

Supporting Information

In Situ Generation of Phosphoryl Alkylindiums and Their Synthtic Application to Arylalkyl Phosphonates *via* Palladium-Catalyzed Cross-Coupling Reactions

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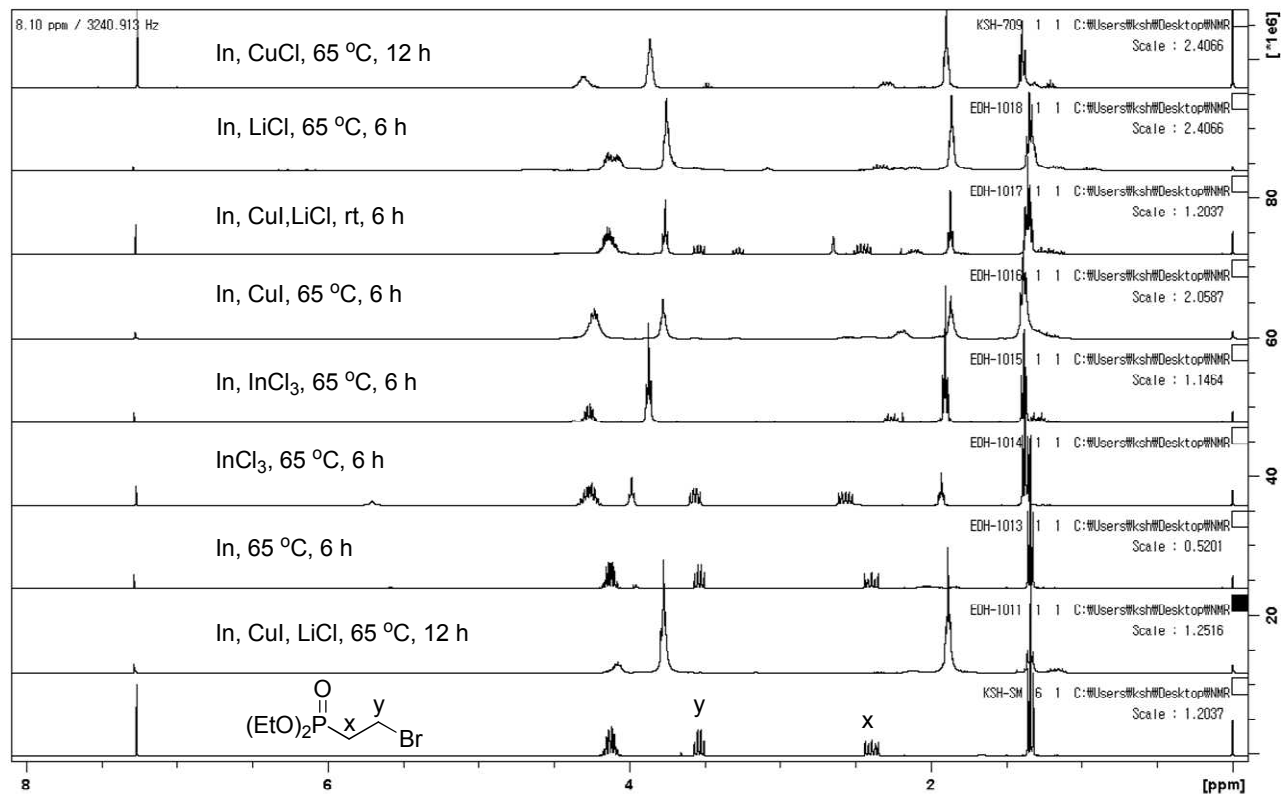
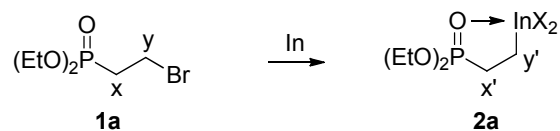
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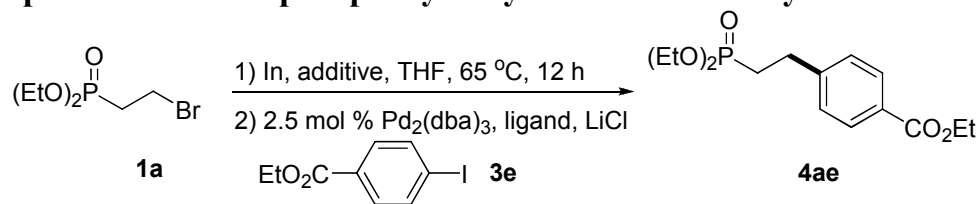
Experimental Section

General: Reactions were carried out in oven-dried glassware under nitrogen atmosphere. All commercial reagents were used without purification, and all solvents were reaction grade. *N,N*-Dimethylacetamide, *N,N*-dimethylformamide, 1-methyl-2-pyrrolidinone, dimethyl sulfoxide was freshly distilled from calcium hydride under nitrogen. All indium, copper iodide, copper chloride, palladium catalysts, and lithium chloride were purchased from chemical companies and used directly without further purifications. All reaction mixtures were stirred magnetically and were monitored by thin-layer chromatography using silica gel pre-coated glass plates, which were visualized with UV light and then, developed using either iodine or a solution of anisaldehyde. Flash column chromatography was carried out using silica gel (230-400 mesh). ^1H NMR (400 MHz) and ^{13}C NMR (100 MHz) spectra were recorded on NMR spectrometer. Deuterated chloroform was used as the solvent, and chemical shift values (δ) are reported in parts per million relative to the residual signals of this solvent (δ 7.26 for ^1H and δ 77.2 for ^{13}C). Infrared spectra were recorded on FT-IR spectrometer as either a thin film pressed between two sodium chloride plates or as a solid suspended in a potassium bromide disk. Mass spectra were obtained from the KBSI on high resolution mass spectrometer. Melting points were determined in open capillary tube using Electrothermal 9100 apparatus.

