Heteroatom Chemistry
Volume 18, Number 7, 2007

Reaction of Diethyl Thiocyanatomethylphosphonate with Aldehydes as a Route to Diethyl *Z*-1-Alkenylphosphonates

Roman Błaszczyk and Tadeusz Gajda

Institute of Organic Chemistry, Department of Chemistry, Technical University of Lodz, Zeromskiego St. 116, 90-924 Lodz, Poland

Received 18 September 2006; revised 3 December 2006

ABSTRACT: *Diastereoselective synthesis of diethyl Z-1-alkenylphosphonates from easily available diethyl thiocyanatomethylphosphonate and aromatic aldehydes has been developed. Olefination of the aldehydes occurs under mild conditions and affords the title compounds with moderate yields. A plausible mechanism of the above-mentioned reaction is also discussed.* © 2007 Wiley Periodicals, Inc. Heteroatom Chem 18:732–739, 2007; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/hc.20371

INTRODUCTION

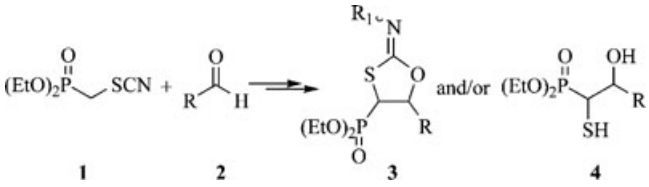
Organic thiocyanates are valuable tools for the synthesis of a wide variety of organosulfur compounds [1]. Increasing interest in the chemistry of bifunctional organic compounds containing both phosphorus and sulfur moieties resulted in the efficient synthesis of racemic [2] as well as optically active 1-(thiocyanato)alkylphosphonates [3], their application in the preparation of the α-sulfanylphosphonates [3], potential metalloenzyme inhibitors.

Being inspired by the work of Hayashi et al. [4] who found the condensation of thiocyanatoacetic acid esters with aromatic aldehydes as a route to 2-imino-1,3-oxathiolanes, we focused our attention on the reactions of diethyl thiocyanatomethylphosphonate **1** with aldehydes **2**, which could lead to new derivatives of 2-imino-[1,3]-oxathiolan-4-yl)phosphonates **3** and/or 2-hydroxy-1-mercaptophosphonates **4** (Scheme 1). However, the above-mentioned reactions afforded α,β-unsaturated phosphonates instead of the desired products **3** and **4**. This observation prompted us to direct our investigations toward the synthesis of alkenylphosphonates.

Alkenylphosphonates are important intermediates in organic chemistry [5], especially for the synthesis of carbo- and heterocyclic compounds [5a,6] as well as various functionalized phosphonates [5a,7].

Although a number of methodologies have been developed for the synthesis of *E*-1-alkenylphosphonates [8], there is still a place for the new protocols directed to the preparation of *Z*-alkenylphosphonates [5a]. So far, these compounds are available by Horner–Wadsworth–Emmons (HWE) olefination of aldehydes with tetrakis(2,2,2-trifluoroethyl)methylenebisphosphonate [9], palladium-catalyzed coupling of dialkyl phosphites with *Z*-1-bromo-1-alkenes [10], and copper-promoted substitution of vinyl bromides with dialkyl and diphenyl phosphites in the presence of base [11]. Other convenient methodologies are

Correspondence to: Tadeusz Gajda; e-mail: tmgajda@p.lodz.pl.



SCHEME 1 Expected route to 2-imino-[1,3]-oxathiolan-4-yl)phosphonates **3** and 2-hydroxy-1-mercaptophosphonates **4**.

based on catalytic reduction of the 1-alkynyl-[7h,12] and 1,2-dienylphosphonates [13] and addition of "zirconocene" [14] or lithium organocuprates and Grignard reagents [12a] to 1-alkynylphosphonates. Also nucleophilic additions of organometallic reagents to diethyl 1-(trimethylsilyl)vinylphosphonate [15] and Peterson olefination of acetaldehyde with dialkyl (trimethylsilyl)methylphosphonates [16] seem to be useful for the preparation of *Z*-alkenylphosphonates. Other attractive methods involve stereospecific palladium acetate-catalyzed reaction of *Z*-alkenylboronates with triethyl phosphite [17], acid cleavage of *E*-α-triphenylstannylvinylphosphonates [17,18], palladium- and nickel catalyzed coupling reactions of *Z*-α-bromoalkenylphosphonates with arylboronic acids [8b], and finally the reaction of *O*,*O*-diethyl *S*-(2-oxoalkyl)dithiophosphates and *Se*-(2-oxoalkyl)selenophosphates with sodium diethyl phosphite [19].

RESULTS AND DISCUSSION

Herein, we present the results of our investigation on the olefination of carbonyl compounds by means of diethyl thiocyanatomethylphosphonate **1**, affording the corresponding diethyl *Z*-1-alkenylphosphonates **5** in moderate yields and in high stereoselectivity.

The starting diethyl thiocyanatomethylphosphonate [2a] **1** was prepared in 87% yield via nucleophilic displacement of diethyl (4-nitrobenzenesulfonyloxymethyl)-phosphonate [20] with potassium thiocyanate in the presence of catalytic amounts of 18-crown-6. The presented synthesis is a modification of the procedure described previously for the preparation of diisopropyl 1-(thiocyanato)alkylphosphonates [3].

Our initial studies concentrated on the optimization of the conditions of the olefination reaction. Thus, benzaldehyde **2a** was chosen as a model carbonyl compound, and selected bases (NaH, *t*-BuOK, lithium diisopropylamide(LDA)) were used for metalation of **1** (Scheme 2). The results are presented in

TABLE 1 Diethyl 1-Alkenylphosphonates (**5/6a–g**) Prepared

Entry	*Products* ***5/6***	*R*	***5/6*** *Z*/*E*[a]	*Yield*[b] *(%)*
1	**a**	Ph	98/2	60 (55)
2	**a**	Ph	65/35[c]	75 (60)
3	**a**	Ph	–[d]	–
4	**b**	2-$MeOC_6H_4$	91/9	40 (21)
5	**c**	2-MeC_6H_4	97/3	51 (32)
6	**d**	4-$O_2NC_6H_4$	5/95	33 (22)[e]
7	**e**	1-Naphthyl	91/9	45 (26)
8	**f**	2-Furyl	72/28	50 (31)
9	**g**	(*E*)-PhCH=CH	84/16	65 (41)

[a]Diastereomers ratios measured by ^{1}H and ^{31}P NMR of the crude reaction mixture.
[b]Yields of pure, isolated diastereomers **5/6**. Yields in parentheses refer to single *Z*-**5a-c,e-g** separated after flash chromatography.
[c]2 Equivalents of *t*-BuOK, at −70°C for 2 h was applied.
[d]2 Equivalents of LDA, at −70°C for 10 min was applied.
[e]Yield of pure *E*-**6d**.

