Base-Mediated Tandem Reaction of α-Aryloxyacetophenones with Phosphonates: Selective Synthesis of Enol Phosphates

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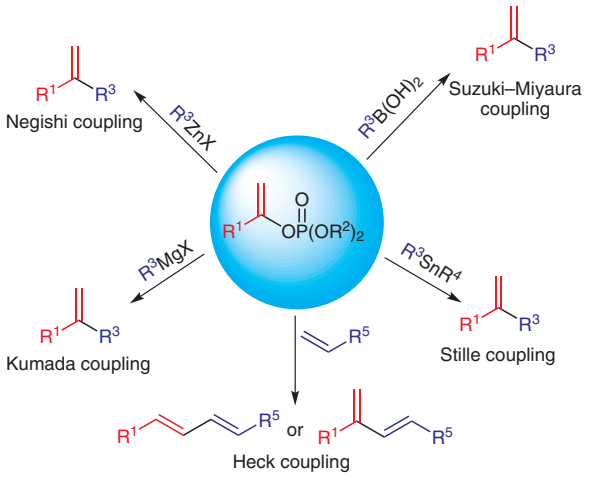
Abstract: A new, simple method for the synthesis of enol phosphates by base-mediated tandem reaction of α-aryloxyacetophenones with phosphonates is described. In the presence of Cs_2CO_3, a variety of α-aryloxyacetophenones smoothly underwent the sequential O–P bond-forming/C–O bond cleavage/isomerization tandem reaction with phosphonates at room temperature, providing the corresponding enol phosphates in moderate to excellent yields.

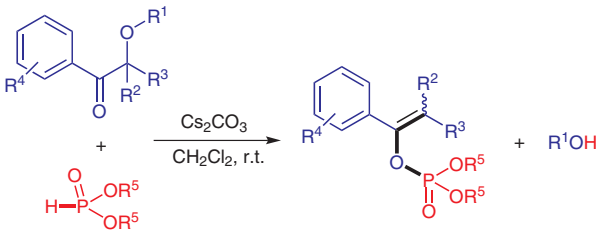
Key words: base, tandem reaction, α-aryloxyacetophenone, phosphonate, enol phosphate

Phosphonate-containing compounds are important because they often display a multitude of robust biologically important properties serving as pharmacological agents, as well as they have found widespread applications as versatile intermediates in organic synthesis.[1] Among the known phosphonate-containing compounds, enol phosphates are particularly attractive and have proven their worth in organic synthesis: for example, in the cross-coupling reactions, such as the Stille,[1l,2] Negishi,[1f,n,3] Kumada,[1c,m,4] Suzuki–Miyaura,[1f,1i–k,5] and Heck couplings (Scheme 1).[1e,h,6]



Scheme 1 The cross-coupling reactions of enol phosphates

As a consequence, the preparation of enol phosphates occupies a place of particular importance in organic chemistry. The general method for enol phosphate preparation includes the quenching of lithium enolates with dialkyl phosphorochloridates.[7,8] However, the method suffers from harsh reaction conditions including use of strong bases (often LDA or KHMDS) and instable phosphoryl chlorides, which significantly limits its application in organic synthesis. Herein, we wish to report a new, simple method for the synthesis of enol phosphates by sequential O–P bond-forming/C–O bond cleavage/isomerization tandem reaction of α-aryloxyacetophenones with phosphonates and Cs_2CO_3 at room temperature under mild conditions (Equation 1).[9,10]



Equation 1

Our investigation began with the reaction between 1-phenyl-2-(*o*-tolyloxy)ethanone (**1a**) and dimethyl phosphonate (**2a**) under basic conditions to screen the optimal reaction conditions, and the results are summarized in Table 1. Initially, a series of bases were tested (Table 1, entries 1–7). Screening revealed that while either $KHCO_3$, KF, or KHMDS has no effect on the reaction in dichloromethane at room temperature (entries 1–3), the other bases, such as LDA, CsF, *t*-BuOK, K_2CO_3, K_3PO_4, and Cs_2CO_3, displayed some activities (entries 4–9). For example, treatment of 1-phenyl-2-(*o*-tolyloxy)ethanone (**1a**) with dimethyl phosphonate (**2a**) and CsF afforded the desired product **3** in 26% yield (entry 5). To our delight, the yield of **3** was enhanced sharply to 93% in the presence of 2 equivalents of Cs_2CO_3 (entry 9). Subsequently, the amount of Cs_2CO_3 was examined, and it turned out that two equivalents of Cs_2CO_3 were the most suitable for the reaction (entries 9–11). In the light of the above results, the effect of solvents was next evaluated (entries 9 and

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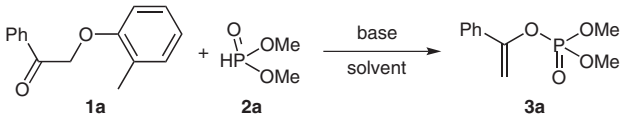
12–15). Although the yield of **3** was reduced to some extent, solvents such as MeCN, toluene, and THF still showed high activity for the reaction (entries 12–14). However, DMF was less effective, lowering the yield to 52% (entry 15). It is noteworthy that the optimal reaction conditions are amenable to large-scale reaction: 92% yield of **3a** was still obtained when 2 mmol of **1a** was added (entry 16).

