Pd(DIPHOS)$_2$-Catalyzed Cross-Coupling Reactions of Organoborons with Free or Polymer Bound Aryl Halides

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Supporting Information:

2a. A mixture of 2-bromonaphthalene (2 mmol) and Pd(DIPHOS)$_2$ (24 mg, 0.01 mmol) in THF (12 mL) was stirred at rt for 20 min before the addition of a solution of phenylboronic acid (2 mmol) in THF-MeOH (4 mL). After stirring for 10 min, 2 M K_2CO_3 (4 mmol) was added with stirring. The reaction mixture was then heated to reflux for 4 h. Thereafter, the reaction was cooled before the addition of EtOAc (10 mL). The reaction mixture was then passed through a pad of Hyflo Super Cel and washed with EtOAc, and the combined filtrate was evaporated to dryness. After the residue was dissolved in water and extracted with EtOAc, the organic layer was dried over anhydrous Na_2SO_4, concentrated and the product was purified by recrystallization (Et_2O). ^{1}H NMR (500MHz, $CDCl_3$) δ 7.40 (t, *J* = 7.55 Hz, 1H), 7.48-7.54 (m, 4H), 7.74-7.77 (m, 3H), 7.87-7.94 (m, 3H), 8.06 (s, 1H); ^{13}C NMR (125.75 Hz, $CDCl_3$)[1] δ 126.00, 126.22, 126.34, 126.69, 127.76, 127.84, 128.06, 128.62, 128.82, 129.26, 133.04, 134.11, 138.99, 141.56; MS (EIMS) m/z 204 (100). Anal.Calcd for $C_{16}H_{12}$: C, 90.14; H, 5.63. Found: C, 89.81; H, 5.96.

2b. A mixture of 4-bromonitrobenzene (1 mmol) and Pd(DIPHOS)$_2$ (12 mg, 0.01 mmol) in THF (10 mL) was stirred at rt for 20 min before the addition of a solution of 4-formylphenylboronic acid (1 mmol) in THF-MeOH (4 mL). After stirring for 10 min, 2 M K_2CO_3 (2.1 mmol) was added with stirring. The reaction mixture was then heated to reflux for 5 h. Thereafter, the reaction was cooled before the addition of EtOAc (10 mL). The reaction mixture was then passed through a pad of Hyflo Super Cel and washed with EtOAc, and the combined filtrate was evaporated to dryness. After the residue was dissolved in water and extracted with EtOAc, the organic layer was dried over anhydrous Na_2SO_4, concentrated and the product was purified by recrystallization (Et_2O-CH_2Cl_2). ^{1}H NMR (500MHz, $CDCl_3$) δ 7.79 (d, *J* = 8.49 Hz, 4H), 8.02 (d, *J* = 8.49 Hz, 2H), 8.34 (d, 2H, *J* = 9.43 Hz, 2H, 10.11 (s, 1H); ^{13}C NMR (125.75 Hz, $CDCl_3$) δ 124.69, 128.51, 128.65, 130.86, 136.65, 144.90, 146.44, 148.15, 192.07; MS (EIMS) m/z 227 (100), 152 (85). Anal.Calcd for $C_{13}H_9NO_3$: C, 67.53; H, 3.90; N, 6.06. Found: C, 67.77; H, 3.80; N, 5.68.