¹H NMR comparison of the insertion reaction performed under various conditions



Reaction optimization of 2-phosphoryl ethylindiums with ethyl 4-iodobenzoate



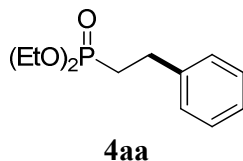
entry	additive	ligand	solvent	temp (°C)	time (h)	yeild ^a (%)
1 ^b	CuI / LiCl	-	DMA	90	10	71
2 ^b	CuI	-	DMA	90	10	70
3 ^c	InCl ₃	-	DMA	90	2	40 (60 ^d)
4 ^{c,e}	InCl ₃	-	DMA	90	2	55 (45 ^d)
5	CuI	Ph ₃ P	DMA	80	12	75
6	CuI	Ph ₃ P	THF	70	12	37
7	CuI	Ph ₃ P	NMP	80	12	54
8	CuI	Ph ₃ P	DMSO	80	12	57
9	CuI	Ph ₃ P	DMF	80	12	51
10	CuI	Ph ₃ P	dioxane	80	12	23
11	CuI	(4-MeO-C ₆ H ₄) ₃ P	DMA	80	12	43
13	CuI	DPPP	DMA	80	12	N.R.
14	CuI	DPPE	DMA	80	12	N.R.
15	CuI	DPPF	DMA	80	12	67
16	CuI	DPEphos	DMA	80	12	81
17	CuI	Xantphos	DMA	80	12	24
18	CuI	(C ₆ F ₅) ₃ P	DMA	80	12	50
12	CuI	(4-CF ₃ -C ₆ H ₄) ₃ P	DMA	80	12	85
19 ^f	CuI	(4-CF ₃ -C ₆ H ₄) ₃ P	DMA	80	12	73
20 ^g	CuI	(4-CF ₃ -C ₆ H ₄) ₃ P	DMA	80	12	90

^a NMR yield using mesitylene as an internal standard. ^b *Chem. Commun.* **2011**, 47, 4778. ^c *J. Am. Chem. Soc.* **2010**, 132, 15852. ^d Diethyl (1,1'-biphenyl)-4,4'-dicarboxylate. ^e Pd(PPh₃)₄ was used as catalyst. ^f Pd(OAc)₂ was used as catalyst. ^g The reaction was conducted with 5 mol % Pd₂(dba)₃ and 20 mol % (4-CF₃-C₆H₄)₃P. ^h Pd₂(dba)₃CHCl₃ was used as catalyst.

Pd-catalyzed cross-couplings of phosphoryl alkylindiums with aryl bromides:

General procedure A (4aa, 4al – 4ap, 4ar, 4fe)

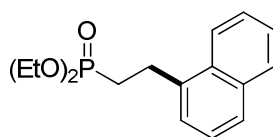
Diethyl phenethylphosphonate (4aa)^{2a} : To an test tube was added diethyl (2-bromoethyl)phosphonate¹ (171.5 mg, 0.70 mmol), indium (160.8 mg, 1.4 mmol), CuCl (138.6 mg, 1.4 mmol), and THF (3.0 mL) sequentially. The reaction was stirred at 65 °C for 12 h. Then, it was concentrated under vacuuo. The residue was dissolved in DMSO (1 mL) and transferred to another test tube. Pd₂(dba)₃ (22.89 mg, 0.025 mmol), CyJohnphos (35.1 mg, 0.1 mmol), LiCl (21.2 mg, 0.5 mmol), and iodobenzene (71.4 mg, 0.35 mmol) was added to the test tube sequentially. The reaction mixture was stirred at 70 °C temperature. After 3 h, the reaction mixture was filtered and then, concentrated in vacuuo. The residue was subjected to flash column chromatography on silica gel (ethyl acetate:hexane = 1:1) to give diethyl phenethylphosphonate (67.0 mg, 79%).



colorless liquid. ¹H NMR (400 MHz, CDCl₃) δ 7.32 - 7.28 (m, 2H), 7.23 - 7.19 (m, 3H), 4.14 - 4.06 (m, 4H), 2.95 - 2.89 (m, 2H), 2.10 - 2.01 (m, 2H), 1.32 (t, *J* = 7.06 Hz, 6H); ¹³C NMR (100 MHz, CDCl₃) δ 141.10 (d, *J* = 17.71 Hz), 128.57, 128.04, 126.33, 61.59, 61.53, 28.63, 28.58, 27.61 (d, *J* = 139.39 Hz), 26.93, 16.49, 16.43; ³¹P NMR (161 MHz, CDCl₃) δ 30.77; IR (film) 2982, 2931, 2911, 1455, 1392, 1241, 1055, 1028, 965, 795, 699, 510 cm⁻¹; HRMS (EI) : *m/z* calcd. For C₁₂H₁₉O₃P: 242.1072; found : 242.1071.