Table 1 Screening Optimal Conditions[a]

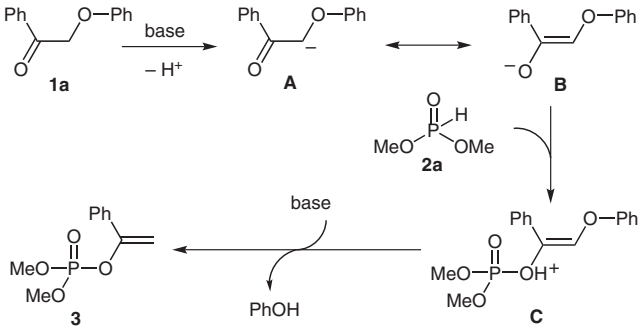


Entry	Base (equiv)	Solvent	Yield (%)[b]
1	$KHCO_3$ (2)	CH_2Cl_2	trace
2	KF (2)	CH_2Cl_2	trace
3	KHMDS (2)	CH_2Cl_2	trace
4	LDA (2)	CH_2Cl_2	9
5	CsF (2)	CH_2Cl_2	26
6	*t*-BuOK (2)	CH_2Cl_2	25
7	K_2CO_3 (2)	CH_2Cl_2	45
8	K_3PO_4 (2)	CH_2Cl_2	64
9	Cs_2CO_3 (2)	CH_2Cl_2	93
10	Cs_2CO_3 (1.2)	CH_2Cl_2	61
11	Cs_2CO_3 (3)	CH_2Cl_2	94
12	Cs_2CO_3 (2)	MeCN	88
13	Cs_2CO_3 (2)	toluene	82
14	Cs_2CO_3 (2)	THF	70
15	Cs_2CO_3 (2)	DMF	52
16[c]	Cs_2CO_3 (2)	CH_2Cl_2	92

[a] Reaction conditions: **1a** (0.2 mmol), **2a** (0.3 mmol), base (2.0 equiv), and solvent (2 mL) at r.t.
[b] Isolated yield.
[c] Compounds **1a** (2.0 mmol) and **2a** (2.5 mmol) were used.

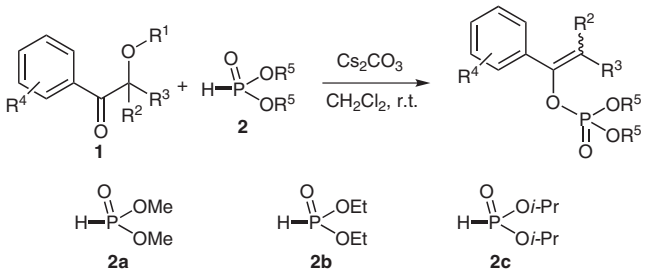
As shown in Table 2, the scope of both α-aryloxyacetophenones and phosphonates was explored under the optimal reaction conditions. In the presence of Cs_2CO_3, the R^1O leaving groups in α-aryloxyacetophenones **1b–i** were first investigated (Table 2, entries 1–8). The results demonstrated that numerous leaving groups, such as ArO and AcO, were perfectly compatible with the optimal conditions (entries 1–8), and three groups, PhO, *p*-$MeOC_6H_4O$, and *o*-IC_6H_4O, are more efficient giving the desired product **3** in quantitative yields (entries 1, 3, and 6). As a consequence, α-aryloxyacetophenones with a PhO as leaving group were employed to further screen the scope of the reaction (entries 9–21). To our delight, treatment of 2-phenoxy-1-phenylethanone (**1b**) with diethyl phosphonate (**2b**) and diisopropyl phosphonate (**2c**) was carried out smoothly to afford the corresponding enol phosphates **4** and **5** in 99% and 88% yield, respectively (entries 9 and 10). Screening disclosed that substituents, such as methyl, methoxy, or fluoro groups, on the aromatic ring of the arylethanone moiety were uniformly well tolerated under the optimal conditions (entries 11–14). For example, substrate **1l** bearing a bulky *o*-MeO group was reacted with phosphonate **2a** and Cs_2CO_3 to form the desired product **8** in 87% yield (entry 13). It was noted that 1-(naphthalen-1-yl)-2-phenoxyethanone (**1n**) was also suitable for the reaction resulting in quantitative yields (entry 15). Encouraged by the above results, a variety of α-substituted substrates **1o–t** were subsequently examined in the presence of phosphonate **2a** and Cs_2CO_3 (entries 16–21). Interestingly, one or two substituents, even containing active CN or $PhSO_2$ functional groups, on the α-position of the 1-aryl-2-phenoxyethanone moiety were perfectly tolerated. Substrate **1o** with a methyl group, for instance, underwent the reaction with phosphonate **2a** and Cs_2CO_3 to form the target product **11** in 91% yield with the 1:1 ratio of *Z*/*E*-isomers (entry 16). Two other α-monosubstituted substrates **1p** and **1q** with a CN or a $PhSO_2$ group also provided a mixture of *Z*/*E*-isomers in excellent yields (entries 17 and 18). Notably, unsymmetric α-disubstituted substrate **1r**, bearing both a methyl group and a 2-cyanoethyl group, was successfully reacted with phosphonate **2a** and Cs_2CO_3 leading to the desired product **14** in 88% yield (the ratio of *Z*/*E*-isomers = 1:1, entry 19). We were pleased to find that the optimized conditions were consistent with the symmetric α-disubstituted substrates **1s** and **1t**, providing the corresponding products **15** and **16** in 84% and 43% yield, respectively (entries 20 and 21).

