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# Asymmetric synthesis of cyclopropyl phosphonates using chiral terpenyl sulfonium and selenonium ylides

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ABSTRACT

The asymmetric cyclopropanation of a vinylphosphonate using optically active sulfonium and selenonium ylides derived from (−)-menthol and (+)-limonene was developed. The ylides were generated in situ by the reaction of the corresponding sulfonium or selenonium salt in the presence of potassium carbonate or DBU as a base. The transfer of the CHPh and $CHCO_2Et$ groups into the cyclopropane ring showed moderate diastereoselectivity and excellent enantioselectivity (up to 99:1) for the *trans*- and *cis*-products. The absolute configuration of phenyl cyclopropyl was assigned based on comparison to their tolyl analogues.
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## 1. Introduction

Sulfur ylides, a well known class of organic compounds, have been used as alkylidene transfer agents since the early work of Corey.[1] The potential of sulfur ylides for the preparation of optically active epoxides has been the subject of research in different laboratories.[2,3] Various chalcogenes have been investigated for either a one pot reaction or two step procedure with pre-isolation of the chalcogen-onium salt.[4]

Although initial asymmetric cyclopropanation reactions using chiral sulfur ylides were not the focus of interest, recently the chiral ylide route became one of the most important methods.[5] Various sulfonium ylides were applied effectively, for example, camphor-derived sulfonium ylides were used to prepare 1-aminocyclopropanecarboxylic acids in 44–95% yield, with >99:1 dr and 10–92% ee.[6] The reaction of ester-stabilized sulfonium ylides with cyclopentenone gave the corresponding cyclopropane, and was a crucial step in the synthesis of the pharmacologically important compound (+)-LY354740.[7] Chiral telluronium ylides were used in asymmetric cyclopropanations to give chiral cyclopropanes in yields of up to 99% with excellent diastereoselectivities and enantioselectivities.[8] The first example of the application of chiral selenonium ylides in the asymmetric synthesis of enantiomerically enriched cyclopropanes was achieved using *exo* and *endo*-camphor-derived selenonium salts. In the reaction with various α,β-unsaturated carbonyl compounds, trisubstituted cyclopropanes were obtained with high diastereoselectivities (dr 90:10–>99:1).[9]

In our previous studies, we prepared a series of acyclic and cyclic terpenyl sulfides and selenides, derived from *p*-menthane, carane, and pinane groups, and successfully used them for asymmetric epoxidation.[10] For example, isoselenocineole **1**, the selenium analogue of isothiocineole **2**, the most effective sulfide used in asymmetric epoxidation and aziridination, was prepared, and used for the epoxidation of styrene (dr 39:61, er *trans* 81:19).

Herein we decided to test terpenyl selenides and sulfides, derived from (−)-menthol and (+)-limonene, in the asymmetric synthesis of cyclopropyl phosphonates, mediated by the corresponding chiral ylides.

## 2. Results and discussion

Recently, our interest has been mainly focused on chiral cyclopropyl phosphonates,[11] as key intermediates in the asymmetric synthesis of constrained phosphonic analogues of natural and non-natural amino acids, exhibiting in some cases biological and therapeutic activity. For this reason, our investigations were performed using vinyl phosphonates as Michael acceptors. The reactivity of the olefin was increased by the introduction of a second electron-withdrawing substituent on the α-carbon atom (**3**: X = $CO_2Et$, **4**: X = $SO_2Ph$), which could also be useful in further application of the obtained cyclopropanes. Benzyl terpenyl sulfonium and selenonium salts **5**–**9** were prepared by our methodology based on the reaction of the corresponding sulfides and selenides with benzyl bromide in the presence of $AgBF_4$.[10] The ylide was generated in situ by the reaction of an appropriate onium salt with

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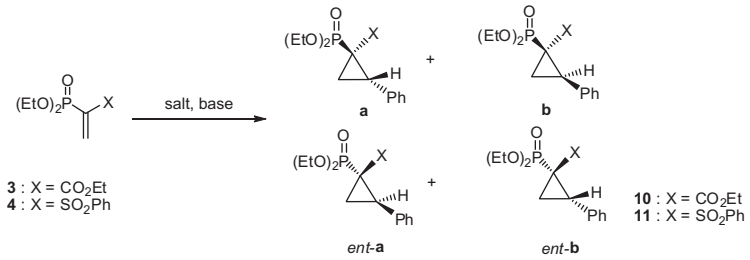
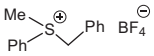
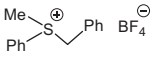
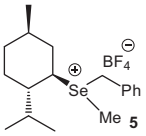
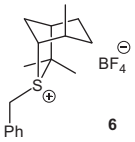
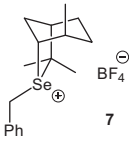
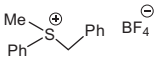
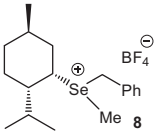
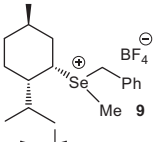
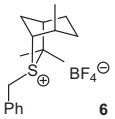
the electrophile, performed in the presence of potassium carbonate or DBU as a base. The results of the asymmetric cyclopropanation are presented in Table 1.

Inspection of the data contained in Table 1 shows that the cyclopropanation of vinyl phosphonates **3** and **4** occurred with moderate to good yield. The *trans*/*cis* ratio was determined by analysis of the $^{31}P$ and $^{1}H$ NMR spectra of the crude products and in some cases, confirmed by HPLC to establish the ratio of the enantiomers.[12] In the case of phosphoryl acrylate **3** we observed almost no diastereoselectivity. For vinyl phosphonate **4** the ratio of *trans*/*cis* diastereomers was much higher, approximately 4:1, however, it was not caused by the terpenyl moiety in the ylide, since almost the same ratio was observed for the reaction with the racemic ylide (entry 6).