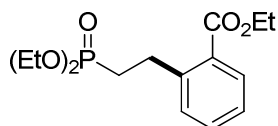
General procedure B (4ab – 4ak)

Diethyl 2-(naphthyl)ethylphosphonate (4ab)^{2b} : To an test tube was added diethyl (2-bromoethyl)phosphonate (122.6 mg, 0.50 mmol), indium (114.8 mg, 1.0 mmol), CuCl (99.0 mg, 1.0 mmol), and THF (1.5 mL) sequentially. The reaction was stirred at 65 °C for 12 h. Then, it was concentrated under vacuuo. Then the residue was dissolved in DMSO (1 mL) and transferred to another test tube. Pd₂(dba)₃ (22.89 mg, 0.025 mmol), CyJohnphos (35.1 mg, 0.1 mmol), LiCl (21.2 mg, 0.5 mmol), and 2-iodonaphthalene (88.9 mg, 0.35 mmol) was added to the test tube sequentially. The reaction mixture was stirred at 70 °C temperature. After 6 h reaction mixture was filtered and then, concentrated in vacuuo. The residue was subjected to flash column chromatography on silica gel (ethyl acetate:hexane = 1:1) to give diethyl 2-(naphthyl)ethylphosphonate (88.2 mg, 86%).



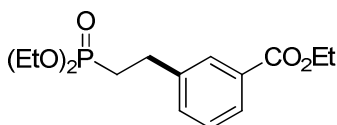
4ab

colorless liquid. ^1H NMR (400 MHz, CDCl_3) δ 8.02 (d, $J = 8.44$ Hz, 1H), 7.87 (d, $J = 7.92$ Hz, 1H), 7.74 (d, $J = 7.92$ Hz, 1H), 7.56 - 7.47 (m, 2H), 7.42 - 7.35 (m, 2H), 4.21 - 4.08 (m, 4H), 3.41 - 3.35 (m, 2H), 2.22 - 2.13 (m, 2H), 1.32 (t, $J = 7.09$ Hz, 6H); ^{13}C NMR (100 MHz, CDCl_3) δ 137.08 (d, $J = 17.48$ Hz), 133.92, 131.37, 128.91, 127.23, 126.17, 125.69, 125.66, 125.57, 123.30, 61.68, 61.61, 27.02 (d, $J = 139.05$ Hz), 25.91, 25.87, 16.53, 16.47; ^{31}P NMR (161 MHz, CDCl_3) δ 30.84; IR (film) 2981, 2928, 2907, 1596, 1510, 1442, 1392, 1243, 1053, 1027, 963, 798, 777, 532 cm^{-1} ; HRMS (EI) : m/z calcd. For $\text{C}_{16}\text{H}_{21}\text{O}_3\text{P}$: 292.1228; found : 292.1230.



4ac

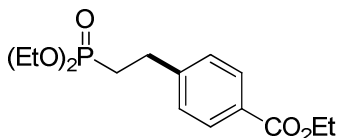
Ethyl 2-(2-(diethoxyphosphoryl)ethyl)benzoate (4ac)^{2c} : colorless liquid (70.4 mg, 64%). ^1H NMR (400 MHz, CDCl_3) δ 7.90 (d, $J = 8.08$ Hz, 1H), 7.43 (t, $J = 7.40$ Hz, 1H), 7.30 (d, $J = 9.08$ Hz, 2H), 4.37 (q, $J = 7.15$ Hz, 2H), 4.16 - 4.07 (m, 4H), 3.25 - 2.19 (m, 2H), 2.16 - 2.07 (m, 2H), 1.40 (t, $J = 7.14$ Hz, 3H), 1.33 (t, $J = 7.06$ Hz, 6H); ^{13}C NMR (100 MHz, CDCl_3) δ 167.27, 142.73 (d, $J = 17.87$ Hz), 132.18, 130.97, 130.85, 129.67, 126.49, 61.54, 61.48, 60.97, 27.89, 27.85, 27.52 (d, $J = 138.08$ Hz), 16.47, 16.41, 14.27; ^{31}P NMR (161 MHz, CDCl_3) δ 30.92; IR (film) 2982, 2936, 2908, 1716, 1601, 1576, 1448, 1392, 1366, 1245, 1055, 1028, 965, 793, 756, 508 cm^{-1} ; HRMS (EI) : m/z calcd. For $\text{C}_{15}\text{H}_{23}\text{O}_5\text{P}$: 314.1283; found : 314.1286.



