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Palladium(II)-Catalyzed Ortho-Arylation of Benzylic Phosphonic Monoesters Using Potassium Aryltrifluoroborates

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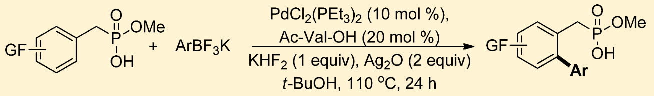
Supporting Information

ABSTRACT: The new monophosphonic acid directing group was successfully utilized in the Pd (II)-catalyzed ortho-arylation of benzylic phosphonic monoesters using potassium aryltrifluoroborates. A wide range of benzylic phosphonic monoesters underwent clean ortho-arylation in high yields, and excellent functional group tolerance was also observed.



INTRODUCTION

Organophosphonates have attracted considerable attention due to their wide applications in organic chemistry, medicinal chemistry, and material science.[1] A particularly important class of organophosphonates is benzylic phosphonates, which are common structural motifs in biological chemistry[2] and have already become a powerful tool in construction of alkene derivatives via the Horner−Wadsworth−Emmons reaction in organic synthesis.[3]

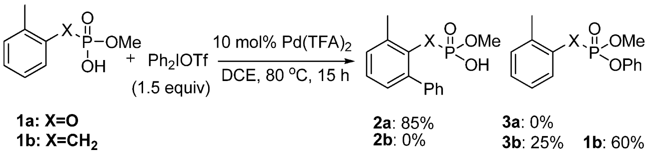
During recent decades, significant progress in transition metal-catalyzed C−H bond activation methodology has been made for ortho-functionalizations of arenes.[4] In particular, a directing group-based C−H activation approach has flourished in the construction of new C−C and C−heteroatom bonds. Among various ortho-directing groups, carbonyl derivatives are widely utilized along with N-derived groups.[5,6] Despite many available ortho-directing groups, the development of new, efficient directing groups still constitutes an important synthetic challenge.

In connection with our interest in C−H functionalization of arenes, we have reported Pd(II)-catalyzed ortho-alkenylation using new monophosphoric acid directing groups.[7,8] As extension of our work, we have investigated ortho-arylation of benzylic phosphonate monoesters. In analogous studies, Yu reported the Pd(II)-catalyzed ortho-arylation of benzylic acids using arylboron reagents and also found remarkable beneficial effects of amino acid ligands.[9]

RESULTS AND DISCUSSION

Recently, we have succeeded in achieving Pd(II)-catalyzed ortho-arylation of **1a** using diaryliodonium triflates.[10a] To achieve arylation of aryl benzylic phosphonates, when the same reaction was attempted using **1b**, somewhat surprisingly, O-phenylation occurred to some extent without the formation of **2b** (Scheme 1). O-Arylation of phenols using diaryliodonium triflates was recently noted.[11] The reaction was sensitive to the oxidant used, and the desired product **2b** was not formed in any cases. To achieve ortho-arylation, we next screened several organoboron reagents using 10 mol % $Pd(OAc)_2$ catalyst and AgOAc oxidant (3 equiv) in refluxing dioxane. As shown in Table 1, phenylation occurred to some extent using reagent **I** (entries 1 and 2), but reagent **II**, **III**, and **IV** were totally ineffective and no reaction occurred (entries 3, 4, and 5). Inspired by recent reports on the C−H arylation of phenylacetic acids,[9] we next used potassium aryltrifluoroborate salts as a coupling partner but the initial result was not very promising.[12,13] The ortho-arylation of **4** using $PhBF_3K$ in refluxing *tert*-amyl alcohol did not go to completion, yielding a 70:30 mixture of **4** and **5** (entry 6). The reaction was accelerated significantly in the presence of an amino acid ligand, but the nature of amino acid ligands did not influence the reaction greatly. Furthermore, poor mono-substitutions together with some remaining starting materials were noted (entries 7−10). Among the bases tested in this study, KHF_2 gave the best result, although the starting material was not consumed completely (entries 11−13).

Scheme 1. Reaction of 1a and 1b with Ph_2IOTf



To search for the optimum condition, when **1b** was treated with $PhBF_3K$ using 10 mol % $Pd(OAc)_2$ catalyst, 20 mol % Ac-Val-OH ligand, and AgOAc oxidant in refluxing *tert*-butyl alcohol for 24 h, a 63:32 mixture of **2b** and **1b** was obtained (entry 1, Table 2). Ag_2O oxidant was equally effective (entry 2), and Boc-Val-OH ligand was slightly less effective (entry 3). After many futile experiments to search for the completion of the reaction, the effectiveness of other Pd(II) catalysts was investigated. $PdCl_2$ was inferior to $Pd(OAc)_2$ (entry 4), whereas $PdCl_2(PPh_3)_2$ was equally effective as $Pd(OAc)_2$ but was not good enough to be used (entry 5). Gratifyingly,

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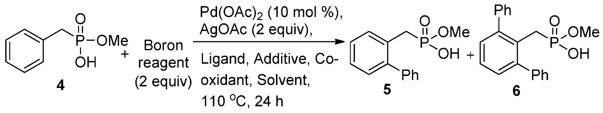
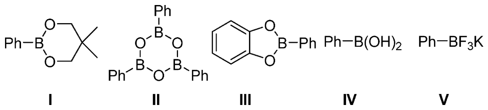
Table 1. Optimization of Reaction Conditions



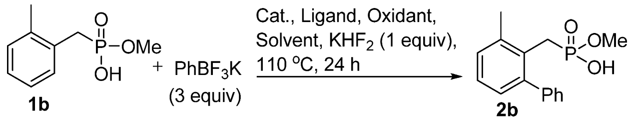
entry	boron reagent[a]	ligand (20 mol %)	additive (1 equiv)	co-oxidant (2 equiv)	solvent	yield (%)[b] (5:6:4)[c]
1	**I**	–	–	–	DMF	20:0:80
2	**I**	–	K_2HPO_4	BQ	dioxane	30:0:70
3	**II**	–	K_2HPO_4	BQ	dioxane	0:0:100
4	**III**	–	K_2HPO_4	BQ	dioxane	0:0:100
5	**IV**	–	–	–	dioxane	0:0:100
6	**V**	–	$KHCO_3$	BQ	^{t}amylOH	30:0:70[d]
7	**V**	Boc-Ala-OH	$KHCO_3$	–	^{t}BuOH	35:15:50
8	**V**	Boc-Val-OH	$KHCO_3$	–	^{t}BuOH	42:29:29
9	**V**	Boc-Ile-OH·0.5 H_2O	$KHCO_3$	–	^{t}BuOH	50:23:27
10	**V**	Ac-Val-OH	$KHCO_3$		^{t}BuOH	43:32:25
11	**V**	Ac-Val-OH	K_2HPO_4	–	^{t}BuOH	39:13:48
12	**V**	Ac-Val-OH	Li_2CO_3	–	^{t}BuOH	38:20:42
13	**V**	Ac-Val-OH	KHF_2	–	^{t}BuOH	57:25:18

[a] Structures of boron reagents:



[b] The yield and ratio was determined by ^{1}H NMR analysis. [c] The mixture was converted to its methyl ester with diazomethane. [d] The reaction was carried out using Ag_2CO_3 (2 equiv) at 130 °C for 24 h.

Table 2. Optimization of Reaction Conditions



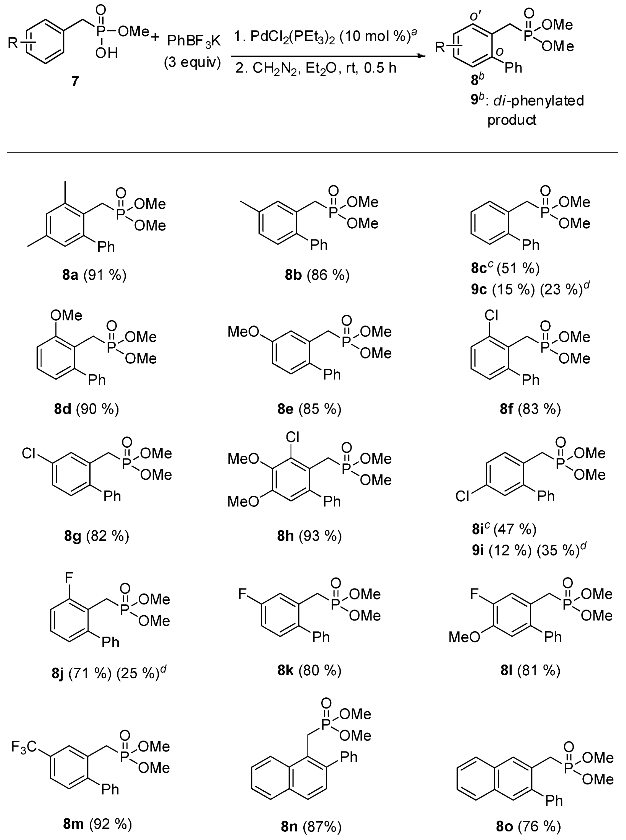
entry	cat. (10 mol %)	ligand (20 mol %)	oxidant (2 equiv)	solvent	yield (%)[a] (2b:1b)
1	$Pd(OAc)_2$	Ac-Val-OH	AgOAc	^{t}BuOH	63:32
2	$Pd(OAc)_2$	Ac-Val-OH	Ag_2O	^{t}BuOH	65:26
3	$Pd(OAc)_2$	Boc-Val-OH	Ag_2O	^{t}BuOH	49:43
4	$PdCl_2$	Ac-Val-OH	Ag_2O	^{t}BuOH	11:76
5	$PdCl_2(PPh_3)_2$	Ac-Val-OH	Ag_2O	^{t}BuOH	62:27
6	$PdCl_2(PEt_3)_2$	Ac-Val-OH	Ag_2O	^{t}BuOH	85:8[b]
7	$PdCl_2(PEt_3)_2$	–	Ag_2O	^{t}BuOH	62:28
8	$PdCl_2(PEt_3)_2$	Boc-Val-OH	Ag_2O	^{t}BuOH	60:34
9	$PdCl_2(PEt_3)_2$	Ac-Val-OH	AgOAc	^{t}BuOH	23:70
10	$PdCl_2(PEt_3)_2$	Ac-Val-OH	Ag_2CO_3	^{t}BuOH	10:81
11	$PdCl_2(PEt_3)_2$	Ac-Val-OH	$Na_2S_2O_8$	^{t}BuOH	0:100
12	$PdCl_2(PEt_3)_2$	Ac-Val-OH	$Cu(OAc)_2$	^{t}BuOH	0:100
13	$PdCl_2(PEt_3)_2$	Ac-Val-OH	Ag_2O	DMSO	12:80
14	$PdCl_2(PEt_3)_2$	Ac-Val-OH	Ag_2O	toluene	35:21
15	$PdCl_2(PEt_3)_2$	Ac-Val-OH	Ag_2O	dioxane	36:17
16	$PdCl_2(PEt_3)_2$	Ac-Val-OH	Ag_2O	DMF	62:30

[a] The yield and ratio was determined by ^{1}H NMR analysis. [b] **2b** was converted to its methyl ester **2c** with diazomethane.