Much more interesting observations were obtained from the analysis of the enantiomers. Evidently, their ratio depends on the chiral substituent bonded to the sulfonium or selenonium salts used in the reaction. Menthol-derived selenonium salts **5** and **9** provided cyclopropanation of the Michael acceptor **4** (entry 8) with approximately 27% ee. Application of the benzyl sulfonium salt of

**Table 1**
Cyclopropanation—transfer of CHPh




| Entry | Salt | Michael acceptor | Reaction condition | Total yield (%) | *trans*/*cis* | Ratio of *trans* enantiomers l/h | Ratio of *cis* enantiomers l/h |
|---|---|---|---|---|---|---|---|
| 1 |  | **3** | DBU, MeCN | 62 | 52.2:47.8[b] | 50.0/50.0 | 50.0/50.0 |
| 2 |  | **3** | $K_2CO_3$, $CH_2Cl_2$ | 93 | 55.6:44.4[a]<br>54.1:45.9[b] | 50.0/50.0 | 50.0/50.0 |
| 3 |  **5** | **3** | $K_2CO_3$, $CH_2Cl_2$ | 54 | 47.0:53.0[a] | 43.5/56.5 | 40.3/59.7 |
| 4 |  **6** | **3** | DBU, acetone | 82 | 57.0:43.0[a] | 6.8/93.2 | 9.0/91.0 |
| 5 |  **7** | **3** | DBU, acetone | 20 | 56.0:44.0[a] | 5.9/94.1 | 9.4/90.6 |
| 6 |  | **4** | DBU, MeCN | 90 | 76.8:23.2[a] | 50.0/50.0 | 50.0/50.0 |
| 7 |  **8** | **4** | $K_2CO_3$, $CH_2Cl_2$ | 20 | 80.0:20.0[a] | —[c] | —[c] |
| 8 |  **9** | **4** | DBU, MeCN | 53 | 76.2:23.8[a] | 63.3/36.7 | 78.5/21.5 |
| 9 |  **6** | **4** | DBU, MeCN | 79 | 77.8:22.2[a]<br>81.0:19.0[b] | 2.2/97.8 | 1.0/99.0 |

l—Lower $R_f$ in HPLC; h—higher $R_f$ in HPLC.
[a] The ratio of diastereomers determined by NMR.
[b] The ratio of diastereomers determined by HPLC.
[c] Inseparable impurities disturbed the precise determination of the enantiomeric ratio.

isothiocineole **6** gave enantioselectivities of 82–98% ee for the sulfonium salt (entries 4 and 9) and 88–92% ee for the selenonium salt **7** prepared from isoselenocineole (entry 5).

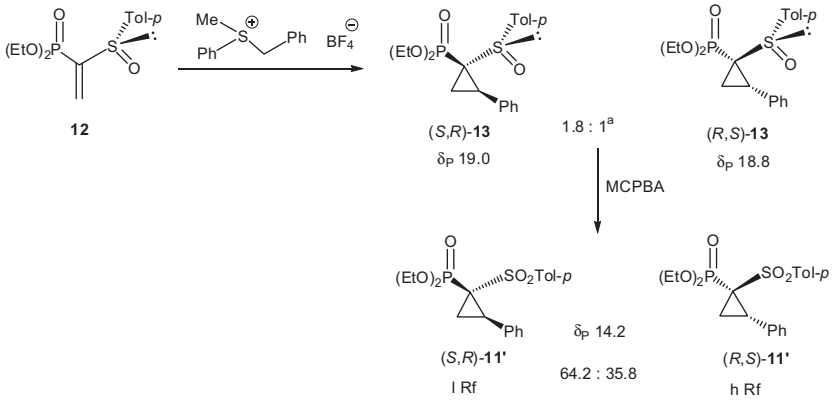
In order to gain further insight into the configuration of the obtained cyclopropanes, cyclopropanation of enantiomerically pure (*S*)-(+)-(1-diethoxyphosphoryl) vinyl *p*-tolyl sulfoxide **12** was performed.[13] The reaction of **12** with benzylmethylphenylsulfonium salt in the presence of DBU gave only *trans*-diastereomers **13**, which were oxidized to the sulfone *trans*-**11**′ and analyzed by HPLC. Based on the established mechanism,[13b] the absolute configuration of the major diastereomer in this experiment was assigned as (*S*,*R*). This allowed us to relate the configuration of *trans*-**11**′ with the retention factor: lower $R_f$—(*S*,*R*), higher $R_f$—(*R*,*S*), assuming that the small structural difference between **11** and **11**′ should not affect their polarity (Scheme 1).

Based on this assumption it appeared that the menthol-derived selenonium ylide gave (*S*,*R*)-**11**, but the major cyclopropane **11**, formed using an isothiocineole derived ylide, had an (*R*,*S*)-configuration. The stereochemical outcome of these reactions can be rationalized by considering the preference of the electrophile to approach the more favored conformation of the ylide, as proposed by Aggarwal[3b] to explain the high enantioselectivity of asymmetric epoxidation and aziridination (Scheme 2).