4ad

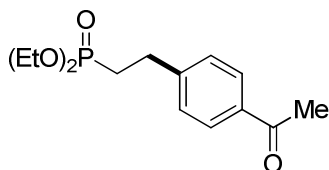
Ethyl 3-(2-(diethoxyphosphoryl)ethyl)benzoate (4ad) : colorless liquid (82.6 mg, 75%). ^1H NMR (400 MHz, CDCl_3) δ 7.91 - 7.89 (m, 2H), 7.42 - 7.35 (m, 2H), 4.38 (q, $J = 7.14$ Hz, 2H), 4.15 - 4.06 (m, 4H), 3.01 - 2.94 (m, 2H), 2.12 - 2.03 (m, 2H), 1.40 (t, $J = 7.12$ Hz, 3H), 1.32 (t, $J = 7.06$ Hz, 6H); ^{13}C NMR (100 MHz, CDCl_3) δ 166.55, 141.25 (d, $J = 17.50$ Hz), 132.63, 130.80, 129.09, 128.58, 127.62, 61.66, 61.59, 61.00, 28.48, 28.43, 27.48 (d, $J = 140.10$ Hz), 16.48, 16.42, 14.33; ^{31}P NMR (161 MHz, CDCl_3) δ

30.28; IR (film) 2982, 2934, 2908, 1716, 1608, 1588, 1445, 1392, 1368, 1283, 1242, 1200, 1055, 1028, 968, 754, 598 cm^{-1} ; HRMS (EI) : m/z calcd. For $\text{C}_{15}\text{H}_{23}\text{O}_5\text{P}$: 314.1283; found : 314.1281.



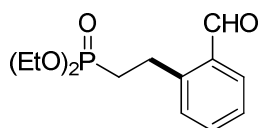
4ae

Ethyl 4-(2-(diethoxyphosphoryl)ethyl)benzoate (4ae)^{2d} : colorless liquid (97.1 mg, 88%). ^1H NMR (400 MHz, CDCl_3) δ 7.98 (d, $J = 6.56$ Hz, 2H), 7.28 (d, $J = 9.45$ Hz, 1H), 4.37 (q, $J = 7.12$ Hz, 2H), 4.14 - 4.06 (m, 4H), 3.01 - 2.94 (m, 2H), 2.10 - 2.02 (m, 2H), 1.39 (t, $J = 7.14$ Hz, 3H), 1.32 (t, $J = 7.06$ Hz, 6H); ^{13}C NMR (100 MHz, CDCl_3) δ 166.46, 146.18 (d, $J = 16.99$ Hz), 129.87, 128.72, 128.06, 61.69, 61.63, 60.87, 28.69, 28.64, 27.22 (d, $J = 140.42$ Hz), 16.49, 16.43, 14.33; ^{31}P NMR (161 MHz, CDCl_3) δ 30.19; IR (film) 2982, 2934, 2907, 1716, 1611, 1445, 1416, 1392, 1367, 1279, 1244, 1055, 1026, 964, 792 cm^{-1} ; HRMS (EI) : m/z calcd. For $\text{C}_{15}\text{H}_{23}\text{O}_5\text{P}$: 314.1283; found : 314.1285.



4af

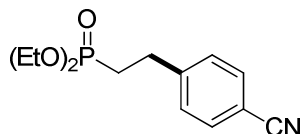
Diethyl 4-acetylphenethylphosphonate (4af) : colorless liquid (82.0 mg, 82%). ^1H NMR (400 MHz, CDCl_3) δ 7.90 (d, $J = 7.96$ Hz, 2H), 7.31 (d, $J = 7.31$ Hz, 2H), 4.15 - 4.09 (m, 4H), 2.59 (s, 3H), 2.12 - 2.03 (m, 2H), 1.32 (t, $J = 7.04$ Hz, 6H); ^{13}C NMR (100 MHz, CDCl_3) δ 197.74, 146.53 (d, $J = 16.95$ Hz), 135.51, 128.72, 128.33, 61.88, 61.81, 28.64, 28.60, 27.13 (d, $J = 140.67$ Hz), 26.59, 16.48, 16.42; ^{31}P NMR (161 MHz, CDCl_3) δ 29.98; IR (film) 2983, 2931, 2859, 1682, 1607, 1414, 1360, 1268, 1243, 1055, 1029, 963, 821, 597, 582 cm^{-1} ; HRMS (EI) : m/z calcd. For $\text{C}_{14}\text{H}_{21}\text{O}_4\text{P}$: 284.1177; found : 284.1174.



4ag

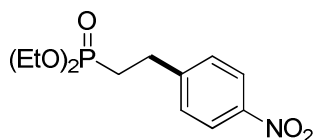
Diethyl 2-formylphenethylphosphonate (4ag) : colorless liquid (75.8 mg, 80%). ^1H NMR (400 MHz, CDCl_3) δ 10.19 (s, 1H), 7.81 (d, $J = 7.56$ Hz, 1H), 7.53 (t, $J = 7.48$ Hz, 1H), 7.43 (t, $J = 7.34$ Hz, 1H), 7.34 (d, $J = 7.44$ Hz, 1H), 4.16 - 4.08 (m, 4H), 3.34 - 3.27 (m, 2H), 2.11 - 2.02 (m, 2H), 1.33 (t, $J = 7.04$ Hz, 6H); ^{13}C NMR (100 MHz, CDCl_3) δ 192.69, 143.31 (d, $J = 16.93$ Hz), 133.96, 133.85, 133.64,

131.12, 127.15, 61.67, 61.61, 27.21 (d, $J = 138.87$ Hz), 26.29, 26.25, 16.46, 16.40; ^{31}P NMR (161 MHz, CDCl_3) δ 30.22; IR (film) 2982, 2930, 2853, 2741, 1695, 1599, 1574, 1448, 1393, 1242, 1208, 1055, 1028, 966, 760, 512 cm^{-1} ; HRMS (EI) : m/z calcd. For $\text{C}_{13}\text{H}_{19}\text{O}_4\text{P}$: 270.1021; found : 270.1023.