A possible mechanism for the present transformation as outlined in Scheme 2 is proposed.[7,8] In the presence of a base, deprotonation of the α-position in substrate **1a** can take place readily to form the enol form **B**. Subsequently, the addition of phosphate **2a** to intermediate **B** affords intermediate **C**. Finally, sequential the C–O bond cleavage and isomerization of intermediate **C** take place to give the desired enol phosphate **3** and PhOH with the aid of a base.



Scheme 2 Possible mechanism for the formation of enol phosphates

Table 2 Cs_2CO_3-Mediated Synthesis of Enol Phosphates[a]



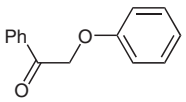
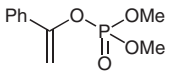
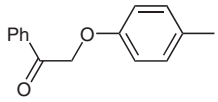
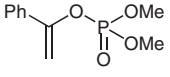
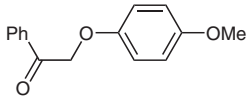
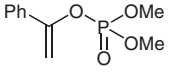
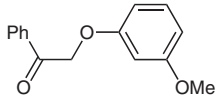
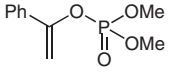
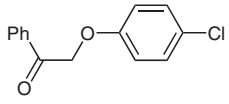
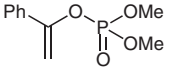
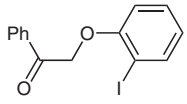
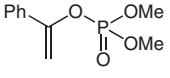
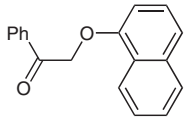
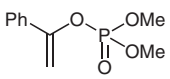
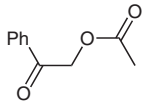
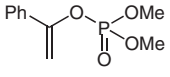
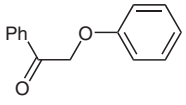
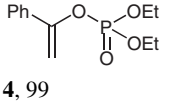
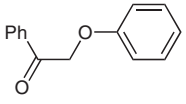
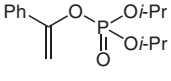
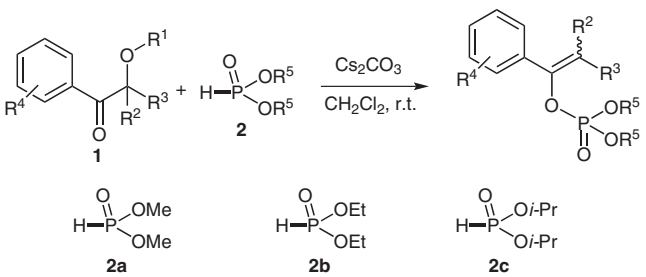
Entry	Substrate **1**	**2**	Product, yield[b] (%)
1	 **1b**	**2a**	 **3**, 99
2	 **1c**	**2a**	 **3**, 82
3	 **1d**	**2a**	 **3**, ~100
4	 **1e**	**2a**	 **3**, 88
5	 **1f**	**2a**	 **3**, 82
6	 **1g**	**2a**	 **3**, 98
7	 **1h**	**2a**	 **3**, 95
8	 **1i**	**2a**	 **3**, 91
9	 **1b**	**2b**	 **4**, 99
10	 **1b**	**2c**	 **5**, 81

Table 2 Cs_2CO_3-Mediated Synthesis of Enol Phosphates[a] (continued)



