $^1J(C,H)=127$, C(2″)); 21.0 (*q*, $^1J(C,H)=129$, Me–C(2′)); 14.7 (*q*, $^1J(C,H)=130$, C(5′)). CI-MS (NH_3): 508 (0.2, $[M+18]^+$),475 (2), 230 (100), 215 (46), 163 (43), 91 (13). Anal. calc. for $C_{29}H_{46}O_4S$ (490.74): C 70.98, H 9.45, S 6.53; found: C 70.96, H 9.38, S 6.45.

Table 1. *Crystal Data and Structure Refinement of* (±)-**10**

Empirical formula	$C_{29}H_{46}O_4S$	$F(000)$	2144
M_r	490.72	Crystal size [mm]	n/a
Temperature [K]	293(2)	θ Range [°]	3.60 to 25.00
Wavelength [Å]	0.71069	Reflect. collected	28763
Crystal system	monoclinic	Independent reflect.	9991
Space group	*Cc*	Refinement method	Full-matrix least-squares on F^2
Unit-cell dimensions *a* [Å]	45.646(5)	Data/restraints/parameters	9991/2/615
b [Å]	10.970(5)	Goodness-of-fit on F^2	1.069
c [Å]	11.982(5)	Final *R* indices ($I>2\sigma(I)$)	$R_1=0.0722$, $w2R_2=0.1798$
β [°]	97.224(5)	*R* indices (all data)	$R_1=0.0911$, $w2R_2=0.1931$
V [Å^3]	5952(4)	Weights	$[\sigma^2(F_o^2)+(0.0922\cdot P)^2+7.01\cdot P]^{-1}$
Z	8	where $P=$	$(\mathrm{Max}(F_o^2, 0)+2\cdot F_c^2)/3$
Density calc. [g cm^{-3}]	1.095	Largest difference peak	0.226 and −0.249
Absorption coeff. [mm^{-1}]	0.138	and hole [e·A^{-3}]	

Data of (±)-**11**: Colorless crystals (see *Table 2*). M.p. 128–130° (*m*, (MeOH). UV (MeCN): 287 (2800), 215 (13000). IR (KBr): 2960, 2930, 1735, 1460, 1380, 1310, 1140, 1105, 1070, 1030, 960, 930, 875, 765, 650. ^{1}H-NMR (400 MHz, $CDCl_3$): 7.00–6.91 (*m*, 2 arom. H); 5.33 (*dq*, $^3J(3',4')=10.6$, $^4J(2',3')=1.1$, H–C(3′)); 4.92 (*q*, $^3J(1'',2'')=6.5$, H–C(1″)); 4.86 (*d*, $^3J(1',2)=3.5$, H–C(1′)); 4.05 (*dq*, $^3J(3',4')=10.6$, $^3J(4',5')=6.8$, H–C(4′)); 3.71, 3.09, 2.83 (3*sept*., $^3J(Me_2CH-Ar, Me_2CH-Ar)=6.9$, 3 Me_2CH-Ar); 2.74 (*s*, $MeSO_2$); 2.42–1.75 (*m*, H–C(2), $H_2C(3)$, $H_2C(4)$, $H_2C(5)$); 1.66 (*d*, $^4J(2',3')=1.1$, Me–C(2′)); 1.43 (*d*, $^3J(1'',2'')=6.5$, Me(2″)); 1.41 (*d*, $^3J(4',5')=6.8$, Me(5′)); 1.24–1.12 (*m*, 2 Me_2CH-Ar); 1.24 (*d*, $^3J(Me_2CH-Ar, Me_2CH-Ar)=6.9$, Me_2CH-Ar). ^{13}C-NMR (100.6 MHz, $CDCl_3$): 218.4 (*s*, C(1)); 148.1, 147.1, 145.3, 144.7 (4*s*, 3 arom. C, C(2′)); 134.5 (*s*, arom. C); 122.9, 120.5 (2*d*, $^1J(C,H)=152$, 153, 2 arom. C); 121.1 (*d*, $^1J(C,H)=160$, C(3′)); 73.1 (*d*, $^1J(C,H)=140$, C(1′)); 71.1 (*d*, $^1J(C,H)=140$, C(1″)); 57.2 (*d*, $^1J(C,H)=137$, C(4′)); 54.3 (*d*, $^1J(C,H)=123$, C(2)); 38.5 (*t*, $^1J(C,H)=132$, C(5)); 37.2 (*q*, $^1J(C,H)=138$, $MeSO_2$); 33.9, 29.03, 28.97 (3*d*, $^1J(C,H)=126$, 128, 128, 3 Me_2CH-Ar); 25.5, 25.0, 24.7, 23.93, 23.87 (5*q*, $^1J(C,H)=125$, 3 Me_2CH-Ar); 24.5, 20.9 (2*t*, $^1J(C,H)=128$, 134, C(3), C(4)); 20.7 (*q*, $^1J(C,H)=126$, C(2″)); 20.1 (*q*, $^1J(C,H)=126$, $Me-C(2')$); 14.4 (*q*, $^1J(C,H)=130$, C(5′)). CI-MS (NH_3): 508 (100, $[M+18]^+$), 475 (5), 335 (6), 231 (99), 215 (22), 163 (29), 91 (9). Anal. calc. for $C_{29}H_{46}O_4S$ (490.74): C 70.98, H 9.45, S 6.53; found: C 70.82, H 9.40, S 6.57.