2c. A mixture of ethyl 4-bromobenzoate (1 mmol) and Pd(DIPHOS)$_2$ (12 mg, 0.01 mmol) in THF (10 mL) was stirred at rt for 20 min before the addition of a solution of 4-formylphenylboronic acid (1 mmol) in THF-MeOH (4 mL). After stirring for 10 min, Et_3N (3 mmol) was added with stirring. The reaction mixture was then heated to reflux for 10 h. Thereafter, the reaction was cooled before the addition of EtOAc (10 mL). The reaction mixture was then passed through a pad of Hyflo Super Cel and washed with EtOAc, and the combined filtrate was evaporated to dryness. After the residue was dissolved in water and extracted with EtOAc, the organic layer was dried over anhydrous Na_2SO_4, concentrated and the crude product was purified by column chromatography (silica gel, 5-10% EtOAc-petroleum ether). ^{1}H NMR (500MHz, $CDCl_3$) δ 1.43 (t, *J* = 7.45 Hz, 3H), 4.42 (q, *J* = 7.45 Hz, 2H), 7.71 (d, *J* = 8.38 Hz, 2H), 7.80 (d, *J* = 8.38 Hz, 2H), 7.99 (d, *J* = 8.38 Hz, 2H), 8.16 (dd, *J* = 8.39, 1.86 Hz, 2H), 10.08 (s, 1H); ^{13}C NMR (125.75 Hz, $CDCl_3$) δ 14.72, 61.54, 127.69, 128.29, 130.62, 130.69, 136.17, 144.32, 146.33, 166.63, 192.12; MS (EIMS) m/z 254 (42), 209 (100). Anal.Calcd for $C_{16}H_{14}O_3$: C, 74.13; H, 5.40. Found: C, 74.08; H, 5.26.

2d. A mixture of *N*-(3-bromophenyl)phthalimide (1.5 mmol) and Pd(DIPHOS)$_2$ (24 mg, 0.02 mmol) in DMF (10 mL) was stirred at rt for 20 min before the addition of phenylboronic acid (1.5 mmol).

After stirring for 10 min, K_2CO_3 (2 mmol) was added with stirring. The reaction mixture was then heated at 75 ^oC for 2 h. Thereafter, the reaction was cooled before the addition of EtOAc (10 mL). The reaction mixture was then passed through a pad of Hyflo Super Cel and washed with EtOAc, and the combined filtrate was evaporated to dryness. After the residue was dissolved in water and extracted with EtOAc, the organic layer was dried over anhydrous Na_2SO_4, concentrated and the crude product was purified by recrystallization (MeOH-CH_2Cl_2). ^{1}H NMR (500MHz, $CDCl_3$) δ 7.37 (t, *J* = 7.46 Hz, 1H), 7.44 (d, *J* = 7.46 Hz, 1H), 7.46 (d, *J* = 7.46 Hz, 2H), 7.59 (t, *J* = 7.46 Hz, 1H), 7.63 (t, *J* = 7.46 Hz, 3H), 7.67 (s, 1H), 7.82 (dd, *J* = 5.59, 2.79 Hz, 2H), 7.98 (dd, *J* = 5.59, 2.79 Hz, 2H); ^{13}C NMR (125.75 Hz, $CDCl_3$) δ 124.18, 125.67, 125.83, 127.26, 127.70, 128.08, 129.23, 129.86, 132.20, 132.55, 134.84, 140.63, 142.80, 167.68; MS (EIMS) m/z 299 (87), 157 (70); 76 (100). Anal.Calcd for $C_{20}H_{13}NO_2$: C, 79.20; H, 4.29; N, 4.62. Found: C, 79.38; H, 4.17; N, 4.59.

2e. A mixture of 4-bromonitrobenzene (1 mmol) and Pd(DIPHOS)$_2$ (12 mg, 0.01 mmol) in THF (10 mL) was stirred at rt for 20 min before the addition of a solution of 4-vinylphenylboronic acid (1 mmol) in THF-MeOH (4 mL). After stirring for 10 min, 2 M K_2CO_3 (2.1 mmol) was added with stirring. The reaction mixture was then heated to reflux for 5 h. Thereafter, the reaction was cooled before the addition of EtOAc (10 mL). The reaction mixture was then passed through a pad of Hyflo Super Cel and washed with EtOAc, and the combined filtrate was evaporated to dryness. After the residue was dissolved in water and extracted with EtOAc, the organic layer was dried over anhydrous Na_2SO_4, concentrated and the product was purified by column chromatography (silica gel, 10-15% EtOAc-petroleum ether). ^{1}H NMR (500MHz, $CDCl_3$) δ 5.36 (d, *J* = 11.01 Hz, 1H), 5.87 (d, *J* = 18.36 Hz, 1H), 6.78 (dd, *J* = 11.01, 18.36 Hz, 1H), 7.55 (d, *J* = 8.26 Hz, 2H), 7.62 (d, *J* = 8.26 Hz, 2H), 7.79 (d, *J* = 9.18 Hz, 2H), 8.31 (d, *J* = 9.18 Hz, 2H); ^{13}C NMR (125.75 Hz, $CDCl_3$) δ 115.12, 124.13, 124.13, 126.97, 126.97, 127.51, 127.51, 127.51, 127.51, 135.99, 137.92, 138.27, 146.99, 147.02; MS (EIMS) m/z 225 (100), 178 (58). Anal.Calcd for $C_{14}H_{11}NO_2$: C, 74.66; H, 4.88; N, 6.22. Found: C, 74.53; H, 4.70; N, 6.12.