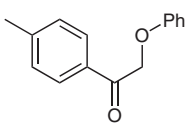
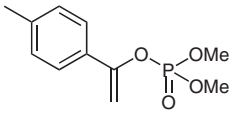
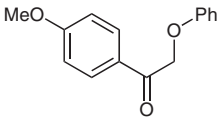
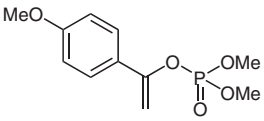
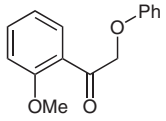
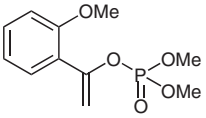
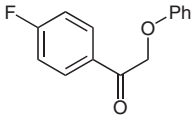
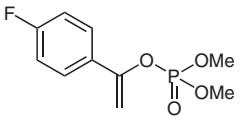
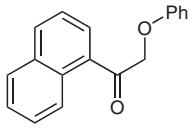
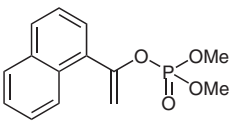
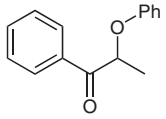
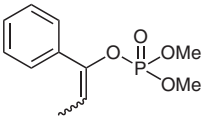
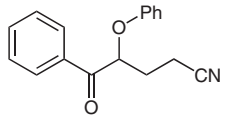
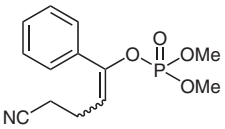
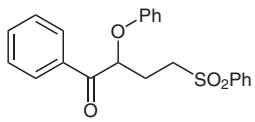
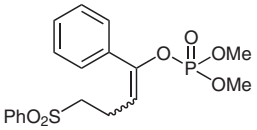
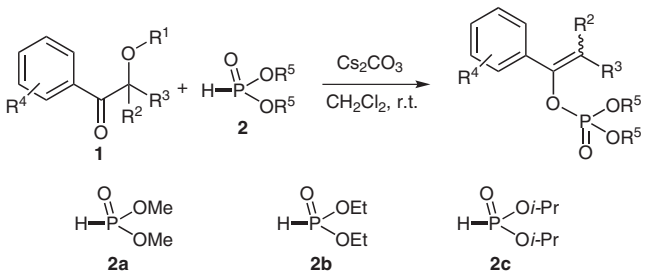
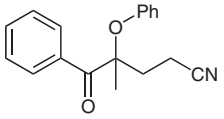
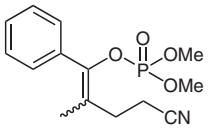
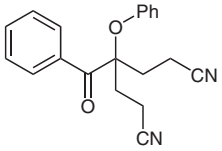
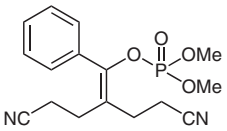
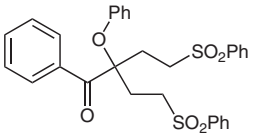
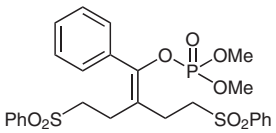
Entry	Substrate **1**	**2**	Product, yield[b] (%)
11	 **1j**	**2a**	 **6**, 98
12	 **1k**	**2a**	 **7**, 96
13	 **1l**	**2a**	 **8**, 87
14	 **1m**	**2a**	 **9**, 77
15	 **1n**	**2a**	 **10**, 99
16	 **1o**	**2a**	 **11**, 91 (1:1)
17	 **1p**	**2a**	 **12**, 70 (2:3)
18	 **1q**	**2a**	 **13**, 92 (2:3)

Table 2 Cs_2CO_3-Mediated Synthesis of Enol Phosphates[a] (continued)



Entry	Substrate **1**	**2**	Product, yield[b] (%)
19	 **1r**	**2a**	 **14**, 88 (1:1)
20	 **1s**	**2a**	 **15**, 84
21	 **1t**	**2a**	 **16**, 43

[a] Reaction conditions: **1** (0.2 mmol), phosphonate **2** (0.3 mmol), Cs_2CO_3 (2 equiv), CH_2Cl_2 (2 mL) at r.t. under air atmosphere.
[b] Isolated yield. The *Z*/*E* ratio is given in parentheses.

In summary, we have developed a new, simple method for the synthesis of enol phosphates under mild conditions. In the presence of Cs_2CO_3, a variety of α-aryloxyacetophenone compounds selectively underwent the sequential O–P bond-forming/C–O bond-cleavage/isomerization tandem reaction with phosphonates leading to enol phosphates in moderate to excellent yields. Importantly, this method is simple and mild with a wide range of substrates compatibility, which makes the applications of enol phosphates more attractive in organic synthesis.

IR spectra of the liquid products were recorded as neat films between KBr plates on a Bruker vertex 70 spectrophotometer. NMR spectroscopy was performed on a Bruker advanced spectrometer operating at 500 MHz (^{1}H NMR) and 125 MHz (^{13}C NMR). Mass spectrometric analysis was performed on GC-MS analysis (Shimadzu GCMS-QP2010) and ESI-Q-TOF (Bruker MicroQTOF-II).

Base-Catalyzed Synthesis of Vinyl Phosphates; General Procedure

To a Schlenk tube were added α-aryloxyacetophenone **1** (0.2 mmol), phosphonate **2** (0.3 mmol), Cs_2CO_3 (130 mg, 0.4 mmol), and CH_2Cl_2 (2 mL). Then the contents of the tube were stirred at r.t. under air atmosphere for the indicated time until complete consumption of starting material as monitored by TLC (eluent: hexane–EtOAc, 1:1) and GC-MS analysis. After completion of the reaction, the reaction mixture was diluted with Et_2O (5 mL), and washed with brine (3 × 1 mL). The aqueous phase was extracted with Et_2O (3 × 2 mL). The combined organic layers were dried (Na_2SO_4) and concentrated in vacuo. The resulting residue was purified by column chromatography on silica gel (hexane–EtOAc, 2:1) to afford the desired product (Table 2).

Dimethyl 1-Phenylvinyl Phosphate (3)[1g]

Yield: 42.9 mg (94%); colorless oil.

IR (KBr): 1708, 1491, 1454, 1234, 1181, 1042 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.60–7.58 (m, 2 H), 7.39–7.35 (m, 3 H), 5.31 (t, *J* = 2.5 Hz, 1 H), 5.22 (t, *J* = 2.5 Hz, 1 H), 3.87 (s, 3 H), 3.84 (s, 3 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 152.2 (d, $J_{C,P}$ = 6.4 Hz, 1 C), 134.0 (d, $J_{C,P}$ = 6.9 Hz, 1 C), 129.2, 128.4, 125.1, 97.4 (d, $J_{C,P}$ = 3.6 Hz, 1 C), 54.9 (d, $J_{C,P}$ = 5.9 Hz, 1 C).

LRMS (EI, 70 eV): *m*/*z* (%) = 228 (M$^+$, 16), 213 (7), 116 (20), 102 (100).