$PdCl_2(PEt_3)_2$ catalyst was found to be most effective for arylation of **1b** under the same conditions (entry 6).[14] Among the oxidants tested in this study, $Na_2S_2O_8$ and $Cu(OAc)_2$ were totally ineffective (entries 11 and 12) and Ag_2O gave the best results (entry 6). Furthermore, the reaction was sensitive to solvent, and *tert*-butyl alcohol was found to be the superior solvent (entries 13–16).

After establishing the optimal reaction conditions, we applied this new arylation protocol to a series of benzylic phosphonic monoesters as shown in Table 3. For facile purification, the crude arylated products were methylated using diazomethane to furnish the corresponding methyl esters **8**. The reaction was not influenced significantly by either electron-donating or electron-withdrawing groups on the arenes. For instance, substrates bearing electron-donating groups (Me and OMe) were converted to the arylated products in good to excellent yields (**8a**–**e**). However, the position of the substituents on the arenes could not be ignored on the transformation. Undoubtly, monoarylated products were obtained if the ortho position was blocked (**8a**, **8d**). In the case of meta-substituted phosphonic acids, the reaction occurred at the less sterically hindered position to give the only monoarylated products (**8b**, **8e**). When the reaction was carried out with methyl hydrogen phenylphosphonate (**7c**) using 1.1 equiv of $PhBF_3K$, a 51:15 mixture of **8c** and **9c** along with recovery of **7c** (23%). For para-substituted substrate **7i**, a similar result was obtained. The *o*- and *m*-chloro-substituted substrates underwent ortho-phenylation cleanly, giving the desired products (**8f**, **8g**, **8h**) in high yields, whereas the fluoro-substituted substrates were influenced to some extent by the ortho- and meta-substitution. The meta-substituted substrates worked well to afford the products in excellent yields (**8k**, **8l**), while the ortho-substituted substrate slowed down the reaction, yielding **8j** in 71% yield together with recovery of starting material **7j** (25%). Notably, phosphonic monoester **7m** bearing a strong electron-withdrawing CF_3 group underwent clean phenylation to give **8m** in 92% yield. Naphthyl derivatives also worked well to give the corresponding arylated products **8n** and **8o** in 87% and 76%, respectively. As shown in Scheme 2, the phenylation of a secondary and a tertiary benzylic substrate was briefly examined and two noteworthy features were found. First, secondary

Table 3. Substrate Scope of Benzyl Phosphoric Acids



7

8^b

9^b: *di*-phenylated product

8a (91 %)

8b (86 %)

8c^c (51 %)
9c (15 %) (23 %)^d

8d (90 %)

8e (85 %)

8f (83 %)

8g (82 %)

8h (93 %)

8i^c (47 %)
9i (12 %) (35 %)^d

8j (71 %) (25 %)^d

8k (80 %)

8l (81 %)

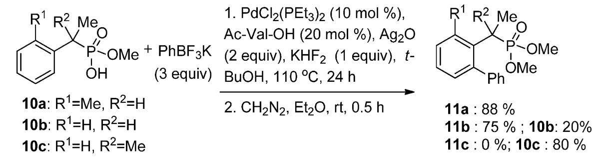
8m (92 %)

8n (87%)

8o (76 %)

^{a}The reaction was carried out with Ac-Val-OH (20 mol %), Ag$_2$O (2 equiv), KHF$_2$ (1 equiv) in *t*-BuOH at 110 °C for 24 h. ^{b}Isolated yield. ^{c}1.1 equiv of PhBF$_3$K was used. ^{d}The isolated yield of the recovered starting material.

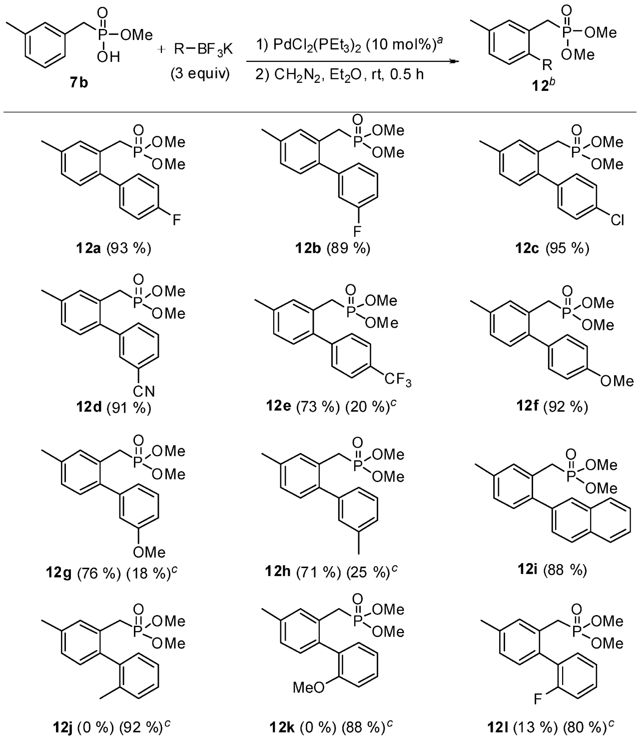
Scheme 2. Ortho-Phenylation of 10 with PhBF$_3$K



10a: R^1=Me, R^2=H
10b: R^1=H, R^2=H
10c: R^1=H, R^2=Me

11a : 88 %
11b : 75 % ; **10b**: 20%
11c : 0 %; **10c** : 80 %

Table 4. Substrate Scope of Potassium Aryltrifluoroborates



7b

12^b

12a (93 %)

12b (89 %)

12c (95 %)

12d (91 %)

12e (73 %) (20 %)^c

12f (92 %)

12g (76 %) (18 %)^c

12h (71 %) (25 %)^c

12i (88 %)

12j (0 %) (92 %)^c

12k (0 %) (88 %)^c

12l (13 %) (80 %)^c

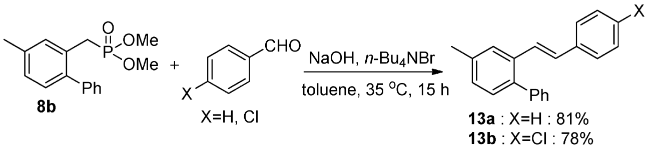
^{a}The reaction was carried out with Ac-Val-OH (20 mol %), Ag$_2$O (2 equiv), and KHF$_2$ (1 equiv) in *t*-BuOH at 110 °C for 24 h. ^{b}Isolated yield. ^{c}Isolated yield of the recovered **7b**.

substrate **10a** underwent smooth phenylation to give **11a** in 88% yield but tertiary substrate **10c** failed probably due to steric hindrance. Second, selective monophenylation at the ortho-position was achieved with **10b**.

To further determine the scope of the method, structurally different potassium aryltrifluoroborates were utilized under the standard conditions (Table 4). Potassium aryltrifluoroborates containing electron-withdrawing groups (F, Cl, CN) reacted with **7b** to afford the corresponding ortho-arylated products in high yields (**12a–d**). In the case of the strong electron-withdrawing CF$_3$ group, the arylation slowed, yielding **12e** (73%) along with recovery of **7b** (20%). This catalytic system also effectively promoted the cross-coupling of **7b** with boron reagents bearing electron-donating groups (OMe and Me) to provide the desired products in moderate to excellent yields. Although potassium 4-methoxyphenyltrifluoroborate worked as an excellent coupling partner as shown in **12f**, the meta-substituted boron reagents slowed the reaction considerably (**12g** and **12h**), probably arising from the steric hindrance of the meta-substituents. Consistent with this observation, the ortho-substituted aryltrifluoroborates could not be used as the coupling partners. Thus, **12j** and **12k** were not obtained, although **12l** was isolated only in 13% yield. Furthermore, potassium vinyl and *n*-butyl trifluoroborate failed to undergo ortho-alkenylation and alkylation under the standard conditions.

To demonstrate further transformations of the ortho-arylated products using the Horner–Wadsworth–Emmons reaction (Scheme 3),[3,15] **8b** was treated with benzaldehyde using sodium hydroxide and *n*-tetrabutylammonium bromide in toluene at 35 °C for 15 h to give the desired product **13a** in 81% yield. A similar result was also obtained with *p*-chlorobenzaldehyde.

Scheme 3. Horner–Wadworth–Emmons Reaction of 8b



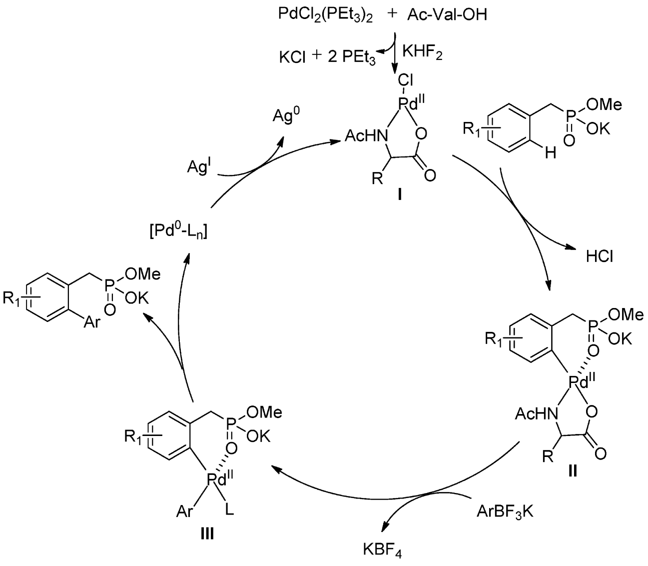
8b

X=H, Cl

13a : X=H : 81%
13b : X=Cl : 78%

On the basis of the previous studies of Pd(II)-catalyzed C–H arylation reactions,[9] we envisioned that the process might be promoted by the Pd(II) species **I** as shown in Scheme 4, which activated C–H bond to generate the palladacyclic complex **II** with the assistance of phosphonic directing group. Subsequent transmetalation and reductive elimination would afford the ortho-arylated product along with liberation of Pd(0). Reoxidation with silver(I) oxide regenerates the active Pd(II) species **I**.

Scheme 4. A Plausible Mechanism



■ CONCLUSION

We have developed a new, efficient method for direct ortho-arylation of benzylic phosphonic monoesters using potassium aryltrifluoroborates via Pd(II)-catalyzed C−H activation. The present arylation approach is not influenced significantly by the electronic properties of two coupling partners and would be very useful to prepare various biaryl compounds through further functionalizations using the Horner−Wadsworth−Emmons reactions.

■ EXPERIMENTAL SECTION

General Methods. A variety of chemical reagents were commercially purchased and used without further purification. Analytical TLC was carried out on precoated plates and visualized with UV light or stained with potassium permanganate. ^{1}H and ^{13}C NMR spectra were measured at 298 K on 400 Fourier transform NMR spectrometer. Chemical shifts were reported in δ (ppm), relative to the internal standard of TMS. The signals observed were described as follows: s (singlet), d (doublet), t (triplet), q (quartet), m (multiplet). The number of protons (*n*) for a given resonance was indicated as *n*H. Coupling constants are reported as *J* value in hertz. ^{13}C NMR is reported as δ (ppm) downfield from TMS and relative to the signal of chloroform-*d* (δ 77.00, triplet). Mass spectrometry was obtained using a Q-tof high resolution mass spectrometer.

