Tetrahedron 68 (2012) 9924–9929

Contents lists available at SciVerse ScienceDirect

Tetrahedron

journal homepage: www.elsevier.com/locate/tet

Phenyldioxaborolane promoted synthesis of bisphosphine compounds

Yin-Wei Sun [a], Peng-Long Zhu [a], Qin Xu [a,*], Min Shi [a,b,*,†]

[a] Key Laboratory for Advanced Materials and Institute of Fine Chemicals, School of Chemistry & Molecular Engineering, East China University of Science and Technology, 130 Mei-Long Road, Shanghai 200237, China
[b] State Key Laboratory of Organometallic Chemistry, Shanghai Institute of Organic Chemistry, Chinese Academy of Sciences, 354 Fenglin Road, Shanghai 200032, China

ARTICLE INFO

Article history:
Received 7 August 2012
Received in revised form 18 September 2012
Accepted 21 September 2012
Available online 26 September 2012

Keywords:
Phenyldioxaborolane
Arylboronic acids
Bisphosphine compounds
Phosphoryl group migration

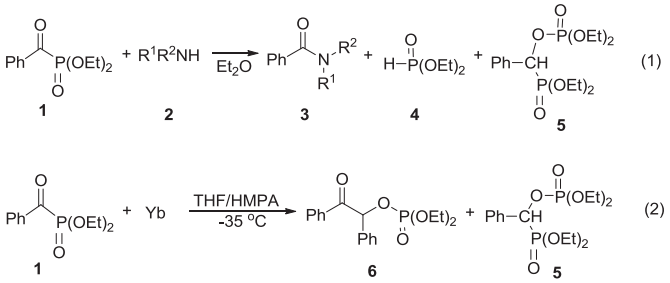
ABSTRACT

Bisphosphine compounds have a wide range of applications. In this paper, we reported that bisphosphine compounds could be prepared in moderate to good yields from dialkyl acylphosphonates under mild conditions in the presence of phenyldioxaborolane and potassium hydroxide via a C–P bond cleavage and a subsequent 1,2-migration of phosphoryl group.

1. Introduction

Organic compounds containing P–C and P–O bonds are not particularly frequent in nature, but, many of them have diverse biological activities and have been widely used in pharmacology.[1] Bisphosphines are important classes of organic compounds, for example, bisphosphonates have been used in the treatment of diseases of bone and calcium metabolism of which osteoporosis was the most common form.[2] More importantly, they can act as inhibitors of proteolytic enzymes, such as rennin,[3] as agents affecting the growth of plants,[4] or as haptens for the development of catalytic antibodies.[5] Besides their valuable applications, the use of them in the production of the dangerous compounds, such as sarin- and soman-type chemical warfare agents must be also noted.[6] Since the last 20 years, many synthetic methods have been developed for the synthesis of these target compounds in a one-pot manner.[2a,7] But these methods usually need harsh reaction conditions, such as at very high temperatures. The synthesis of these compounds under mild conditions is still highly desirable.

Early in 1980, Hata and co-workers have reported that the C–P bond of dialkyl acylphosphonates **1** can be cleaved by amines **2**, affording amides **3** and phosphates **4** in moderate yields (Scheme 1, Eq. 1).[8] In this process a small amount of α-(phosphoryloxy)benzylphosphonates **5** have been isolated. Late, Taniguchi's group found that ethyl benzoylphosphonate **1** can react with Yb metal in THF/hexamethylphosphoramide (HMPA) to produce a mixture of diethyl 1,2-diphenyl-2-oxoethyl phosphate **6** and diethyl l,l-(diethylphosphoryloxy)-l-phenylmethylphosphonate **5** in moderate yields at −35 °C (Scheme 1, Eq. 2).[9] However, these reactions are not very efficient, giving the corresponding diphosphine compounds only in moderate yields via a P–C(OH)–P to P–CH–O–P rearrangement.[10]



Scheme 1. Hata's and Taniguchi's previous work on the preparation of bisphosphines.

Based on these previous reports, we envisaged to use inexpensive reagents to synthesize bisphosphine compounds under mild conditions. Herein, we wish to report the C–P bond cleavage of dialkyl alkenylphosphonates or dialkyl arylallylphosphonates and the subsequent rearrangement in the presence of base and phenyldioxaborolane or phenyl boronic acid to give the corresponding bisphosphine compounds under mild conditions.

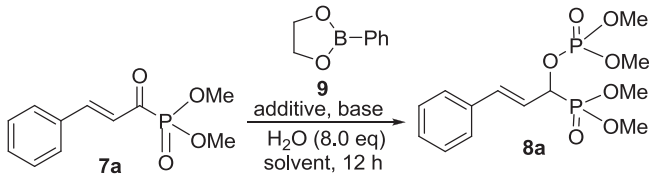
* Corresponding authors. E-mail address: mshi@mail.sioc.ac.cn (M. Shi).
† Fax: +86 21 64166128.

0040-4020/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.tet.2012.09.088

2. Results and discussion

We initially used (*E*)-dimethyl cinnamoylphosphonate **7a** as the substrate in the presence of a weak Lewis acid phenyldioxaborolane **9** and an inorganic base potassium hydroxide (KOH) to examine the reaction outcome and found that (*E*)-1-(dimethoxyphosphoryl)-3-phenylallyl dimethyl phosphate **8a** was formed (Table 1, entry 1). Next, we attempted to optimize the reaction conditions and the results are summarized in Table 1. The diphosphine compound **8a** could be afforded in 87% yield based on two molecules of compound **7a** to generate one product of **8a** in THF in the presence of 2.0 equiv of KOH and 2.0 equiv of **9** (Table 1, entry 4). Reducing the employed amount of KOH or **9** could significantly decrease the yield of **8a** (Table 1, entries 3–6) and the addition of electrophilic reagents, such as benzaldehyde and benzyl alcohol reduced the yield of **8a** (Table 1, entries 1 and 2). The use of strong Lewis acid $Yb(OTf)_3$ gave complex product mixtures (Table 1, entry 7). On the comparison of weak Lewis acids $Si(OEt)_4$, $Al(OH)_3$ or $B(OH)_3$ and $PhB(OH)_2$, the use of 2.0 equiv of boronic acid gave the better results (Table 1, entries 8–13). None of **8a** could be formed either in the absence of a Lewis acid or in the absence of a base (Table 1, entries 14 and 15). The examination of base revealed that KOH is the best one to give **8a** in higher yield (Table 1, entries 16–18). THF is the most suitable solvent for this transformation (Table 1, entries 19–22). We finally determined optimal conditions of the reaction is using 2.0 equiv of 2-phenyl-1,3,2-dioxaborolane **9** as an additive, 2.0 equiv of potassium hydroxide as a base, and carrying out the reaction in THF for 12 h.