Diethyl 1-Phenylvinyl Phosphate (4)[1g]

Yield: 50.7 mg (99%); colorless oil.

IR (KBr): 1712, 1490, 1448, 1232, 1177, 1038 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.60–7.58 (m, 2 H), 7.38–7.34 (m, 3 H), 5.29 (t, *J* = 2.5 Hz, 1 H), 5.23 (t, *J* = 2.5 Hz, 1 H), 4.25–4.17 (m, 4 H), 1.36–1.33 (m, 6 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 152.3 (d, $J_{C,P}$ = 8.0 Hz, 1 C), 134.3, 129.1, 128.4, 125.2, 97.3 (d, $J_{C,P}$ = 3.6 Hz, 1 C), 64.5 (d, $J_{C,P}$ = 6.1 Hz, 1 C), 16.1 (d, $J_{C,P}$ = 6.6 Hz, 1 C).

LRMS (EI, 70 eV): *m*/*z* (%) = 256 (M$^+$, 10), 199 (7), 130 (81), 102 (100).

Diisopropyl 1-Phenylvinyl Phosphate (5)[1g]

Yield: 46.0 mg (81%); colorless oil.

IR (KBr): 1715, 1556, 1446, 1232, 1143, 1039 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.60–7.58 (m, 2 H), 7.38–7.33 (m, 3 H), 5.27 (t, *J* = 2.5 Hz, 1 H), 5.24 (t, *J* = 2.5 Hz, 1 H), 4.78–4.72 (m, 2 H), 1.37 (s, 3 H), 1.33 (s, 3 H), 1.32 (s, 3 H), 1.26 (s, 3 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 152.4 (d, $J_{C,P}$ = 7.4 Hz, 1 C), 134.6 (d, $J_{C,P}$ = 7.3 Hz, 1 C), 128.9, 128.3, 125.2, 97.0 (d, $J_{C,P}$ = 3.4 Hz, 1 C), 73.4 (d, $J_{C,P}$ = 6.0 Hz, 1 C), 23.7 (d, $J_{C,P}$ = 4.8 Hz, 1 C), 23.5 (d, $J_{C,P}$ = 5.3 Hz, 1 C).

LRMS (EI, 70 eV): *m*/*z* (%) = 284 (M$^+$, 10), 144 (61), 102 (100).

Dimethyl 1-*p*-Tolylvinyl Phosphate (6)

Yield: 47.4 mg (98%); colorless oil.

IR (KBr): 1716, 1555, 1183, 1095 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.48 (d, *J* = 8.0 Hz, 2 H), 7.17 (d, *J* = 8.5 Hz, 2 H), 5.25 (t, *J* = 2.5 Hz, 1 H), 5.16 (t, *J* = 2.5 Hz, 1 H), 3.85 (s, 3 H), 3.83 (s, 3 H), 2.36 (s, 3 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 152.3 (d, $J_{C,P}$ = 7.8 Hz, 1 C), 139.2, 131.2 (d, $J_{C,P}$ = 6.6 Hz, 1 C), 129.0, 125.0, 96.5 (d, $J_{C,P}$ = 3.5 Hz, 1 C), 54.8 (d, $J_{C,P}$ = 6.1 Hz, 1 C), 21.1.

LRMS (EI, 70 eV): *m*/*z* (%) = 242 (M$^+$, 26), 227 (16), 127 (33), 116 (100).

HRMS (EI): *m*/*z* calcd for $C_{11}H_{15}O_4P$ (M$^+$): 242.0708; found: 242.0705.

1-(4-Methoxyphenyl)vinyl Dimethyl Phosphate (7)

Yield: 49.5 mg (96%); colorless oil.

IR (KBr): 1725, 1568, 1195, 1103 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.53–7.52 (m, 2 H), 6.89–6.88 (m, 2 H), 5.17 (t, *J* = 2.5 Hz, 1 H), 5.10 (t, *J* = 2.5 Hz, 1 H), 3.86 (s, 3 H), 3.84 (s, 3 H), 3.82 (s, 3 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 160.3, 152.1 (d, $J_{C,P}$ = 8.0 Hz, 1 C), 126.6 (d, $J_{C,P}$ = 9.3 Hz, 1 C), 113.8, 95.6 (d, $J_{C,P}$ = 3.5 Hz, 1 C), 55.3, 54.8 (d, $J_{C,P}$ = 6.3 Hz, 1 C).

LRMS (EI, 70 eV): *m*/*z* (%) = 258 (M^+, 30), 227 (4), 131 (100).

HRMS (EI): *m*/*z* calcd for $C_{11}H_{15}O_5P$ (M^+): 258.0657; found: 258.0654.

1-(2-Methoxyphenyl)vinyl Dimethyl Phosphate (8)
Yield: 44.9 mg (87%); colorless oil.

IR (KBr): 1703, 1497, 1450, 1228, 1178, 1044 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.53–7.51 (m, 1 H), 7.33–7.30 (m, 1 H), 6.89–6.92 (m, 2 H), 5.46 (t, *J* = 2.5 Hz, 1 H), 5.37 (t, *J* = 2.0 Hz, 1 H), 3.87 (s, 3 H), 3.82 (s, 3 H), 3.80 (s, 3 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 157.1, 149.2 (d, $J_{C,P}$ = 8.0 Hz, 1 C), 130.1, 128.8, 123.2 (d, $J_{C,P}$ = 6.0 Hz, 1 C), 120.3, 111.1, 102.7 (d, $J_{C,P}$ = 4.0 Hz, 1 C), 55.4, 54.6 (d, $J_{C,P}$ = 6.1 Hz, 1 C).