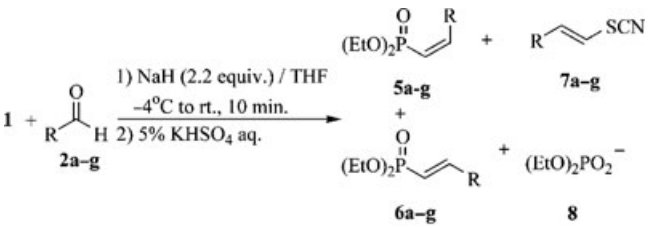
Table 1. Diastereoselectivity of the olefination was determined by means of ^{1}H and ^{31}P NMR spectra of crude reaction mixtures. The detailed stereochemical analysis will be discussed further.

The results summarized in Table 1 show that the application of 2.2 equivalents of sodium hydride, at the temperature of −4°C, afforded diethyl styrylphosphonates **5a** and **6a** in good yields (60%) and high *Z*-stereoselectivity (*E*/*Z* = 2/98, Table 1, entry 1). It is noteworthy that the reaction was completed very quickly (about 10 min). In turn, the use of potassium *tert*-butoxide, at −70°C for 2 h, resulted in better yields in comparison to sodium hydride, however at the expense of stereoselectivity (*E*/*Z* = 35/65, Table 1, entry 2). Lithium diisopropylamide (LDA) afforded a mixture of unidentified organophosphorus compounds (Table 1, entry 3).

In addition, we found that, regardless of the conditions applied, the crude reaction mixture contained a considerable amount of *E*-(2-thiocyanatovinyl)-benzene **7a** and diethyl phosphate **8**. These byproducts could be, however, easily separated from alkenylphosphonates **5/6a** by standard aqueous workup and flash chromatography.

The presence of side products in the crude reaction mixture was confirmed by ^{1}H NMR spectrum, showing two doublets at 6.5 and 6.9 ppm with trans vicinal-coupling constant ($^3J_{HH}$ = 15.00 Hz) diagnostic for **7a**, as well as by the signal of phosphate **8** at 1.0 ppm in the ^{31}P NMR. The ^{1}H NMR data are in agreement with those obtained for *E*-(2-thiocyanatovinyl)-benzene **7a** prepared independently [21].

The data given in Table 1 indicate that the olefination of benzaldehyde **2a** by means of **1** and sodium hydride gave the desired diethyl styrylphosphonates



5–7	R
a	Ph
b	2-MeC_6H_4
c	2-MeC_6H_4
d	4-$O_2NC_6H_4$
e	1-naphthyl
f	2-furyl
g	(*E*)-PhCH=CH

SCHEME 2 Diethyl 1-alkenylphosphosphonates **5/6a–g** prepared.

5/6a in good yields and simultaneously with high diastereoselectivity.

All other olefination reactions were executed in compliance with this optimized protocol. Thus, according to Scheme 2, a range of representative aldehydes underwent olefination with **1** in the presence of 2.2 equivalents of sodium hydride at −4°C to give, after chromatography, pure diethyl 1-alkenylphosphonates **5a–g** and **6a–g** in moderate yields (Scheme 2). The results are summarized in Table 1.

The above-mentioned transformations occurred with high *Z*-diastereoselectivity ($Z/E = 98{:}2$ to 72:28), and single *Z*-diastereomers **5a–c, e–g** could be easily isolated from the reaction mixtures by flash chromatography. 4-Nitrobenzaldehyde **2d** was the exception, for which irrespectively of the conditions applied, high *E*-diastereoselectivity was observed ($Z/E = 5/95$, Table 1, entry 6). The reaction is limited to α,β-unsaturated (cinnamaldehyde) and aromatic aldehydes. Unfortunately, the method gave no satisfactory results for aliphatic aldehydes and ketones for which mixtures of unidentified organophosphorus compounds were formed.

The assignment of the stereochemistry of the double bond of diethyl 1-alkenylphosphonates **5** and **6** was based on the values of vicinal proton–proton ($^3J_{HH}$), carbon–phosphorus ($^3J_{CP}$), and proton–phosphorus ($^3J_{HP}$) coupling constants. The ^{31}P NMR chemical shifts and selected diagnostic couplings constants of the diethyl 1-alkenylphosphonates **5**, and **6** are summarized in Table 2.