*(−)-(2*S*)- and (2*R*)-2-[(1*S*,2*Z*,4*R*)-2-Methyl-4-(methylsulfonyl)-1-[(*S*)-1-(2,4,6-triisopropylphenyl)ethoxy]-pent-2-en-1-yl}cyclohexanone* ((−)-**13a** and **14a**). As described for (±)-**10** and (±)-**11**, with dienyl ether (−)-**4a** [6] (50 mg, 0.152 mmol) and (trimethylsilyloxy)cyclohexene (**12**) (0.1 ml, 0.5 mmol). Purification by CC (SiO_2, AcOEt/light petroleum ether 1:3, R_f ((−)-**13a**) = 0.28) gave as a first fraction pure (−)-**13a** (55 mg, 72%).

Table 2. *Crystal Data and Structure Refinement of* (±)**11**

Empirical formula	$C_{29}H_{46}O_4S$	Absorption coeff. [mm^{-1}]	0.146
M_r	490.72	$F(000)$	536
Temperature [K]	90(2)	Crystal size [mm]	$0.32 \times 0.2 \times 0.1$
Wavelength [Å]	0.71073	θ Range [°]	2.63 to 27.99
Crystal system	triclinic	Index ranges	$-11 \le h \le 11$, $-15 \le k \le 14$, $-20 \le l \le 19$
Space group	$P\bar{1}$		
Unit-cell dimensions a [Å]	8.875(2)	Reflect. collected	13068
b [Å]	11.554(2)	Independent reflect.	6040
c [Å]	15.292(3)	Refinement method	Full-matrix least-squares on F^2
α [°]	71.93(3)	Data/restraints/parameters	6004/0/308
β [°]	74.20(3)	Goodness-of-fit on F^2	5.741
γ [°]	74.68(3)	Final R indices ($I > 2\sigma(I)$)	$R_1 = 0.0460$, $w2R_2 = 0.0770$
V [Å^3]	1406.3(5)	R indices (all data)	$R_1 = 0.0590$, $wR_2 = 0.1943$
Z	2	Weights	$[\sigma^2(F_o^2)]^{-1}$
Density calc. [g cm^{-3}]	1.159	Largest difference peak and hole [$e \cdot A^{-3}$]	0.367 and −0.469

A second fraction afforded a 2.4:1 mixture of (−)-**13a** and **14a** (16 mg, total yield: 93%). The crude mixture containing a 14.1:1 mixture of (−)-**13a** and **14a** was examined by ^{1}H-NMR spectroscopy.

