Suzuki-Miyaura Cross-Coupling of Benzylic Carbonates with Arylboronic Acids

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Supporting Information

General and Materials. NMR spectra were measured with Bruker AVANCE 400 (9.4 T magnet) spectrometer. IR spectra were measured with Nicolet Magna 560. Elemental analyses were performed by Service Centre of Elementary Analysis of Organic Compounds in Kyushu University. Flash column chromatographies were performed with silica gel 60 (230–400 mesh, Merck).

All reactions were conducted under nitrogen atmosphere. DMF was distilled from calcium hydride. All benzylic carbonates were prepared from esterification of the corresponding alcohols with methyl chloroformate in the presence of Et₃N, and were purified with flash column chromatography. [Pd(η^3 -C₃H₅)Cl]₂ was prepared according to literatures,¹ but was commercially available. All boronic acids and DPPent were purchased from Aldrich.

General Procedure of Cross-Coupling of Benzylic Carbonates with Arylboronic Acids (Table 2). Under nitrogen atmosphere, a benzylic methyl carbonate **1** (1.0 mmol) was added to a suspension of arylboronic acid **2** (1.1 mmol), potassium carbonate (304 mg, 2.2 mmol), [Pd(η^3 -C₃H₅)Cl]₂ (1.8 mg, 5.0 μ mol), and 1,5-bis(diphenylphosphino)pentane (4.4 mg, 10 μ mol) in DMF (1.0 ml). When **1** was solid, DMF (1.0 ml) was added to a mixture of all solid materials. The suspension was stirred at 80 °C until **1** was completely consumed (monitored by GC). After brine was added, the mixture was extracted several times with hexane. The combined organic layer was dried with MgSO₄, and was evaporated under reduced pressure. The residue was purified by flash column chromatography (EtOAc/hexane) to give the desired product.

Diphenylmethane² (3a) (Entry 1 in Table 2). The general procedure was followed with benzyl methyl carbonate (**1a**) (167 mg, 1.00 mmol) and phenylboronic acid (**2a**) (134 mg, 1.10 mmol) in the presence of 2 mol % DPPent–palladium catalyst. The crude product was purified by flash column chromatography (hexane) to give **3a** (135 mg, 80%) as colorless oil: ¹H NMR (400 MHz, CDCl₃, TMS) δ 3.97 (s, 2H), 7.16–7.21 (m, 6H), 7.27 (t, *J* = 7.5 Hz, 4H); ¹³C {¹H} NMR (100 MHz, CDCl₃) δ 41.9, 126.0, 128.4, 128.9, 141.1.

2-Benzyltoluene³ (3b) (Entry 2 in Table 2). The general procedure was followed with methyl 2-methylbenzyl carbonate (**1b**) (181 mg, 1.00 mmol) and **2a** (135 mg, 1.11 mmol) in the presence of 2 mol % DPPent–palladium catalyst. The crude product was purified by flash column chromatography (hexane) to give **3b** (160 mg, 88%) as colorless oil: ¹H NMR (400 MHz, CDCl₃, TMS) δ 2.23 (s, 3H), 3.98 (s, 2H), 7.07–7.20 (m, 7H), 7.26 (t, *J* = 7.4 Hz, 2H); ¹³C {¹H} NMR (100 MHz, CDCl₃) δ 19.6, 39.4, 125.9, 126.0, 126.4, 128.4, 128.7, 129.9, 130.3, 136.6, 138.9, 140.4.

4-Benzylanisole⁴ (3c) (Entry 3 in Table 2). The general procedure was followed with 4-methoxybenzyl methyl carbonate (**1c**) (196 mg, 1.00 mmol) and **2a** (134 mg, 1.10 mmol). The crude product was purified by flash column chromatography (EtOAc/hexane) to give **3c** (187 mg, 94%) as pale yellow oil: ¹H NMR (400 MHz, CDCl₃, TMS) δ 3.77 (s, 3H), 3.92 (s, 2H), 6.82 (d, *J* = 8.5 Hz, 2H), 7.10 (d, *J* = 8.5 Hz, 2H), 7.15–7.20 (m, 3H), 7.27 (t, *J* = 7.3 Hz, 2H); ¹³C {¹H} NMR (100 MHz, CDCl₃) δ 41.0, 55.2, 113.9, 125.9, 128.4, 128.8, 129.8, 133.2, 141.6, 157.9.