General Procedure for Preparation of Dimethyl Benzylic Phosphonates.[16] To a solution of benzylic alcohol (1.0 mmol) in anhydrous toluene (10 mL) were added ZnI_2 (1.5 mmol) and $P(OMe)_3$ (2.0 mmol) under nitrogen. The reaction mixture was heated to 110 °C for 15 h under nitrogen. After being cooled to room temperature, the solvent was removed in vacuo. The residue was diluted with diethyl ether (20 mL), washed with 2 N NaOH (2 × 5 mL) and brine, and dried over anhydrous Na_2SO_4. After removal of the solvent, the residue was purified via flash column chromatography on silica gel (hexane/ethyl acetate = 2:1) to afford dimethyl benzylic phosphonate. Spectral data of dimethyl benzylic phosphonates of **1b**, **4**, **7a**−**g**, **7i**−**l**, **7n**, **7o** are reported previously.[7a]

Dimethyl 2-Chloro-3,4-dimethoxybenzylphosphonate. Yield: 229.4 mg, 78%, colorless liquid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.12 (dd, *J* = 8.6, 3.0 Hz, 1H), 6.79 (d, *J* = 8.6 Hz, 1H), 3.84 (d, *J* = 2.6 Hz, 6H), 3.69 (s, 3H), 3.66 (s, 3H), 3.33 (s, 1H), 3.28 (s, 1H).; ^{13}C NMR (101 MHz, $CDCl_3$) δ 152.8 (d, *J* = 3.5 Hz), 145.7 (d, *J* = 3.0 Hz), 128.9 (d, *J* = 8.0 Hz), 126.1 (d, *J* = 5.5 Hz), 122.4 (d, *J* = 9.1 Hz), 110.8 (d, *J* = 3.4 Hz), 60.6, 56.1, 52.8 (d, *J* = 6.8 Hz), 29.4 (d, *J* = 140.3 Hz).; ^{31}P NMR (162 MHz, $CDCl_3$) δ 28.2.; IR (film) ν 2953, 2358, 1597, 1490, 1267, 1031, 860, 734.; HRMS (ESI) *m*/*z* calcd for $C_{11}H_{17}O_5PCl$ $(M + H)^+$ 295.0502, found 295.0504.

Dimethyl 3-(Trifluoromethyl)benzylphosphonate. Yield: 180.0 mg, 67%, colorless liquid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.54−7.47 (m, 3H), 7.45 (t, *J* = 7.9 Hz, 1H), 3.71 (s, 3H), 3.68 (s, 3H), 3.24 (s, 1H), 3.19 (s, 1H).; ^{13}C NMR (101 MHz, $CDCl_3$) δ 133.1 (d, *J* = 6.2 Hz), 132.5 (d, *J* = 9.0 Hz), 131.0 (dd, *J* = 33.0, 2.2 Hz), 129.1 (d, *J* = 3.0 Hz), 126.4 (dd, *J* = 6.9, 3.7 Hz), 124.0 (q, *J* = 270.6 Hz), 123.9 (t, *J* = 3.7 Hz), 52.9 (d, *J* = 6.8 Hz), 32.8 (d, *J* = 139.0 Hz).; ^{31}P NMR (162 MHz, $CDCl_3$) δ 27.6.; ^{19}F NMR (377 MHz, $CDCl_3$) δ −62.7.; IR (film) ν 2956, 1450, 1330, 1126, 1033, 889, 702.; HRMS (ESI) *m*/*z* calcd for $C_{10}H_{13}O_3F_3P$ $(M + H)^+$ 269.0554, found 269.0554.

Dimethyl 1-*o*-Tolylethylphosphonate. Yield: 171.0 mg, 75%, colorless liquid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.48−7.46 (m, 1H), 7.23−7.09 (m, 3H), 3.68 (d, *J* = 10.6 Hz, 3H), 3.50−3.48 (m, 1H), 3.48 (d, *J* = 10.5 Hz, 3H), 2.37 (d, *J* = 1.1 Hz, 3H), 1.54 (dd, *J* = 18.7, 7.3 Hz, 3H).; ^{13}C NMR (101 MHz, $CDCl_3$) δ 136.3 (d, *J* = 6.0 Hz), 136.1 (d, *J* = 7.0 Hz), 130.4 (d, *J* = 2.4 Hz), 127.9 (d, *J* = 4.8 Hz), 126.9 (d, *J* = 3.2 Hz), 126.3 (d, *J* = 3.1 Hz), 53.3 (d, *J* = 7.1 Hz), 52.8 (d, *J* = 7.4 Hz), 33.1 (d, *J* = 138.0 Hz), 19.9, 15.8 (d, *J* = 5.2 Hz).; ^{31}P NMR (162 MHz, $CDCl_3$) δ 32.9.; IR (film) ν 3051, 2953, 2357, 1462, 1265, 1037, 827, 732.; HRMS (ESI) *m*/*z* calcd for $C_{11}H_{18}O_3P$ $(M + H)^+$ 229.0994, found 229.0995.

Dimethyl 1-Phenylethylphosphonate. Yield: 154.1 mg, 72%, colorless liquid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.29−7.23 (m, 4H), 7.19 (dd, *J* = 4.7, 2.2 Hz, 1H), 3.62 (d, *J* = 10.6 Hz, 3H), 3.46 (d, *J* = 10.5 Hz, 3H), 3.14 (dd, *J* = 22.7, 7.4 Hz, 1H), 1.51 (dd, *J* = 18.5, 7.4 Hz, 3H).; ^{13}C NMR (101 MHz, $CDCl_3$) δ 137.68 (d, *J* = 6.9 Hz), 128.60 (d, *J* = 6.7 Hz), 128.54 (d, *J* = 2.7 Hz), 127.18 (d, *J* = 3.2 Hz), 53.04 (dd, *J* = 48.9, 7.1 Hz), 38.08 (d, *J* = 137.8 Hz), 15.54 (d, *J* = 5.1 Hz).; ^{31}P NMR (162 MHz, $CDCl_3$) δ 32.1.; IR (film) ν 2954, 1633, 1494, 1454, 1219, 1029,823, 763, 700.; HRMS (ESI) *m*/*z* calcd for $C_{10}H_{16}O_3P$ $(M + H)^+$ 215.0837, found 215.0842.

Dimethyl 2-Phenylpropan-2-ylphosphonate. Yield: 157.3 mg, 69%, colorless liquid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.56−7.54 (m, 2H), 7.35 (t, *J* = 7.7 Hz, 2H), 7.26−7.25 (m, 1H), 3.57 (s, 3H), 3.55 (s, 3H), 1.61 (s, 3H), 1.60 (s, 3H).; ^{13}C NMR (101 MHz, $CDCl_3$) δ 141.3 (d, *J* = 5.0 Hz), 128.1 (d, *J* = 2.7 Hz), 127.6 (d, *J* = 5.3 Hz), 126.8 (d, *J* = 3.2 Hz), 53.4 (d, *J* = 7.4 Hz), 39.3 (d, *J* = 136.4 Hz), 23.9 (d, *J* = 4.1 Hz).; ^{31}P NMR (162 MHz, $CDCl_3$) δ 34.6.; IR (film) ν 2955, 1645, 1497, 1231, 1053, 1028, 806, 698.; HRMS (ESI) *m*/*z* calcd for $C_{11}H_{18}O_3P$ $(M + H)^+$ 229.0994, found 229.0992.

General Procedure for Preparation of Methyl Hydrogen Benzylic Phosphonate 7.[2a] To a solution of dimethyl benzylic phosphonate (0.5 mmol) in $SOCl_2$ (0.5 mL) was added a catalytic amount of DMF (3.7 mg, 0.05 mmol) at room temperature. The reaction mixture was allowed to stir at reflux for 3 h. Excess $SOCl_2$ was removed, and the residue was diluted with dichloromethane (10 mL). Cool water (1.0 mL) was then added to the solution at 0 °C, and the mixture was stirred for 10 min. The organic layer was separated and washed with brine, dried over $MgSO_4$, filtered, and concentrated in vacuo. The resulting residue was purified by flash chromatography on silica (dichloromethane/methanol = 20:1) to afford methyl hydrogen benzylic phosphonate 7. The spectral data of **1b**, **4**, **7a**−**g**, **7i**−**l**, **7n**, **7o** have been reported previously.[7a]

Methyl Hydrogen 2-Chloro-3,4-dimethoxybenzylphosphonate (7h). Yield: 122.0 mg, 83%, colorless liquid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.14−7.06 (m, 1H), 6.77 (d, *J* = 8.6 Hz, 1H), 3.88−3.77 (m, 6H), 3.63−3.58 (m, 3H), 3.28 (s, 1H), 3.23 (s, 1H).; ^{13}C NMR (101 MHz, $CDCl_3$) δ 152.7 (d, *J* = 2.9 Hz), 145.6, 129.1 (d, *J* = 7.9 Hz), 126.1 (d, *J* = 5.6 Hz), 122.5 (d, *J* = 9.0 Hz), 110.6 (d, *J* = 3.4 Hz), 60.5, 56.0, 52.2 (d, *J* = 6.8 Hz), 29.9 (d, *J* = 142.0 Hz).; ^{31}P NMR (162 MHz, $CDCl_3$) δ 29.9.; IR (film) ν 2852, 2358, 1635, 1489, 1043, 989.; HRMS (ESI) *m*/*z* calcd for $C_{10}H_{15}O_5PCl$ $(M + H)^+$ 281.0346, found 281.0343.

Methyl Hydrogen 3-(Trifluoromethyl)benzylphosphonate (7m). Yield: 108.6 mg, 81%, yellow oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.43 (br, 1H), 7.51 (d, *J* = 11.3 Hz, 2H), 7.47−7.38 (m, 2H), 3.55 (d, *J* = 11.2 Hz, 3H), 3.13 (s, 1H), 3.08 (s, 1H).; ^{13}C NMR

(101 MHz, $CDCl_3$) δ 133.3 (d, *J* = 6.3 Hz), 132.4 (d, *J* = 9.2 Hz), 130.9 (dd, *J* = 32.3, 3.1 Hz), 128.9 (d, *J* = 3.0 Hz), 126.5 (dd, *J* = 6.7, 3.7 Hz), 123.9 (q, *J* = 272.7 Hz), 123.8 (t, *J* = 3.6 Hz), 52.0 (d, *J* = 7.1 Hz), 33.1 (d, *J* = 141.2 Hz).; IR (film) ν 2987, 1450, 1330, 1167, 1126, 1049, 740, 702.; ^{31}P NMR (162 MHz, $CDCl_3$) δ 29.1.; ^{19}F NMR (377 MHz, $CDCl_3$) δ −62.7.; HRMS (ESI) *m*/*z* calcd for $C_9H_{11}O_3PF_3$ $(M + H)^+$ 255.0398, found 255.0397.