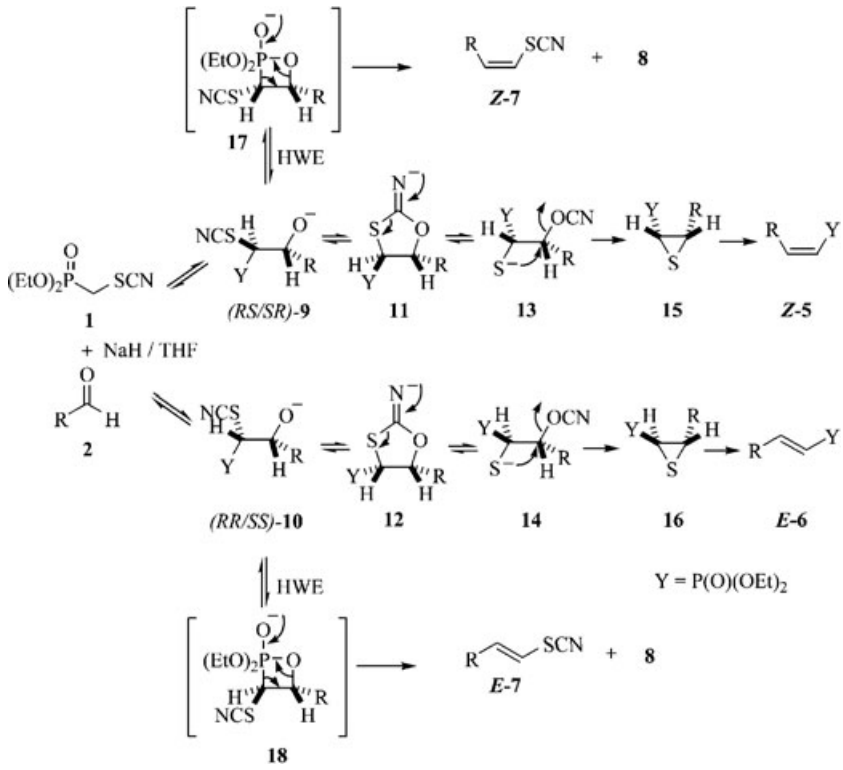
Thus, the values of $^3J_{CP}$ (8–10 Hz) and $^3J_{HH}$ (13–14 Hz) for diethyl *Z*-1 alkenylphosphonates **5** are smaller than the ones for *E*-**6**, ($J = 23$–25 Hz and $J = 16$–17 Hz, respectively). The reverse relation is observed when it comes to $^3J_{HP}$. For *Z*-**5** vicinal-coupling, constants $^3J_{HP}$ are around 47–51 Hz, whereas the *E*-**6** are characterized by the value in the range of 22–23 Hz. These results are in agreement with the literature data [14a,22]. In addition in all ^{31}P NMR spectra, the signals of the *Z*-isomers **5** appear at higher field than the ones of the *E*-**5** [7h,12a,22d].

Plausible mechanistic pathways of the olefination are shown in Scheme 3. The competitive Horner–Wadsworth–Emmons reaction, resulted in the formation of *E*-(2-thiocyanato-vinyl)-arenes **7**, is responsible for decreased yields of alkenylphosphonates **5** and **6**. The stereochemistry of olefination is determined by combination of the stereoselectivity

TABLE 2 ^{31}P NMR Chemical Shifts (δ) and Selected Vicinal-Coupling Constants (*J*) of Diethyl 1-alkenylphosphonates **5** and **6**

Entry	*Compounds* ***5/6***	*R*	^{31}P *NMR* δ	^1H *NMR* $^3J_{HH}$	^1H *NMR* $^3J_{HP}$	^{13}C *NMR* $^3J_{CP}$
1	***Z*-5a**	Ph	16.31	14.24	51.07	8.74
2	***E*-6a**		19.82	17.46	22.58	–[a]
3	***Z*-5b**	2-$MeOC_6H_4$	16.90	14.11	51.79	8.43
4	***E*-6b**		20.71	17.73	23.67	–[a]
5	***Z*-5c**	2-MeC_6H_4	16.17	13.84	51.08	8.36
6	***E*-6c**		19.54	17.46	–[b]	–[a]
7	***Z*-5d**	4-$O_2NC_6H_4$	14.35	14.36	47.00	–[a]
8	***E*-6d**		17.46	17.53	22.26	23.52
9	***Z*-5e**	1-Naphthyl	14.35	13.71	50.12	–[b]
10	***E*-6e**		17.45	17.28	22.34	–[b]
11	***Z*-5f**	2-Furyl	16.22	14.76	49.10	10.32
12	***E*-6f**		19.99	17.51	22.51	25.66
13	***Z*-5g**	PhCH=CH	17.77	12.84	50.60	–[b]
14	***E*-6g**		20.78	16.72	–[b]	–[b]

[a] Too low concentration for accurate measurement.
[b]Overlapped with other signals.



SCHEME 3 Plausible mechanistic pathways of the olefination of aldehydes with **1**.

of the initial carbon–carbon bond-forming step and reversible formation of the intermediates **9, 10** and **17, 18**.

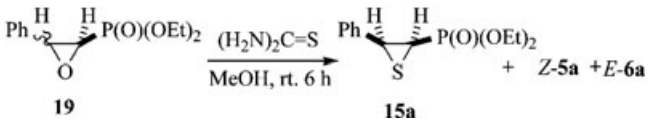
According to Scheme 3, in the first, reversible step [23] primary oxyanion intermediates **9** and **10**, formed from aldehyde and metalated **1**, are converted into appropriate cyanate derivatives **13** and **14** via oxathiolanimine derivatives **11** and **12**. The intermediate formation of oxathiolanimines has been previously postulated in the ring opening of epoxides with thiocyanates [24] and in the reactions of thiocyanate acetic acid esters with aldehydes [4]. Such ring closure and subsequent intramolecular migration of the cyano group from sulfur to oxygen requires synperiplanar orientation of the oxygen anion and thiocyanate group. Hence, (*RS/SR*)-**9**, in comparison to (*RR/SS*)-**10**, reacts faster via the less hindered transition state to give **13** as a major product. Above-mentioned steps seem to be also reversible. Subsequent S_N2-type cyclization of **13** and **14** leads to thiiranes **15** and **16** with inversion of configuration at the carbon adjacent to the phosphoryl moiety.

The episulfides are well-known precursors of olefins [24]. Spontaneous desulfurization of the above-mentioned episulfides, triggered by sodium hydride, causes the conversion of **15** and **16** into the corresponding alkenylphosphonates **5** and **6**. Such extrusion of sulfur is known to proceed stereospecifically with retention of configuration [20,22e,25], giving *Z*-**5** as a major isomer.

The reversed outcome of the olefination of *p*-nitrobenzaldehyde **2d** is still open for discussion. However, it could be rationalized by fast isomerization of the primarily formed *Z*-alkenylphosphonate **5d** into the thermodynamically stable *E*-**6d** under the reaction conditions. Slow isomerization of the other *Z*-**5** was also observed upon prolonged standing at room temperature.

On the other hand, in the competitive HWE reaction, oxyanion intermediates **9** and **10** could decompose via transient four-centered intermediates **17** and **18** to yield (2-thiocyanato-vinyl)-arenes **7** (Scheme 3). The formation of *E*-**7** is definitely preferred. Faster formation (from **10**) and syn-cycloelimination of less sterically hindered oxaphosphetane **18** is responsible for such stereochemical outcome [23].