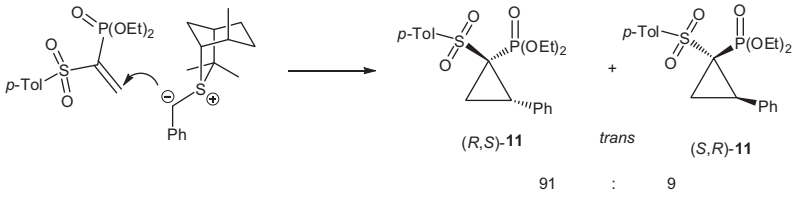
Encouraged by the results obtained for the benzylidene transfer reaction, we performed the synthesis of the corresponding salts with an ethyl acetate substituent. Thus, isoselenocineole **1** and isothiocineole **2** were treated with 2-bromo ethyl acetate in the presence of the silver salt ($AgBF_4$) to give the corresponding selenonium **14** and sulfonium **15** salts. The reaction was carried out using two methods; by Aggarwal's methodology (path A) and by our method without the solvent addition (path B) (Scheme 3).

The cyclopropanation of phosphonates **3** and **4** with transfer of the $CHCO_2Et$ group is presented in Table 2.

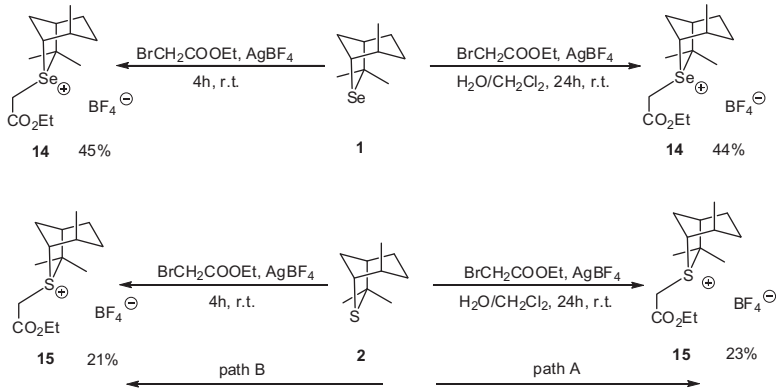
The high stereoselectivity observed in reactions with a ylide containing a strong electron withdrawing substituent ($CO_2Et$) suggests the absence, or insignificant participation of epimerization of the betaine intermediate proposed by Aggarwal (Scheme 4).[5b] This was probably due to the presence of the second electron with-




**Scheme 1.**

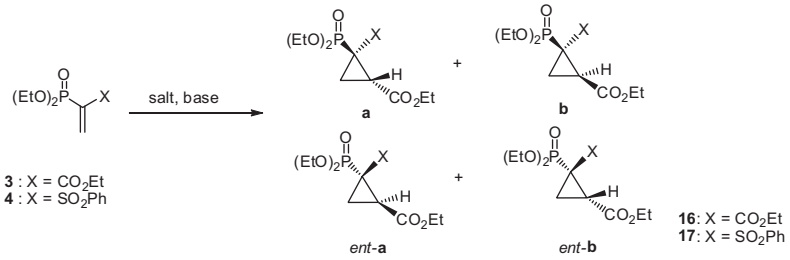


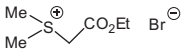
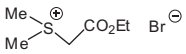
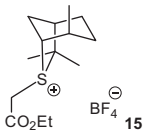
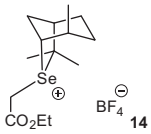
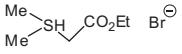
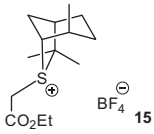
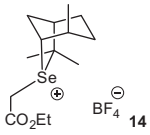

**Scheme 2.**



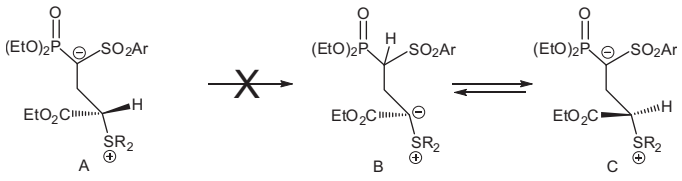

**Scheme 3.** Synthesis of isoselenocineole and isothiocineole.

**Table 2**
Cyclopropanation—transfer of $CHCO_2Et$ group




| Entry | Salt | Michael acceptor | Reaction condition | Total yield (%) | *trans*/*cis* | Ratio of *cis* enantiomers l/h | Ratio of *trans* enantiomers l/h |
|---|---|---|---|---|---|---|---|
| 1 |  | **3** | $K_2CO_3$, $CH_2Cl_2$ | <10 | 60.0:40.0[a] | — | — |
| 2 |  | **3** | DBU, MeCN | 72 | 60.0:40.0[a] | 50.0/50.0 | 50.0/50.0 |
| 3 |  **15** | **3** | DBU, MeCN | 91 | 62.0:38.0[a] | 99.0/1.0 | 99.0/1.0 |
| 4 |  **14** | **3** | DBU, MeCN | 86 | 65.0:35.0[a] | 98.0/2.0 | 99.0/1.0 |
| 5 |  | **4** | DBU, MeCN | 72 | 71.4:28.6[a] | 50.0/50.0 | 50.0/50.0 |
| 6 |  **15** | **4** | DBU, MeCN | 84 | 70.4:29.6[a] | 4.2/95.8 | 5.0/95.0 |
| 7 |  **14** | **4** | DBU, MeCN | 75 | 72.5:27.5[a] | 1.6/98.4 | 2.5/97.5 |

l—lower $R_f$ in HPLC; h—higher $R_f$ in HPLC.
[a] The ratio of diastereomers determined by NMR.




**Scheme 4.** Plausible carboanionic species.

drawing substituent in the Michael acceptor, which better stabilized the carboanionic species A.