Data of (−)-**13a**: Colorless crystals (see *Table 3*). M.p. 146–148° (light petroleum ether/Et_2O). $[\alpha]_D^{25} = -94$, $[\alpha]_{578}^{25} = -100$, $[\alpha]_{546}^{25} = -115$, $[\alpha]_{436}^{25} = -212$, $[\alpha]_{405}^{25} = -265$ ($c = 2.5$, $CHCl_3$).UV (MeCN): 216 (15100). IR (KBr): 2965, 2870, 1715, 1610, 1450, 1370, 1280, 1140, 1075, 1035, 965, 880, 775, 505. ^{1}H-NMR (400 MHz, $CDCl_3$): 7.03–6.92 (*m*, 2 arom. H); 5.40 (*dq*, $^3J(3',4') = 10.8$, $^4J(2',3') = 1.3$, H−C(3′)); 5.13 (*q*, $^3J(1'',2'') = 6.6$, H−C(1″)); 4.50 (*d*, $^3J(1',2) = 7.9$, H−C(1)); 4.41 (*dq*, $^3J(3',4') = 10.8$, $^3J(4',5') = 6.7$, H−C(4′)); 3.82, 3.20, 2.86 (3*sept.*, ^3J(Me_2CH−Ar, Me_2CH−Ar) = 6.9, 3 Me_2CH−Ar); 2.89 (*s*, $MeSO_2$); 2.63–1.67 (*m*, H−C(2), H_2C(3), H_2C(4), H_2C(5), H_2C(6)); 1.89 (*d*, $^4J(2',3') = 1.3$, Me−C(2′)); 1.54 (*d*, $^3J(4',5') = 6.7$, Me(5′)); 1.49 (*d*, $^3J(1'',2'') = 6.6$, Me(2″)); 1.26–1.17 (*m*, 2 Me_2CH−Ar); 1.25 (*d*, ^3J(Me_2CH−Ar, Me_2CH−Ar) = 6.9, Me_2CH−Ar). ^{13}C-NMR (100.6 MHz, $CDCl_3$): 211.8 (*s*, C(1)); 148.1, 146.9, 145.5, 144.3 (4*s*, 3 arom. C, C(2′)); 134.8 (*s*, arom. C), 122.8, 120.3 (2*d*, ^1J(C,H) = 149, 153, 2 arom. C); 119.4 (*d*, ^1J(C,H) = 157, C(3′)); 77.3 (*d*, ^1J(C,H) = 158, C(1′)); 75.8 (*d*, ^1J(C,H) = 140, C(1″)); 58.5 (*d*, ^1J(C,H) = 140, C(4′)); 56.2 (*d*, ^1J(C,H) = 128, C(2)); 42.7 (*t*, ^1J(C,H) = 125, C(6)); 37.3 (*q*, ^1J(C,H) = 138, $MeSO_2$); 33.8 (*d*, ^1J(C,H) = 126, Me_2CH−Ar); 31.5, 28.5, 24.93 (3*t*, ^1J(C,H) = 133, 134, 134, C(3), C(4), C(5)); 29.0, 28.9 (2*d*, ^1J(C,H) = 123, 130, 2 Me_2CH−Ar); 25.03, 24.97, 24.8, 24.2, 23.9 (5*q*, ^1J(C,H) = 124, 3 Me_2CH−Ar); 22.9 (*q*, ^1J(C,H) = 129, C(2″)); 20.9 (*q*, ^1J(C,H) = 128, *Me*−C(2′)); 15.5 (*q*, ^1J(C,H) = 130, C(5′)). CI-MS (NH_3): 522 (75, $[M+18]^+$), 504 (2, $M^{+\bullet}$), 480 (5), 425 (7), 381 (1), 274 (74), 248 (10), 231 (100), 177 (20), 149 (4), 91 (6). Anal. calc. for $C_{30}H_{48}O_4S$ (504.77): C 71.39, H 9.58, S 6.35; found: C 71.48, H 9.60, S 6.32.

Data of **14a**: ^{1}H-NMR (400 MHz, $CDCl_3$): 7.03–6.92 (*m*, 2 arom. H); 5.43 (*dq*, $^3J(3',4') = 10.8$, $^4J(2',3') = 1.3$, H−C(3′)); 5.25 (*q*, $^3J(1'',2'') = 6.7$, H−C(1″)); 4.70 (*d*, $^3J(1',2) = 8.0$, H−C(1′)); 4.26 (*dq*, $^3J(3',4') = 10.8$, $^3J(4',5') = 6.8$, H−C(4′)); 3.72, 3.28 (2 br. *s*, 2 Me_2CH−Ar); 2.89 (*s*, $MeSO_2$); 2.86 (*sept.*, ^3J(Me_2CH−Ar, Me_2CH−Ar) = 6.8, Me_2CH−Ar); 2.64–1.65 (*m*, H−C(2), H_2C(3), H_2C(4), H_2C(5), H_2C(6)); 1.89 (*d*, $^4J(2',3') = 1.3$, Me−C(2′)); 1.46, 1.35 (2*d*, $^3J(4',5') = 6.8$, $^3J(1'',2'') = 6.7$, Me(5′), Me(2″)); 1.26–1.17 (*m*, 3 Me_2CH−Ar).

*2.5:1 Mixture of (2*S*)- and (2*R*)-2-[(1*S*,2*Z*,4*R*)-1-Hydroxy-2-methyl-4-(methylsulfonyl)pent-2-en-1-yl]cyclohexanone or (2*S*)-2-[(1*R*,2*Z*,4*S*)-1-Hydroxy-2-methyl-4-(methylsulfonyl)pent-2-en-1-yl]cyclohexanone* (**15** and **16**). A 2.4:1 mixture of (−)-**13a** and **14a** (16 mg, 0.032 mmol), $CDCl_3$ (0.35 ml), and CF_3COOH (40 µl, 0.54 mmol) was stirred at 25° for 25 min. After neutralization with sat. aq. $NaHCO_3$ (10 ml), the mixture was extracted with CH_2Cl_2 (3 × 10 ml). The combined org. extracts were dried ($MgSO_4$), the solvent was evaporated, and the residue purified by FC (SiO_2, AcOEt/CH_2Cl_2 1:1) to give a 2.5:1 mixture of **15** and **16** as a colorless oil (4 mg, 49%). IR (film): 3500, 2935, 2865, 1715, 1650, 1455, 1415, 1380, 1295, 1135, 1030, 955, 765, 735. CI-MS (NH_3): 274 (1, $M^{+\bullet}$), 259 (1), 248 (4), 231 (100), 215 (12), 191 (9), 149 (5), 109 (11), 95 (19). Anal. calc. for $C_{13}H_{22}O_4S$ (274.37): C 56.91, H 8.08; found: C 56.82, H 8.0.