^{31}P and ^{1}H NMR spectroscopy, together with some additional experiments, were applied to account for the formation of the postulated intermediates. At first, olefination of benzaldehyde **2a** with **1** was performed using 1 equivalent of sodium



SCHEME 4 Synthesis of *cis*-episulfide **15a**.

hydride, instead of standard 2.2 equivalents. The ^{31}P NMR spectrum of the crude reaction mixture exhibited three signals, the major one at 20.39 ppm assigned to *cis*-episulfide **15a**, and two minors at 16.32 and 16.71 ppm were ascribed to *Z*-**5a** and the other compound, whose structure has not been established.

The configuration of episulfides could be assigned on the basis of diagnostic vicinal proton–proton coupling constants of the episulfide ring ($^3J_{HH}^{trans} < {}^3J_{HH}^{cis}$) [26]. Thus, ^1H NMR spectrum of the above-mentioned reaction mixture shows, among other signals, two double doublets of the thiirane ring protons at 3.15 ppm ($^3J_{HH} = 7.25$ Hz. $^2J_{PH} = 9.7$ Hz) and 4.30 ppm ($^3J_{HH} = 7.25$ Hz. $^3J_{PH} = 11.5$ Hz), respectively. The value of 7.25 Hz is in agreement with the literature data for *cis*-episulfides [26], thus immediately confirming the configuration of **15a**.

Attempted isolation of **15a** from the reaction mixture failed. During chromatography, extrusion of sulfur from **15a** took place and only *Z*-**5a** was isolated.

Conversion of oxiranes into the corresponding thiiranes by an oxygen-sulfur exchange reaction is known as a convenient route to episulfides [27]. Moreover, Inokawa and Yamamoto [28] described the efficient synthesis of dimethyl 1,2-epithio-1-methylethanephosphonate from the appropriate epoxide. However, synthesis of **15a** by an independent way has finished with limited success. We found, as shown in Scheme 4, that treatment of diethyl (3-phenyl-oxiranyl)-phosphonates [7h,12a] **19** (cis/trans = 91/9) with thiourea in methanol at room temperature for 6 h produced a mixture of starting **19** (64%, $\delta_P = 17.27$), *cis*-episulfide **15a** (6%, $\delta_P = 20.7$), diethyl *Z*-styrylphosphonate **5a** (21%, $\delta_P = 16.3$), and diethyl *E*-styrylphosphonate **6a** (9%, $\delta_P = 19.8$), as determined by ^{31}P NMR. Unfortunately, as a result of desulfurization, the concentration of **15a** in the reaction mixture was very low. The thiiranes, substituted by aromatic residues and electron-withdrawing groups, are known to form olefins even at room temperature [4]. Nevertheless, this experiment confirmed the intermediate formation of *cis*-episulfides during the olefination of aldehydes with **1**.

In conclusion, the results presented in this paper demonstrate that easily available diethyl thiocyanatomethylphosphonate **1** can be the useful starting material for the stereoselective synthesis of diethyl *Z*-1-alkenylphosphonates **5**, derived from aromatic aldehydes.

EXPERIMENTAL

NMR spectra were recorded on a Bruker Avance DPX 250 instrument at 250.13 MHz for ^1H NMR, 62.90 MHz for ^{13}C NMR, and 101.3 MHz for ^{31}P NMR in $CDCl_3$ solution, using tetramethylsilane as internal and 85% H_3PO_4 as external standard. Positive chemical shifts are downfield from external 85% H_3PO_4 for ^{31}P NMR spectra. Chemical shifts (δ) are indicated in ppm and coupling constants (J) in Hz. Elemental analyses were performed on a Perkin–Elmer PE 2400 analyzer. IR spectra were measured on a Specord M80 (Zeiss) instrument and are reported in cm^{-1}. Flash chromatography was performed with glass column packed with Baker silica gel (30–60 μm). Melting points were determined in open capillaries and are uncorrected. All reagents were purchased from Fluka and were used without further purification.

E-(2-Thiocyanato-vinyl)-benzene **7a** was prepared as described in the literature [21]. Diethyl (4-nitrobenzenesulfonyloxymethyl)-phosphonate was obtained from diethyl hydroxymethylphosphonate and 4-nitrobenzenesulfonyl chloride in the same way as described previously [20]. Diethyl (3-phenyl-oxiranyl)-phosphonates **19** (cis/trans = 91/9) were obtained in 50% yield by dioxirane epoxidation of diethyl styrylphosphonates **5a**/**6a** ($Z/E = 91/9$), according to the literature method [7h,12].

*Diethyl Thiocyanatomethylphosphonate (**1**) [2a]*

The title compound was obtained by modification of the method described previously [3]. The solution of diethyl (4-nitrobenzenesulfonyloxymethyl)-phosphonate (8.20 g, 23 mmol), KSCN (8.98 g, 92 mmol), and 18-crown-6 (0.62 g, 2.3 mmol, 10 mol%) in CH_3CN (230 mL) was refluxed for 3 h. Then, the solvent was evaporated under reduced pressure and the solid residue was extracted with diethyl ether (3×80 mL). Ether was evaporated under reduced pressure, and the yellow oily residue was distilled under reduced pressure (bulb to bulb, 150°C, 0.05 mmHg) to give analytically pure **1** (2.22 g, 87% yield), as a colorless oil. IR (film): $\nu = 2160$ cm^{-1} (s), 2984 (m), 1260 (s), 1024 (m). ^1H NMR (250 MHz, $CDCl_3$): $\delta = 1.40$ (t, $^3J_{H,H} = 7.06$ Hz, 6H, $2CH_3CH_2O$), 3.15 (d, $^2J_{H,P} = 12.53$ Hz, 2H, CH_2P), 4.24 (qt, $^3J_{H,H} = 7.08$ Hz, 4H, $2CH_3CH_2O$) ppm. ^{13}C NMR (63 MHz, $CDCl_3$): $\delta = 15.9$ (d, $^3J_{C,P} = 5.83$ Hz,

2CH_3CH_2O), 25.3 (d, $^1J_{C,P} = 150$, 5 Hz, CH_2P), 63.1 (d, $^2J_{C,P} = 5.8$ Hz, 2CH_3CH_2O), 72.8 (SCN) ppm. ^{31}P NMR (101 MHz, $CDCl_3$): $\delta = 18.63$. $C_6H_{12}NO_3PS$ (209.20): calcd. C 34.45, H 5.78, N 6.70; found C 34.35, H 5.76, N 6.72.