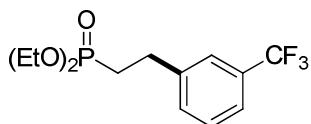
4ah

Diethyl 4-cyanophenethylphosphonate (4ah) : colorless liquid (76.9 mg, 82%). ^1H NMR (400 MHz, CDCl_3) δ 7.53 - 7.51 (m, 2H), 7.48 - 7.39 (m, 2H), 4.14 - 4.06 (m, 4H), 2.99 - 2.93 (m, 2H), 2.09 - 1.99 (m, 2H), 1.32 (t, $J = 7.06$ Hz, 6H); ^{13}C NMR (100 MHz, CDCl_3) δ 142.30 (d, $J = 16.23$ Hz), 132.73, 131.62, 130.10, 129.33, 118.65, 112.52, 61.68, 61.61, 28.28, 28.24, 27.06 (d, $J = 141.02$ Hz), 16.40, 16.34; ^{31}P NMR (161 MHz, CDCl_3) δ 29.58 ; IR (film) 2983, 2931, 2907, 2229, 1482, 1441, 1390, 1237, 1053, 1028, 968, 798, 689 cm^{-1} ; HRMS (EI) : m/z calcd. For $\text{C}_{13}\text{H}_{18}\text{NO}_3\text{P}$: 267.1024; found : 267.1026.



4ai

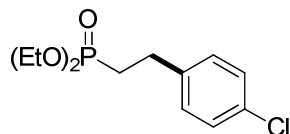
Diethyl 4-nitrophenethylphosphonate (4ai)^{2c} : colorless liquid (82.5 mg, 82%). ^1H NMR (400 MHz, CDCl_3) δ 8.17 (d, $J = 8.72$ Hz, 2H), 7.38 (d, $J = 8.80$ Hz, 2H), 4.13 - 4.07 (m, 4H), 3.07 - 3.00 (m, 2H), 2.12 - 2.03 (m, 2H), 1.32 (t, $J = 7.08$ Hz, 6H); ^{13}C NMR (100 MHz, CDCl_3) δ 148.57 (d, $J = 16.56$ Hz), 146.71, 129.00, 123.84, 61.81, 61.75, 28.66, 28.62, 27.04 (d, $J = 141.50$ Hz), 16.50, 16.44; ^{31}P NMR (161 MHz, CDCl_3) δ 29.46 ; IR (film) 2984, 2935, 2907, 1601, 1519, 1444, 1392, 1347, 1241, 1054, 1028, 966, 855, 831, 538 cm^{-1} ; HRMS (EI) : m/z calcd. For $\text{C}_{12}\text{H}_{18}\text{NO}_5\text{P}$: 287.0923; found : 287.0924.



4aj

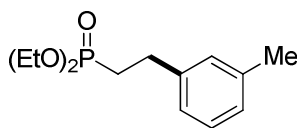
Diethyl 3-(trifluoromethyl)phenethylphosphonate (4aj) : colorless liquid (86.9 mg, 80%). ^1H NMR (400 MHz, CDCl_3) δ 7.49 (m, 2H), 7.42 - 7.40 (m, 2H), 4.14 - 4.06 (m, 4H), 3.02 - 2.95 (m, 2H), 2.11 - 2.02 (m, 2H), 1.31 (t, $J = 7.09$ Hz, 6H); ^{13}C NMR (100 MHz, CDCl_3) δ 141.92, 141.75, 131.56, 130.88 (d, $J = 32.32$ Hz), 129.00, 124.85 (q, $J = 3.84$ Hz), 123.26 (q, $J = 3.84$ Hz), 124.10 (d, $J = 272.16$ Hz), 61.70,

61.63, 28.53, 28.48, 27.37 (d, $J = 140.69$ Hz), 16.45, 16.39; ^{31}P NMR (161 MHz, CDCl_3) δ 30.01; IR (film) 2985, 2934, 2911, 1450, 1393, 1327, 1242, 1164, 1124, 1056, 1029, 967, 800, 702, 510 cm^{-1} ; HRMS (EI) : m/z calcd. For $\text{C}_{13}\text{H}_{18}\text{F}_3\text{O}_3\text{P}$: 310.0946; found : 310.0945.



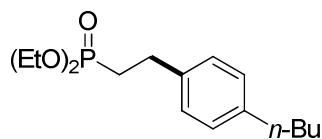
4ak

Diethyl 4-chlorophenethylphosphonate (4ak)^{2d}: colorless liquid (88.3 mg, 91%). ^1H NMR (400 MHz, CDCl_3) δ 7.27 (m, 2H), 7.14 (d, $J = 8.48$ Hz, 2H), 4.13 - 4.06 (m, 4H), 2.92 - 2.85 (m, 2H), 2.06 - 1.98 (m, 2H), 1.32 (t, $J = 7.10$ Hz, 6H); ^{13}C NMR (100 MHz, CDCl_3) δ 139.41 (d, $J = 17.33$ Hz), 132.11, 129.43, 128.65, 61.65, 61.59, 28.05, 28.01, 27.51 (d, $J = 140.00$ Hz), 16.48, 16.42; ^{31}P NMR (161 MHz, CDCl_3) δ 30.27; IR (film) 2983, 2932, 2907, 1492, 1445, 1393, 1240, 1055, 1028, 965, 813, 655, 539 cm^{-1} ; HRMS (EI) : m/z calcd. For $\text{C}_{12}\text{H}_{18}\text{ClO}_3\text{P}$: 276.0682; found : 276.0685.