Table 1
Optimization of the reaction conditions

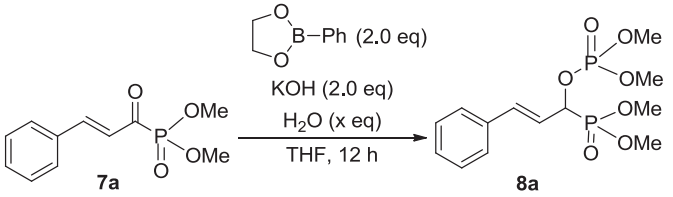


Entry[a]	Additive (equiv)	Base (equiv)	Solvent	Yield (%)[b]
1[c]	**9**[d] (2.0)	KOH (2.0)	THF	54
2[e]	**9** (0.1)	KOH (0.1)	THF	22
3	**9** (0.1)	KOH (0.1)	THF	45
4	**9** (2.0)	KOH (2.0)	THF	87
5	**9** (2.0)	KOH (0.2)	THF	84
6	**9** (0.2)	KOH (2.0)	THF	14
7	$Yb(OTf)_3$ (2.0)	KOH (2.0)	THF	Complex
8	$Si(OEt)_4$ (2.0)	KOH (2.0)	THF	67
9	$Al(OH)_3$ (2.0)	KOH (2.0)	THF	Complex
10	$B(OH)_3$(0.1)	KOH (0.1)	THF	59[f]
11	$B(OH)_3$ (0.5)	KOH (0.5)	THF	67
12[g]	$B(OH)_3$ (2.0)	KOH (2.0)	THF	84
13	$PhB(OH)_2$ (2.0)	KOH (2.0)	THF	86
14	None	KOH (2.0)	THF	Complex
15	**9** (2.0)	None	THF	N.R.
16	**9** (2.0)	K_2CO_3 (2.0)	THF	83
17	**9** (2.0)	Et_3N (2.0)	THF	62
18	**9** (2.0)	DIEA (2.0)	THF	64
19	**9** (2.0)	KOH (2.0)	DCM	72
20	**9** (2.0)	KOH (2.0)	Toluene	53
21	**9** (2.0)	KOH (2.0)	CH_3CN	77
22	**9** (2.0)	KOH (2.0)	Et_2O	52

[a] Reaction was carried out with 0.1 mmol **7a** in 1.0 mL solvent.
[b] Isolate yield based on two molecules of compound **7a** generating one product **8a**.
[c] 1.0 equiv of benzaldehyde was added.
[d] **9** was 2-phenyl-1,3,2-dioxaborolane.
[e] 1.0 equiv of benzyl alcohol was added.
[f] 91% cinnamic acid was observed.
[g] Reaction was carried out within 3 h.

We also found the water has great influence on the yield of **8a**. The influence of water content on the yield of **8a** in this reaction has been shown in Table 2. Adding 8.0 equiv (15 μL) of water in anhydrous THF produced **8a** in 87% yield (Table 2, entry 4). The addition of water >8.0 equiv (15 μL) or <8.0 equiv (15 μL) all decreased the yield of **8a** (Table 2, entries 1–3 and 5–11). When the water content increased to more than 22 equiv (40 μL), the influence of water content on the yield was not obvious (Table 2, entries 8–11).

Table 2
The influence of water on the yield of **8a**

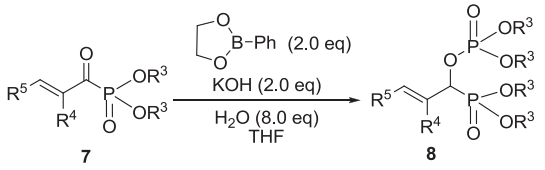


Entry[a]	H_2O (equiv)	Yield of **8a** (%)[b]
1	None	52
2	1.1	50[c]
3	5.6	64
4	8.0	87
5	11	80
6	14	77
7	22	61
8	33	62
9	44	62
10	56	60
11	111	60

[a] Reaction was carried out with 0.1 mmol **7a**, 2.0 equiv 2-phenyl-1,3,2-dioxaborolane and 2.0 equiv KOH in 1.0 mL THF.
[b] Isolate yield based on two molecules of compound **7a** generating one product **8a**.
[c] 61% 2-hydroxyethyl cinnamate **10** was observed (see Supplementary data).

Having identified the optimal conditions, we next examined the substrate generality in the reaction. We found that increasing the steric bulkiness of ester moiety of phosphate group on the substrate decreased the yield of **8** (Table 3, entries 1–3). The

Table 3
Synthesis of bisphosphine compounds **8** with dialkyl acylphosphonates **7** and phenyldioxaborolane

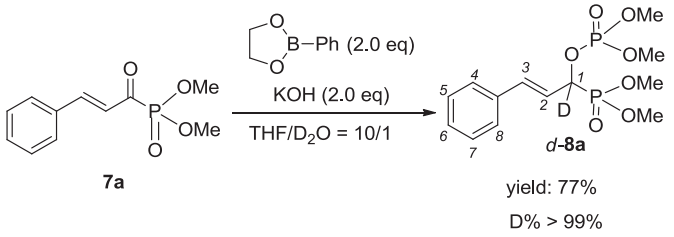


Entry[a]	No.	R^3	R^4	R^5	Yield (%)[b]
					8
1	**7a**	Me	H	C_6H_5	**8a**, 87
2	**7b**	Et	H	C_6H_5	**8b**, 58
3	**7c**	^{i}Pr	H	C_6H_5	**8c**, 47
4	**7d**	Me	Me	C_6H_5	**8d**, 84
5	**7e**	Me	H	*o*-BrC_6H_4	**8e**, 77
6	**7f**	Me	H	*p*-ClC_6H_4	**8f**, 85
7	**7g**	Me	H	*p*-MeC_6H_4	**8g**, 75
8	**7h**	Me	H	*m*-MeC_6H_4	**8h**, 56
9	**7i**	Me	H	*o*-F, *p*-BrC_6H_3	**8i**, 51
10	**7j**	Me	H	*p*-$NO_2C_6H_4$	Complex
11	**7k**	Me	H	*o*-MeO, *p*-BrC_6H_3	**8k**, 83
12	**7l**	Me	H	*m*-$MeOC_6H_4$	**8l**, 73
13	**7m**	Me	H	*p*-$MeOC_6H_4$	Complex
14	**7n**	Me	H	CO	Complex
15	**7o**	Me	H	Me	**8o**, 71

[a] Reaction was carried out with 0.1 mmol **7** in 1.0 mL solvent.
[b] Isolate yield based on two molecules of compound **7** generating one product **8**.