General Procedure for the Preparation of Diethyl 1-Alkenylphosphonates **5/6a–g** *Using NaH As a Base.*

To a cooled to −4°C suspension of sodium hydride (0.158 g, 6.6 mmol) in anhydrous THF (20 mL), the solution of aldehyde **2a–g** (3.15 mmol) and **1** (0.627 g, 3 mmol) in THF (5 mL) was added dropwise for 20 min. Then the reaction mixture was stirred for 10 min from −4 to 0°C and for 10 min at room temperature. The resultant mixture was quenched with 5% aqueous solution of $KHSO_4$. Solvent was evaporated under reduced pressure; the residue was dissolved in CH_2Cl_2 (80 mL) and washed with 5% $KHSO_4$ (10 mL). Water layer was re-extracted with CH_2Cl_2 (20 mL). The combined organic layers were washed successively with brine (2 × 5 mL) and H_2O (5 mL), dried over anhydrous $MgSO_4$, and evaporated under reduced pressure to give the mixture of diethyl 1-alkenylphosphonates **5/6**. Analytically pure phosphonates **5/6** or single *Z*-isomers **5** (*E*-isomer in case of **6d**) were isolated after flash chromatography on silica gel. The results are summarized in Tables 1 and 2.

*Diethyl Z-Styrylphosphonate (***5a***) [7e,12a].* *Z*-**5a** was isolated by flash chromatography (ethyl acetate/hexane, 5:7) as a yellow oil. Yield: 55%. IR (film): $\nu = 2984$ (m), 1608 (s), 1244 (s), 1028 (m), 728 (s) cm^{-1}. ^1H NMR (250 MHz, $CDCl_3$): $\delta = 1.19$ (t, $^3J_{H,H} = 7.00$ Hz, 6H, 2C$H_3$$CH_2O$), 4.00 (qt, $^3J_{H,H} = 7.23$, Hz, 4H, 2CH_3CH_2O), 5.81 (t, $^3J_{H,H} = {}^2J_{H,P} = 14.24$, Hz, 1H, C$H$P), 7.29 (dd, $^3J_{H,H} = 14.23$, $^3J_{H,P} = 51.07$ Hz, 1H, CHCHP), 7.26–7.70 (m, 5H, H_{ar}) ppm. ^{13}C NMR (63 MHz, $CDCl_3$): $\delta = 15.9$ (d, $^3J_{C,P} = 6.3$ Hz, 2$C$$H_3CH_2O$), 61.6 (d, $^2J_{C,P} = 6.3$ Hz, 2$CH_3C$$H_2O$), 116.8 (d, $^1J_{C,P} = 188.7$ Hz, CHP), 128.1, 129.2, 129.5 (C_{ar}), 135.2 (d, $^3J_{C,P} = 8.7$ Hz, CCHCHP), 148.3 (CHCHP) ppm. ^{31}P NMR (101 MHz, $CDCl_3$): $\delta = 16.31$. $C_{12}H_{17}O_3P$ (240.24): calcd. C 59.99, H 7.13; found C 59.81, H 7.10.

*Diethyl Z-[2-(2-Methoxy-phenyl)-vinyl]-phosphonate (***5b***) [7h,29].* *Z*-**5b** was isolated by flash chromatography (ethyl acetate/hexane, 2:1) as a yellow oil. Yield: 21%. IR (film): $\nu = 2984$ (m), 1600 (s), 1248 (s), 1028 (s), 756 (s) cm^{-1}. ^1H NMR (250 MHz, $CDCl_3$): $\delta = 1.16$ (dt, $^3J_{H,H} = 7.06$, $^4J_{H,P} = 0.54$ Hz, 6H, 2C$H_3$$CH_2O$), 3.84 (s, 3H, C$H_3$O), 3.96 (broad qt, $^3J_{H,H} = 7.13$ Hz, 4H, 2CH_3CH_2O), 5.80 (dd, $^3J_{H,H} = 14.11$, $^3J_{H,P} = 17.16$ Hz, 1H, CHP), 6.86 (d, $^3J_{H,H} = 8.30$ Hz, 1H, H_{ar}), 6.97 (t, $^3J_{H,H} = 7.54$ Hz, 1H, H_{ar}), 7.33 (bt, $^3J_{H,H} = 7.99$ Hz, 1H, H_{ar}), 7.53 (dd, $^3J_{H,H} = 14.09$, $^3J_{H,P} = 51.79$ Hz, 1H, CHCHP), 7.84 (bd, $^3J_{H,H} = 7.64$ Hz, 1H, H_{ar}) ppm. ^{13}C NMR (63 MHz, $CDCl_3$): $\delta = 15.8$ (d, $^3J_{C,P} = 6.6$ Hz, 2$C$$H_3CH_2O$), 55.2 ($CH_3O$), 61.3 (d, $^2J_{C,P} = 5.9$ Hz, 2CH_3CH_2O), 109.7 (C_{ar}), 115.9 (d, $^1J_{C,P} = 185.9$ Hz, CHP), 119.9 (C_{ar}), 124.3 (d, $^3J_{C,P} = 8.4$ Hz, CCHCHP), 130.5 (C_{ar}) 143.9 (CHCHP), 157.0 (C_{ar}) ppm. ^{31}P NMR (101 MHz, $CDCl_3$): $\delta = 16.90$. $C_{13}H_{19}O_4P$ (270.26): calcd. C 57.77, H 7.09; found C 57.65, H 7.08.