Some information about the configuration of cyclopropanes **17** was obtained by the same method, which was applied for phenylcyclopropane **11**. In this case, we analyzed, by HPLC, the mixture of sulfones **17′**, formed via oxidation of the corresponding sulfoxides **19**, which were obtained earlier, applying the cyclopropanation of enantiomerically pure (*S*)-(+)-(1-diethoxyphosphoryl) vinyl *p*-tolyl sulfoxide **18** with EDSA (Scheme 5).[11c]

In this case, *cis*-(1*S*,2*S*)-**17′** and *trans*-(1*S*,2*R*)-**17′** were also the less polar enantiomers, which suggests such configuration should be assigned to the minor enantiomers of **17**.

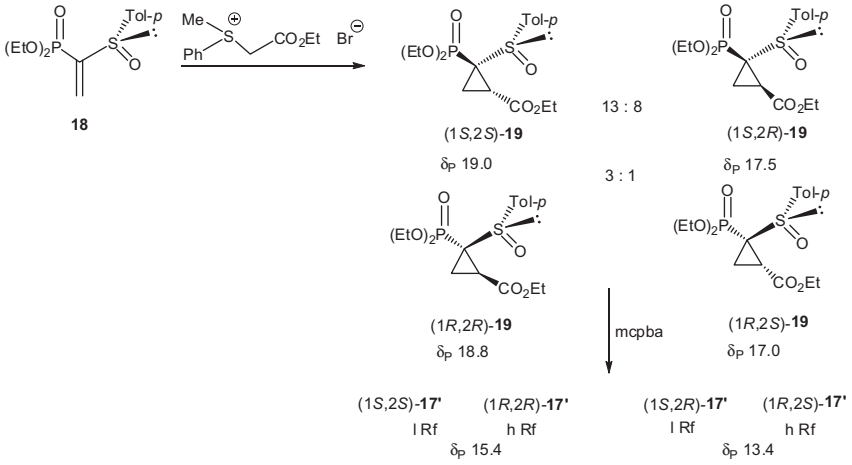
## 3. Conclusion

A series of cyclopropanations using terpene selenides derived from (−)-menthol and (+)-limonene was examined. It has been shown that the corresponding salts obtained from cyclic isoselenocineole gave better enantioselectivities than the salt obtained from methyl menthyl selenides, derived from menthol. A comparison of the reactivities of the salts obtained from isoselenocineole with those formed using its sulfur analogue isothiocineole, proves the similar diastereoselectivity and enantioselectivity of these two reactants. In both cases, excellent enantioselectivity was observed, especially for the cyclopropanation with the salt containing an acetate moiety in its structure.

## 4. Experimental

### 4.1. General

$^1H$, $^{13}C$ and $^{31}P$ NMR spectra were recorded on a Bruker Avance III 600, Bruker Avance III 500, Bruker Avance III 400, and Bruker AC 200 Spectrometer, using deuterochloroform as solvent. Mass spec-




**Scheme 5.**

tra were recorded on Finnigan MAT95. IR spectra were recorded on Ati Mattson FTIR Spectrometer. The optical rotations were measured on a Perkin–Elmer 241 MC photopolarimeter in acetone solution. The microanalyses were performed on Elemental Analyzer EA 1108. TLC was carried out on silica gel plates (Merck F254) and silica gel 60 (70–230 ASTM) was used for chromatography. THF was freshly distilled over potassium/benzophenone.

### 4.2. General procedure for the synthesis of sulfonium and selenonium salts

#### 4.2.1. Method A

The chalcogenide (2.0 mmol) was dissolved in dichloromethane (1 ml) after which benzyl bromide (4.0 mmol) and a solution of silver triflate (2.0 mmol) in water (2 ml) were added. The resulting biphasic mixture was stirred at rt for 1 day. Water (5 ml) and dichloromethane (5 ml) were then added and the layers were separated. The aqueous organic layer was extracted with dichloromethane ($3 \times 3$ ml). The combined organic layer was dried over $MgSO_4$ and the solvent was removed under reduced pressure. The crude product was dissolved in the minimum amount of dichloromethane and then added dropwise to rapidly stirred diethyl ether (10 ml). The precipitate was filtered and washed with diethyl ether ($3 \times 10$ ml).

#### 4.2.2. Method B

$AgBF_4$ (2.5 mmol) was carefully added to a mixture of chalcogenide (2.5 mmol) and benzyl bromide (6.3 mmol) at 0 °C under an argon atmosphere. The resulting mixture was stirred at rt for 4 h. The crude product was dissolved in dichloromethane (10 ml) and filtered through Celite. The solvent was removed under reduced pressure, then diethyl ether (10 ml) was added and decanted. The precipitate was washed with diethyl ether ($3 \times 10$ ml).

#### 4.2.3. (1*R*,4*R*,5*R*,6*R*)-6-(2-Ethoxy-2-oxoethyl)-4,7,7-trimethyl-6-selenabicyclo[3.2.1]octan-6-ium tetrafluoroborate 14