2f. A mixture of 4-bromoanisole (1 mmol) and Pd(DIPHOS)$_2$ (12 mg, 0.01 mmol) in THF (10 mL) was stirred at rt for 20 min before the addition of a solution of phenylboronic acid (1 mmol) in THF-MeOH (3 mL). After stirring for 10 min, 2 M K_2CO_3 (2.1 mmol) was added with stirring. The reaction mixture was then heated to reflux for 10 h. Thereafter, the reaction was cooled before the addition of EtOAc (10 mL). The reaction mixture was then passed through a pad of Hyflo Super Cel and washed with EtOAc, and the combined filtrate was evaporated to dryness. After the residue was dissolved in water and extracted with EtOAc, the organic layer was dried over anhydrous Na_2SO_4, concentrated and the product was purified by column chromatography (silica gel, 2-5% EtOAc-petroleum ether). ^{1}H NMR (500MHz, $CDCl_3$)[2,3] δ 3.86 (s, 3H), 6.99 (dd, *J* = 6.62, 2.21 Hz, 2H), 7.31 (m, 1H), 7.43 (t, *J* = 7.35 Hz, 2H), 7.53 – 7.57 (m, 4H); ^{13}C NMR (125.75 Hz, $CDCl_3$) δ 55.33, 114.21, 126.64, 126.73, 128.15, 128.71, 133.79, 140.84, 159.16; MS (EIMS) m/z 184 (59), 169 (34), 84 (100). Anal.Calcd for $C_{13}H_{12}O$: C, 80.81; H, 6.21. Found: C, 80.42; H, 6.25.

2g. A mixture of 4-bromo-7-chloroquinoline (1 mmol) and Pd(DIPHOS)$_2$ (12 mg, 0.01 mmol) in THF (8 mL) was stirred at rt for 20 min before the addition of a solution of phenylboronic acid (1 mmol) in THF-MeOH (4 mL). After stirring for 10 min, 2 M K_2CO_3 (2.1 mmol) was added with stirring. The reaction mixture was then heated to reflux for 4 h. Thereafter, the reaction was cooled before the addition of EtOAc (10 mL). The reaction mixture was then passed through a pad of Hyflo Super Cel and washed with EtOAc, and the combined filtrate was evaporated to dryness. After the residue was dissolved in water and extracted with EtOAc, the organic layer was dried over anhydrous Na_2SO_4, concentrated and the product was purified by recrystallization (Et_2O). ^{1}H NMR (500MHz, $CDCl_3$) δ 7.36 (d, *J* = 4.71, 1H), 7.45 – 7.56 (m, 6H), 7.88 (d, *J* = 8.48 Hz, 1H), 8.19 (d, *J* = 1.88 Hz, 1H), 8.96

(d, J = 4.71 Hz, 1H); ^{13}C NMR (125.75 Hz, $CDCl_3$) δ 121.86, 125.66, 127.86, 128.38, 128.46, 129.20, 129.33, 129.85, 136.26, 137.60, 148.59, 149.95, 150.65; MS (EIMS) m/z 239 (69), 204 (100). Anal.Calcd for $C_{15}H_{10}ClN$: C, 74.07; H, 4.18; N, 5.76. Found: C, 74.36; H, 4.33; N, 5.44.