LRMS (EI, 70 eV): *m*/*z* (%) = 258 (M^+, 29), 227 (3), 131 (100), 127 (65).

HRMS (EI): *m*/*z* calcd for $C_{11}H_{15}O_5P$ (M^+): 258.0657; found: 258.0656.

1-(4-Fluorophenyl)vinyl Dimethyl Phosphate (9)
Yield: 37.9 mg (77%); colorless oil.

IR (KBr): 1700, 1487, 1455, 1043 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.58–7.56 (m, 2 H), 7.07–7.04 (m, 2 H), 5.24 (t, *J* = 2.5 Hz, 1 H), 5.20 (t, *J* = 2.5 Hz, 1 H), 3.87 (s, 3 H), 3.84 (s, 3 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 162.2, 151.4, 129.7, 127.1 (d, $J_{C,P}$ = 8.0 Hz, 1 C), 115.4 (d, $J_{C,P}$ = 21.9 Hz, 1 C), 97.2, 54.8 (d, $J_{C,P}$ = 4.9 Hz, 1 C).

LRMS (EI, 70 eV): *m*/*z* (%) = 246 (M^+, 14), 231 (9), 120 (100), 109 (23).

HRMS (EI): *m*/*z* calcd for $C_{10}H_{12}FO_4P$ (M^+): 246.0457; found: 246.0453.

Dimethyl 1-(Naphthalen-1-yl)vinyl Phosphate (10)
Yield: 55.0 mg (99%); colorless oil.

IR (KBr): 1709, 1488, 1465, 1040 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 8.06 (s, 1 H), 7.88–7.86 (m, 1 H), 7.84–7.81 (m, 2 H), 7.67–7.65 (m, 1 H), 7.52–7.48 (m, 2 H), 5.45 (t, *J* = 2.5 Hz, 1 H), 5.32 (t, *J* = 2.5 Hz, 1 H), 3.89 (s, 3 H), 3.87 (s, 3 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 152.2 (d, $J_{C,P}$ = 7.9 Hz, 1 C), 133.5, 133.0, 131.2 (d, $J_{C,P}$ = 6.6 Hz, 1 C), 128.4 (d, $J_{C,P}$ = 46.9 Hz, 1 C), 127.6, 126.6 (d, $J_{C,P}$ = 27.6 Hz, 1 C), 124.6, 122.7, 98.0 (d, $J_{C,P}$ = 3.3 Hz, 1 C), 54.9 (d, $J_{C,P}$ = 6.0 Hz, 1 C).

LRMS (EI, 70 eV): *m*/*z* (%) = 278 (M^+, 39), 263 (9), 166 (26), 152 (100).

HRMS (EI): *m*/*z* calcd for $C_{14}H_{15}O_4P$ (M^+): 278.0708; found: 278.0706.

Dimethyl (*Z*/*E*)-1-Phenylprop-1-enyl Phosphate (11)
Yield: 44.0 mg (91%); *Z*/*E* = 1:1; colorless oil.

IR (KBr): 1716, 1699, 1654, 1552, 1184, 1099, 1033 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.51–7.49 (m, 2 H), 7.47–7.45 (m, 2 H), 7.40–7.37 (m, 2 H), 7.35–7.32 (m, 3 H), 7.30–7.27 (m, 1 H), 5.78–5.73 (m, 1 H), 5.70–5.65 (m, 1 H), 3.75 (s, 3 H), 3.73 (s, 3 H), 3.72 (s, 3 H), 3.71 (s, 3 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 146.7 (d, $J_{C,P}$ = 9.0 Hz, 1 C), 146.2 (d, $J_{C,P}$ = 8.9 Hz, 1 C), 135.5, 133.8 (d, $J_{C,P}$ = 4.3 Hz, 1 C), 128.5 (d, $J_{C,P}$ = 9.5 Hz, 1 C), 128.2 (d, $J_{C,P}$ = 10.5 Hz, 1 C), 128.1, 125.2, 112.2 (d, $J_{C,P}$ = 6.4 Hz, 1 C), 111.8 (d, $J_{C,P}$ = 5.1 Hz, 1 C), 54.7 (d, $J_{C,P}$ = 6.1 Hz, 1 C), 54.5 (d, $J_{C,P}$ = 6.0 Hz, 1 C), 12.9, 11.6.

LRMS (EI, 70 eV): *m*/*z* (%) = 242 (M^+, 19), 127 (100), 115 (66).

HRMS (EI): *m*/*z* calcd for $C_{11}H_{15}O_4P$ (M^+) 242.0708; found: 242.0705.

(*Z*/*E*)-4-Cyano-1-phenylbut-1-enyl Dimethyl Phosphate (12)
Yield: 39.3 mg (70%); *Z*/*E* = 3:2; *Z*-isomer: 15.7 mg, *E*-isomer: 23.6 mg.