*Diethyl Z-(2-o-Tolyl-vinyl)-phosphonate (***5c***) [7h,29].* *Z*-**5c** was isolated by flash chromatography (ethyl acetate/hexane, 2:1) as a yellow oil. Yield: 32%. IR (film): $\nu = 2984$ (m), 1608 (m), 1244 (s), 1028 (s), 780 (m) cm^{-1}. ^1H NMR (250 MHz, $CDCl_3$): $\delta = 1.12$ (dt, $^3J_{H,H} = 7.08$, $^4J_{H,P} = 0.46$ Hz, 6H, 2C$H_3$$CH_2O$), 2.29 (s, 3H, C$H_3$), 3.78–4.01 (m, 4H, 2$CH_3CH_2$O), 5.90 (dd, $^3J_{H,H} = 13.84$, $^2J_{H,P} = 17.80$ Hz, 1H, CHP), 7.42 (dd, $^3J_{H,H} = 13.83$, $^3J_{H,P} = 51.08$ Hz, 1H, CHCHP), 7.13–7.28 (m, 3H, H_{ar}), 7.59–7.65 (m, 1H, H_{ar}) ppm. ^{13}C NMR (63 MHz, $CDCl_3$): $\delta = 15.4$ (d, $^3J_{C,P} = 6.6$ Hz, CH_3CH_2O), 19.0 (CH3), 60.7 (d, $^2J_{C,P} = 5.7$ Hz, 2$CH_3C$$H_2O$), 117.6 (d, $^1J_{C,P} = 185.9$ Hz, CHP), 124.8, 128.3, 128.7, 128.8 (C_{ar}) 134.6 (d, $^3J_{C,P} = 8.4$ Hz, CCHCHP), 135.1 (C_{ar}), 146.6 (CHCHP) ppm. ^{31}P NMR (101 MHz, $CDCl_3$): $\delta = 16.17$. $C_{13}H_{19}O_3P$ (254.26): calcd. C 61.41, H 7.53; found C 61.30, H 7.50.

*Diethyl E-[2-(4-Nitro-phenyl)-vinyl]-phosphonate (***5d***) [30].* *E*-**5d** was isolated by flash chromatography (chloroform/acetone, 3:1) as a yellow crystalline solid, mp. 104–106°C. Lit [30] mp. 102–103.5°C. Yield: 22%. IR (film): $\nu = 2984$ (m), 1598 (m), 1240 (s), 1022 (s), 780 (m) cm^{-1}. ^1H NMR (250 MHz, $CDCl_3$): $\delta = 1.38$ (t, $^3J_{H,H} = 7.07$ Hz, 6H, 2C$H_3$$CH_2O$), 4.17 (broad qt, $^3J_{H,H} = 7.00$ Hz, 4H, 2CH_3CH_2O), 6.44 (dd, $^3J_{H,H} = 17.53$, $^2J_{H,P} = 16.28$ Hz, 1H, CHP,), 7.54 (dd, $^3J_{H,H} = 17.54$, $^3J_{H,P} = 22.26$ Hz, 1H, CHCHP), 7.65 (d, $^3J_{H,H} = 8.72$ Hz, 2H, H_{ar}), 8.25 (d, $^3J_{H,H} = 8.75$ Hz, 2H, H_{ar}) ppm. ^{13}C NMR (63 MHz, $CDCl_3$): $\delta = 16.2$ (d, $^3J_{C,P} = 6.2$ Hz, 2$C$$H_3CH_2O$,) 61.9 (d, $^2J_{C,P} = 5.6$ Hz, 2CH3CH2O), 119.3 (d, $^1J_{C,P} = 190.0$ Hz, CHP), 123.9, 128.1 (C_{ar}), 140.6 (d, $^3J_{C,P} = 23.5$ Hz, CCHCHP), 145.2 (CHCHP), 148.2 (C_{ar}) ppm. ^{31}P NMR (101 MHz, $CDCl_3$): $\delta = 17.46$. $C_{12}H_{16}NO_5P$ (285.23): calcd. C 50.53, H 5.65, N 4.91; found C 50.47, H 5.60, N 4.88.

*Diethyl Z-(2-Naphthalen-1-yl-vinyl)-phosphonate (***5e***) [7e,12].* *Z*-**5e** was isolated by flash

chromatography (ethyl acetate/toluene, 10:1) as a yellow oil. Yield: 26%. IR (film): $\nu = 2984$ (m), 1608 (w), 1244 (s), 1028 (s), 784 (m) cm^{-1}. ^1H NMR (250 MHz, $CDCl_3$): $\delta = 0.98$ (t, $^3J_{H,H} = 7.06$ Hz, 6H, $2CH_3CH_2O$), 3.67–4.93 (m, 4H, $2CH_3CH_2O$), 6.12 (dd, $^3J_{H,H} = 13.71$, $^2J_{H,P} = 17.98$ Hz, 1H, C*H*P), 7.40–7.61 (m, 3H, H_{ar}), 7.77–7.92 (m, 4H, H_{ar}), 7.90 (dd, $^3J_{H,H} = 13.77$, $^3J_{H,P} = 50.12$ Hz, 1H, C*H*CHP) ppm. ^{13}C NMR (63 MHz, $CDCl_3$): $\delta = 15.9$ (d, $^3J_{C,P} = 6.6$ Hz, $2CH_3CH_2O$), 61.7 (d, $^2J_{C,P} = 6.0$ Hz, $2CH_3CH_2O$), 120.0 (d, $^1J_{C,P} = 186.2$ Hz, *C*HP), 124.0, 125.2, 125.9, 126.4, 127.4, 128.5, 129.2, 130.3, 131.0, 133.0 (C_{ar}, *C*CHCHP), 146.3 (*C*HCHP) ppm. ^{31}P NMR (101 MHz, $CDCl_3$): $\delta = 14.35$. $C_{16}H_{19}O_3P$ (290.29): calcd. C 66.20, H 6.60; found C 66.05, H 6.57.