Methyl Hydrogen 1-*o*-Tolylethylphosphonate (10a). Yield: 90.1 mg, 79%, yellow oil; ^1H NMR (400 MHz, $CDCl_3$) δ 7.43 (d, *J* = 7.5 Hz, 1H), 7.22−7.08 (m, 3H), 3.54−3.47 (m, 3H), 3.47−3.36 (m, 1H), 2.36 (s, 3H), 1.52 (dd, *J* = 18.7, 7.3 Hz, 3H).; ^{13}C NMR (101 MHz, $CDCl_3$) δ 136.6 (d, *J* = 8.1 Hz), 136.2 (d, *J* = 6.7 Hz), 130.3 (d, *J* = 2.5 Hz), 127.8 (d, *J* = 4.8 Hz), 126.8 (d, *J* = 3.2 Hz), 126.2 (d, *J* = 3.2 Hz), 51.9 (d, *J* = 7.5 Hz), 32.9 (d, *J* = 140.0 Hz), 19.9, 15.5 (d, *J* = 5.1 Hz).; ^{31}P NMR (162 MHz, $CDCl_3$) δ 34.2.; IR (film) ν 3003, 2250, 1705, 1361, 1223, 1051, 918, 732.; HRMS (ESI) *m*/*z* calcd for $C_{10}H_{16}O_3P$ $(M + H)^+$ 215.0837, found 215.0836.

Methyl Hydrogen 1-Phenylethylphosphonate (10b). Yield: 73.0 mg, 73%, colorless liquid; ^1H NMR (400 MHz, $CDCl_3$) δ 11.02 (br, 1H), 7.34−7.25 (m, 4H), 7.25−7.17 (m, 1H), 3.48 (d, *J* = 10.8 Hz, 3H), 3.12 (dd, *J* = 23.2, 7.4 Hz, 1H), 1.52 (dd, *J* = 18.7, 7.5 Hz, 3H).; ^{13}C NMR (101 MHz, $CDCl_3$) δ 137.8 (d, *J* = 7.1 Hz), 128.7 (d, *J* = 6.5 Hz), 128.4 (d, *J* = 2.6 Hz), 127.0 (d, *J* = 3.2 Hz), 52.0 (d, *J* = 7.4 Hz), 37.9 (d, *J* = 140.1 Hz), 15.2 (d, *J* = 5.0 Hz). ^{31}P NMR (162 MHz, $CDCl_3$) δ 32.7.; IR (film) ν 2953, 2850, 1602, 1494, 1454, 821, 783, 765, 732, 698.; HRMS (ESI) *m*/*z* calcd for $C_9H_{14}O_3P$ $(M + H)^+$ 201.0681, found 201.0688.

Methyl Hydrogen 2-Phenylpropan-2-ylphosphonate (10c). Yield: 75.3 mg, 66%, yellow oil; ^1H NMR (400 MHz, $CDCl_3$) δ 9.03 (br, 1H), 7.43 (d, *J* = 1.7 Hz, 1H), 7.37 (ddd, *J* = 7.1, 3.7, 1.9 Hz, 1H), 7.23−7.13 (m, 2H), 3.59 (d, *J* = 11.2 Hz, 3H), 3.06 (s, 1H), 3.01 (s, 1H).; ^{13}C NMR (101 MHz, $CDCl_3$) δ 141.3, 128.0, 127.7 (d, *J* = 4.3 Hz), 126.6, 52.2 (d, *J* = 7.2 Hz), 38.5 (d, *J* = 140.1 Hz), 23.6.; ^{31}P NMR (162 MHz, $CDCl_3$) δ 35.7.; IR (film) ν 3053, 2985, 1419, 1265, 1047, 976, 895, 739, 704.; HRMS (ESI) *m*/*z* calcd for $C_{10}H_{16}O_3P$ $(M + H)^+$ 215.0837, found 215.0841.

$Pd(TFA)_2$-Catalyzed Reaction of Benzylic Phosphonic Monoester 1b with Diphenyliodium Triflate. To a mixture of benzylic phosphonic monoester **1b** (20.0 mg, 0.1 mmol) and Ph_2IOTf (64.5 mg, 0.15 mmol) in 1,2-dichloroethane (1.5 mL) was added $Pd(TFA)_2$ (3.3 mg, 0.01 mmol). The reaction mixture was heated at 110 °C for 15 h in a sealed vial and then cooled to room temperature. The crude mixture was filtered through a cotton plug to remove the solid residues, and concentrated in vacuo. The crude mixture was diluted with EtOAc (1 mL) and washed with aqueous $Na_2S_2O_3$ (1 mL). The aqueous layer was further extracted with EtOAc (3 mL × 3), and the combined organic layer was concentrated in vacuo. The residue was purified by flash chromatography (dichloromethane/acetone = 20:1) to afford the O-phenylated product **3b** (6.9 mg, 25%) and the starting material **1b** (12.0 mg, 60%).

Methyl Phenyl 2-Methylbenzylphosphonate (3b). Yield: 6.9 mg, 25%, colorless liquid; ^1H NMR (400 MHz, $CDCl_3$) δ 7.33−7.26 (m, 3H), 7.21−7.11 (m, 4H), 7.10−7.06 (m, 2H), 3.69 (d, *J* = 11.0 Hz, 3H), 3.38 (s, 1H), 3.33 (d, *J* = 0.9 Hz, 1H), 2.39 (d, *J* = 1.7 Hz, 3H).; ^{13}C NMR (101 MHz, $CDCl_3$) δ 150.7 (d, *J* = 9.0 Hz), 137.1 (d, *J* = 6.9 Hz), 130.7 (d, *J* = 5.7 Hz), 130.6 (d, *J* = 3.5 Hz), 129.2 (d, *J* = 9.7 Hz), 127.4 (d, *J* = 3.9 Hz), 126.2 (d, *J* = 3.6 Hz), 124.8, 120.3 (d, *J* = 4.4 Hz), 53.4 (d, *J* = 7.3 Hz), 30.7 (d, *J* = 139.1 Hz), 20.0.; ^{31}P NMR (162 MHz, $CDCl_3$) δ 24.7.; IR (film) ν 2958, 1591, 1489, 1261, 1205, 1041, 927, 802.; HRMS (ESI) *m*/*z* calcd for $C_{15}H_{18}O_3P$ $(M + H)^+$ 277.0994, found 277.0992.

Typical Procedure for the Ortho-Arylation of Benzylic Phosphonic Monoester 7a. To a mixture of benzylic phosphonic monoester **7a** (21.5 mg, 0.1 mmol) and $PhBF_3K$ (50.2 mg, 0.3 mmol) in *tert*-butyl alcohol (1.5 mL) were added $PdCl_2(PEt_3)_2$ (4.2 mg, 0.01 mmol), Ac-Val-OH (3.5 mg, 0.02 mmol), KHF_2 (7.8 mg, 0.1 mmol), and Ag_2O (46.4 mg, 0.2 mmol). The reaction mixture was heated at 110 °C for 24 h in a sealed vial. After the reaction mixture was cooled to 0 °C, EtOAc (10 mL) and 2.0 N HCl solution (1 mL) were added. The organic layer was separated and washed with brine, it was dried over anhydrous $MgSO_4$ and concentrated in vacuo to yield the crude product, which was subjected to silica gel column chromatography (dichloromethane/acetone = 10:1) to get the acid. The crude acid was dissolved in diethyl ether and treated with an excess amount of CH_2N_2 in diethyl ether at room temperature for 0.5 h. Diethyl ether was evaporated under reduced pressure and the crude product was purified by passing through silica gel flash column (dichloromethane/acetone = 20:1) to afford **8a** (27.6 mg, 91%).

Dimethyl (3-Methylbiphenyl-2-yl)methylphosphonate (2c). Yield: 23.6 mg, 81%; yellow liquid; ^1H NMR (400 MHz, $CDCl_3$) δ 7.46−7.38 (m, 2H), 7.34 (dd, *J* = 7.2, 5.5 Hz, 3H), 7.19 (dd, *J* = 4.0, 2.7 Hz, 2H), 7.08−7.05 (m, 1H), 3.42 (s, 3H), 3.40 (s, 3H), 3.36 (s, 1H), 3.31 (s, 1H), 2.51 (d, *J* = 1.5 Hz, 3H).; ^{13}C NMR (101 MHz, $CDCl_3$) δ 143.3 (d, *J* = 6.4 Hz), 142.1, 138.1 (d, *J* = 5.5 Hz), 129.8 (d, *J* = 3.8 Hz), 129.6, 128.4 (d, *J* = 3.6 Hz), 128.1, 127.8 (d, *J* = 3.1 Hz), 127.0 (s), 126.7 (d, *J* = 4.1 Hz), 52.3 (d, *J* = 6.9 Hz), 27.4 (d, *J* = 137.5 Hz), 20.9 (d, *J* = 1.4 Hz).; ^{31}P NMR (162 MHz, $CDCl_3$) δ 29.0.; IR (film) ν 2953, 1462, 1252, 1055, 1029, 888, 839,704.; HRMS (ESI) *m*/*z* calcd for $C_{16}H_{20}O_3P$ $(M + H)^+$ 291.1150, found 291.1148.

Dimethyl (3,5-Dimethylbiphenyl-2-yl)methylphosphonate (8a). Yield: 27.6 mg, 91%; yellow liquid; ^1H NMR (400 MHz, $CDCl_3$) δ 7.41 (dd, *J* = 10.2, 4.4 Hz, 2H), 7.32 (dd, *J* = 7.1, 5.2 Hz, 3H), 7.02 (s, 1H), 6.89 (s, 1H), 3.42 (s, 3H), 3.39 (s, 3H), 3.32 (s, 1H), 3.26 (s, 1H), 2.46 (d, *J* = 1.4 Hz, 3H), 2.30 (d, *J* = 2.5 Hz, 3H).; ^{13}C NMR (101 MHz, $CDCl_3$) δ 143.1 (d, *J* = 6.3 Hz), 142.2, 137.9 (d, *J* = 5.4 Hz), 136.2 (d, *J* = 4.2 Hz), 130.7 (d, *J* = 3.8 Hz), 129.5, 129.2 (d, *J* = 3.6 Hz), 128.1, 126.9, 124.5 (d, *J* = 10.0 Hz), 52.3 (d, *J* = 6.9 Hz), 27.0 (d, *J* = 137.8 Hz), 20.8 (d, *J* = 5.7 Hz).; ^{31}P NMR (162 MHz, $CDCl_3$) δ 29.3.; IR (film) ν 2953, 1472, 1251, 1055, 1029, 819, 779, 704.; HRMS (ESI) *m*/*z* calcd for $C_{17}H_{22}O_3P$ $(M + H)^+$ 305.1307, found 305.1308.