Table 3. *Crystal Data and Structure Refinement of* (−)-**13a**

Empirical formula	$C_{30}H_{48}O_4S$	Morphology Pinacoids	$\{10\bar{1}\}$, {101}
M_r	504.74	Pedions	(110), (011)
Temperature [K]	293(2)	Fracture plane	$(0\bar{1}0)$
Wavelength [Å]	0.71073	θ Range [°]	3.08 to 27.99
Crystal system	monoclinic	Index ranges	$13 \le h \le 13$, $-12 \le k \le 11$, $-20 \le l \le 21$
Space group	$P2_1$		
Unit-cell dimensions a [Å]	10.037(2)	Reflect. collected	13656
b [Å]	9.408(2)	Independent reflect.	6306
c [Å]	15.971(3)	Refinement method	Full-matrix least-squares on F^2
β [°]	103.03(3)	Data/restraints/parameters	6306/1/316
V [Å^3]	1469.2(5)	Goodness-of-fit on F^2	5.423
Z	2	Final R indices ($I > 2\sigma(I)$)	$R_1 = 0.0426$, $wR_2 = 0.0744$
Density calc. [g cm^{-3}]	1.141	R indices (all data)	$R_1 = 0.0452$, $wR_2 = 0.0746$
Absorption coeff. [mm^{-1}]	0.141	Weights	$[\sigma^2(F_o^2)]^{-1}$
$F(000)$	552	Absolute structure parameter	0.11(6)
Crystal size [mm]	$0.7 \times 0.5 \times 0.2$	Largest difference peak and hole [e · A^{-3}]	0.225 and −0.223

Data of **15**: ^{1}H-NMR (400 MHz, $CDCl_3$): 5.41 (*dq*, $^3J(3',4') = 10.8$, $^4J(2',3') = 1.4$, H−C(3′)); 4.69 (*dd*, $^3J(1',2) = 9.3$, $^3J(1',HO-C(1')) = 2.0$, H−C(1′)); 4.06 (*dq*, $^3J(3',4') = 10.8$, $^3J(4',5') = 6.8$, H−C(4′)); 3.68 (*d*, $^3J(HO-C(1'),1') = 2.0$, HO−C(1′)); 2.91 (*s*, $MeSO_2$); 2.60–1.65 (*m*, H−C(2), $H_2C(3)$, $H_2C(4)$, $H_2C(5)$, $H_2C(6)$); 1.83 (*d*, $^4J(2',3') = 1.4$, Me−C(2′)); 1.44 (*d*, $^3J(4',5') = 6.8$, Me(5′)). ^{13}C-NMR (100.6 MHz, $CDCl_3$): 216.0 (*s*, C(1)); 141.2 (*s*, C(2′)); 123.8 (*d*, $^1J(C,H) = 157$, C(3′)); 69.6 (*d*, $^1J(C,H) = 141$, C(1)); 57.2 (*d*, $^1J(C,H) = 137$, C(4′)); 53.1 (*d*, $^1J(C,H) = 128$, C(2)); 42.5 (*t*, $^1J(C,H) = 128$, C(6)); 38.2 (*q*, $^1J(C,H) = 138$, $MeSO_2$); 29.9, 27.5, 24.7(3*t*, $^1J(C,H) = 129$, C(3), C(4), C(5)); 18.5 (*q*, $^1J(C,H) = 128$, *Me*−C(2)); 12.6 (*q*, $^1J(C,H) = 129$, C(5′)).