*Diethyl Z-(2-Furan-2-yl-vinyl)-phosphonate (***5f***) [7e,12].* *Z*-**5f** was isolated by flash chromatography (chloroform/acetone, 13:1) as a yellow oil. Yield: 31%. IR (film): $\nu = 2984$ (m), 1624 (m), 1244 (s), 1024 (s), 756 (w) cm^{-1}. ^1H NMR (250 MHz, $CDCl_3$): $\delta = 1.26$ (t, $^3J_{H,H} = 7.09$ Hz, 6H, $2CH_3CH_2O$), 4.11 (dq, $^3J_{H,H} = 7.00$, $^3J_{H,P} = 7.79$ Hz, 4H, $2CH_3CH_2O$), 5.57 (t, $^3J_{H,H} = {}^2J_{H,P} = 14.76$ Hz, 1H, C*H*P) 7.01 (dd, $^3J_{H,H} = 14.67$, $^3J_{H,P} = 49.10$ Hz, 1H, C*H*CHP), 6.47 (dd, $^3J_{H,H} = 3.6$, $^3J_{H,H} = 1.8$ Hz, 1H, H_{ar}), 7.20 (d, $^3J_{H,H} = 3.5$ Hz, 1H, H_{ar}), 7.50 (bd, $^3J_{H,H} = 1.7$ Hz, 1H, H_{ar}) ppm. ^{13}C NMR (63 MHz, $CDCl_3$): $\delta = 16.2$ (d, $^3J_{C,P} = 6.29$ Hz, $2CH_3CH_2O$), 61.8 (d, $^2J_{C,P} = 5.28$ Hz, $2CH_3CH_2O$), 111.0 (d, $^1J_{C,P} = 188.63$ Hz, *C*HP), 112.3, 115.3 (C_{ar}) 134.1 (*C*HCHP), 144.1 (C_{ar}), 150.9 (d, $^3J_{C,P} = 10.32$ Hz, *C*CHCHP) ppm. ^{31}P NMR (101 MHz, $CDCl_3$): $\delta = 16.22$. $C_{10}H_{15}O_4P$ (230.20): calcd. C 52.18, H 6.57; found C 52.20, H 6.50.

*Diethyl (1Z,3E)-(4-Phenyl-buta-1,3-dienyl)-phosphonate (***5g***) [31].* *Z*-**5g** was isolated by flash chromatography (ethyl acetate/toluene, 10:1) as a yellow oil. Yield: 41%. IR (film): $\nu = 2984$ (s), 1604 (s), 1584 (s), 1244 (s), 1028 (s), 784 (w) cm^{-1}. 1H NMR (250 MHz, $CDCl_3$): $\delta = 1.34$ (t, $^3J_{H,H} = 7.00$ Hz, 6H, $2CH_3CH_2O$), 4.11 (broad qt, $^3J_{H,H} = 7.16$ Hz, 4H, $2CH_3CH_2O$), 5.56 (dd, $^3J_{H,H} = 12.84$, $^2J_{H,P} = 16.83$ Hz, 1H, C*H*P), 6.75 (d, $^3J_{H,H} = 15.58$ Hz, 1H, C*H*Ph), 7.00 (dt, $^3J_{H,H} = 12.13$, $^3J_{H,P}$ 50.60 Hz, 1H, C*H*CHP), 7.28–7.52 (m, 5H, H_{ar}), 7.80 (bdd, $^3J_{H,H} = 15.57$, $^3J_{H,H} = 11.34$ Hz, C*H*CHPh) ppm. ^{13}C NMR (63 MHz, $CDCl_3$): $\delta = 16.2$ (d, $^3J_{C,P} = 6.4$ Hz, $2CH_3CH_2O$), 61.8 (d, $^2J_{C,P} = 5.4$ Hz, $2CH_3CH_2O$), 111.0 (d, $^1J_{C,P} = 195.0$ Hz, *C*HP), 112.0 (C_{ar}), 112.2 (C_{vin}), 113.8, 115.3 (C_{ar}), 134.1, 144.1 (C_{vin}), 151.0 (C_{ar}) ppm. ^{31}P NMR (101 MHz, $CDCl_3$): $\delta = 17.77$. $C_{14}H_{19}O_3P$ (266.27): calcd. C 63.15, H 7.19; found C 63.01, H 7.21.

REFERENCES

[1] (a) Erian, A. W.; Sherif, S. M. Tetrahedron 1999, 55, 7957–8024; (b) Gulea, M.; Masson, S. Top Curr Chem 2003, 229, 161–198.

[2] (a) Kashemirov, B. A.; Osipov, V. N.; Savenkov, N. F.; Chvertkin, B. Ya.; Khokhlov, P. S. Zh Obshch Khim 1992, 62, 1268–1271; (b) Firouzabadi, H.; Iranpoor, N.; Sobhani, S. Synthesis 2004, 290–294.

[3] Gulea, M.; Hammerschmidt, F.; Marchand, P.; Masson, S.; Pisljagic, V.; Wuggenig, F. Tetrahedron: Asymmetry 2003, 14, 1829–1836.

[4] (a) Hayashi, T. Bull Chem Soc Jpn 1972, 45, 1507–1515; (b) Hayashi, T.; Akano, M.; Yokono, T.; Uzawa, J.; Kambe, S.; Midorikawa, H. Bull Chem Soc Jpn 1972, 45, 578–584; (c) Kambe, S.; Hayashi, T.; Yasuda, H.; Midorikawa, H. Bull Chem Soc Jpn 1971, 44, 1357–1361.

[5] (a) Minami, T.; Motoyoshiya, J. Synthesis 1992, 333–349; (b) Minami, T.; Okauchi, T.; Kouno, R. Synthesis 2001, 349–357; (c) Mikołajczyk, M.; Balczewski, P.; Top Curr Chem 2003, 223, 161–214.

[6] (a) Kuono, R.; Okauchi, T.; Nakamura, M.; Ichikawa, J.; Minami, T. J Org Chem 1998, 63, 6239–6246; (b) Kuono, R.; Tsubota, T.; Okauchi, T;. Minami, T. J Org Chem 2000, 65, 4326–4332; (c) Al-Badri, H.; Collignon, N.; Maddaluno, J.; Masson, S. J Chem Soc Perkin Trans 1, 1999, 2255–2266. (d) Al-Badri, H.; Collignon, N.; Maddaluno, J.; Masson, S. Tetrahedron 2000, 56, 3909–3919.