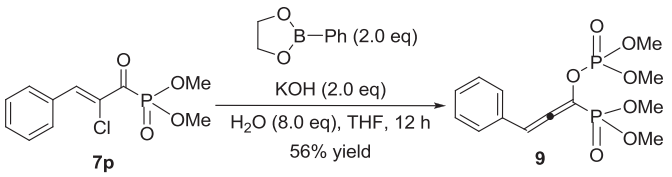
electronic property of aromatic R^5 group also has significant impact on the yield of **8**. When aromatic R^5 group has a strongly electron-withdrawing group (such as NO_2) or a strongly electron-donating group (such as MeO) at the *para*-position or R^5 group is a hetero aromatic group, none of the desired product could be obtained (Table 3, entries 10, 13, and 14). In other cases, the reactions proceeded smoothly to give the desired products in moderate to good yields (Table 3, entries 4–9 and 11–12). The use of substrate **7o**, in which R^5 is a methyl group, afforded the corresponding diphosphine compound **8o** in 71% yield (Table 3, entry 15).

To clarify the reaction mechanism, a deuterium labeling experiment has been carried out using D_2O instead of H_2O, we found that the corresponding *d*-**8a** was formed in 77% yield with 99% D content at the C1 position (Scheme 2). Based on the deuterium labeling experiment and Fitch's previous work,[10a] a plausible reaction mechanism is proposed in Scheme 3 although it has not been unequivocally established. Initially, the in situ generated OH^- acts as a nucleophilic trigger to cleave the C–P bond of **7** to give an anionic intermediate **I** and compound **II**. Compound **II** has been identified by spectroscopic data (see Supplementary data along with the formation of 2-hydroxyethyl cinnamate if using phenyldioxaborolane as a weak Lewis acid). Intermediate **I** attacks another molecule of dimethyl acryloylphosphonate **7** to give the corresponding intermediate **III**, which subsequently undergoes 1,2-migration of phosphoryl group to produce bisphosphine compound **8**. In this process, weak Lewis acid phenyldioxaborolane can stabilize the in situ generated anionic intermediate **I** through the coordination with the boron atom, which may play an important in this transformation.



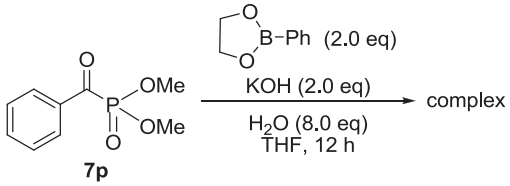
Scheme 2. Experiment of using D_2O as an additive.

Furthermore, we found that treatment of substrate **7p** under the standard conditions gave allenic compound **9** in 56% yield (Scheme 4).



Scheme 4. Synthesis of 1-(dimethoxyphosphoryl)-3-phenylpropa-1,2-dienyl dimethyl phosphate.

For the substrates of simple acylphosphonates, none of the desired products could be obtained under the optimal conditions and the reaction gave complex product mixtures (Scheme 5).



Scheme 5. Simple acylphosphonate **7p** as the substrate in this reaction.

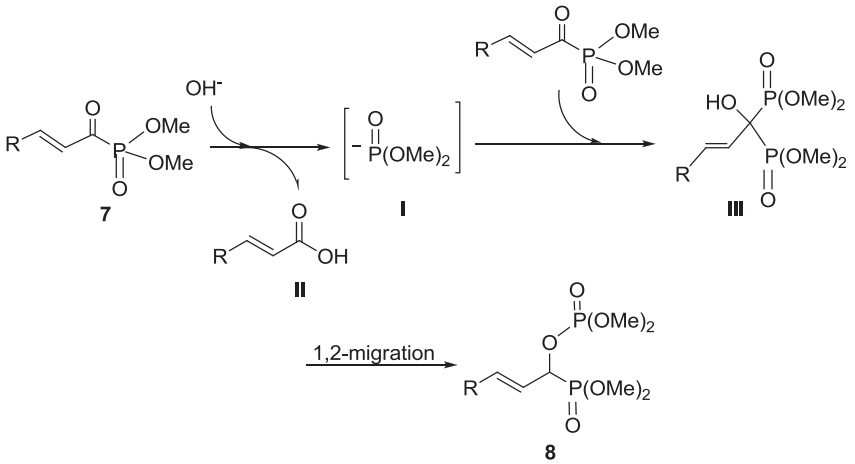
3. Conclusion

In summary, we have reported a novel method to synthesize bisphosphoryl group containing compounds from dialkyl alkenylphosphonates or dialkyl arylallylphosphonates in the presence of phenyldioxaborolane and potassium hydroxide via a C–P bond cleavage and a subsequent 1,2-migration of phosphoryl group. In this reaction, we used phenyldioxaborolane as a weak Lewis acid as a promoting agent to give the products in moderate to good yields under mild conditions.

4. Experimental section

4.1. General remarks

All reactions and manipulations were performed using standard Schlenk techniques. NMR spectra were recorded with a Varian Mercury *vx* or Bruker spectrometer at 400 MHz (^{1}H NMR), 100 MHz (^{13}C NMR), 162 MHz (^{31}P NMR), 376 MHz (^{19}F NMR) in $CDCl_3$, respectively. Internal TMS (δ=0.0 ppm) was used as the reference for ^{1}H NMR. ^{31}P NMR spectra were referenced to external 85% H_3PO_4. ^{19}F NMR spectra were referenced to external CF_3CCl_3. Mass spectra



Scheme 3. A plausible mechanism for the formation of bisphosphine compound **8**.

were recorded on the HP-5989 instrument by EI/ESI methods. Infrared spectra were recorded on a Perkin–Elmer PE-983 spectrometer with absorption in cm^{-1}. Organic solvents used were dried by standard methods when necessary. Commercially obtained reagents were used without further purification. All reactions were monitored by TLC with Huanghai GF_{254} silica gel coated plates. Flash column chromatography was carried out using by using 300–400 mesh silica gel at increased pressure.