4-Benzyl-1-(trifluoromethyl)benzene (3d) (Entry 4 in Table 2). The general procedure was followed with methyl 4-(trifluoromethyl)benzyl carbonate (**1d**) (234 mg, 1.01 mmol) and **2a** (134 mg, 1.10 mmol). The crude product was purified by flash column chromatography (hexane) to give **3d**

(223 mg, 94%) as pale yellow oil: ^1H NMR (400 MHz, CDCl_3 , TMS) δ 4.02 (s, 2H), 7.15–7.33 (m, 7H), 7.53 (d, $J = 8.1$ Hz, 2H); ^{13}C $\{^1\text{H}\}$ NMR (100 MHz, CDCl_3) δ 41.7, 124.3 (q, $J = 272$ Hz), 125.4 (q, $J = 4$ Hz), 126.5, 128.5 (q, $J = 33$ Hz), 128.6, 128.9, 129.2, 140.0, 145.2; Anal. Calcd for $\text{C}_{14}\text{H}_{11}\text{F}_3$: C, 71.18; H, 4.69. Found: C, 71.24; H, 4.62.

Methyl 4-Benzylbenzoate⁵ (3e) (Entry 5 in Table 2). The general procedure was followed with 4-(methoxycarbonyl)benzyl methyl carbonate (**1e**) (224 mg, 1.00 mmol) and **2a** (135 mg, 1.10 mmol). The crude product was purified by flash column chromatography (EtOAc/hexane) to give **3e** (185 mg, 82%) as colorless oil: ^1H NMR (400 MHz, CDCl_3 , TMS) δ 3.89 (s, 3H), 4.03 (s, 2H), 7.17 (d, $J = 7.3$ Hz, 2H), 7.19–7.32 (m, 5H), 7.95 (d, $J = 8.2$ Hz, 2H); ^{13}C $\{^1\text{H}\}$ NMR (100 MHz, CDCl_3) δ 41.9, 52.0, 126.4, 128.1, 128.6, 128.9, 129.8, 140.1, 146.5, 167.0.

4-Benzyl-1-chlorobenzene⁴ (3f) (Entry 6 in Table 2). The general procedure was followed with 4-chlorobenzyl methyl carbonate (**1f**) (204 mg, 1.02 mmol) and **2a** (134 mg, 1.10 mmol). The crude product was purified by flash column chromatography (hexane) to give **3f** (171 mg, 84%) as colorless oil: ^1H NMR (400 MHz, CDCl_3 , TMS) δ 3.94 (s, 2H), 7.10 (d, $J = 8.3$ Hz, 2H), 7.15 (d, $J = 7.2$ Hz, 2H), 7.17–7.31 (m, 5H); ^{13}C $\{^1\text{H}\}$ NMR (100 MHz, CDCl_3) δ 41.2, 126.3, 128.5, 128.8, 130.2, 131.9, 139.6, 140.5.

1-Benzyl-naphthalene⁶ (3g) (Entry 7 in Table 2). The general procedure was followed with methyl (1-naphthyl)methyl carbonate (**1g**) (214 mg, 0.99 mmol) and **2a** (135 mg, 1.10 mmol). The crude product was purified by flash column chromatography (EtOAc/hexane) to give **3g** (197 mg, 90%) as colorless solid: ^1H NMR (400 MHz, CDCl_3 , TMS) δ 4.46 (s, 2H), 7.16–7.22 (m, 3H), 7.24–7.31 (m, 3H), 7.39–7.49 (m, 3H), 7.76 (d, $J = 8.2$ Hz, 1H), 7.84–7.88 (m, 1H), 7.97–8.02 (m, 1H); ^{13}C $\{^1\text{H}\}$ NMR (100 MHz, CDCl_3) δ 39.0, 124.3, 125.5, 125.9, 126.0, 127.1, 127.3, 128.4, 128.6, 128.7, 132.1, 133.9, 136.6, 140.6.

4-Benzylanisole⁴ (3c) (Entry 8 in Table 2). The general procedure was followed with **1a** (167 mg, 1.01 mmol) and 4-methoxyphenylboronic acid (**2b**) (166 mg, 1.09 mmol). The crude product was purified by flash column chromatography (EtOAc/hexane) to give **3c** (179 mg, 90%) as pale yellow oil. The ^1H and ^{13}C NMR spectra of the product were identical with those of **3c** obtained from entry 3 in Table 2.

4-Benzyl-1-(trifluoromethyl)benzene (3d) (Entry 9 in Table 2). The general procedure was followed with **1a** (170 mg, 1.02 mmol) and 4-(trifluoromethyl)phenylboronic acid (**2c**) (209 mg, 1.10 mmol). The crude product was purified by flash column chromatography (hexane) to give **3d** (196 mg, 81%) as pale yellow oil. The ^1H and ^{13}C NMR spectra of the product were identical with those of **3d** obtained from entry 4 in Table 2.