***Z*-Isomer**
Colorless oil.

IR (KBr): 1717, 1711, 1658, 1558, 1193, 1036 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.53 (d, *J* = 7.0 Hz, 2 H), 7.38–7.35 (m, 3 H), 5.68–5.65 (m, 1 H), 3.74 (s, 3 H), 3.72 (s, 3 H), 2.74–2.70 (m, 2 H), 2.57 (t, *J* = 7.0 Hz, 2 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 148.0 (d, $J_{C,P}$ = 8.5 Hz, 1 C), 134.5, 129.0, 128.4, 125.6, 119.2, 112.9 (d, $J_{C,P}$ = 6.4 Hz, 1 C), 54.9 (d, $J_{C,P}$ = 5.8 Hz, 1 C), 22.3, 17.0 (d, $J_{C,P}$ = 2.6 Hz, 1 C).

LRMS (EI, 70 eV): *m*/*z* (%) = 281 (M^+, 1), 155 (45), 127 (100), 115 (59).

HRMS (EI): *m*/*z* calcd for $C_{13}H_{16}NO_4P$ (M^+): 281.0817; found: 281.0820.

***E*-Isomer**
Colorless oil.

IR (KBr): 1718, 1708, 1659, 1550, 1199, 1044 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.43–7.40 (m, 5 H), 5.69–5.66 (m, 1 H), 3.75 (s, 3 H), 3.73 (s, 3 H), 2.50 (t, *J* = 7.0 Hz, 2 H), 2.43 (t, *J* = 7.0 Hz, 2 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 148.7 (d, $J_{C,P}$ = 8.5 Hz, 1 C), 133.1 (d, $J_{C,P}$ = 4.5 Hz, 1 C), 129.4, 128.5 (d, $J_{C,P}$ = 1.5 Hz, 1 C), 118.7, 112.6 (d, $J_{C,P}$ = 4.9 Hz, 1 C), 54.7 (d, $J_{C,P}$ = 6.1 Hz, 1 C), 23.6, 17.6.

LRMS (EI, 70 eV): *m*/*z* (%) = 281 (M^+, 1), 155 (45), 127 (100), 115 (59).

HRMS (EI): *m*/*z* (EI) calcd for $C_{13}H_{16}NO_4P$ (M^+): 281.0817; found: 281.0820.

Dimethyl (*Z*/*E*)-1-Phenyl-4-(phenylsulfonyl)but-1-enyl Phosphate (13)
Yield: 72.9 mg (92%); *Z*/*E* = 2:3; *Z*-isomer: 29.1 mg, *E*-isomer: 43.8 mg.

***Z*-Isomer**
Colorless oil.

IR (KBr): 1720, 1650, 1556, 1144, 1042 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 7.95 (d, *J* = 7.0 Hz, 2 H), 7.65 (t, *J* = 7.5 Hz, 1 H), 7.57 (t, *J* = 7.5 Hz, 2 H), 7.45–7.43 (m, 2 H), 7.35–7.31 (m, 3 H), 5.57–5.54 (s, 1 H), 3.68 (s, 3 H), 3.65 (s, 3 H), 3.32 (t, *J* = 7.5 Hz, 2 H), 2.80–2.75 (m, 2 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 147.8 (d, $J_{C,P}$ = 8.9 Hz, 1 C), 139.0, 134.6, 133.7, 129.3, 128.9, 128.2 (d, $J_{C,P}$ = 26.8 Hz, 1 C), 125.5, 112.3 (d, $J_{C,P}$ = 6.4 Hz, 1 C), 54.9 (d, $J_{C,P}$ = 2.5 Hz, 1 C), 54.8 (d, $J_{C,P}$ = 6.0 Hz, 1 C), 19.9.

LRMS (EI, 70 eV): *m*/*z* (%) = 396 (M^+, 1), 155 (22), 127 (100).

HRMS (EI): *m/z* calcd for $C_{18}H_{21}O_6PS$ (M^+): 396.0797; found: 396.0795.

***E*-Isomer**
Colorless oil.

IR (KBr): 1722, 1648, 1559, 1148, 1043 cm^{-1}.

^1H NMR (500 MHz): δ = 7.84 (d, *J* = 7.5 Hz, 2 H), 7.64 (t, *J* = 7.5 Hz, 1 H), 7.53 (t, *J* = 7.5 Hz, 2 H), 7.36–7.32 (m, 5 H), 5.59–5.56 (s, 1 H), 3.71 (s, 3 H), 3.69 (s, 3 H), 3.18–3.15 (m, 2 H), 2.60–2.54 (m, 2 H).

^{13}C NMR (125 MHz): δ = 148.0 (d, $J_{C,P}$ = 8.5 Hz, 1 C), 138.6, 133.8, 133.0 (d, $J_{C,P}$ = 4.3 Hz, 1 C), 129.3 (d, $J_{C,P}$ = 2.4 Hz, 1 C), 128.3 (d, $J_{C,P}$ = 20.8 Hz, 1 C), 128.0, 112.2 (d, $J_{C,P}$ = 4.8 Hz, 1 C), 55.5, 54.6 (d, $J_{C,P}$ = 6.3 Hz, 1 C), 21.1.

LRMS (EI, 70 eV): *m/z* (%) = 396 (M^+, 1), 155 (22), 127 (100).

HRMS (EI): *m/z* calcd for $C_{18}H_{21}O_6PS$ (M^+): 396.0797; found: 396.0795.