4.2. The typical reaction procedure and the spectroscopic data of the product (*E*)-1-(dimethoxyphosphoryl)-3-phenylallyl dimethyl phosphate (Table 3, entry 1, 8a)

Into an oven-dried reaction flask under Ar gas protection were added phosphate **7a** (0.3 mmol), phenyl borate esters (0.6 mmol), potassium hydroxide (0.6 mmol), THF (3.0 mL), and H_2O (0.045 mL, 8.0 equiv). The reaction mixture was stirred at room temperature for 12 h, then the solvent was removed under reduced pressure and the residue was purified by a flash column chromatography. This is a new compound, a colorless liquid (301 mg, 87% yield). ^1H NMR ($CDCl_3$, 400 MHz, TMS) δ 3.68 (d, 3H, J=11.6 Hz, CH_3), 3.74–3.80 (m, 9H, CH_3), 5.18–5.26 (m, 1H, CH), 6.21–6.28 (m, 1H, =CH), 6.78 (dd, 1H, J_1=7.6 Hz, J_2=15.6 Hz, =CH), 7.21–7.29 (m, 3H, Ar), 7.36 (d, 2H, J=7.2 Hz, Ar); ^{31}P NMR ($CDCl_3$, 162 MHz, 85% H_3PO_4) δ 1.31 (d, J=29.0 Hz), 18.99 (d, J=31.4 Hz); ^{13}C NMR ($CDCl_3$, 100 MHz, TMS) δ 53.85, 53.92, 53.96, 54.03, 54.44, 54.51, 54.52, 54.58, 73.8 (dd, J_1=6.7 Hz, J_2=173.9 Hz), 120.1 (dd, J_1=2.3 Hz, J_2=4.3 Hz), 126.9 (d, J=1.6 Hz), 128.7, 135.4 (d, J=2.1 Hz), 136.0, 136.1; IR (CH_2Cl_2): ν 2958, 2856, 1648, 1496, 1374, 1261, 1184, 1025, 850, 829, 753, 694 cm^{-1}; MS (EI) m/z (%): 350 [M^+] (12.0), 224 (10.3), 115 (100), 97 (7.5), 85 (7.3), 83 (6.4), 71 (10.0), 57 (11.7), 55 (6.7); HRMS (EI) calcd for $C_{13}H_{20}O_7P_2$ [$M]^+$ requires: 350.0684, found: 350.0685.

Compounds **8b**–**8o** were synthesized by adopting the same procedure described for **8a**, using 0.1 mmol of dialkyl acylphosphonates.

4.3. (*E*)-1-(Diethoxyphosphoryl)-3-phenylallyl diethyl phosphate (Table 3, entry 2, 8b)

A known compound,[11] a colorless liquid (35.4 mg, 58% yield). ^1H NMR ($CDCl_3$, 400 MHz, TMS) δ 1.26–1.36 (m, 12H, CH_3), 4.05–4.29 (m, 8H, CH), 5.22–5.30 (m, 1H, CH), 6.27–6.35 (m, 1H, =CH), 6.84 (dd, 1H, J_1=3.6 Hz, J_2=15.6 Hz, =CH), 7.23–7.38 (m, 3H, Ar), 7.42 (d, 2H, J=7.2 Hz, Ar); ^{31}P NMR ($CDCl_3$, 162 MHz, 85% H_3PO_4) δ −1.13 (d, J=33.2 Hz), 16.76 (d, J=30.6 Hz); ^{13}C NMR ($CDCl_3$, 100 MHz, TMS) δ 15.68, 15.75, 16.09, 16.14, 16.15, 16.19, 63.14, 63.20, 63.22, 63.30, 63.79, 63.85, 63.89, 63.94, 73.7 (dd, J_1=7.3 Hz, J_2=172.6 Hz), 120.4 (d, J=2.6 Hz), 126.55, 126.57, 128.3, 128.4, 135.3 (dd, J_1=12.1 Hz, J_2=15.7 Hz); IR (CH_2Cl_2): ν 2984, 2911, 1448, 1393, 1258, 1164, 1099, 1016, 966, 885, 825, 750 cm^{-1}; MS (EI) m/z (%): 406 [M^+] (13.2), 254 (5.2), 197 (6.0), 196 (6.2), 127 (4.6), 117 (5.4), 116 (8.7), 115 (100), 99 (6.9), 81 (4.5); HRMS (EI) calcd for $C_{17}H_{28}O_7P_2$ [$M]^+$ requires: 406.1310, found: 406.1312.

4.4. (*E*)-1-(Diisopropoxyphosphoryl)-3-phenylallyl diisopropyl phosphate (Table 3, entry 3, 8c)

A new compound, a colorless liquid (32.3 mg, 47% yield). ^1H NMR ($CDCl_3$, 400 MHz, TMS) δ 1.15–1.29 (m, 24H, CH_3), 4.50–4.57 (m, 1H, CH), 4.63–4.75 (m, 3H, CH), 5.07–5.15 (m, 1H, CH), 6.16–6.24 (m, 1H, =CH), 6.73 (dd, 1H, J_1=4.0 Hz, J_2=15.6 Hz, =CH), 7.19–7.33 (m, 5H, Ar); ^{31}P NMR ($CDCl_3$, 162 MHz, 85% H_3PO_4) δ −2.71 (d, J=36.9 Hz), 15.14 (d, J=37.4 Hz); ^{13}C NMR ($CDCl_3$, 100 MHz, TMS) δ 23.47, 23.52, 23.55, 23.61, 23.70, 23.75, 23.83, 23.88, 23.99, 24.02, 24.11, 24.14, 71.95, 72.02, 72.06, 72.14, 72.76, 72.82, 72.83, 72.9, 74.4 (dd, J_1=7.4 Hz, J_2=175.3 Hz), 121.2 (d, J=4.4 Hz), 126.7 (d, J=2.8 Hz), 127.4, 128.2, 128.5, 134.2, 135.3 (d, J=13.3 Hz), 135.7 (d, J=50.9 Hz); IR (CH_2Cl_2): ν 2980, 1715, 1496, 1467, 1385, 1257, 1178, 1142, 976, 898, 746, 665 cm^{-1}; MS (EI) m/z (%): 462 [M^+] (6.5), 378 (9.6), 336 (14.7), 294 (38.0), 197 (22.4), 196 (18.1), 125 (15.9), 116 (12.6), 115 (100), 99 (16.8); HRMS (EI) calcd for $C_{21}H_{36}O_7P_2$ [$M]^+$ requires: 462.1936, found: 462.1941.