4al

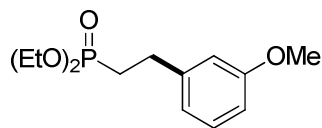
Diethyl 3-methylphenethylphosphonate (4al) : colorless liquid (73.6 mg, 82%). ^1H NMR (400 MHz, CDCl_3) δ 7.19 (t, $J = 7.72$ Hz, 1H), 7.02 (m, 3H), 4.12 - 4.07 (m, 4H), 2.91 - 2.84 (m, 2H), 2.33 (s, 3H), 2.09 - 2.00 (m, 2H), 1.33 (t, $J = 7.06$ Hz, 6H); ^{13}C NMR (100 MHz, CDCl_3) δ 140.97 (d, $J = 17.76$ Hz), 138.19, 128.86, 128.48, 127.06, 125.02, 61.59, 61.53, 28.52, 28.48, 27.65 (d, $J = 139.10$ Hz), 21.38, 16.51, 16.45; ^{31}P NMR (161 MHz, CDCl_3) δ 30.90; IR (film) 2982, 2930, 2911, 2869, 1609, 1487, 1445, 1392, 1241, 1056, 1029, 966, 787, 697, 509 cm^{-1} ; HRMS (EI) : m/z calcd. For $\text{C}_{13}\text{H}_{21}\text{O}_3\text{P}$: 256.1228; found : 256.1228.



4am

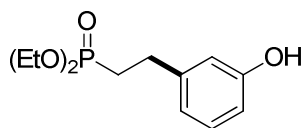
Diethyl 4-butylphenethylphosphonate (4am): colorless liquid (81.6 mg, 78%). ^1H NMR (400 MHz, CDCl_3) δ 7.11 (s, 1H), 4.13 - 4.06 (m, 4H), 2.91 - 2.85 (m, 2H), 2.58 (d, $J = 7.74$ Hz, 2H), 2.09 - 2.00 (m, 2H), 1.61 - 1.54 (m, 2H), 1.37 - 1.33 (m, 2H), 1.31 (t, $J = 7.08$ Hz, 6H); ^{13}C NMR (100 MHz, CDCl_3) δ

140.96, 138.13 (d, $J = 18.21$ Hz), 128.59, 127.89, 61.58, 61.51, 35.22, 33.72, 28.19, 28.14, 27.66 (d, $J = 138.74$ Hz), 22.36, 16.50, 16.45, 13.96; ^{31}P NMR (161 MHz, CDCl_3) δ 30.98 ; IR (film) 2978, 2958, 2930, 2858, 1643, 1514, 1444, 1392, 1243, 1058, 965, 810, 497 cm^{-1} ; HRMS (EI) : m/z calcd. For $\text{C}_{16}\text{H}_{27}\text{O}_3\text{P}$: 298.1698; found : 298.1698.



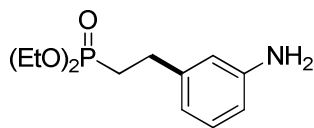
4an

Diethyl 3-methoxyphenethylphosphonate (4an)^{2f} : colorless liquid (77.2 mg, 81%). ^1H NMR (400 MHz, CDCl_3) δ 7.21 (t, $J = 7.52$ Hz, 1H), 6.79 (d, $J = 7.48$ Hz, 1H), 6.75 (s, 2H), 4.15 - 4.07 (m, 4H), 3.80 (s, 3H), 2.93 - 2.86 (m, 2H), 2.09 - 2.01 (m, 2H), 1.33 (t, $J = 7.08$ Hz, 6H); ^{13}C NMR (100 MHz, CDCl_3) δ 159.79, 142.64 (d, $J = 17.74$ Hz), 129.56, 120.36, 113.81, 111.67, 61.61, 61.54, 55.18, 28.67, 28.63, 27.56 (d, $J = 129.37$ Hz), 16.49, 16.43; ^{31}P NMR (161 MHz, CDCl_3) δ 30.71 ; IR (film) 2982, 2938, 2911, 2836, 1601, 1585, 1490, 1455, 1258, 1241, 1154, 1029, 967, 787, 694 cm^{-1} ; HRMS (EI) : m/z calcd. For $\text{C}_{13}\text{H}_{21}\text{O}_4\text{P}$: 272.1177; found : 272.1177.



4ao

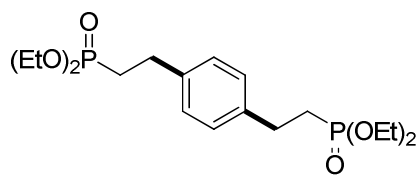
Diethyl 3-hydroxyphenethylphosphonate (4ao) : colorless liquid (68.8 mg, 76%). ^1H NMR (400 MHz, CDCl_3) δ 8.24 (s, 1H), 7.14 (t, $J = 7.82$ Hz, 1H), 6.79 (s, 1H), 6.71 (t, $J = 8.28$ Hz, 2H), 4.15 - 4.06 (m, 4H), 2.91 - 2.84 (m, 2H), 2.12 - 2.03 (m, 2H), 1.32 (t, $J = 7.06$ Hz, 6H); ^{13}C NMR (100 MHz, CDCl_3) δ 157.05, 142.16 (d, $J = 17.81$ Hz), 129.70, 119.33, 115.02, 113.68, 61.97, 61.91, 28.50, 28.45, 27.36 (d, $J = 139.88$ Hz), 16.44, 16.38; ^{31}P NMR (161 MHz, CDCl_3) δ 31.01; IR (film) 3201, 2984, 2936, 2910, 1601, 1589, 1483, 1457, 1227, 1209, 1054, 1028, 972, 787, 695, 510 cm^{-1} ; HRMS (EI) : m/z calcd. For $\text{C}_{12}\text{H}_{19}\text{O}_4\text{P}$: 258.1021; found : 258.1019.