[7] (a) Yokomatsu, T.; Yoshida, Y.; Suemune, K.; Yamagishi, T.; Shibuya, S. Tetrahedron: Asymmetry 1995, 6, 365–368; (b) Wiemer, D. F. Tetrahedron 1997, 53, 16609–16644; (c) Kim, D. Y.; Rhie, D. Y. Tetrahedron 1997, 53, 13603–13608; (d) Cravotto, G.; Giovenzana, G.B.; Pagliarin, R.; Palmisano, G.; Sisti, M. Tetrahedron: Asymmetry 1998, 9, 745–748; (e) Yokomatsu, T;. Yamagishi, T.; Suemune, K.; Yoshida, Y.; Shibuya, S. Tetrahedron 1998, 54, 767–780; (f) Thomas, A. A.; Sharpless, K. B. J Org Chem 1999, 64, 8379–8385; (g) Ojea, V.; Ruiz, M.; Shapiro, G.; Pombo–Viller, E. J Org Chem 2000, 65, 1984–1995; (h) Cristau, H-J.; Pirat, J-L;. Drag, M.; Kafarski, P. Tetrahedron Lett 2000, 41, 9781–9785; (i) Fazio, A.; Loreto, M. A.; Tardella, A. Tetrahedron Lett 2001, 42, 2185–2187; (j) Kobayashi, Y;. William, A. D.; Tokoro, Y. J Org Chem 2001, 66, 7903–7906; (k) Kobayashi, Y.; William, A. D.; Tokoro, Y. J Org Chem 2001, 66, 7903–7906; (l) Ruiz, M.; Fernández, M. C.; Díaz, A.; Quintela, J. M.; Ojea, V. J Org Chem 2003, 68, 7634–7645; (m) Qi, X.; Lee, S. H.; Kwon, J. Y.; Kim, Y.; Kim, S. J.; Lee, Y. S.; Yoon, J. J Org Chem 2003, 68, 9140–9143.

[8] For recent works, see: (a) Sakada, R.; Matsumoto, H.; Seto, K. Synthesis 1993, 705–713. (b) Kobayashi, Y.; William, A. D. Adv Synth Catal 2004, 346, 1749–1757; (c) Wang, C.; Pan, Y.; Yang, D. J Organomet Chem 2005, 690, 1705–1709; (d) Krawczyk, H.; Albrecht, Ł. Synthesis 2005, 2887–2896, and references cited therein.

[9] Davis, A. A.; Rosen, J. J.; Kiddle, J. Tetrahedron Lett 1998, 39, 6263–6266.

[10] (a) Hirao, T.; Masunaga, T.; Ohshiro, Y.; Agawa, T. Tetrahedron Lett 1980, 21, 3595–3598; (b) Hirao, T.; Masunaga, T.; Yamada, N.; Ohshiro, Y.; Agawa, T. Bull Chem Soc Jpn 1982, 55, 909–913.

[11] Ogawa, T.; Usuki, N.; Ono, N. J Chem Soc, Perkin Trans 1 1998, 2953–2958.
[12] (a) Cristau, H-J.; Mbianda, X. Y.; Beziat, Y.; Gasc, M. B. J Organomet Chem 1997, 529, 301–311; (b) Iorga, B.; Eymery, F.; Carmichael, D.; Savignac, P. Eur J Org Chem 2000, 3103–3115.
[13] (a) Glamkowski, E. J.; Gal, G.; Purick, R.; Davidson, A. J.; Sletzinger, M. J Org Chem 1970, 35, 3510–3512; (b) Brel, V. K.; Stang, P. J. Eur J Org Chem 2003, 224–229.
[14] (a) Quantar, A. A.; Srebnik, M. Org Lett 2001, 3, 1379–1381; (b) Quantar, A. A.; Srebnik, M. J Organomet Chem 2005, 690, 2504–2514.
[15] Chang, K.; Ku, B.; Oh, D. Y. Synth Commun 1989, 19, 1891–1896.
[16] Savignac, P.; Teulede, M-P.; Collignon, N. J Organomet Chem 1987, 323, 135–144.
[17] Kabalka, G. W.; Guchhait, S. K. Org Lett 2003, 3, 729–731.
[18] (a) Mimouni, N.; About-Jaudet, E.; Collignon, N. Synth Commun 1991, 21, 2341–2348; (b) Mimouni, N.; Al Badri, H.; About-Jaudet, E.; Collignon, N. Synth Commun 1995, 25, 1921–1932.
[19] Skowrońska, A.; Dybowski, P. Heteroatom Chem 1991, 2, 55–61.
[20] Boesen, T.; Madsen, C.; Henriksen, U.; Dahl, O. J Chem Soc, Perkin Trans 1 2000, 2015–2021.
[21] Guy, R. G.; Pearson, I. Bull Chem Soc Jpn 1976, 49, 2310–2314.
[22] (a) Quin, L. D.; Verkade, J. G. in Phosphorus-31 NMR Spectroscopy in Stereochemical Analysis; Verkade, J. G. Quin, L. D. (Eds); VCH: Deerfield Beach, FL 1987, p. 401; (b) Duncan, M.; Gallagher, M. J. Org Magn Reson 1981, 15, 37–42; (c) Benezra, C. Tetrahedron Lett 1969, 4471–4474; (d) Sainz-Díaz, C. I.; Gálvez-Ruano, E.; Hernández-Laguna, A.; Bellanato, J. J Org Chem 1995, 60, 74–83; (e) Macigiewicz, I.; Dybowski, P.; Skowrońska, A. Polish J Chem 1998, 72, 2389–2393.
[23] Maryanoff, B. C.; Reitz, A. B. Chem Rev 1989, 89, 863–927.
[24] Sander, M. Chem Rev 1966, 66, 297–339.
[25] (a) Neureiter, N. P.; Bordwell, F. G. J Am Chem Soc 1959, 81, 578–580; (b) Denney, D. B.; Boskin, M. J. J Am Chem Soc 1960, 82, 4736–4738.
[26] Dybowski, P.; Skowrońska, A. Synthesis 1997, 1134–1136.
[27] Meier, H. Houben-Weyl, 4th ed.; Klamann, D. (Ed.); Georg Thieme: Stuttgart, 1985; Vol.: E11/2, p. 1482.
[28] Inokawa, S.; Yamamoto, H. Phosphorus Sulfur 1983, 16, 79–81.
[29] Mikołajczyk, M.; Grzejszczak, S.; Midura, W.; Zatorski, A. Synthesis 1976, 396–398.
[30] Jin, Xu, X.; Huang, G.; Huang, Y. Synthesis 1983, 556–558.
[31] Xu, Y.; Flavin, M. T.; Xu, Z. J Org Chem 1996, 61, 7697–7701.