4.5. (*E*)-1-(Dimethoxyphosphoryl)-2-methyl-3-phenylallyl dimethyl phosphate (Table 3, entry 4, 8d)

A new compound, a colorless liquid (45.7 mg, 84% yield). ^1H NMR ($CDCl_3$, 400 MHz, TMS) δ 2.01 (dd, 3H, J_1=0.8 Hz, J_2=1.6 Hz, CH_3), 3.68 (dd, 3H, J_1=0.8 Hz, J_2=11.6 Hz, CH_3), 3.74–3.81 (m, 9H, CH_3), 5.10 (dd, 1H, J_1=10.4 Hz, J_2=14.0 Hz, CH), 6.65 (d, 1H, J=3.2 Hz, =CH), 7.17–7.30 (m, 5H, Ar); ^{31}P NMR ($CDCl_3$, 162 MHz, 85% H_3PO_4) δ 1.34 (d, J=34.3 Hz), 19.05 (d, J=34.5 Hz); ^{13}C NMR ($CDCl_3$, 100 MHz, TMS) δ 14.71, 14.72, 53.79, 53.86, 53.88, 53.95, 54.40, 54.46, 54.51, 54.57, 78.0 (dd, J_1=6.8 Hz, J_2=171 Hz), 127.3, 128.2, 129.0 (d, J=1.6 Hz), 130.3 (d, J=2.9 Hz), 131.5 (d, J=12.5 Hz), 136.0 (d, J=1.6 Hz); IR (CH_2Cl_2): ν 2980, 1467, 1451, 1385, 1257, 1179, 1106, 976, 899, 820, 746, 694 cm^{-1}; MS (EI) m/z (%): 364 [M^+] (2.7), 239 (9.4), 238 (73.4), 223 (15.6), 206 (8.4), 130 (8.4), 129 (100), 128 (56.6), 127 (10.0), 109 (8.9); HRMS (EI) calcd for $C_{14}H_{22}O_7P_2$ [$M]^+$ requires: 364.0841, found: 364.0843.

4.6. (*E*)-3-(2-Bromophenyl)-1-(dimethoxyphosphoryl)allyl dimethyl phosphate (Table 3, entry 5, 8e)

A new compound, a colorless liquid (49.4 mg, 77% yield). ^1H NMR ($CDCl_3$, 400 MHz, TMS) δ 3.80–3.89 (m, 12H, CH_3), 5.32–5.40 (m, 1H, CH), 6.25–6.33 (m, 1H, =CH), 7.14–7.18 (m, 1H, Ar), 7.20 (dd, 1H, J_1=4.4 Hz, J_2=16.0 Hz, =CH), 7.28–7.32 (m, 1H, Ar), 7.54–7.60 (m, 2H, Ar); ^{31}P NMR ($CDCl_3$, 162 MHz, 85% H_3PO_4) δ 1.22 (d, J=29.6 Hz), 18.39 (d, J=27.7 Hz); ^{13}C NMR ($CDCl_3$, 100 MHz, TMS) δ 53.86, 53.93, 54.10, 54.17, 54.57, 54.58, 54.63, 54.64, 73.2 (dd, J_1=6.6 Hz, J_2=171 Hz), 123.3 (dd, J_1=2.1 Hz, J_2=4.3 Hz), 123.8 (d, J=2.1 Hz), 127.3 (d, J=2.5 Hz), 127.6, 129.7, 132.9, 133.7 (d, J=12.0 Hz), 135.4 (d, J=2.6 Hz); IR (CH_2Cl_2): ν 2957, 2855, 1465, 1263, 1185, 1021, 897, 850, 828, 753 cm^{-1}; MS (EI) m/z (%): 428 [M^+] (16.8), 430 (17.8), 304 (11.0), 302 (11.8), 196 (6.3), 195 (93.2), 194 (6.9), 193 (100), 187 (6.5), 109 (13.7); HRMS (EI) calcd for $C_{13}H_{19}O_7P_2Br$ [$M]^+$ requires: 427.9789, found: 427.9793.

4.7. (*E*)-3-(4-Chlorophenyl)-1-(dimethoxyphosphoryl)allyl dimethyl phosphate (Table 3, entry 6, 8f)

A new compound, a colorless liquid (48.9 mg, 85% yield). ^1H NMR ($CDCl_3$, 400 MHz, TMS) δ 3.76 (d, 3H, J=11.2 Hz, CH_3), 3.82–3.88 (m, 9H, CH_3), 5.28 (ddd, 1H, J_1=8.4 Hz, J_2=13.6 Hz, J_3=21.6 Hz, CH), 6.26–6.33 (m, 1H, =CH), 6.81 (dd, 1H, J_1=3.6 Hz, J_2=16.0 Hz, =CH), 7.31 (d, 2H, J=8.4 Hz), 7.37 (d, 2H, J=8.0 Hz); ^{31}P NMR ($CDCl_3$, 162 MHz, 85% H_3PO_4) δ 1.24 (d, J=31.8 Hz), 18.74 (d, J=30.9 Hz); ^{13}C NMR ($CDCl_3$, 100 MHz, TMS) δ 53.71, 53.78, 53.86, 53.93, 54.34, 54.40, 54.42, 54.48, 73.4 (dd, J_1=6.5 Hz, J_2=173 Hz), 120.6 (dd, J_1=1.6 Hz, J_2=4.4 Hz), 128.0 (d, J=1.3 Hz), 128.7, 133.7 (d, J=2.4 Hz), 134.2, 134.4 (d, J=13.1 Hz); IR (CH_2Cl_2): ν 2957, 2855, 1492, 1459, 1261, 1185, 1025, 894, 848, 832, 796 cm^{-1}; MS (EI) m/z (%): 384 [M^+] (19.6), 260 (7.8), 259 (6.2), 258 (18.9), 243 (7.0), 151 (29.6), 150 (9.3), 149 (100), 109 (10.5); HRMS (EI) calcd for $C_{13}H_{19}O_7P_2Cl$ [$M]^+$ requires: 384.0295, found: 384.0297.