Dimethyl (4-Methylbiphenyl-2-yl)methylphosphonate (8b). Yield: 25.0 mg, 86%; yellow liquid; ^1H NMR (400 MHz, $CDCl_3$) δ 7.45−7.32 (m, 6H), 7.14 (t, *J* = 7.3 Hz, 2H), 3.59 (s, 3H), 3.56 (s, 3H), 3.21 (s, 1H), 3.15 (s, 1H), 2.39 (s, 3H).; ^{13}C NMR (101 MHz, $CDCl_3$) δ 141.1, 139.8 (d, *J* = 8.1 Hz), 137.2 (d, *J* = 3.2 Hz), 131.1 (d, *J* = 4.6 Hz), 130.4 (d, *J* = 2.7 Hz), 129.6, 128.2, 127.8 (d, *J* = 3.3 Hz), 127.0, 52.6 (d, *J* = 6.8 Hz), 29.3 (d, *J* = 138.1 Hz), 21.1.; IR (film) ν 2954, 1458, 1257, 1057, 1031, 867, 761, 704.; ^{31}P NMR (162 MHz, $CDCl_3$) δ 29.5.; HRMS (ESI) *m*/*z* calcd for $C_{16}H_{20}O_3P$ $(M + H)^+$ 291.1150, found 291.1152.

Dimethyl Biphenyl-2-ylmethylphosphonate (8c). Yield: 14.1 mg, 51%; yellow liquid; ^1H NMR (400 MHz, $CDCl_3$) δ 7.57−7.52 (m, 1H), 7.46−7.40 (m, 2H), 7.40−7.35 (m, 3H), 7.33 (dd, *J* = 7.4, 2.1 Hz, 1H), 7.30 (dd, *J* = 5.4, 3.7 Hz, 1H), 7.25 (d, *J* = 5.4 Hz, 1H), 3.59 (s, 3H), 3.56 (s, 3H), 3.24 (s, 1H), 3.18 (s, 1H).; ^{13}C NMR (101 MHz, $CDCl_3$) δ 142.6 (d, *J* = 8.3 Hz), 141.1, 130.5 (d, *J* = 0.8 Hz), 130.5 (d, *J* = 3.3 Hz), 129.5, 128.7 (d, *J* = 8.7 Hz), 128.3, 127.5 (d, *J* = 3.4 Hz), 127.2, 127.0 (d, *J* = 3.5 Hz), 52.7 (d, *J* = 6.8 Hz), 29.4 (d, *J* = 138.3 Hz).; IR (film) ν 2953, 1481, 1254, 1051, 1030, 858, 746, 704.; ^{31}P NMR (162 MHz, $CDCl_3$) δ 29.3.; HRMS (ESI) *m*/*z* calcd for $C_{15}H_{18}O_3P$ $(M + H)^+$ 277.0994, found 277.0994.

Dimethyl (3-Phenylbiphenyl-2-yl)methylphosphonate (9c). Yield: 5.3 mg, 15%; yellow liquid; ^1H NMR (400 MHz, $CDCl_3$) δ 7.46−7.40 (m, 8H), 7.37−7.33 (m, 2H), 7.32−7.30 (m, 1H), 7.23 (d, *J* = 7.6 Hz, 2H), 3.45 (s, 1H), 3.39 (s, 1H), 3.18 (s, 3H), 3.15 (s, 3H).; ^{13}C NMR (101 MHz, $CDCl_3$) δ 143.7 (d, *J* = 6.0 Hz), 142.1, 130.0 (d, *J* = 3.7 Hz), 129.7, 128.2, 127.1, 126.9 (d, *J* = 10.2 Hz), 126.6 (d, *J* = 4.0 Hz), 51.8 (d, *J* = 6.8 Hz), 27.0 (d, *J* = 136.3 Hz).; ^{31}P NMR (162 MHz, $CDCl_3$) δ 28.7.; IR (film) ν 2951, 1456, 1256, 1057, 1032, 868,761, 704.; HRMS (ESI) *m*/*z* calcd for $C_{21}H_{22}O_3P$ $(M + H)^+$ 353.1307, found 353.1304.

Dimethyl (3-Methoxybiphenyl-2-yl)methylphosphonate (8d). Yield: 27.6 mg, 90%; yellow liquid; ^1H NMR (400 MHz, $CDCl_3$) δ 7.44−7.38 (m, 2H), 7.37−7.32 (m, 3H), 7.239−7.239 (m, 1H), 6.88 (dd, *J* = 16.7, 8.0 Hz, 2H), 3.91 (s, 3H), 3.50 (s, 3H), 3.47 (s, 3H), 3.35 (s, 1H), 3.30 (s, 1H).; ^{13}C NMR (101 MHz, $CDCl_3$) δ 157.7 (d, *J* = 5.3 Hz), 144.0 (d, *J* = 6.7 Hz), 141.2, 129.5, 128.1, 127.5 (d, *J* = 3.9 Hz), 127.1, 122.9 (d, *J* = 3.5 Hz), 118.5 (d, *J* = 10.4 Hz), 109.4 (d, *J* = 3.4 Hz), 55.7, 52.2 (d, *J* = 6.5 Hz), 24.1 (d, *J* = 138.3 Hz).;

IR (film) ν 2953, 1573, 1470, 1260, 1032, 886, 764, 706.; ^{31}P NMR (162 MHz, $\mathrm{CDCl_3}$) δ 29.8.; HRMS (ESI) m/z calcd for $\mathrm{C_{16}H_{20}O_4P}$ $(\mathrm{M + H})^+$ 307.1099, found 307.1092.

Dimethyl (4-Methoxybiphenyl-2-yl)methylphosphonate (8e). Yield: 26.1 mg, 85%; yellow liquid; ^{1}H NMR (400 MHz, $\mathrm{CDCl_3}$) δ 7.42 (d, J = 7.5 Hz, 2H), 7.34 (d, J = 7.3 Hz, 3H), 7.18 (d, J = 8.4 Hz, 1H), 7.10 (s, 1H), 6.86 (d, J = 8.5 Hz, 1H), 3.85 (s, 3H), 3.60 (s, 3H), 3.58 (s, 3H), 3.21 (s, 1H), 3.16 (s, 1H).; ^{13}C NMR (101 MHz, $\mathrm{CDCl_3}$) δ 158.8, 140.8, 135.2 (d, J = 8.3 Hz), 131.5 (d, J = 2.7 Hz), 129.9 (d, J = 8.8 Hz), 129.7, 128.3, 126.9, 115.5 (d, J = 4.8 Hz), 112.9 (d, J = 3.4 Hz), 55.4, 52.7 (d, J = 6.8 Hz), 29.6 (d, J = 138.1 Hz).; ^{31}P NMR (162 MHz, $\mathrm{CDCl_3}$) δ 29.2.; IR (film) ν 2955, 1608, 1485, 1234, 1030, 712, 705.; HRMS (ESI) m/z calcd for $\mathrm{C_{16}H_{20}O_4P}$ $(\mathrm{M + H})^+$ 307.1099, found 307.1097.

Dimethyl (3-Chlorobiphenyl-2-yl)methylphosphonate (8f). Yield: 25.8 mg, 83%; yellow liquid; ^{1}H NMR (400 MHz, $\mathrm{CDCl_3}$) δ 7.36 (t, J = 7.5 Hz, 3H), 7.30 (d, J = 7.2 Hz, 1H), 7.26 (d, J = 7.2 Hz, 2H), 7.15 (dd, J = 7.8, 2.4 Hz, 1H), 7.07 (d, J = 7.5 Hz, 1H), 3.45 (s, 1H), 3.43 (s, 3H), 3.40 (s, 3H), 3.41 (s, 1H),; ^{13}C NMR (101 MHz, $\mathrm{CDCl_3}$) δ 144.8 (d, J = 6.1 Hz), 140.9, 135.3 (d, J = 6.5 Hz), 129.4, 129.2 (d, J = 3.6 Hz), 128.9 (d, J = 3.6 Hz), 128.3, 127.7 (d, J = 3.9 Hz), 127.5, 52.4 (d, J = 6.7 Hz), 28.1 (d, J = 138.3 Hz).; IR (film) ν 2953, 1562, 1452, 1265, 1031, 870, 793, 164, 704.; ^{31}P NMR (162 MHz, $\mathrm{CDCl_3}$) δ 27.5.; HRMS (ESI) m/z calcd for $\mathrm{C_{15}H_{17}O_3PCl}$ $(\mathrm{M + H})^+$ 311.0604, found 311.0608.

Dimethyl (4-Chlorobiphenyl-2-yl)methylphosphonate (8g). Yield: 25.5 mg, 82%; yellow liquid; ^{1}H NMR (400 MHz, $\mathrm{CDCl_3}$) δ 7.51 (t, J = 2.4 Hz, 1H), 7.43 (dd, J = 7.9, 6.3 Hz, 2H), 7.36 (ddd, J = 8.3, 6.9, 1.5 Hz, 3H), 7.30−7.26 (m, 1H), 7.21−7.17 (m, 1H), 3.63 (s, 3H), 3.60 (s, 3H), 3.19 (s, 1H), 3.13 (s, 1H).; ^{13}C NMR (101 MHz, $\mathrm{CDCl_3}$) δ 141.1 (d, J = 8.2 Hz), 139.9, 133.3 (d, J = 4.0 Hz), 131.7 (d, J = 2.8 Hz), 130.8 (d, J = 8.8 Hz), 130.2 (d, J = 4.9 Hz), 129.4, 128.4, 127.5, 127.2 (d, J = 3.5 Hz), 52.8 (d, J = 6.8 Hz), 29.4 (d, J = 138.7 Hz).; ^{31}P NMR (162 MHz, $\mathrm{CDCl_3}$) δ 28.4.; IR (film) ν 2953, 1635, 1476, 1252, 1030, 888, 809, 704.; HRMS (ESI) m/z calcd for $\mathrm{C_{15}H_{17}O_3PCl}$ $(\mathrm{M + H})^+$ 311.0604, found 311.0607.

Dimethyl (3-Chloro-4,5-dimethoxybiphenyl-2-yl)methylphosphonate (8h). Yield: 34.4 mg, 93%; yellow liquid; ^{1}H NMR (400 MHz, $\mathrm{CDCl_3}$) δ 7.48−7.40 (m, 2H), 7.39−7.31 (m, 3H), 7.26 (s, 1H), 3.91 (s, 3H), 3.85 (s, 3H), 3.50 (s, 3H), 3.47 (s, 3H), 3.43 (s, 1H), 3.37 (s, 1H).; ^{13}C NMR (101 MHz, $\mathrm{CDCl_3}$) δ 151.9 (d, J = 3.8 Hz), 144.9, 141.1 (d, J = 1.6 Hz), 139.5 (d, J = 6.5 Hz), 129.8 (d, J = 6.0 Hz), 129.5, 128.3, 127.5, 120.9 (d, J = 10.5 Hz), 113.1 (d, J = 3.6 Hz), 60.6, 56.1, 52.3 (d, J = 6.7 Hz), 27.9 (d, J = 139.5 Hz).; ^{31}P NMR (162 MHz, $\mathrm{CDCl_3}$) δ 28.0.; IR (film) ν 2955, 1562, 1487, 1349, 1273, 1031, 886, 704.; HRMS (ESI) m/z calcd for $\mathrm{C_{17}H_{20}O_5PClNa}$ $(\mathrm{M + Na})^+$ 393.0635, found 393.0630.