Data of **16**: ^{1}H-NMR (400 MHz, $CDCl_3$): 5.16 (*dq*, $^3J(3',4') = 9.8$, $^4J(2',3') = 1.4$, H−C(3′)); 4.70 (*dd*, $^3J(1',HO-C(1')) = 2.3$, H−C(1′)); 4.23 (*dq*, $^3J(3',4') = 9.8$, $^3J(4',5') = 6.9$, H−C(4′)); 2.86 (*s*, $MeSO_2$); 2.76–1.65 (*m*, H−C(2), $H_2C(3)$, $H_2C(4)$, $H_2C(5)$, $H_2C(6)$); 1.75 (*d*, $^4J(2',3') = 1.4$, Me−C(2′)); 1.57 (*d*, $^3J(4',5') = 6.9$, Me(5′)). ^{13}C-NMR (100.6 MHz, $CDCl_3$): 215.1 (*s*, C(1)); 145.5 (*s*, C(2′)); 119.8 (*d*, $^1J(C,H) = 151$, C(3′)); 69.1 (*d*, $^1J(C,H) = 145$, C(1′)); 58.0 (*d*, $^1J(C,H) = 141$, C(4′)); 53.5 (*d*, $^1J(C,H) = 127$, C(2)); 42.8 (*t*, $^1J(C,H) = 128$, C(6)); 37.0 (*q*, $^1J(C,H) = 138$, $MeSO_2$); 30.7, 28.7, 25.0 (3*t*, $^1J(C,H) = 129$, C(3), C(4), C(5)); 19.2 (*q*, $^1J(C,H) = 128$, *Me*−C(2′)); 15.3 (*q*, $^1J(C,H) = 129$, C(5′)).

*(−)-(2*S*)- and (2*R*)-2-[(1*S*,2*Z*,4*R*)-2-Methyl-4-(methylsulfonyl)-1-((*S*)-1-phenylethoxy)pent-2-en-1-yl]cyclohexanone* ((−)-**13b** and (−)-**14b**)[3]. As described for (−)-**13a** with (+)-**4b** (148 mg, 0.73 mmol) and **12** (0.25 ml, 1.25 mmol). CC (SiO_2, AcOEt/light petroleum ether 1:3, R_f ((−)-**13b**) = 0.15, R_f ((−)-**14b**) = 0.11) afforded (+)-**4b** (29 mg, 0.14 mmol), (−)-**13b** (55 mg, 20%), and (−)-**14b** (33 mg, 12%) and a mixture of (−)-**13b** and (−)-**14b** (18 mg, 7%). ^{1}H-NMR of the crude product showed a 1.6:1 mixture of (−)-**13b** and (−)-**14b**.

Data of (−)-**13b**: Colorless oil. $[\alpha]_D^{25} = -58$, $[\alpha]_{578}^{25} = -60$, $[\alpha]_{546}^{25} = -68$, $[\alpha]_{436}^{25} = -124$ ($c = 1.0$, $CHCl_3$). IR (film): 2935, 2865, 1710, 1450, 1370, 1300, 1135, 1080, 1035, 955, 855, 760, 700. ^{1}H-NMR (400 MHz, $CDCl_3$): 7.41–7.20 (*m*, 5 arom. C); 5.39 (*dq*, $^3J(3',4') = 10.2$, $^4J(2',3') = 1.1$, H−C(3′)); 4.64 (*q*, $^3J(1'',2'') = 6.2$, H−C(1″)); 4.14 (*d*, $^3J(1',2) = 9.6$, H−C(1′)); 4.07 (*dq*, $^3J(3',4') = 10.2$, $^3J(4',5') = 6.7$, H−C(4′)); 2.81 (*s*, $MeSO_2$); 2.62–1.67 (*m*, H−C(2), $H_2C(3)$, $H_2C(4)$, $H_2C(5)$, $H_2C(6)$); 1.81 (*d*, $^4J(2',3') = 1.1$, Me−C(2′)); 1.50 (*d*, $^3J(4',5') = 6.7$, Me(5′)); 1.36 (*d*, $^3J(1'',2'') = 6.2$, Me(2″)). ^{13}C-NMR (100.6 MHz, $CDCl_3$): 211.7 (*s*, C(1)); 143.9, 142.0 (2*s*, arom. C, C(2′)); 128.2 (*d*, $^1J(C,H) = 159$, 2 arom. C); 126.8 (*d*, $^1J(C,H) = 160$, 2 arom. C); 126.0 (*d*, $^1J(C,H) = 158$, arom. C); 121.8 (*d*, $^1J(C,H) = 154$, C(3′)); 73.8, 72.2 (2*d*, $^1J(C,H) = 143$, 148, C(1′), C(1″)); 58.6 (*d*, $^1J(C,H) = 140$, C(4′)); 54.4 (*d*, $^1J(C,H) = 123$, C(2)); 43.0 (*t*, $^1J(C,H) = 131$, C(6)); 37.6 (*q*, $^1J(C,H) = 138$, $MeSO_2$); 32.2, 29.0, 24.9 (3*t*, $^1J(C,H) = 126$, C(3), C(4), C(5)); 22.2 (*q*, $^1J(C,H) = 130$, C(2″)); 19.6 (*q*, $^1J(C,H) = 130$, *Me*−C(2′)); 15.6 (*q*, $^1J(C,H) = 126$, C(5′)). CI-MS (NH_3): 374 (1, $M^{+\cdot}$), 320 (11), 292 (47), 257 (32), 179 (26), 122 (13), 105 (39). Anal. calc. for $C_{21}H_{56}O_4S$ (374.50): C 67.35, H 7.00, S 8.56; found: C 67.33, H 7.24, S 8.65.