4.8. (*E*)-1-(Dimethoxyphosphoryl)-3-*p*-tolylallyl dimethyl phosphate (Table 3, entry 7, 8g)

A new compound, a colorless liquid (40.8 mg, 75% yield). ^1H NMR ($CDCl_3$, 400 MHz, TMS) δ 2.35 (s, 3H, CH_3), 3.74 (d, J=11.6 Hz,

CH_3), 3.81–3.87 (m, 9H, CH_3), 5.23–5.31 (m, 1H, CH), 6.23–6.30 (m, 1H, =CH), 6.82 (dd, 1H, J_1=3.6 Hz, J_2=15.6 Hz, =CH), 7.15 (d, 2H, J=8.0 Hz, Ar), 7.33 (d, 2H, J=8.0 Hz, Ar); ^{31}P NMR ($CDCl_3$, 162 MHz, 85% H_3PO_4) δ 1.32 (d, J=30.8 Hz), 19.15 (d, J=31.3 Hz); ^{13}C NMR ($CDCl_3$, 100 MHz, TMS) δ 21.1, 53.78, 53.85, 53.88, 53.95, 54.35, 54.41, 54.42, 54.49, 73.9 (dd, J_1=6.7 Hz, J_2=173 Hz), 118.8 (dd, J_1=2.0 Hz, J_2=4.2 Hz), 126.8 (d, J=1.7 Hz), 129.3, 132.5 (d, J=1.7 Hz), 136.2 (d, J=13.1 Hz), 138.7; IR (CH_2Cl_2): ν 2957, 2855, 1454, 1262, 1185, 1031, 895, 849, 770 cm^{-1}; MS (EI) m/z (%): 364 [M$^+$] (20.5), 239 (10.6), 238 (22.0), 223 (16.6), 130 (9.5), 129 (100), 128 (14.2), 127 (6.0), 109 (6.7); HRMS (EI) calcd for $C_{14}H_{22}O_7P_2$ [M]$^+$ requires: 364.0841, found: 364.0844.

4.9. (*E*)-1-(Dimethoxyphosphoryl)-3-*m*-tolylallyl dimethyl phosphate (Table 3, entry 8, 8h)

A new compound, a colorless liquid (30.6 mg, 56% yield). ^{1}H NMR ($CDCl_3$, 400 MHz, TMS) δ 2.35 (s, 3H, CH_3), 3.73–3.87 (m, 12H, CH_3), 5.24–5.32 (m, 1H, CH), 6.30 (ddd, 1H, J_1=5.6 Hz, J_2=7.6 Hz, J_3=15.6 Hz, =CH), 6.82 (dd, 1H, J_1=3.6 Hz, J_2=15.6 Hz, =CH), 7.12–7.13 (m, 1H, Ar), 7.23–7.30 (m, 3H, Ar); ^{31}P NMR ($CDCl_3$, 162 MHz, 85% H_3PO_4) δ 1.28 (d, J=31.1 Hz), 19.05 (d, J=31.3 Hz); ^{13}C NMR ($CDCl_3$, 100 MHz, TMS) δ 21.2, 53.77, 53.84, 53.88, 53.94, 54.35, 54.42, 54.48, 73.7 (dd, J_1=6.7 Hz, J_2=172.8 Hz), 119.6 (dd, J_1=1.6 Hz, J_2=3.2 Hz), 124.0 (d, J=1.5 Hz), 127.4 (d, J=1.4 Hz), 128.5, 129.4, 135.1 (d, J=1.8 Hz), 136.2 (d, J=13.4 Hz), 138.2; IR (CH_2Cl_2): ν 2958, 2855, 1603, 1455, 1261, 1185, 1025, 882, 847, 776, 746 cm^{-1}; MS (EI) m/z (%): 364 [M$^+$] (20.6), 239 (8.4), 238 (18.5), 223 (8.1), 206 (5.4), 130 (10.2), 129 (100), 128 (13.7), 127 (6.2); HRMS (EI) calcd for $C_{14}H_{22}O_7P_2$ [M]$^+$ requires: 364.0841, found: 364.0843.

4.10. (*E*)-3-(4-Bromo-2-fluorophenyl)-1-(dimethoxyphosphoryl)allyl dimethyl phosphate (Table 3, entry 9, 8i)

A new compound, a colorless liquid (34.0 mg, 51% yield). ^{1}H NMR ($CDCl_3$, 400 MHz, TMS) δ 3.77–3.88 (m, 12H, CH_3), 5.26–5.35 (m, 1H, CH), 6.38–6.45 (m, 1H, =CH), 6.88–6.93 (m, 1H, =CH), 7.24–7.31 (m, 2H, Ar), 7.33–7.37 (m, 1H, Ar); ^{31}P NMR ($CDCl_3$, 162 MHz, 85% H_3PO_4) δ 1.17 (d, J=29.6 Hz), 18.35 (d, J=29.5 Hz); ^{19}F NMR ($CDCl_3$, 376 MHz, CF_3CCl_3) δ −116.4; ^{13}C NMR ($CDCl_3$, 100 MHz, TMS) δ 53.9, 54.0, 54.1, 54.2, 54.59, 54.64, 54.65, 54.72, 73.6 (dd, J_1=6.5 Hz, J_2=171.8 Hz), 119.4, 119.7, 122.3 (d, J=1.4 Hz), 122.4 (d, J=3.1 Hz), 122.6 (d, J=2.5 Hz), 123.66, 123.70, 123.74, 123.76, 126.8 (dd, J_1=2.8 Hz, J_2=11.8 Hz), 127.7 (d, J=3.9 Hz), 128.9 (dd, J_1=1.9 Hz, J_2=3.6 Hz); IR (CH_2Cl_2): ν 2958, 2855, 1600, 1484, 1265, 1186, 1027, 850, 802, 731 cm^{-1}; MS (EI) m/z (%): 446 [M$^+$] (23.1), 448 (23.0), 322 (11.5), 320 (10.1), 213 (93.9), 211 (100), 187 (9.48), 132 (7.20), 109 (21.5); HRMS (EI) calcd for $C_{13}H_{18}O_7FP_2Br$ [M]$^+$ requires: 445.9695, found: 445.9697.