Dimethyl (5-Chlorobiphenyl-2-yl)methylphosphonate (8i). Yield: 14.6 mg, 47%; yellow liquid; ^{1}H NMR (400 MHz, $\mathrm{CDCl_3}$) δ 7.50−7.41 (m, 3H), 7.41−7.28 (m, 5H), 3.60 (s, 3H), 3.58 (s, 3H), 3.18 (s, 1H), 3.12 (s, 1H).; ^{13}C NMR (101 MHz, $\mathrm{CDCl_3}$) δ 144.2 (d, J = 8.3 Hz), 139.8, 132.7 (d, J = 4.2 Hz), 131.8 (d, J = 4.9 Hz), 130.3 (d, J = 2.9 Hz), 129.3, 128.4, 127.7, 127.6 (d, J = 3.4 Hz), 127.4 (d, J = 8.7 Hz), 52.7 (d, J = 6.7 Hz), 28.9 (d, J = 138.8 Hz).; ^{31}P NMR (162 MHz, $\mathrm{CDCl_3}$) δ 28.7.; IR (film) ν 2955, 1636. 1472, 1250, 1057, 1031, 864, 806, 704.; HRMS (ESI) m/z calcd for $\mathrm{C_{15}H_{17}O_3PCl}$ $(\mathrm{M + H})^+$ 311.0604, found 311.0600.

Dimethyl (5-Chloro-3-phenylbiphenyl-2-yl)methylphosphonate (9i). Yield: 4.6 mg, 12%; yellow liquid; ^{1}H NMR (400 MHz, $\mathrm{CDCl_3}$) δ 7.41 (dd, J = 17.0, 7.0 Hz, 10H), 7.24 (d, J = 0.8 Hz, 2H), 3.38 (s, 1H), 3.32 (s, 1H), 3.19 (s, 3H), 3.16 (s, 3H).; ^{13}C NMR (101 MHz, $\mathrm{CDCl_3}$) δ 145.2 (d, J = 6.0 Hz), 140.8, 132.2 (d, J = 4.9 Hz), 129.7 (d, J = 3.8 Hz), 129.5, 128.3, 127.5, 125.8 (d, J = 10.3 Hz), 51.9 (d, J = 6.7 Hz), 26.6 (d, J = 136.8 Hz).; IR (film) ν 2954, 1636, 1570, 1423, 1265, 1058, 1034, 736, 702.; ^{31}P NMR (162 MHz, $\mathrm{CDCl_3}$) δ 28.1.; HRMS (ESI) m/z calcd for $\mathrm{C_{21}H_{21}O_3PCl}$ $(\mathrm{M + H})^+$ 387.0917, found 387.0917.

Dimethyl (3-Fluorobiphenyl-2-yl)methylphosphonate (8j). Yield: 21.0 mg, 71%; yellow liquid; ^{1}H NMR (400 MHz, $\mathrm{CDCl_3}$) δ 7.37 (dd, J = 10.2, 4.2 Hz, 2H), 7.30 (ddd, J = 4.6, 3.3, 2.2 Hz, 3H), 7.23−7.19 (m, 1H), 7.00 (dd, J = 16.4, 8.2 Hz, 2H), 3.48 (s, 3H), 3.45 (s, 3H), 3.25 (d, J = 2.3 Hz, 1H), 3.19 (d, J = 2.3 Hz, 1H).; ^{13}C NMR (101 MHz, $\mathrm{CDCl_3}$) δ 161.3(dd, J = 246.9, 5.9 Hz), 144.8 (d, J = 3.5 Hz), 140.0, 129.4, 128.3, 128.1 (dd, J = 9.3, 3.8 Hz), 127.5, 126.2 (t, J = 3.2 Hz), 117.5 (dd, J = 15.7, 10.1 Hz), 114.3 (dd, J = 22.8, 3.5 Hz), 52.5 (d, J = 6.4 Hz), 23.5 (dd, J = 139.4, 3.3 Hz).; ^{31}P NMR (162 MHz, $\mathrm{CDCl_3}$) δ 27.8 (d, J = 3.6 Hz).; ^{19}F NMR (376 MHz, $\mathrm{CDCl_3}$) δ −113.3 (d, J = 3.7 Hz).; IR (film) ν 2953, 1636, 1464, 1265, 1032, 902, 736, 702.; HRMS (ESI) m/z calcd for $\mathrm{C_{15}H_{17}O_3PF}$ $(\mathrm{M + H})^+$ 295.0899, found 295.0899.

Dimethyl (4-Fluorobiphenyl-2-yl)methylphosphonate (8k). Yield: 23.6 mg, 80%; yellow liquid; ^{1}H NMR (400 MHz, $\mathrm{CDCl_3}$) δ 7.47−7.41 (m, 2H), 7.35 (dd, J = 12.8, 7.3 Hz, 3H), 7.23 (dd, J = 12.4, 5.4 Hz, 2H), 7.01 (d, J = 8.1 Hz, 1H), 3.63 (s, 3H), 3.60 (s, 3H), 3.20 (s, 1H), 3.14 (s, 1H).; ^{13}C NMR (101 MHz, $\mathrm{CDCl_3}$) δ 161.9 (d, J = 242.4 Hz), 140.1, 138.7 (dd, J = 9.5, 4.8 Hz), 131.9 (dd, J = 8.2, 2.8 Hz), 131.0 (t, J = 8.4 Hz), 129.6, 128.4, 127.4, 117.0 (dd, J = 22.3, 4.8 Hz), 114.0 (dd, J = 21.1, 3.4 Hz), 52.7 (d, J = 6.7 Hz), 29.6 (d, J = 138.6 Hz).; ^{31}P NMR (162 MHz, $\mathrm{CDCl_3}$) δ 28.5 (d, J = 2.1 Hz).; ^{19}F NMR (376 MHz, $\mathrm{CDCl_3}$) δ −114.9 (d, J = 2.6 Hz).; IR (film) ν 2955, 1609, 1483, 1252, 1031, 956, 816, 708.; HRMS (ESI) m/z calcd for $\mathrm{C_{15}H_{17}O_3PF}$ $(\mathrm{M + H})^+$ 295.0899, found 295.0898.

Dimethyl (4-Fluoro-5-methoxybiphenyl-2-yl)methylphosphonate (8l). Yield: 26.3 mg, 81%; yellow liquid; ^{1}H NMR (400 MHz, $\mathrm{CDCl_3}$) δ 7.43 (d, J = 7.4 Hz, 2H), 7.37 (dd, J = 9.1, 7.6 Hz, 3H), 7.25 (d, J = 7.4 Hz, 1H), 6.84 (d, J = 8.7 Hz, 1H), 3.87 (s, 3H), 3.63 (s, 3H), 3.60 (s, 3H), 3.11 (s, 1H), 3.05 (s, 1H).; ^{13}C NMR (101 MHz, $\mathrm{CDCl_3}$) δ 151.4 (dd, J = 246.1, 3.8 Hz), 146.2 (dd, J = 10.8, 3.3 Hz), 140.4, 139.4−13.0 (m), 129.5, 128.4, 127.5, 121.3 (dd, J = 9.0, 6.8 Hz), 117.7 (dd, J = 19.1, 4.5 Hz), 115.4, 56.3, 52.7 (d, J = 6.8 Hz), 28.7 (d, J = 139.5 Hz).; ^{31}P NMR (162 MHz, $\mathrm{CDCl_3}$) δ 28.9.; ^{19}F NMR (376 MHz, $\mathrm{CDCl_3}$) δ −136.7 (d, J = 2.5 Hz).; IR (film) ν 2955, 1636, 1516, 1232, 1034, 830, 704.; HRMS (ESI) m/z calcd for $\mathrm{C_{16}H_{19}O_4P\ F}$ $(\mathrm{M + H})^+$ 325.1005, found 325.1010.

Dimethyl (4-(Trifluoromethyl)biphenyl-2-yl)methylphosphonate (8m). Yield: 31.7 mg, 92%; yellow liquid; ^{1}H NMR (400 MHz, $\mathrm{CDCl_3}$) δ 7.77 (s, 1H), 7.56 (d, J = 8.1 Hz, 1H), 7.49−7.35 (m, 6H), 3.63 (s, 3H), 3.60 (s, 3H), 3.26 (s, 1H), 3.20 (s, 1H).; ^{13}C NMR (101 MHz, $\mathrm{CDCl_3}$) δ 146.2 (d, J = 9.2 Hz), 139.8, 131.0 (d, J = 2.8 Hz), 130.1 (d, J = 8.8 Hz), 129.2, 128.5, 127.9, 127.5−127.0 (m), 123.7 (t, J = 3.6 Hz), 52.8 (d, J = 6.8 Hz), 29.5 (d, J = 138.8 Hz).; ^{31}P NMR (162 MHz, $\mathrm{CDCl_3}$) δ 28.1.; ^{19}F NMR (376 MHz, $\mathrm{CDCl_3}$) δ −62.5.; IR (film) ν 2954, 1636, 1332, 1126, 1032, 899, 704.; HRMS (ESI) m/z calcd for $\mathrm{C_{16}H_{17}O_3PF_3}$ $(\mathrm{M + H})^+$ 345.0866, found 345.0867.

Dimethyl (2-Phenylnaphthalen-1-yl)methylphosphonate (8n). Yield: 28.5 mg, 87%; yellow liquid; ^{1}H NMR (400 MHz, $\mathrm{CDCl_3}$) δ 8.03 (d, J = 3.6 Hz, 1H), 7.89−7.84 (m, 1H), 7.83−7.77 (m, 1H), 7.74 (s, 1H), 7.50−7.42 (m, 6H), 7.40 (dd, J = 6.1, 2.6 Hz, 1H), 3.58 (s, 3H), 3.55 (s, 3H), 3.39 (s, 1H), 3.33 (s, 1H).; ^{13}C NMR (101 MHz, $\mathrm{CDCl_3}$) δ 141.1, 140.7 (d, J = 7.0 Hz), 132.6 (d, J = 3.5 Hz), 132.3 (d, J = 2.6 Hz), 129.7, 129.5 (d, J = 6.6 Hz), 129.3, 128.3, 127.5 (d, J = 7.4 Hz), 127.3, 127.1 (d, J = 8.9 Hz), 126.2, 52.7 (d, J = 6.8 Hz), 29.5 (d, J = 138.4 Hz).; ^{31}P NMR (162 MHz, $\mathrm{CDCl_3}$) δ 29.2.; IR (film) ν 2953, 1636, 1497, 1265, 1057, 1034, 815, 736, 702.; HRMS (ESI) m/z calcd for $\mathrm{C_{19}H_{20}O_3P}$ $(\mathrm{M + H})^+$ 327.1150, found 327.1148.