2h. A mixture of 4-bromo-7-chloroquinoline (1 mmol) and Pd(DIPHOS)$_2$ (12 mg, 0.01 mmol) in THF (8 mL) was stirred at rt for 20 min before the addition of a solution of diethyl(3-pyridyl)borane (1 mmol) in THF-MeOH (4 mL). After stirring for 10 min, 2 M K_2CO_3 (2.1 mmol) was added with stirring. The reaction mixture was then heated to reflux for 12 h. Thereafter, the reaction was cooled before the addition of EtOAc (10 mL). The reaction mixture was then passed through a pad of Hyflo Super Cel and washed with EtOAc, and the combined filtrate was evaporated to dryness. After the residue was dissolved in water and extracted with EtOAc, the organic layer was dried over anhydrous Na_2SO_4, concentrated and the product was purified by recrystallization (Et_2O). ^{1}H NMR (500MHz, $CDCl_3$) δ 7.37 (d, J = 3.81 Hz, 1H), 7.51 (d, J = 1.91 Hz, 1H); 7.53 (dd, J = 3.81, 1.91 Hz, 1H), 7.79 (d, J = 8.58 Hz, 1H), 7.83 – 7.85 (m, 1H), 8.22 (d, J = 1.91 Hz, 1H), 8.77 – 8.79 (m, 2H), 8.99 (d, J = 3.81 Hz, 1H); ^{13}C NMR (125.75 Hz, $CDCl_3$) δ 122.08, 123.85, 125.32, 126.91, 128.56, 129.43, 133.71, 136.08, 137.14, 145.15, 149.53, 150.23, 150.39, 151.38; MS (EIMS) m/z 240 (95). Anal.Calcd for $C_{14}H_9ClN$: C, 69.70; H, 3.73; N, 11.61. Found: C, 69.64; H, 3.62; N, 11.28.

2i. A mixture of iodobenzene (1 mmol) and Pd(DIPHOS)$_2$ (12 mg, 0.01 mmol) in THF (8 mL) was stirred at rt for 20 min before the addition of a solution of phenylboronic acid (1 mmol) in THF-MeOH (4 mL). After stirring for 10 min, 2 M K_2CO_3 (2.1 mmol) was added with stirring. The reaction mixture was then heated to reflux for 4 h. Thereafter, the reaction was cooled before the addition of EtOAc (10 mL). The reaction mixture was then passed through a pad of Hyflo Super Cel and washed with EtOAc, and the combined filtrate was evaporated to dryness. After the residue was dissolved in water and extracted with EtOAc, the organic layer was dried over anhydrous Na_2SO_4, concentrated and the product was purified by column chromatography (silica gel, 10% EtOAc-petroleum ether). Analytical data were in complete accord with an authentic sample.

2j. A mixture of 3-iodobenzoic acid (1 mmol) and Pd(DIPHOS)$_2$ (12 mg, 0.01 mmol) in THF (8 mL) was stirred at rt for 20 min before the addition of a solution of phenylboronic acid (1 mmol) in THF-MeOH (4 mL). After stirring for 10 min, 2 M K_2CO_3 (2.1 mmol) was added with stirring. The reaction mixture was then heated to reflux for 3 h. Thereafter, the reaction was cooled before the addition of EtOAc (10 mL). The reaction mixture was then passed through a pad of Hyflo Super Cel and washed with EtOAc, and the combined filtrate was evaporated to dryness. After the residue was dissolved in water and extracted with EtOAc, the organic layer was dried over anhydrous Na_2SO_4, concentrated and recrystallized from ether. Analytical data were in complete accord with an authentic sample.