4.11. (*E*)-3-(4-Bromo-2-methoxyphenyl)-1-(dimethoxyphosphoryl)allyl dimethyl phosphate (Table 3, entry 11, 8k)

A new compound, a colorless liquid (57.2 mg, 83% yield). ^{1}H NMR ($CDCl_3$, 400 MHz, TMS) δ 3.76 (d, 3H, J=11.2 Hz, CH_3), 3.81–3.87 (m, 12H, CH_3), 5.23–5.31 (m, 1H, CH), 6.31–6.39 (m, 1H, =CH), 7.01–7.08 (m, 3H, =CH and Ar), 7.31 (d, 1H, J=8.0 Hz, Ar); ^{31}P NMR ($CDCl_3$, 162 MHz, 85% H_3PO_4) δ 1.26 (d, J=30.7 Hz), 18.97 (d, J=28.8 Hz); ^{13}C NMR ($CDCl_3$, 100 MHz, TMS) δ 53.89, 53.96, 54.03, 54.10, 54.47, 54.52, 54.60, 55.7, 74.1 (dd, J_1=7.3 Hz, J_2=173.2 Hz), 114.5, 121.1 (d, J=3.0 Hz), 123.1, 123.4 (d, J=1.4 Hz), 123.7, 128.5, 130.2 (d, J=13.2 Hz), 157.6; IR (CH_2Cl_2): ν 2956, 2854, 1588, 1487, 1461, 1400, 1247, 1184, 1025, 849, 802 cm^{-1}; MS (EI) m/z (%): 458 [M$^+$] (20.8), 460 (21.1), 334 (22.8), 332 (21.4), 319 (20.1), 225 (92.0), 224 (24.5), 223 (100), 109 (23.6); HRMS (EI) calcd for $C_{14}H_{21}O_8P_2Br$ [M]$^+$ requires: 457.9895, found: 457.9900.

4.12. (*E*)-1-(Dimethoxyphosphoryl)-3-(3-methoxyphenyl)allyl dimethyl phosphate (Table 3, entry 12, 8l)

A new compound, a colorless liquid (41.6 mg, 73% yield). ^{1}H NMR ($CDCl_3$, 400 MHz, TMS) δ 3.75 (d, 3H, J=11.6 Hz, CH_3), 3.82–3.88 (m, 12H, CH_3), 5.25–5.32 (m, 1H, CH), 6.28–6.35 (m, 1H, =CH), 6.80–6.87 (m, 2H, =CH, Ar), 6.96 (s, 1H, Ar), 7.03 (d, 1H, J=7.6 Hz, Ar), 7.24–7.30 (m, 1H, Ar); ^{31}P NMR ($CDCl_3$, 162 MHz, 85% H_3PO_4) δ 1.30 (d, J=31.3 Hz), 18.92 (d, J=30.6 Hz); ^{13}C NMR ($CDCl_3$, 100 MHz, TMS) δ 53.84, 53.90, 53.96, 54.03, 54.43, 54.49, 54.56, 55.2, 73.7 (dd, J_1=6.7 Hz, J_2=173.1 Hz), 112.0, 114.4, 119.5 (d, J=1.3 Hz), 120.3 (dd, J_1=2.6 Hz, J_2=4.6 Hz), 129.6, 135.9 (d, J=13.6 Hz), 136.7 (d, J=2.4 Hz), 159.7; IR (CH_2Cl_2): ν 2957, 2854, 1599, 1581, 1457, 1263, 1030, 848, 778, 748 cm^{-1}; MS (EI) m/z (%): 380 [M$^+$] (16.6), 255 (4.7), 254 (17.3), 239 (11.5), 222 (3.9), 146 (8.4), 145 (100), 115 (8.2), 109 (4.6); HRMS (EI) calcd for $C_{14}H_{22}O_8P_2$ [M]$^+$ requires: 380.0790, found: 380.0794.

4.13. (*E*)-1-(Dimethoxyphosphoryl)but-2-enyl dimethyl phosphate (Table 3, entry 15, 8o)

A new compound, a colorless liquid (30.7 mg, 71% yield). ^{1}H NMR ($CDCl_3$, 400 MHz, TMS) δ 1.73 (t, 3H, J=4.8 Hz, CH_3), 3.67–3.79 (m, 12H, CH_3), 4.95–5.02 (m, 1H, CH), 5.53–5.61 (m, 1H, =CH), 5.92–6.01 (m, 1H, =CH); ^{31}P NMR ($CDCl_3$, 162 MHz, 85% H_3PO_4) δ 1.06 (d, J=32.7 Hz), 19.69 (d, J=33.0 Hz); ^{13}C NMR ($CDCl_3$, 100 MHz, TMS) δ 17.9, 53.55, 53.62, 53.66, 53.73, 54.21, 54.28, 54.34, 73.5 (dd, J_1=6.7 Hz, J_2=174 Hz), 122.4 (dd, J_1=1.2 Hz, J_2=3.6 Hz), 134.2 (d, J=13.1 Hz); IR (CH_2Cl_2): ν 2959, 2856, 1450, 1257, 1185, 1025, 999, 881, 848, 782 cm^{-1}; MS (EI) m/z (%): 288 [M$^+$] (5.2), 180 (6.3), 179 (100), 163 (6.4), 162 (11.7), 127 (55.1), 109 (15.3), 93 (6.0), 79 (5.5); HRMS (EI) calcd for $C_8H_{18}O_7P_2$ [M]$^+$ requires: 288.0528, found: 288.0531.