Dimethyl (3-Phenylnaphthalen-2-yl)methylphosphonate (8o). Yield: 24.8 mg, 76%, colorless liquid; ^{1}H NMR (400 MHz, $\mathrm{CDCl_3}$) δ 8.03 (d, J = 3.6 Hz, 1H), 7.90−7.84 (m, 1H), 7.82−7.79 (m, 1H), 7.74 (s, 1H), 7.50−7.44 (m, 6H), 7.41 (dd, J = 6.2, 2.5 Hz, 1H), 3.58 (s, 3H), 3.56 (s, 3H), 3.39 (s, 1H), 3.34 (s, 1H).; ^{13}C NMR (101 MHz, $\mathrm{CDCl_3}$) δ 141.1, 140.7 (d, J = 7.1 Hz), 132.6 (d, J = 3.5 Hz), 132.3 (d, J = 2.5 Hz), 129.7, 129.5, 129.4, 129.3 (d, J = 2.2 Hz), 127.9 (d, J = 1.5 Hz), 127.5 (d, J = 1.2 Hz), 127.1, 127.0, 126.3, 126.2, 52.7 (d, J = 6.8 Hz), 29.5 (d, J = 138.5 Hz).; ^{31}P NMR (162 MHz, $\mathrm{CDCl_3}$) δ 29.1.; IR (film) ν 3055, 2953, 2237, 1409, 1246, 1031, 910, 731, 704.; HRMS (ESI) m/z calcd for $\mathrm{C_{19}H_{20}O_3P}$ $(\mathrm{M + H})^+$ 327.1150, found 327.1143.

Dimethyl 1-(3-Methylbiphenyl-2-yl)ethylphosphonate (11a). Yield: 26.9 mg, 88%; yellow liquid; ^{1}H NMR (400 MHz, $\mathrm{CDCl_3}$)

δ 7.42−7.35 (m, 4H), 7.18−7.16 (m, 3H), 7.04−7.03 (m, 1H), 3.75−3.63 (m, 1H), 3.55 (d, J = 10.7 Hz, 3H), 3.40 (d, J = 10.5 Hz, 3H), 2.70 (d, J = 1.2 Hz, 3H), 1.53 (dd, J = 18.4, 7.5 Hz, 3H).; ^{13}C NMR (101 MHz, CDCl$_3$) δ 144.0 (d, J = 9.2 Hz), 142.7, 138.5 (d, J = 4.5 Hz), 133.8 (d, J = 4.7 Hz), 131.6 (d, J = 3.0 Hz), 129.8, 128.1 (d, J = 1.6 Hz), 127.9, 127.0, 126.4 (d, J = 2.8 Hz), 52.8 (d, J = 6.8 Hz), 52.2 (d, J = 7.2 Hz), 34.6 (d, J = 138.0 Hz), 21.5, 14.4 (d, J = 3.9 Hz).; ^{31}P NMR (162 MHz, CDCl$_3$) δ 32.8.; IR (film) ν 2953, 1630, 1458, 1238, 1036, 820, 702.; HRMS (ESI) m/z calcd for C$_{17}$H$_{22}$O$_3$P (M + H)$^+$ 305.1307, found 305.1309.

Dimethyl 1-(Biphenyl-2-yl)ethylphosphonate (11b). Yield: 23.8 mg, 82%, colorless liquid; ^{1}H NMR (400 MHz, CDCl$_3$) δ 7.71 (d, J = 7.8 Hz, 1H), 7.45−7.28 (m, 7H), 7.23 (d, J = 7.6 Hz, 1H), 3.62 (d, J = 10.6 Hz, 3H), 3.50 (t, J = 8.3 Hz, 3H), 3.55−3.39 (m, 1H), 1.49 (dd, J = 18.7, 7.3 Hz, 3H).; ^{13}C NMR (101 MHz, CDCl$_3$) δ 142.2 (d, J = 9.7 Hz), 141.2, 135.7 (d, J = 5.4 Hz), 130.3 (d, J = 2.0 Hz), 129.3, 128.3, 128.4 (d, J = 4.5 Hz), 128.3, 127.7 (d, J = 2.9 Hz), 126.8 (d, J = 2.7 Hz), 52.9 (dd, J = 60.5, 7.1 Hz), 33.3 (d, J = 138.8 Hz), 17.2 (d, J = 4.8 Hz).; ^{31}P NMR (162 MHz, CDCl$_3$) δ 33.0; IR (film) ν 2953, 1741, 1494, 1234, 1058, 1031, 825, 775, 750, 704.; HRMS (ESI) m/z calcd for C$_{16}$H$_{20}$O$_3$P (M + H)$^+$ 291.1150, found 219.1156.

Dimethyl (4′-Fluoro-4-methylbiphenyl-2-yl)methylphosphonate (12a). Yield: 28.7 mg, 93%; yellow liquid; ^{1}H NMR (400 MHz, CDCl$_3$) δ 7.33 (dd, J = 8.6, 5.5 Hz, 3H), 7.10 (dd, J = 11.3, 6.1 Hz, 4H), 3.62 (s, 3H), 3.59 (s, 3H), 3.15 (s, 1H), 3.10 (s, 1H), 2.39 (s, 3H).; ^{13}C NMR (101 MHz, CDCl$_3$) δ 162.1 (d, J = 246.1 Hz), 138.7 (d, J = 8.0 Hz), 137.4 (d, J = 3.4 Hz), 137.0 (s), 131.2 (d, J = 8.6 Hz), 131.1 (d, J = 5.5 Hz), 130.4 (d, J = 2.6 Hz), 128.5 (d, J = 8.6 Hz), 127.9 (d, J = 3.5 Hz), 115.1 (d, J = 21.2 Hz), 52.7 (d, J = 6.8 Hz), 29.4 (d, J = 138.5 Hz), 21.1.; ^{31}P NMR (162 MHz, CDCl$_3$) δ 29.3.; ^{19}F NMR (377 MHz, CDCl$_3$) δ −115.7 (d, J = 3.0 Hz).; IR (film) ν 2955, 1634, 1489, 1223, 1159, 1032, 816, 735.; HRMS (ESI) m/z calcd for C$_{16}$H$_{19}$O$_3$PF (M + H)$^+$ 309.1056, found 309.1053.

Dimethyl (3′-Fluoro-4-methylbiphenyl-2-yl)methylphosphonate (12b). Yield: 27.5 mg, 89%; yellow liquid; ^{1}H NMR (400 MHz, CDCl$_3$) δ 7.38−7.34 (m, 2H), 7.15−7.10 (m, 3H), 7.10−7.05 (m, 2H), 3.62 (s, 3H), 3.59 (s, 3H), 3.18 (s, 1H), 3.12 (s, 1H), 2.39 (s, 3H).; ^{13}C NMR (101 MHz, CDCl$_3$) δ 162.6 (d, J = 246.3 Hz), 143.3 (d, J = 7.7 Hz), 138.5 (d, J = 8.1 Hz), 137.7 (d, J = 3.5 Hz), 131.2 (d, J = 4.9 Hz), 130.2 (d, J = 2.8 Hz), 129.7 (d, J = 8.4 Hz), 128.4 (d, J = 8.6 Hz), 127.9 (d, J = 3.5 Hz), 125.4 (d, J = 2.6 Hz), 116.6 (d, J = 21.4 Hz), 113.9 (d, J = 20.9 Hz), 52.7 (d, J = 6.8 Hz), 29.4 (d, J = 138.5 Hz), 21.2.; ^{31}P NMR (162 MHz, CDCl$_3$) δ 29.2.; ^{19}F NMR (377 MHz, CDCl$_3$) δ −113.2.; IR (film) ν 2956, 1614, 1585, 1265, 1186, 1057, 1031, 852, 736.; HRMS (ESI) m/z calcd for C$_{16}$H$_{19}$O$_3$PF (M + H)$^+$ 309.1056, found 309.1053.

Dimethyl (4′-Chloro-4-methylbiphenyl-2-yl)methylphosphonate (12c). Yield: 30.9 mg, 95%; yellow liquid; ^{1}H NMR (400 MHz, CDCl$_3$) δ 7.39 (d, J = 8.5 Hz, 2H), 7.31 (d, J = 8.5 Hz, 3H), 7.11 (s, 2H), 3.62 (s, 3H), 3.60 (s, 3H), 3.15 (s, 1H), 3.09 (s, 1H), 2.39 (s, 3H).; ^{13}C NMR (101 MHz, CDCl$_3$) δ 139.5, 138.6 (d, J = 8.1 Hz), 137.6 (d, J = 3.4 Hz), 133.1, 131.2 (d, J = 4.9 Hz), 130.9, 130.3 (d, J = 2.8 Hz), 128.4, 127.9 (d, J = 3.5 Hz), 52.7 (d, J = 6.8 Hz), 29.4 (d, J = 138.6 Hz), 21.1.; ^{31}P NMR (162 MHz, CDCl$_3$) δ 29.2.; IR (film) ν 2953, 1636, 1481, 1250, 1057, 1031, 815, 735.; HRMS (ESI) m/z calcd for C$_{16}$H$_{19}$O$_3$PCl (M + H)$^+$ 325.0760, found 325.0760.

Dimethyl (3′-Cyano-4-methylbiphenyl-2-yl)methylphosphonate (12d). Yield: 28.8 mg, 91%; yellow liquid; ^{1}H NMR (400 MHz, CDCl$_3$) δ 8.32 (s, 1H), 8.02 (d, J = 7.6 Hz, 1H), 7.53 (t, J = 7.6 Hz, 1H), 7.47 (d, J = 7.6 Hz, 1H), 7.25−7.20 (m, 2H), 7.15 (d, J = 8.0 Hz, 1H), 3.72 (s, 3H), 3.70 (s, 3H), 3.07 (s, 1H), 3.02 (s, 1H), 2.40 (s, 3H).; ^{13}C NMR (101 MHz, CDCl$_3$) δ 169.2, 140.3, 139.3 (d, J = 7.8 Hz), 137.6 (d, J = 3.7 Hz), 132.7, 132.1, 131.8 (d, J = 4.6 Hz), 130.1 (d, J = 2.9 Hz), 129.3, 128.9, 128.1 (d, J = 3.9 Hz), 127.3, 53.0 (d, J = 6.9 Hz), 30.3 (d, J = 138.8 Hz), 21.1.; ^{31}P NMR (162 MHz, CDCl$_3$) δ 29.8.; IR (film) ν 2958, 1635, 1506, 1265, 1057, 1032, 812, 736.; HRMS (ESI) m/z calcd for C$_{17}$H$_{19}$NO$_3$P (M + H)$^+$ 316.1103, found 316.1096.