4ap

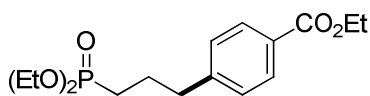
Diethyl 3-aminophenethylphosphonate (4ap) : yellow liquid (45.1 mg, 50%). ^1H NMR (400 MHz, CDCl_3) δ 7.08 (t, $J = 8.06$ Hz, 1H), 6.59 (d, $J = 7.52$ Hz, 1H), 6.53 (s, 2H), 4.15 - 4.05 (m, 4H), 3.64 (s,

2H), 2.85 - 2.78 (m, 2H), 2.07 - 1.99 (m, 2H), 1.33 (t, $J = 7.06$ Hz, 6H); ^{13}C NMR (100 MHz, CDCl_3) δ 146.57, 142.26 (d, $J = 17.45$ Hz), 129.48, 118.24, 114.79, 113.16, 61.58, 61.52, 28.58, 28.53, 27.51 (d, $J = 139.10$ Hz), 16.50, 16.44; ^{31}P NMR (161 MHz, CDCl_3) δ 30.96; IR (film) 3433, 3348, 3233, 2982, 2931, 2907, 1606, 1493, 1463, 1236, 1030, 969, 787, 696 cm^{-1} ; HRMS (EI) : m/z calcd. For $\text{C}_{12}\text{H}_{20}\text{NO}_3\text{P}$: 257.1181; found : 257.1181.



4aq

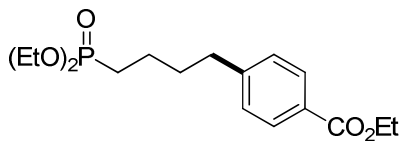
Tetraethyl 2,2'-(1,4-phenylene)bis(ethane-2,1-diyl)diphosphonate (4aq) : To an test tube was added diethyl (2-bromoethyl)phosphonate (257.3 mg, 1.05 mmol), indium (168.8 mg, 1.5 mmol), CuCl (145.5 mg, 1.5 mmol), and THF (4 mL) sequentially. The reaction was stirred at 65 $^{\circ}\text{C}$ for 12 h. Then, it was concentrated under vacuo. Then the residue was dissolved in DMSO (1 mL) and transferred to another test tube. $\text{Pd}_2(\text{dba})_3$ (45.8 mg, 0.05 mmol), CyJohnphos (70.1 mg, 0.2 mmol), LiCl (42.4 mg, 1.0 mmol), and 1,4-diiodobenzene (115.5 mg, 0.35 mmol) was added to the test tube sequentially. The reaction mixture was stirred at 70 $^{\circ}\text{C}$ temperature. After 3 h reaction mixture was filtered and then, concentrated in vacuo. The residue was subjected to flash column chromatography on silica gel (ethyl acetate:hexane = 1:1) to give Tetraethyl 2,2'-(1,4-phenylene)bis(ethane-2,1-diyl)diphosphonate (94.7 mg, 66%). colorless liquid. ^1H NMR (400 MHz, CDCl_3) δ 7.14 (s, 4H), 4.15 - 4.05 (m, 8H), 2.92 - 2.85 (m, 4H), 2.07 - 1.99 (m, 4H), 1.34 (t, $J = 7.06$ Hz, 12H); ^{13}C NMR (100 MHz, CDCl_3) δ 139.05 (d, $J = 17.81$ Hz), 128.23, 61.59, 61.53, 28.19, 28.15, 27.65 (d, $J = 139.29$ Hz), 16.49, 16.43; ^{31}P NMR (161 MHz, CDCl_3) δ 30.72; IR (film) 2983, 2932, 2911, 1445, 1392, 1240, 1055, 1028, 965, 812, 535 cm^{-1} ; HRMS (EI) : m/z calcd. For $\text{C}_{18}\text{H}_{32}\text{O}_6\text{P}_2$: 406.1674; found : 406.1671.