[3]) Absolute configurations could not be established unambiguously. They are proposed to be analogous to those given for (−)-**13a** and **14a**.

Data of (−)-**14b**: Colorless oil. $[\alpha]_D^{25} = -17$, $[\alpha]_{578}^{25} = -18$, $[\alpha]_{546}^{25} = -21$, $[\alpha]_{436}^{25} = -32$ ($c = 0.9$, $CHCl_3$). IR (film): 2935, 2865, 1710, 1450, 1375, 1300, 1130, 1080, 1040, 955, 765, 700. ^{1}H-NMR (400 MHz, $CDCl_3$): 7.41–7.20 (*m*, 5 arom. C); 5.39 (*dq*, $^3J(3',4') = 10.2$, $^4J(2',3') = 1.1$, H−C(3′)); 4.64 (*q*, $^3J(1'',2'') = 6.2$, H−C(1″)); 4.14 (*d*, $^3J(1',2) = 9.6$, H−C(1′)); 4.07 (*dq*, $^3J(3',4') = 10.2$, $^3J(4',5') = 6.7$, H−C(4′)); 2.81 (*s*, $MeSO_2$); 2.62–1.67 (*m*, H−C(2), $H_2C(3)$, $H_2C(4)$, $H_2C(6)$); 1.81 (*d*, $^4J(2',3') = 1.1$, Me−C(2′)); 1.50 (*d*, $^3J(4',5') = 6.7$, Me(5′)); 1.36 (*d*, $^3J(1'',2'') = 6.2$, Me(2″)). ^{13}C-NMR (100.6 MHz, $CDCl_3$): 211.0 (*s*, C(1)); 143.2, 141.3 (2*s*, arom. C, C(2′)); 128.2 (*d*, $^1J(C,H) = 162$, 2 arom. C); 126.9 (*d*, $^1J(C,H) = 160$, 2 arom. C); 123.2 (*d*, $^1J(C,H) = 156$, arom. C); 121.8 (*d*, $^1J(C,H) = 154$, C(3′)); 74.7, 73.0 (2*d*, $^1J(C,H) = 141$, 143, C(1′), C(1″)); 57.7 (*d*, $^1J(C,H) = 139$, C(4′)); 54.1 (*d*, $^1J(C,H) = 128$, C(2)); 42.0 (*t*, $^1J(C,H) = 129$, (C(6)); 37.8 (*q*, $^1J(C,H) = 138$, $MeSO_2$); 30.7, 28.6, 25.9 (3*t*, $^1J(C,H) = 127$, 132, 132, C(3), C(4), C(5)); 22.3 (*q*, $^1J(C,H) = 130$, C(2″)); 19.9 (*q*, $^1J(C,H) = 126$, *Me*−C(2′)); 15.8 (*q*, $^1J(C,H) = 129$, C(5′)). CI-MS (NH_3): 392 (1, $[M+18]^+$), 374 (2, $M^{+\bullet}$), 370 (39), 292 (40), 275 (22), 257 (16), 194 (100), 142 (10), 97 (12), 79 (4).

*(−)-(2*S*)- and (−)-(2*R*)-2-[(1*S*,2*Z*,4*R*)-2-Methyl-4-(methylsulfonyl)-1-[(*S*)-1-(pentafluorophenyl)ethoxy]-pent-2-en-1-yl]cyclohexanone* ((−)-**13c** and (−)-**14c**[3]). As described for (−)-**13a**, with (−)-**4c** (42 mg, 0.14 mmol) and **12** (0.1 ml, 0.5 mmol). ^{1}H-NMR spectrum of the crude product showed a 1.2:1 mixture of (−)-**13c** and (−)-**14c**. CC (SiO_2, AcOEt/light petroleum ether 1:3, R_f ((−)-**13c**) = 0.25, R_f ((−)-**14c**) = 0.21) afforded (−)-**13c** (4 mg, 6%) and (−)-**14c** (7 mg, 13%).