Method A: Yield 45%; method B: yield 44%; white solid; mp 113–114 °C, $[\alpha]_D^{22} = -238.5$ (*c* 0.55, $CHCl_3$). $^1H$ NMR (400 MHz, $CDCl_3$) $\delta$: 1.23 (d, $J_{HH}$ = 7.2 Hz, 3H, C*H*$_3$), 1.36 (t, $J_{HH}$ = 7.2 Hz, 3H, C*H*$_3$), 1.67–1.73 (m, 5H), 1.77–1.91 (m, 5H), 2.41 (s, 1H), 2.46 (s, 1H), 2.61 (d, $J_{HH}$ = 2.1 Hz, 1H), 2.69 (d, $J_{HH}$ = 13.6 Hz, 1H), 4.26–4.34 (m, 3H), 4.48 (d, $J_{HH}$ = 16.0 Hz, 1H), 4.61 (s, 1H) ppm. $^{13}C$ NMR (100.6 MHz, $CDCl_3$) $\delta$: 13.9 (*C*H$_3$); 17.6 (*C*H$_3$); 22.0 (*C*H$_2$); 23.7 (*C*H$_3$); 25.9 (*C*H$_2$); 26.2 (*C*H$_3$); 31.3 (*C*H); 33.7 (*C*H$_2$); 37.7 (*C*H$_2$); 50.6 (*C*H); 63.8 (*C*H$_2$); 67.6 (*C*H); 74.7 (*C*); 166.3 (*C*) ppm. $^{77}Se$ NMR (76.3 MHz, $CDCl_3$) $\delta$: 529.53 ppm. IR ($cm^{-1}$, film): 3583, 2924, 2854, 1711, 1462, 1377, 1303, 1068. Anal. Calcd for $C_{14}H_{25}O_2BF_4Se$: C, 42.99; H, 6.44. Found: C, 43.18; H, 6.39.

#### 4.2.4. (1*R*,4*R*,5*R*,6*R*)-6-(2-Ethoxy-2-oxoethyl)-4,7,7-trimethyl-6-thiabicyclo[3.2.1]octan-6-ium tetrafluoroborate 15

Method A: yield 21%; method B: yield 23%; white solid; mp 110–112 °C, $[\alpha]_D^{21} = -32.0$ (*c* 0.45, $CHCl_3$). $^1H$ NMR (400 MHz, $CDCl_3$) $\delta$: 1.22 (d, $J_{HH}$ = 7.2 Hz, 3H, C*H*$_3$), 1.35 (t, $J_{HH}$ = 7.2 Hz, 3H, C*H*$_3$), 1.59 (d, $J_{HH}$ = 20.0 Hz, 1H), 1.67 (s, 3H, C*H*$_3$), 1.75–1.84 (m, 3H), 1.85 (s, 3H, C*H*$_3$), 2.42–2.45 (m, 2H), 2.51–2.59 (m, 2H), 4.32 (q, $J_{HH}$ = 6.8 Hz, 3H), 4.44 (d, $J_{HH}$ = 17.2 Hz, 1H), 4.61 (d, $J_{HH}$ = 16.8 Hz, 1H) ppm. $^{13}C$ NMR (100.6, $CDCl_3$) $\delta$: 13.9 (*C*H$_3$); 17.5 (*C*H$_3$); 22.2 (*C*H$_2$); 23.0 (*C*H$_3$); 25.0 (*C*H$_2$); 25.3 (*C*H$_3$); 31.7 (*C*H); 32.0 (*C*H$_2$); 40.6 (*C*H$_2$); 50.2 (*C*H); 63.9 (*C*H$_2$); 66.1 (*C*H); 71.7 (*C*); 165.5 (*C*) ppm. IR ($cm^{-1}$, film): 3583, 2923, 2854, 1738, 1462, 1377, 1028. Anal. Calcd for $C_{14}H_{25}O_2BF_4S$: C, 48.85; H, 7.32. Found: C, 49.03; H, 7.26.

### 4.3. General procedure for a cyclopropanation

#### 4.3.1. Method A

In a round-bottom flask equipped with a magnetic stirrer bar, 2 mmol of vinyl phosphonates **3** or **4** and 2.2 mmol of the appropriate sulfonium or selenonium salt were placed in 10 mL of $CH_2Cl_2$. To this suspension were added 0.3 g of $K_2CO_3$ and the mixture stirred vigorously overnight. Filtration and evaporation of the solvent afforded a crude residue, which was purified by chromatography.

#### 4.3.2. Method B

In a round-bottom flask equipped with a magnetic stirrer bar, 2 mmol of vinyl phosphonates **3** or **4** and 2.2 mmol of the appropriate sulfonium or selenonium salt were dissolved in 10 mL of $CH_3CN$ or acetone. To this solution 2.2 mmol of DBU was added and the mixture stirred vigorously overnight. After evaporation of the solvent the residue was purified by chromatography.

#### 4.3.3. Ethyl 1-(diethoxyphosphoryl)-2-phenylcyclopropanecarboxylate 10

*trans*-**7**: $^{31}P$ NMR (81 MHz, $CDCl_3$) $\delta$: 22.6 ppm. $^1H$ NMR (200 MHz, $CDCl_3$) $\delta$: 0.86 (t, 3H, $POCH_2CH_3$, $J_{HH}$ = 7.1 Hz), 1.36 (t, 3H, $POCH_2CH_3$, $J_{HH}$ = 7.1 Hz), 1.40 (t, 3H, $COCH_2CH_3$, $J_{HH}$ = 7.1 Hz), 1.87 (ddd, 1H, CH*cis*, $J_{HH}$ = 5.0, $J_{HH}$ = 9.1, $J_{PH}$ = 14.1 Hz), 2.19 (m, 1H, $CH_{trans}$), 3.07 (ddd, 1H, C*H*Ph, $J_{HH}$ = 7.5, $J_{HH}$ = 9.1, $J_{PH}$ = 16.7 Hz), 3.83 (q, 2H, $COCH_2CH_3$, $J_{HH}$ = 7.1 Hz), 4.13–4.34 (m, 4H, $POCH_2CH_3$),