4.14. 1-(Dimethoxyphosphoryl)-3-phenylpropa-1,2-dienyl dimethyl phosphate (Scheme 4, compound 9)

A new compound, a colorless liquid (31.1 mg, 56% yield). ^{1}H NMR ($CDCl_3$, 400 MHz, TMS) δ 3.71–3.80 (m, 12H, CH_3), 6.99 (dd, 1H, J_1=3.6 Hz, J_2=10.0 Hz, =CH), 7.23–7.32 (m, 3H, Ar), 7.40 (d, 2H, J=7.2 Hz, Ar); ^{31}P NMR ($CDCl_3$, 162 MHz, 85% H_3PO_4) δ −2.17 (d, J=25.4 Hz), 9.88 (d, J=26.7 Hz); ^{13}C NMR ($CDCl_3$, 100 MHz, TMS) δ 53.57, 53.63, 53.67, 53.73, 54.69, 54.75, 54.77, 109.3, 109.4 (d, J=1.5 Hz), 115.1 (dd, J_1=11.1 Hz, J_2=253 Hz), 128.3 (d, J=1.1 Hz), 128.9, 129.4, 130.9 (dd, J_1=1.2 Hz, J_2=6.3 Hz), 201.1 (dd, J_1=4.5 Hz, J_2=25.2 Hz); IR (CH_2Cl_2): ν 3056, 2958, 2856, 1453, 1266, 1185, 1032, 878, 853, 731, 700 cm^{-1}; MS (EI) m/z (%): 348 [M$^+$] (100), 333 (49.6), 239 (23.4), 207 (24.7), 192 (55.0), 129 (42.1), 115 (34.5), 114 (31.7), 109 (48.1), 93 (31.9); HRMS (ESI) calcd for $C_{13}H_{18}O_7P_2Na$ [M+Na]$^+$ requires: 371.0425, found: 371.0439.

Acknowledgements

We thank the Shanghai Municipal Committee of Science and Technology (11JC1402600), National Basic Research Program of China (973)-2009CB825300, the Fundamental Research Funds for the Central Universities and the National Natural Science Foundation of China for financial support (21072206, 20472096, 20872162, 20672127, 21121062 and 20732008).

Supplementary data

The NMR spectroscopic data and charts of the compounds are included in the Supplementary data. Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.tet.2012.09.088.

References and notes

1. (a) Amann, F.; Schaub, C.; Müller, B.; Schmidt, R. R. *Chem.—Eur. J.* **1998**, *4*, 1106–1115; (b) Schaub, C.; Müller, B.; Schmidt, R. R. *Eur. J. Org. Chem.* **2000**, 1745–1758; (c) Schwörer, R.; Schmidt, R. R. *J. Am. Chem. Soc.* **2002**, *124*, 1632–1637; (d) Szymczak, M.; Szymańska, A.; Stawiński, J.; Boryski, J.; Kraszewski, A. *Org. Lett.* **2003**, *5*, 3571–3573.
2. (a) Ruel, R.; Bouvier, J.-P.; Young, R. N. *J. Org. Chem.* **1995**, *60*, 5209–5213; (b) Ding, Y.-X.; Huang, X. *Heteroat. Chem.* **2003**, *14*, 304–308.
3. (a) Dellaria, J. F., Jr.; Maki, R. G.; Stein, H. H.; Cohen, J.; Whittern, D.; Marsh, K.; Hoffman, D. J.; Plattner, J. J.; Perun, T. J. *J. Med. Chem.* **1990**, *33*, 534–542; (b) Kafarski, P.; Lejczak, B. *Phosphorus, Sulfur Silicon Relat. Elem.* **1991**, *63*, 193–215.
4. Zygmunt, J.; Gancarz, R.; Lejeczak, B.; Wieczorek, P.; Kafarski, P. *Bioorg. Med. Chem. Lett.* **1996**, *6*, 2989–2992.
5. Smith, B. A.; Carol, M.; Taylor, S. J.; Benkovic, J. S.; Hirschmann, R. *Tetrahedron Lett.* **1994**, *35*, 6853–6856.
6. Black, R. M.; Clark, R. J.; Read, R. W.; Reid, M. T. J. *J. Chromatogr., A* **1994**, *662*, 301–321.
7. (a) Lecouvey, M.; Mallard, I.; Bailly, T.; Burgada, R.; Leroux, Y. *Tetrahedron Lett.* **2001**, *42*, 8475–8478; (b) Årstad, E.; Skattebøl, L. *Tetrahedron Lett.* **2002**, *43*, 8711–8712; (c) Pachamuthu, K.; Schmidt, R. R. *Chem. Commun.* **2004**, 1078–1079; (d) Griffiths, D. V.; Al-Jeboori, M. J.; Cheong, Y.-K.; Duncanson, P.; Harris, J. E.; Salt, M. C.; Taylor, H. V. *Org. Biomol. Chem.* **2008**, *6*, 577–585; (e) Demir, A. S.; Aybey, A.; Emrullahoglu, M. *Synthesis* **2009**, *10*, 1655–1658; (f) Grün, A.; Molnár, I. G.; Bertók, B.; Greiner, I.; Keglevich, G. *Heteroat. Chem.* **2009**, *20*, 350–354; (g) Keglevich, G.; Grün, A.; Molnár, I. G.; Greiner, I. *Heteroat. Chem.* **2011**, *22*, 640–648; (h) Hosseini, A.; Khalilzadeh, M. A.; Hallajian, S.; Tajbakhsh, M. *Phosphorus, Sulfur Silicon Relat. Elem.* **2011**, *186*, 225–232; (i) Duncanson, P.; Cheong, Y.-K.; Motevalli, M.; Griffiths, D. V. *Org. Biomol. Chem.* **2012**, *10*, 4266–4279.
8. Sekine, M.; Satoh, M.; Yamagata, H.; Hata, T. *J. Org. Chem.* **1980**, *45*, 4162–4167.
9. Taniguchi, Y.; Fujii, N.; Takaki, K.; Fujiwara, Y. *J. Organomet. Chem.* **1995**, *491*, 173–179.
10. (a) Fitch, S. J.; Moedritzer, K. *J. Am. Chem. Soc.* **1962**, *84*, 1876–1879; (b) Griffiths, D. V.; Karim, K.; Harris, J. E. *J. Chem. Soc., Perkin Trans. 1* **1997**, 2539–2544; (c) Demir, A. S.; Emrullahoglu, M.; Pirkin, E.; Akca, N. *J. Org. Chem.* **2008**, *73*, 8992–8997; (d) Cheong, Y.-K.; Duncanson, P.; Griffiths, D. V. *Tetrahedron* **2008**, *64*, 2329–2338.
11. Opaleva, E. N.; Dogadina, A. V.; Lonin, B. I. *Russ. J. Gen. Chem. (Translation of Zhurnal Obshchei Khimii)* **1997**, *67*, 326–327.