6a. Compound **5** (1.5 g) was dissolved in DMF and degassed by passing N_2 through the reaction mixture before Pd(DIPHOS)$_2$ (20 mg, 0.019 mmol) was added with stirring for 20 min. Thereafter, 4-fluorophenylboronic acid (0.60 mmol) and K_2CO_3 (100 mg, 0.7 mmol) were added sequentially. The reaction mixture was then heated at 70-80 ^{o}C for 4 h. After cooling, Et_2O was added and the precipitated solid was filtered, washed with Et_2O, and dried in vacuum. The solid was then dissolved in 1 N NaOH and heated at 90 ^{o}C for 1h. After cooling, the reaction mixture was neutralized with concentrated HCl and extracted with EtOAc. The organic layer was washed with water, dried over anhydrous Na_2SO_4, and solvent was evaporated. The product was then recrystallized from Et_2O (>95% pure as evident from NMR). ^{1}H NMR (500MHz, $CDCl_3$) δ 7.20 (t, J = 9.18 Hz, 2H), 7.62 – 7.65 (m, 2H), 7.68 (d, J = 8.26 Hz, 2H), 8.19 (d, J = 8.26 Hz, 2H); ^{13}C NMR (125.75 Hz, $CDCl_3$) δ 115.64, 115.82, 126.77, 128.87, 130.36, 136.14, 144.58, 161.88, 163.85; MS (EIMS) m/z 216 (100), 199 (63), 170 (54).

6b. Compound **5** (1.5 g) was dissolved in DMF and degassed by passing N_2 through the reaction mixture before $Pd(DIPHOS)_2$ (20 mg, 0.019 mmol) was added with stirring for 20 min. Thereafter, 3-nitrophenylboronic acid (0.60 mmol) and K_2CO_3 (100 mg, 0.7 mmol) were added sequentially. The reaction mixture was then heated at 70-80 ^oC for 3 h. After cooling, Et_2O was added and the precipitated solid was filtered, washed with Et_2O, and dried in vacuum. The solid was then dissolved in 1 N NaOH and heated at 90 ^oC for 1h. After cooling, the reaction mixture was neutralized with concentrated HCl and extracted with EtOAc. The organic layer was washed with water, dried over anhydrous Na_2SO_4, and solvent was evaporated. The product was then recrystallized from Et_2O (>95% pure as evident from NMR). ^1H NMR (500MHz, $CDCl_3$) δ 7.35 – 7.41 (m, 3H), 7.68 (d, *J* = 7.34 Hz, 1H), 7.82 (d, J = 8.26 Hz, 2H), 7.91 (d, *J* = 8.26 Hz, 1H), 8.14 (s, 1H); MS (EIMS) m/z 243 (100), 197 (14), 152 (78).

6c. Compound **5** (1.5 g) was dissolved in DMF and degassed by passing N_2 through the reaction mixture before $Pd(DIPHOS)_2$ (20 mg, 0.019 mmol) was added with stirring for 20 min. Thereafter, 4-vinylphenylboronic acid (0.60 mmol) and K_2CO_3 (100 mg, 0.7 mmol) were added sequentially. The reaction mixture was then heated at 70-80 ^oC for 4 h. After cooling, Et_2O was added and the precipitated solid was filtered, washed with Et_2O, and dried in vacuum. The solid was then dissolved in 1 N NaOH and heated at 90 ^oC for 1h. After cooling, the reaction mixture was neutralized with concentrated HCl and extracted with EtOAc. The organic layer was washed with water, dried over anhydrous Na_2SO_4, and solvent was evaporated. The product was then recrystallized from Et_2O (>95% pure as evident from NMR). ^1H NMR (500MHz, $CDCl_3$) δ 5.22 (d, *J* = 11.06 Hz, 1H), 5.87 (d, *J* = 17.51 Hz, 1H), 6.78 (dd, *J* = 11.06, 17.51 Hz, 1H), 7.45 (d, *J* = 8.29 Hz, 2H), 7.53 (d, *J* = 8.29 Hz, 2H), 7.61 (d, *J* = 8.29 Hz, 2H), 8.03 (d, *J* = 8.29 Hz, 2H); MS (EIMS) m/z 224 (100), 207 (30), 178 (34).

References:

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