7.24–7.30 (m, 5H, $C_6H_5$). $^{13}C$ NMR (125 MHz, $CDCl_3$) $\delta$: 14.5 (s, $OCH_2CH_3$); 16.3 (d, $^3J_{C,P}$ = 7 Hz, $OCH_2CH_3$); 16.4 (d, $^3J_{C,P}$ = 7 Hz, $OCH_2CH_3$); 27.4 (s, $PCCH_2$); 29.6 (d, $^1J_{C,P}$ = 187.6 Hz, *P*C); 29.9 (s, *C*HPh); 62.1 (d, $^2J_{C,P}$ = 5.5 Hz, $POCH_2CH_3$); 62.4 (s, $OCH_2$); 62.6 (d, $^2J_{C,P}$ = 3.7 Hz, $POCH_2CH_3$); 127.2, 128.0, 129.1, 134.7 (d, $^3J_{C,P}$ = 1.8 Hz); 165.4 ($CO_2$). IR (film) 1740, 1220, 1024. Anal. Calcd for $C_{16}H_{23}O_5P$: C, 58.89; H, 7.10. Found: C, 58.64; H, 7.22.

### 4.3.4. Diethyl 1-[(phenyl sulfonyl)-2-phenylcyclopropane]-phosphonate 11

*trans*-**8**: $[\alpha]_D^{22}$ = −47.2 (*c* 0.15, acetone); $^{31}P$ NMR (81 MHz, $CDCl_3$) $\delta$: 14.3 ppm. $^1H$ NMR (200 MHz, $CDCl_3$) $\delta$: 0.89 (t, 3H, $POCH_2CH_3$, $J_{HH}$ = 7.1 Hz), 1.09 (t, 3H, $POCH_2CH_3$, $J_{HH}$ = 7.1 Hz), 1.19–1.30 (m, 1H, CH*H*), 2.17–2.36 (m, 2H, *CH*Ph and *CH*H), 3.41–3.95 (m, 4H, $POCH_2CH_3$), 7.20–7.68 (m, 8H, $C_6H_5$), 7.96–8.06 (m, 2H, $C_6H_5$). $^{13}C$ NMR (125 MHz, $CDCl_3$) $\delta$: 16.0 (d, $^3J_{C,P}$ = 6.2 Hz, $POCH_2CH_3$); 16.4 (d, $^3J_{C,P}$ = 6.7 Hz, $OCH_2CH_3$); 28.4 (s, $PCCH_2$); 31.9 (s, *C*HPh); 39.6 (d, $^1J_{C,P}$ = 177.9 Hz, *P*C); 62.1 (d, $^2J_{C,P}$ = 5.5 Hz, $POCH_2CH_3$); 62.6 (d, $^2J_{C,P}$ = 5.7 Hz, $POCH_2CH_3$); 127.2, 128.0, 129.1, 129.3, 134.7 (d, $^3J_{C,P}$ = 1.8 Hz); 138.2, 143.8, 165.4 ($CO_2$). IR (film) 1745, 1330, 1225, 1024. Anal. Calcd for $C_{19}H_{23}O_2PS$: C, 57.86; H, 5.88. Found: C, 57.41; H, 5.68.

### 4.3.5. Diethyl 1-(diethoxyphosphoryl)cyclopropane-1,2-dicarboxylate 16

*trans*-**15**: Colorless oil. $^{31}P$ NMR (81 MHz, $CDCl_3$) $\delta$: 19.9 ppm. $^1H$ NMR (200 MHz, $CDCl_3$) $\delta$: 1.26 (t, $^3J_{HH}$ = 7.0 Hz, 3H, $CH_3CH_2O$), 1.27 (t, $^3J_{HH}$ = 7.0 Hz, 3H, $CH_3CH_2O$), 1.34 (t, $^3J_{HH}$ = 7.0 Hz, 3H, $CH_3CH_2OP$), 1.37 (t, $^3J_{HH}$ = 7.0 Hz, 3H, $CH_3CH_2OP$), 1.70 (ddd, $^3J_{HH}$ = 8.5 Hz, $^3J_{HH}$ = 4.5 Hz, $^3J_{PH}$ = 16.2 Hz, 1H, PCC*H*H), 1.92 (ddd, $^2J_{HH}$ = 4.5 Hz, $^3J_{HH}$ = 6.2 Hz, $^3J_{PH}$ = 13.1 Hz, 1H, PCCH*H*), 2.45 (ddd, $^3J_{HH}$ = 6.2 Hz, $^3J_{HH}$ = 8.5 Hz, $^3J_{PH}$ = 15.4 Hz, 1H, PCCH), 4.10–4.25 (m, 8H, 2×$CH_2$OP, 2×$CH_2$O). $^{13}C$ NMR (125 MHz, $CDCl_3$) $\delta$: 14.0 (d, $^3J_{PC}$ = 5.5 Hz, $CH_3CH_2OP$); 14.1 (s, $CH_3CH_2O$); 16.3 (s, $CH_3CH_2O$); 17.8 (s, $PCCH_2$); 24.6 (s, *C*HCO$_2$); 29.8 (d, $^1J_{PC}$ = 176.9 Hz, *P*C); 61.5 (s, $CH_2O$); 62.4 (s, $CH_2O$); 62.7 (d, $^2J_{PC}$ = 5.6 Hz, $CH_2OP$); 63.4 (d, $^2J_{PC}$ = 5.6 Hz, $CH_2OP$); 166.1 (d, $^2J_{PC}$ = 5.0 Hz, *C*=O); 169.3 (d, $^3J_{PC}$ = 3.0 Hz, *C*=O) (lit.[14]).