Data of (−)-**13c**: Colorless oil. $[\alpha]_D^{25} = -79$, $[\alpha]_{578}^{25} = -80$, $[\alpha]_{546}^{25} = -92$, $[\alpha]_{436}^{25} = -172$ ($c = 0.4$, $CHCl_3$). IR (film): 2940, 2860, 1710, 1485, 1455, 1300, 1135, 1085, 1035, 940, 760. ^{1}H-NMR (400 MHz, $CDCl_3$): 5.41 (*dq*, $^3J(3',4') = 11.1$, $^4J(2',3') = 1.2$, H−C(3′)); 4.97 (*q*, $^3J(1'',2'') = 6.7$, H−C(1″)); 4.26 (*dq*, $^3J(3',4') = 11.1$, $^3J(4',5') = 6.7$, H−C(4′)); 4.12 (*d*, $^3J(1',2) = 8.3$, H−C(1′)); 2.89 (*s*, $MeSO_2$); 2.79–1.67 (*m*, H−C(2), $H_2C(3)$, $H_2C(4)$, $H_2C(5)$, $H_2C(6)$); 1.87 (*d*, $^4J(2',3') = 1.2$, Me−C(2′)); 1.54 (*d*, $^3J(4',5') = 6.7$, Me(5′)); 1.53 (*d*, $^3J(1'',2'') = 6.7$, Me(2″)). ^{13}C-NMR (100.6 MHz, $CDCl_3$): 211.2 (*s*, C(1)); 144.8 (br. *d*, $^1J(C,F) = 330$, 3 arom. C); 144.2 (br. *d*, $^1J(C,F) = 330$, 2 arom. C); 142.7 (*s*, C(2′)); 121.5 (*d*, $^1J(C,H) = 150$, C(3′)); 118.0 (*s*, arom. C); 74.9 (*d*, $^1J(C,H) = 141$, C(1′)); 67.4 (*d*, $^1J(C,H) = 148$, C(1″)); 58.2 (*d*, $^1J(C,H) = 145$, C(4′)); 55.0 (*d*, $^1J(C,H) = 128$, C(2)); 42.6 (*t*, $^1J(C,H) = 124$, C(6)); 37.6 (*q*, $^1J(C,H) = 139$, $MeSO_2$); 30.7, 28.4, 24.8 (3*t*, $^1J(C,H) = 129$, C(3), C(4), C(5)); 21.0, 20.9 (2*q*, $^1J(C,H) = 129$, C(2″), *Me*−C(2′)); 15.1 (*q*, $^1J(C,H) = 129$, C(5′)). CI-MS (NH_3): 486 (15, $[M+18]^+$), 468 (1, $M^{+\bullet}$), 399 (25), 348 (6), 275 (10), 246 (15), 212 (45), 124 (12), 97 (6).

Data of (−)-**14c**: Colorless oil. $[\alpha]_D^{25} = -45$, $[\alpha]_{578}^{25} = -47$, $[\alpha]_{546}^{25} = -54$, $[\alpha]_{436}^{25} = -95$ ($c = 0.7$, $CHCl_3$). IR (film): 2940, 1710, 1640, 1485, 1455, 1300, 1130, 1085, 935. ^{1}H-NMR (400 MHz, $CDCl_3$): 5.57 (*dq*, $^3J(3',4') = 10.8$, $^4J(2',3') = 1.4$, H−C(3′)); 4.98 (*q*, $^3J(1'',2'') = 6.7$, H−C(1″)); 4.28 (*dq*, $^3J(3',4') = 10.8$, $^3J(4',5') = 6.1$, H−C(4′)); 4.12 (*d*, $^3J(1',2) = 8.3$, H−C(1′)); 2.91 (*s*, $MeSO_2$); 2.36–1.67 (*m*, H−C(2), $H_2C(3)$, $H_2C(4)$, $H_2C(4)$, $H_2C(6)$); 1.83 (*d*, $^4J(2',3') = 1.4$, Me−C(2′)); 1.52 (*d*, $^3J(4',5') = 6.1$, Me(5′)); 1.43 (*d*, $^3J(1'',2'') = 6.7$, Me(2″)). ^{13}C-NMR (100.6 MHz, $CDCl_3$): 209.9 (*s*, C(1)); 144.8 (br. *d*, $^1J(C,F) = 326$, 3 arom. C); 143.5 (br. *d*, $^1J(C,F) = 327$, 2 arom. C); 141.6 (*s*, C(2′)); 122.7 (*d*, $^1J(C,H) = 164$, C(3′)); 117.7 (*s*, arom. C); 118.0 (*s*, arom. C); 75.4 (*d*, $^1J(C,H) = 146$, C(1′)); 67.4 (*d*, $^1J(C,H) = 140$, C(1″)); 57.6 (*d*, $^1J(C,H) = 140$, C(4′)); 54.4 (*d*, $^1J(C,H) = 125$, C(2)); 42.6 (*t*, $^1J(C,H) = 128$, C(6)); 37.9 (*q*, $^1J(C,H) = 140$, $MeSO_2$); 31.5, 29.0, 25.3 (3*t*, $^1J(C,H) = 128$, C(3), C(4), C(5)); 21.7, 21.0 (2*q*, $^1J(C,H) = 125$, C(2″), *Me*−C(2′)); 15.6 (*q*, $^1J(C,H) = 129$, C(5′)). CI-MS (NH_3): 486 (33, $[M+18]^+$), 469 (2, $[M+1]^+$, 468 (1, $M^{+\bullet}$), 399 (22), 348 (19), 310 (14), 275 (18), 222 (26), 139 (22), 97 (5).