Dimethyl (4-Methyl-4′-(trifluoromethyl)biphenyl-2-yl)methylphosphonate (12e). Yield: 26.2 mg, 73%; yellow liquid; ^{1}H NMR (400 MHz, CDCl$_3$) δ 7.68 (d, J = 8.0 Hz, 2H), 7.51 (d, J = 8.0 Hz, 2H), 7.35 (s, 1H), 7.13 (s, 2H), 3.63 (s, 3H), 3.60 (s, 3H), 3.14 (s, 1H), 3.08 (s, 1H), 2.40 (s, 3H).; ^{13}C NMR (101 MHz, CDCl$_3$) δ 144.8, 138.4 (d, J = 8.1 Hz), 138.0 (d, J = 3.4 Hz), 131.3 (d, J = 5.0 Hz), 130.2 (d, J = 2.5 Hz), 130.0, 125.2 (d, J = 3.8 Hz), 52.7 (d, J = 6.8 Hz), 29.5 (d, J = 138.8 Hz), 21.2.; ^{31}P NMR (162 MHz, CDCl$_3$) δ 29.0.; ^{19}F NMR (377 MHz, CDCl$_3$) δ −62.4.; IR (film) ν 2955, 1635, 1618, 1325, 1166, 1124, 1031, 817, 736.; HRMS (ESI) m/z calcd for C$_{17}$H$_{19}$O$_3$PF$_3$ (M + H)$^+$ 359.1024, found 359.1021.

Dimethyl (4′-Methoxy-4-methylbiphenyl-2-yl)methylphosphonate (12f). Yield: 29.5 mg, 92%; yellow liquid; ^{1}H NMR (400 MHz, CDCl$_3$) δ 7.33 (s, 1H), 7.30−7.24 (m, 2H), 7.12 (t, J = 8.3 Hz, 2H), 6.97−6.93 (m, 2H), 3.85 (s, 3H), 3.61 (s, 3H), 3.58 (s, 3H), 3.20 (s, 1H), 3.15 (s, 1H), 2.38 (s, 3H).; ^{13}C NMR (101 MHz, CDCl$_3$) δ 158.7, 139.5, 136.9 (d, J = 3.4 Hz), 133.5, 131.0 (d, J = 4.9 Hz), 130.6, 130.5 (d, J = 2.8 Hz), 128.6 (d, J = 8.7 Hz), 127.8 (d, J = 3.5 Hz), 113.7, 55.3, 52.7 (d, J = 6.8 Hz), 29.3 (d, J = 138.2 Hz), 21.1.; ^{31}P NMR (162 MHz, CDCl$_3$) δ 29.6.; IR (film) ν 2953, 1610, 1493, 1246, 1057, 1034, 812, 735.; HRMS (ESI) m/z calcd for C$_{17}$H$_{22}$O$_4$P (M + H)$^+$ 321.1256, found 321.1259.

Dimethyl (3′-Methoxy-4-methylbiphenyl-2-yl)methylphosphonate (12g). Yield: 24.4 mg, 76%; yellow liquid; ^{1}H NMR (400 MHz, CDCl$_3$) δ 7.32 (dd, J = 13.4, 5.2 Hz, 2H), 7.15 (t, J = 10.7 Hz, 2H), 6.96−6.88 (m, 3H), 3.84 (s, 3H), 3.62 (s, 3H), 3.59 (s, 3H), 3.21 (s, 1H), 3.16 (s, 1H), 2.39 (s, 3H).; ^{13}C NMR (101 MHz, CDCl$_3$) δ 159.4, 142.5, 139.7 (d, J = 10.4 Hz), 137.3, 131.0 (d, J = 4.9 Hz), 130.3, 129.2, 128.4 (d, J = 8.6 Hz), 127.8 (d, J = 3.4 Hz), 122.0, 115.1, 112.9, 55.3, 52.7 (d, J = 6.8 Hz), 29.3 (d, J = 138.3 Hz), 21.1.; ^{31}P NMR (162 MHz, CDCl$_3$) δ 29.6.; IR (film) ν 2955, 1636, 1479, 1223, 1055, 1030, 810, 736, 706.; HRMS (ESI) m/z calcd for C$_{17}$H$_{22}$O$_4$P (M + H)$^+$ 321.1256, found 321.1255.

Dimethyl (3′,4-Dimethylbiphenyl-2-yl)methylphosphonate (12h). Yield: 21.7 mg, 71%; yellow liquid; ^{1}H NMR (400 MHz, CDCl$_3$) δ 7.34 (s, 1H), 7.32−7.27 (m, 1H), 7.19−7.08 (m, 5H), 3.59 (s, 3H), 3.56 (s, 3H), 3.21 (s, 1H), 3.15 (s, 1H), 2.39 (s, 6H).; ^{13}C NMR (101 MHz, CDCl$_3$) δ 141.1, 139.9 (d, J = 8.2 Hz), 137.8, 137.1 (d, J = 3.4 Hz), 131.0 (d, J = 4.9 Hz), 130.4, 130.3 (d, J = 2.2 Hz), 128.1, 127.7 (d, J = 3.5 Hz), 127.7, 126.6, 52.6 (d, J = 6.7 Hz), 29.3 (d, J = 137.9 Hz), 21.5, 21.1.; ^{31}P NMR (162 MHz, CDCl$_3$) δ 29.5.; IR (film) ν 2953, 1634, 1614, 1456, 1250, 1056, 1032, 844, 735, 710.; HRMS (ESI) m/z calcd for C$_{17}$H$_{22}$O$_3$P (M + H)$^+$ 305.1307, found 305.1308.

Dimethyl 5-Methyl-2-(naphthalen-2-yl)benzylphosphonate (12i). Yield: 30.0 mg, 88%; yellow liquid; ^{1}H NMR (400 MHz, CDCl$_3$) δ 7.94−7.81 (m, 4H), 7.56−7.47 (m, 3H), 7.39 (s, 1H), 7.24 (d, J = 7.8 Hz, 1H), 7.15 (d, J = 7.8 Hz, 1H), 3.58 (s, 3H), 3.56 (s, 3H), 3.24 (s, 1H), 3.18 (s, 1H), 2.42 (s, 3H).; ^{13}C NMR (101 MHz, CDCl$_3$) δ 139.7 (d, J = 8.2 Hz), 138.6, 137.3 (d, J = 3.4 Hz), 133.3, 132.3, 131.1 (d, J = 4.9 Hz), 130.6 (d, J = 2.7 Hz), 128.6 (d, J = 8.6 Hz), 128.3, 128.0, 127.9, 127.9, 127.8, 127.7, 126.3, 126.0, 52.6 (d, J = 6.8 Hz), 29.4 (d, J = 138.2 Hz), 21.2.; ^{31}P NMR (162 MHz, CDCl$_3$) δ 29.5.; IR (film) ν 2953, 1636, 1491, 1265, 1057, 1032, 895, 800, 735, 704.; HRMS (ESI) m/z calcd for C$_{20}$H$_{22}$O$_3$P (M + H)$^+$ 341.1307, found 341.1303.

Dimethyl (2′-Fluoro-4-methylbiphenyl-2-yl)methylphosphonate (12l). Yield: 4.0 mg, 13%; yellow liquid; ^{1}H NMR (400 MHz, CDCl$_3$) δ 7.38−7.28 (m, 3H), 7.20 (t, J = 7.1 Hz, 1H), 7.16−7.10 (m, 3H), 3.56 (t, J = 13.5 Hz, 6H), 3.13 (d, J = 19.3 Hz, 2H), 2.40 (s, 3H).; ^{13}C NMR (101 MHz, CDCl$_3$) δ 159.5 (d, J = 245.9 Hz), 138.0 (d, J = 3.3 Hz), 133.1 (d, J = 8.2 Hz), 132.2, 131.1 (d, J = 5.1 Hz), 130.7, 129.7 (d, J = 9.0 Hz), 129.3 (d, J = 8.0 Hz), 128.3 (d, J = 17.6 Hz), 127.9 (d, J = 3.3 Hz), 124.1 (d, J = 3.6 Hz), 115.7 (d, J = 22.5 Hz), 52.6, 29.7 (d, J = 138.4 Hz), 21.2.; ^{31}P NMR (162 MHz, CDCl$_3$) δ 29.1.; ^{19}F NMR (377 MHz, CDCl$_3$) δ −115.0.; IR (film) ν 2955, 1483, 1446, 1254, 1057, 1032, 814, 762.; HRMS (ESI) m/z calcd for C$_{16}$H$_{19}$O$_3$PF (M + H)$^+$ 309.1056, found 309.1050.

Typical Procedure for the Horner−Wadsworth−Emmons Reactions.[15c] To a mixture of dimethyl (4-methylbiphenyl-2-yl)-methylphosphonate (**8b**) (29.1 mg, 0.1 mmol), n-Bu$_4$NBr (6.4 mg, 0.02 mmol), and solid NaOH (6.4 mg, 0.02 mmol) in anhydrous toluene (5.0 mL) at room temperature was added a toluene solution (1 mL) of benzaldehyde (12.7 mg, 0.12 mmol), and the mixture was vigorously stirred at 35 °C for 15 h under nitrogen. After completion of the reaction, H_2O (1 mL) was added to the reaction mixture and the mixture was extracted with diethyl ether (2 × 15 mL). The combined organic extracts were washed with brine, dried over $MgSO_4$, and concentrated in vacuo. The resulting residue was purified by flash chromatography on silica (100:1 hexane/ethyl acetate) to provide compound **13a** (21.9 mg, 81%).

(*E*)-4-Methyl-2-styrylbiphenyl (13a). Yield: 21.9 mg, 81%, colorless liquid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.58 (s, 1H), 7.47−7.33 (m, 7H), 7.30 (t, J = 7.6 Hz, 2H), 7.19 (dd, J = 23.5, 8.1 Hz, 3H), 7.07 (q, J = 16.3 Hz, 2H), 2.45 (s, 3H).; ^{13}C NMR (101 MHz, $CDCl_3$) δ 140.9, 138.5, 137.7, 137.2, 135.2, 130.2, 129.9, 129.2, 128.6, 128.4, 128.1, 127.9, 127.4, 126.9, 126.9, 126.5, 21.2.; IR (film) ν 3024, 2922, 1598, 1261, 1072, 964, 908, 819, 769, 721, 700.; HRMS (ESI) m/z calcd for $C_{21}H_{19}$ $(M + H)^+$ 271.1487, found 271.1487.

(*E*)-2-(4-Chlorostyryl)-4-methylbiphenyl (13b). Yield: 23.7 mg, 78%, colorless liquid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.55 (s, 1H), 7.48−7.32 (m, 5H), 7.31−7.23 (m, 5H), 7.17 (d, J = 7.8 Hz, 1H), 7.02 (dd, J = 38.9, 16.3 Hz, 2H), 2.44 (s, 3H).; ^{13}C NMR (101 MHz, $CDCl_3$) δ 140.8, 138.6, 137.2, 136.2, 134.8, 133.0, 130.3, 129.9, 128.9, 128.7, 128.6, 128.1, 127.9, 127.7, 127.0, 126.4, 21.2.; IR (film) ν 3024, 2922, 1486, 1089, 1010, 964, 908, 812, 761, 732, 702.; HRMS (ESI) m/z calcd for $C_{21}H_{18}Cl$ $(M + H)^+$ 305.1097, found 305.1091.

■ ASSOCIATED CONTENT

Supporting Information

^{1}H and ^{13}C NMR spectra. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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