(*Z*/*E*)-4-Cyano-2-methyl-1-phenylbut-1-enyl Dimethyl Phosphate (14)
Yield: 51.9 mg (88%); *Z*/*E* = 1:1; colorless oil.

IR (KBr): 1716, 1698, 1556, 1552, 1507, 1185, 1031 cm^{-1}.

^1H NMR (500 MHz, $CDCl_3$): δ = 7.41–7.37 (m, 10 H), 3.80 (s, 3 H), 3.78 (s, 3 H), 3.56 (s, 6 H), 3.53 (s, 6 H), 2.69 (t, *J* = 7.5 Hz, 1 H), 2.64–2.61 (m, 1 H), 2.43–2.39 (m, 3 H), 2.37–2.35 (m, 3 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 143.9 (d, $J_{C,P}$ = 8.6 Hz, 1 C), 134.2, 129.4 (d, $J_{C,P}$ = 22.0 Hz, 1 C), 128.9 (d, $J_{C,P}$ = 31.4 Hz, 1 C), 128.2 (d, $J_{C,P}$ = 35.4 Hz, 1 C), 120.4 (d, $J_{C,P}$ = 7.8 Hz, 1 C), 118.8, 54.4 (d, $J_{C,P}$ = 6.1 Hz, 1 C), 54.3 (d, $J_{C,P}$ = 6.1 Hz, 1 C), 52.0 (d, $J_{C,P}$ = 5.5 Hz, 1 C), 29.0, 27.8, 17.6, 15.8 (d, $J_{C,P}$ = 2.9 Hz, 1 C), 15.4, 14.8.

LRMS (EI, 70 eV): *m/z* (%) = 295 (M^+, 1), 249 (27), 216 (8), 155 (36), 127 (73).

HRMS (EI): *m/z* calcd for $C_{14}H_{18}NO_4P$ (M^+): 295.0973; found: 295.0970.

4-Cyano-2-(2-cyanoethyl)-1-phenylbut-1-enyl Dimethyl Phosphate (15)
Yield: 56.1 mg (84%); colorless oil.

IR (KBr): 1720, 1658, 1546, 1279, 1184, 1049 cm^{-1}.

^1H NMR (500 MHz, $CDCl_3$): δ = 7.47–7.42 (m, 5 H), 3.55 (s, 3 H), 3.53 (m, 3 H), 2.70 (t, *J* = 5.0 Hz, 4 H), 2.43–2.38 (m, 4 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 147.1 (d, $J_{C,P}$ = 8.3 Hz, 1 C), 133.2, 129.5 (d, $J_{C,P}$ = 23.6 Hz, 1 C), 128.6, 121.2 (d, $J_{C,P}$ = 8.5 Hz, 1 C), 119.2, 118.4, 54.5 (d, $J_{C,P}$ = 6.1 Hz, 1 C), 26.6, 24.5, 16.0 (d, $J_{C,P}$ = 2.6 Hz, 1 C), 15.7 (d, $J_{C,P}$ = 2.3 Hz, 1 C).

LRMS (EI, 70 eV): *m/z* (%) = 334 (M^+, 1), 253 (2), 208 (53), 168 (100), 127 (73).

HRMS (EI): *m/z* calcd for $C_{16}H_{29}N_2O_4P$ (M^+): 334.1082; found: 334.1080.

Dimethyl 1-Phenyl-4-(phenylsulfonyl)-2-[2-(phenylsulfonyl)ethyl]but-1-enyl Phosphate (16)
Yield: 48.5 mg (43%); colorless oil.

IR (KBr): 1716, 1699, 1650, 1556, 1503, 1307, 1042 cm^{-1}.

^1H NMR (500 MHz, $CDCl_3$): δ = 7.95 (d, *J* = 7.5 Hz, 2 H), 7.72–7.67 (m, 3 H), 7.64–7.59 (m, 3 H), 7.48 (t, *J* = 7.5 Hz, 2 H), 7.36–7.28 (m, 3 H), 7.19 (d, *J* = 7.0 Hz, 2 H), 3.46 (s, 3 H), 3.44 (s, 3 H), 3.33–3.30 (m, 2 H), 3.05–3.01 (m, 2 H), 2.70–2.67 (m, 2 H), 2.37–2.34 (m, 2 H).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 145.8 (d, $J_{C,P}$ = 8.1 Hz, 1 C), 139.0, 138.3, 133.8 (d, $J_{C,P}$ = 6.0 Hz, 1 C), 133.3, 129.4 (d, $J_{C,P}$ = 3.6 Hz, 1 C), 129.3, 128.9, 128.5, 128.1, 127.9, 119.9 (d, $J_{C,P}$ = 8.1 Hz, 1 C), 54.5 (d, $J_{C,P}$ = 6.1 Hz, 1 C), 53.8 (d, $J_{C,P}$ = 40.6 Hz, 1 C), 24.3, 22.1.

LRMS (EI, 70 eV): *m/z* (%) = 564 (M^+, 1), 423 (12), 297 (73), 155 (100), 127 (33).

HRMS (EI): *m/z* calcd for $C_{26}H_{29}O_8PS_2$ (M^+): 564.1042; found: 564.1040.

Supporting Information for this article is available online at http://www.thieme-connect.com/ejournals/toc/synthesis.

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