Crystal-Structure Determination of (±)-**10**, (±)-**11**, *and* (−)-**13a**. The colorless crystals were mounted on a *Bruker CCD* system equipped with graphite-monochromated Mo radiation, and a hemisphere of intensities was collected. The structures were solved by means of SIR97 [15], and refined by means of SHELXT [16]. All non-H-atoms were refined anisotropically, but the H-atoms isotropically. Crystallographic data, see *Tables 1–3* (excluding structure factors) for the structures reported in this paper have been deposited with the *Cambridge Crystallographic Data Centre* as supplementary publication No. CCDC-175446 ((±)-**10**), CCDC-175447 ((±)-**11**), and CCDC-175448 ((−)-**13a**). Copies of the data can be obtained, free of charge, on application to CCDC, 12, Union Road, Cambridge CB2 1EZ, UK (fax: +44(1223)336033; e-mail: deposit@ccdc.cam.ac.uk).

REFERENCES

[1] B. Deguin, J.-M. Roulet, P. Vogel, *Tetrahedron Lett.* **1997**, *38*, 6197; J.-M. Roulet, G. Puhr, P. Vogel, *Tetrahedron Lett.* **1977**, *38*, 6201.
[2] S. Megevand, J. Moore, K. Schenk, P. Vogel, *Tetrahedron Lett.* **2001**, *42*, 673.
[3] X. Huang, P. Vogel, *Synthesis* **2002**, 232.

[4] B. Deguin, P. Vogel, *J. Am. Chem. Soc.* **1992**, *114*, 9210; B. Deguin, P. Vogel, *Tetrahedron Lett.* **1993**, *39*, 6269; T. Fernandez, J. A. Sordo, F. Monnat, B. Deguin, P. Vogel, *J. Am. Chem. Soc.* **1998**, *120*, 13276.
[5] V. Narkevitch, K. Schenk, P. Vogel, *Angew. Chem., Int. Ed.* **2000**, *39*, 1806.
[6] V. Narkevitch, S. Megevand, K. Schenk, P. Vogel, *J. Org. Chem.* **2001**, *66*, 5080.
[7] M. B. M. de Azevedo, A. E. Greene, *J. Org. Chem.* **1995**, *60*, 4940; P. Nebois, A. E. Greene, *J. Org. Chem.* **1996**, *61*, 5210; A. Kanazawa, P. Delair, M. Pourashraf, A. E. Greene, *J. Chem. Soc., Perkin Trans. 1* **1997**, 1911.
[8] P. F. Hudrlik, J. M. Takacs, *J. Org. Chem.* **1978**, *43*, 3861.
[9] C. K. Johnson, Report *ORNL-5138*, 1976, Oak Ridge National Laboratory, Tennesse, USA.
[10] G. H. Posner, D. G. Wettlaufer, *Tetrahedron Lett.* **1986**, *27*, 667.
[11] R. Rieger, E. Breitmaier, *Synthesis* **1990**, 697; M. Flock, M. Nieger, E. Breitmaier, *Liebigs Ann. Chem.* **1993**, 451; G. Zadel, R. Rieger, E. Breitmaier, *Liebigs Ann. Chem.* **1991**, 1343.
[12] T. Mukaiyama, *Org. React.* **1982**, *28*, 203; H. Heathcock, S. K. Davidsen, K. T. Hug, L. A. Flippin, *J. Org. Chem.* **1986**, *51*, 3027.
[13] R. Noyori, I. Nishida, J. Sakata, *J. Am. Chem. Soc.* **1981**, *103*, 2106; S. Murata, C. Suzuki, R. Noyori, *Tetrahedron* **1988**, *44*, 4259.
[14] K. Kraehenbuehl, S. Picasso, P. Vogel, *Helv. Chim. Acta* **1998**, *81*, 1439.
[15] A. Altomare, M. C. Burla, M. Camalli, G. L. Cascarano, C. Giacovazzo, A. Guagliardi, A. G. G. Moliterni, G. Polidori, R. Spagna, *J. Appl. Cryst.* **1999**, *32*, 115.
[16] G. M. Sheldrick, SHELXT, Integrated Structure Determination System, *Bruker Analytical X-Ray Instruments, Inc.*, Madison, Wisconsin, USA, 1996.

Received December 21, 2001