*cis*-**16**: colorless oil. $^{31}P$ NMR (81 MHz, $CDCl_3$) $\delta$: 19.3 ppm. $^1H$ NMR (200 MHz, $CDCl_3$) $\delta$: 1.27 (t, $^3J_{HH}$ = 7.0 Hz, 3H, $CH_3CH_2O$), 1.28 (t, $^3J_{HH}$ = 7.0 Hz, 3H, $CH_3CH_2O$), 1.29 (t, $^3J_{HH}$ = 7.0 Hz, 3H, $CH_3CH_2OP$), 1.37 (t, $^3J_{HH}$ = 7.0 Hz, 3H, $CH_3CH_2OP$), 1.69 (ddd, $^3J_{HH}$ = 4.5 Hz, $^3J_{HH}$ = 8.0 Hz, $^3J_{PH}$ = 9.0 Hz, 1H, PCC*H*H), 1.94 (ddd, $^2J_{HH}$ = 4.5 Hz, $^3J_{HH}$ = 7.7 Hz, $^3J_{PH}$ = 15.0 Hz, 1H, PCCH*H*), 2.59 (ddd, $^3J_{HH}$ = 7.7 Hz, $^3J_{HH}$ = 8.0 Hz, $^3J_{PH}$ = 9.0 Hz, 1H, PCCH), 4.08–4.26 (m, 8H, 2×$CH_2$OP, 2×$CH_2$O). $^{13}C$ NMR (125 MHz, $CDCl_3$) $\delta$: 14.1 (d, $^3J_{PC}$ = 10.0 Hz, $CH_3CH_2OP$); 16.3 (s, $CH_3CH_2O$); 16.4 (s, $CH_3CH_2O$); 17.9 (s, $PCCH_2$); 25.3 (s, PCCH); 26.5 (d, $^1J_{PC}$ = 193.0 Hz, *P*C); 62.7 (s, $CH_3CH_2O$); 62.9 (d, $^2J_{PC}$ = 6.3 Hz, $CH_3CH_2OP$); 63.3 (d, $^2J_{PC}$ = 6.4 Hz, $CH_3CH_2OP$); 64.4 (s, $CH_3CH_2O$); 167.5 (d, $^2J_{PC}$ = 6.2 Hz, *C*=O); 168.7 (d, $^3J_{PC}$ = 7.0 Hz, *C*=O). IR (film) 1740, 1220, 1024. Anal. Calcd for $C_{13}H_{23}O_7P$: C, 48.45; H, 7.19. Found: C, 48.36; H, 7.21.

### 4.3.6. Diethyl-[(phenyl sulfonyl)-2-carboethoxycyclopropane]-phosphonate 17

(1*S*,2*R*) *trans*-**16**: $[\alpha]_D^{21}$ = −33.7 (*c* 0.32, acetone); $^{31}P$ NMR (81 MHz, $CDCl_3$) $\delta$: 13.4 ppm. $^1H$ NMR (200 MHz, $CDCl_3$) $\delta$: 1.15 (t, $^3J_{HH}$ = 7.1 Hz, 3H, $CH_3CH_2O$), 1.24 (t, $^3J_{HH}$ = 7.0 Hz, 3H, $CH_3CH_2O$), 1.30 (t, $^3J_{HH}$ = 7.0 Hz, 3H, $CH_3CH_2O$), 1.92–2.16 (m, 2H, $CH_2$), 3.04 (ddd, 1H, $J_{HH}$ = 7.7, 8.2, $J_{PH}$ = 9.1 Hz), 3.88–4.07 (m, 4H, $CH_2OP$), 4.16 (q, $^3J_{HH}$ = 7.1 Hz, 2H, $CH_2O$), 7.50–7.82 (m, 3H, $C_6H_5$), 7.95–8.00 (m, 2H, $C_6H_5$). $^{13}C$ NMR (125 MHz, $CDCl_3$) $\delta$: 13.9 (s, $CH_3CH_2O$); 15.9 (d, $^3J_{PC}$ = 7.5 Hz, $CH_3CH_2OP$); 16.0 (d, $^3J_{PC}$ = 7.0 Hz, $CH_3CH_2OP$); 29.6 (s, $CH_2$); 42.6 (d, $^1J_{PC}$ = 173.3 Hz); PCS); 62.1 (s, $CH_3CH_2O$); 63.6 (d, $^2J_{PC}$ = 5.9 Hz $CH_3CH_2OP$); 63.7 (d, $^2J_{PC}$ = 5.7 Hz, $CH_3CH_2OP$); 127.8, 129.1, 136.7, 144.5, 167.9 (d, $J$ = 4.5 Hz). Anal. Calcd for $C_{16}H_{23}O_7PS$: C, 49.23; H, 5.94. Found: C, 49.21; H, 5.68.

(1*S*,2*S*) *cis*-**17**: $[\alpha]_D^{21}$ = −42.8 (*c* 0.23, acetone); $^{31}P$ NMR (81 MHz, $CDCl_3$) $\delta$: 15.4 ppm. $^1H$ NMR (200 MHz, $CDCl_3$) $\delta$: 1.16 (t, 3H, $CH_3CHO$), 1.20 (t, 3H, $CH_3CHO$), 1.34 (t, 3H, $CH_3CHO$), 1.84 (ddd, 1H, $J_{HH}$ = 5.5, 8.9, $J_{PH}$ = 9.0 Hz), 2.31 (ddd, 1H, $J_{HH}$ = 5.5, 7.7, $J_{PH}$ = 11.2 Hz), 2.82 (ddd, 1H, $J_{HH}$ = 7.7, 8.9, $J_{PH}$ = 16.6 Hz), 3.94–4.07 (m, 4H, $CH_2OP$), 4.22–4.27 (q, 2H, $CH_2O$) 7.55–7.69 (m, 3H, $C_6H_5$), 7.98–8.05 (m, 2H, $C_6H_5$). $^{13}C$ NMR (125 MHz, $CDCl_3$) $\delta$: 13.9 (s, $CH_3CH_2O$); 15.9 (d, $^3J_{PC}$ = 6.8 Hz, $CH_3CH_2OP$); 16.0 (d, $^3J_{PC}$ = 6.7 Hz, $CH_3CH_2OP$); 29.6 (s, $CH_2$); 42.6 (d, $^1J_{PC}$ = 173.3 Hz PCS); 62.1 (s, $CH_3CH_2O$); 63.6 (d, $^2J_{PC}$ = 5.9 Hz $CH_3CH_2OP$); 63.7 (d, $^2J_{PC}$ = 5.7 Hz, $CH_3CH_2OP$); 127.8, 129.1, 138.5, 142.5, 166.5 (s, C=O).