4de

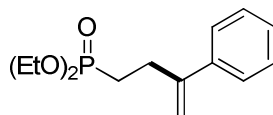
Ethyl 4-(3-(diethoxyphosphoryl)propyl)benzoate (4de) : colorless liquid (70.2 mg, 61%). ^1H NMR (400 MHz, CDCl_3) δ 7.97 (d, $J = 8.24$ Hz, 2H), 7.25 (d, $J = 8.16$ Hz, 2H), 4.37 (q, $J = 7.12$ Hz, 2H), 4.13 - 4.03 (m, 4H), 2.76 (t, $J = 7.52$ Hz, 2H), 2.00 - 1.90 (m, 2H), 1.77 - 1.68 (m, 2H), 1.39 (t, $J = 7.12$ Hz, 3H), 1.31 (t, $J = 7.06$ Hz, 6H); ^{13}C NMR (100 MHz, CDCl_3) δ 166.6, 146.4, 129.7, 128.4, 61.5, 61.4, 60.84, 36.3 (d, $J = 16.89$ Hz), 25.0 (d, $J = 141.45$ Hz), 23.8 (d, $J = 4.59$ Hz), 16.5, 16.3, 14.3; ^{31}P NMR

(161 MHz, CDCl₃) δ 31.69; IR (film) 2982, 2934, 2907, 1716, 1611, 1445, 1416, 1392, 1367, 1279, 1244, 1055, 1026, 964, 792 cm⁻¹; HRMS (EI) : m/z calcd. For C₁₆H₂₅O₅P : 328.1440; found : 328.1438.



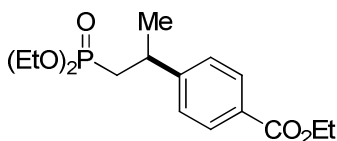
4ee

Ethyl 4-(4-(diethoxyphosphoryl)butyl)benzoate (4ee) : colorless liquid (37.0 mg, 30%). ¹H NMR (400 MHz, CDCl₃) δ 7.96 (d, J = 8.32 Hz, 1H), 7.23 (d, J = 8.28 Hz, 2H), 4.36 (q, J = 7.12 Hz, 2H), 4.13 - 4.03 (m, 4H), 2.68 (t, J = 7.48 Hz, 2H), 1.80 - 1.65 (m, 6H), 1.39 (t, J = 7.12 Hz, 3H), 1.31 (t, J = 7.06 Hz, 6H); ¹³C NMR (100 MHz, CDCl₃) δ 166.6, 147.3, 129.7, 128.3, 128.2, 61.4, 60.8, 35.4, 31.9 (d, J = 16.47 Hz), 25.5 (d, J = 141.09 Hz), 22.1 (d, J = 5.05 Hz), 16.5, 16.4, 14.3; ³¹P NMR (161 MHz, CDCl₃) δ 32.02; IR (film) 2982, 2934, 2907, 1716, 1611, 1445, 1416, 1392, 1367, 1279, 1244, 1055, 1026, 964, 792 cm⁻¹; HRMS (EI) : m/z calcd. For C₁₇H₂₇O₅P : 342.1596; found : 342.1593.



4ar

Diethyl 3-phenylbut-3-enylphosphonate (4ar) : colorless liquid (58.2 mg, 62%). ¹H NMR (400 MHz, CDCl₃) δ 7.40 - 7.26 (m, 5H), 5.31 (s, 1H), 5.11 (d, J = 1.16 Hz), 4.16 - 4.03 (m, 4H), 2.83 - 2.76 (m, 2H), 1.93 - 1.84 (m, 2H), 1.32 (t, J = 7.06 Hz, 6H); ¹³C NMR (100 MHz, CDCl₃) δ 147.30 (d, J = 18.29 Hz), 140.12, 128.44, 127.69, 126.08, 112.62, 61.60, 61.53, 28.13 (d, J = 3.99 Hz), 24.80 (d, J = 140.75 Hz), 16.51, 16.45; ³¹P NMR (161 MHz, CDCl₃) δ 31.50; IR (film) 3082, 3056, 2982, 2931, 2908, 1444, 1392, 1243, 1055, 1028, 967, 780, 705, 516 cm⁻¹; HRMS (EI) : m/z calcd. For C₁₄H₂₁O₃P : 268.1228; found : 268.1225.



4fe

Ethyl 4-(1-(diethoxyphosphoryl)propan-2-yl)benzoate (4fe) : colorless liquid (54.0 mg, 42%). ¹H NMR (400 MHz, CDCl₃) δ 7.98 (d, J = 8.20 Hz, 2H), 7.29 (d, J = 8.24 Hz, 2H), 4.36 (q, J = 7.12 Hz, 2H), 4.12 (qt, J = 7.21 Hz, 1H), 4.04 - 3.86 (m, 3H), 3.33 - 3.21 (m, 1H), 2.16 - 1.98 (m, 2H), 1.38 (t, J = 6.94

Hz, 4H), 1.33 (t, $J = 7.06$ Hz, 2H), 1.24 (t, $J = 7.12$ Hz, 3H), 1.20 (t, $J = 7.10$ Hz, 3H); ^{13}C NMR (100 MHz, CDCl_3) δ 166.49, 151.83 (d, $J = 11.68$ Hz), 129.86, 128.75, 126.73, 61.47 (d, $J = 6.57$ Hz), 61.37 (d, $J = 6.30$ Hz), 60.85, 34.81 (d, $J = 3.59$ Hz), 33.98 (d, $J = 139.46$ Hz), 23.40 (d, $J = 9.63$ Hz), 16.37, 16.31, 14.33; ^{31}P NMR (161 MHz, CDCl_3) δ 29.56; IR (film) 2981, 2933, 2907, 1716, 1392, 1367, 1277, 1105, 1054, 1025, 962, 775, 546 cm^{-1} ; HRMS (EI) : m/z calcd. For $\text{C}_{16}\text{H}_{25}\text{O}_5\text{P}$: 328.1440; found : 328.1436.

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