## References


1. Corey, E. J.; Chaykovsky, M. *J. Am. Chem. Soc.* **1965**, *87*, 1345–1364.
2. (a) Furukawa, N.; Sugihara, Y.; Fujihara, H. *J. Org. Chem.* **1989**, *54*, 4222–4224; (b) Julienne, K.; Metzner, P.; Henryon, V. *J. Chem. Soc., Perkin Trans. 1* **1999**, 731–735. and references cited therein.
3. (a) Illa, O.; Namutebi, M.; Saha, C.; Ostovar, M.; Chen, C. C.; Haddow, M. F.; Nocquet-Thibault, S.; Lusi, M.; McGarrigle, E. M.; Aggarwal, V. K. *J. Am. Chem. Soc.* **2013**, *135*, 11951–11966; (b) Illa, O.; Arshad, M.; Ros, A.; McGarrigle, E. M.; Aggarwal, V. K. *J. Am. Chem. Soc.* **2010**, *132*, 1828–1830; (c) Aggarwal, V. K.; Winn, C. L. *Acc. Chem. Res.* **2004**, *37*, 611–620.
4. (a) McGarrigle, E. M.; Myers, E. L.; Illa, O.; Shaw, M. A.; Riches, S. L.; Aggarwal, V. K. *Chem. Rev.* **2007**, *107*, 5841–5883; (b) Drabowicz, J.; Lewkowski, J.; Ścianowski, J. Selenium Compounds with Valency Higher than Two in Organoselenium Chemistry In Wirth, T., Ed.; Wiley-VCH: Weinheim, 2012; pp 191–256.
5. (a) Bartoli, G.; Bencivenni, G.; Dalpozzo, R. *Synthesis* **2014**, *46*, 979–1029; (b) Riches, S. L.; Saha, C.; Filgueira, N. F.; Grange, E.; McGarrigle, E. M.; Aggarwal, V. K. *J. Am. Chem. Soc.* **2010**, *132*, 7626–7630; (c) Pellissier, H. *Tetrahedron* **2008**, *64*, 7041–7095; (d) Sun, X. L.; Tang, Y. *Acc. Chem. Res.* **2008**, *41*, 937–948.
6. Zhou, R.; Deng, X.; Zheng, J.; Sheng, Q.; Sun, X.; Tang, Y. *Chin. J. Chem.* **2011**, *29*, 995–1000.
7. Aggarwal, V. K.; Grange, E. *Chem. Eur. J.* **2006**, *12*, 568–575.
8. (a) Liao, W. W.; Li, K.; Tang, Y. *J. Am. Chem. Soc.* **2003**, *125*, 13030–13031; (b) Zheng, J. C.; Liao, W. W.; Tang, Y.; Sun, X. L.; Dai, L. X. *J. Am. Chem. Soc.* **2005**, *127*, 12222–12223.
9. Wang, H. Y.; FeiYang, F.; Li, X. L.; Yan, X. M.; Huang, Z. Z. *Chem. Eur. J.* **2009**, *15*, 3784–3789.
10. (a) Banach, A.; Ścianowski, J.; Ozimek, P. *Phosphorus, Sulfur* **2014**, *189*, 274–284; (b) Banach, A. Ścianowski, J; Uzarewicz, M.; Wojtczak, A. 'manuscript in preparation'.
11. (a) Midura, W. H.; Rzewnicka, A. *Synlett* **2014**, 2213–2216; (b) Midura, W. H.; Rzewnicka, A. *Tetrahedron: Asymmetry* **2013**, *24*, 937–941; (c) Midura, W. H.; Krysiak, J. A.; Rzewnicka, A.; Supeł, A.; Łyżwa, P. *Tetrahedron* **2013**, *69*, 730–737; (d) Krysiak, J.; Midura, W. H.; Wieczorek, W.; Sieroń, L.; Mikołajczyk, M. *Tetrahedron: Asymmetry* **2010**, *21*, 1486–1493; (e) Midura, W. H.; Mikołajczyk, M. *Tetrahedron Lett.* **2002**, *43*, 3061–3065.
12. For some experiments, HPLC was performed on mixture of diastereomers.
13. (a) Midura, W. H.; Krysiak, J.; Mikołajczyk, M.; Wieczorek, M. W.; Majzner, W. R. *Chem. Commun.* **1998**, 1109–1110; (b) Midura, W. H.; Krysiak, J. A.; Cypryk, M.; Mikołajczyk, M.; Wieczorek, M. W.; Filipczak, A. D. *Eur. J. Org. Chem.* **2005**, 653–662.
14. Wąsek, K.; Kędzia, J.; Krawczyk, H.; Wojciechowski, J.; Wolf, W. M. *ARKIVOC* **2010**, *IX*, 146–154.