4-(2-Methylbenzyl)anisole (3h) (Entry 10 in Table 2). The general procedure was followed with **1c** (196 mg, 1.00 mmol) and 2-methylphenylboronic acid (**2d**) (150 mg, 1.10 mmol). The crude product was purified by flash column chromatography (EtOAc/hexane) to give **3h** (210 mg, 99%) as colorless oil: ^1H NMR (400 MHz, CDCl_3 , TMS) δ 2.24 (s, 3H), 3.77 (s, 3H), 3.92 (s, 2H), 6.81 (d, $J = 8.6$ Hz, 2H), 7.03 (d, $J = 8.6$ Hz, 2H), 7.05–7.16 (m, 4H); ^{13}C $\{^1\text{H}\}$ NMR (100 MHz, CDCl_3) δ 19.6, 38.5, 55.2, 113.8, 125.9, 126.3, 129.6, 129.7, 130.2, 132.4, 136.5, 139.3, 157.8; Anal. Calcd for $\text{C}_{15}\text{H}_{16}\text{O}$: C, 84.87; H, 7.60. Found: C, 84.74; H, 7.53.

2-Benzylbiphenyl⁷ (3i) (Entry 11 in Table 2). The general procedure was followed with **1a** (166 mg, 1.00 mmol) and 2-biphenylboronic acid (**2e**) (219 mg, 1.11 mmol). The crude product was purified by flash column chromatography (hexane) to give **3i** (213 mg, 87%) as colorless solid: ^1H NMR (400 MHz, CDCl_3 , TMS) δ 3.95 (s, 2H), 6.97 (d, $J = 7.1$, 2H), 7.11–7.38 (m, 12H); ^{13}C $\{^1\text{H}\}$ NMR (100 MHz, CDCl_3) δ 39.0, 125.7, 126.1, 126.9, 127.4, 128.0, 128.2, 128.8, 129.3, 130.1, 130.3, 138.2, 141.4, 141.6, 142.2.

4-(4-Chlorobenzyl)anisole⁸ (3j) (Entry 12 in Table 2). The general procedure was followed with **1c** (196 mg, 1.00 mmol) and 4-chlorophenylboronic acid (**2f**) (173 mg, 1.10 mmol). The crude

product was purified by flash column chromatography (EtOAc/hexane) to give **3j** (197 mg, 85%) as colorless oil: ^1H NMR (400 MHz, CDCl_3 , TMS) δ 3.77 (s, 3H), 3.88 (s, 2H), 6.83 (d, J = 8.6 Hz, 2H), 7.04–7.11 (m, 4H), 7.23 (d, J = 8.4 Hz, 2H); ^{13}C $\{^1\text{H}\}$ NMR (100 MHz, CDCl_3) δ 40.3, 55.2, 114.0, 128.5, 129.8, 130.1, 131.7, 132.6, 140.0, 158.1.

4-(4-Methoxybenzyl)benzaldehyde (3k) (Entry 13 in Table 2). The general procedure was followed with **1c** (197 mg, 1.00 mmol) and 4-formylphenylboronic acid (**2g**) (167 mg, 1.12 mmol). The crude product was purified by flash column chromatography (EtOAc/hexane) to give **3k** (176 mg, 78%) as pale yellow oil: ^1H NMR (400 MHz, CDCl_3 , TMS) δ 3.79 (s, 3H), 3.99 (s, 2H), 6.85 (d, J = 8.6 Hz, 2H), 7.09 (d, J = 8.6 Hz, 2H), 7.33 (d, J = 8.1 Hz, 2H), 7.79 (d, J = 8.1 Hz, 2H), 9.96 (s, 1H); ^{13}C $\{^1\text{H}\}$ NMR (100 MHz, CDCl_3) δ 41.2, 55.2, 114.1, 129.4, 129.9, 130.0, 131.8, 134.6, 148.9, 158.2, 191.9; IR (neat) 1697 cm^{-1} .

***N*-(*tert*-Butoxycarbonyl)-3-(4-methoxybenzyl)aniline (3l) (Entry 14 in Table 2).** The general procedure was followed with **1c** (196 mg, 1.00 mmol) and 3- $\{N$ -(*tert*-butoxycarbonyl)amino}phenylboronic acid (**2h**) (261 mg, 1.10 mmol). The crude product was purified by flash column chromatography (EtOAc/hexane) to give **3l** (288 mg, 92%) as colorless solid: mp 114 $^\circ\text{C}$; ^1H NMR (400 MHz, CDCl_3 , TMS) δ 1.50 (s, 9H), 3.78 (s, 3H), 3.88 (s, 2H), 6.41 (br s, 1H), 6.80–6.86 (m, 3H), 7.09 (d, J = 8.6 Hz, 2H), 7.13–7.21 (m, 3H); ^{13}C $\{^1\text{H}\}$ NMR (100 MHz, CDCl_3) δ 28.3, 41.0, 55.2, 80.4, 113.9, 116.2, 118.9, 123.6, 129.0, 129.9, 133.0, 138.4, 142.6, 152.7, 158.0; IR (thin film) 3336, 1718 cm^{-1} ; Anal. Calcd for $\text{C}_{19}\text{H}_{23}\text{NO}_3$: C, 72.82; H, 7.40; N, 4.47. Found: C, 72.77; H, 7.36; N, 4.42.

{3-(4-Methoxybenzyl)phenyl}methanol (3m) (Entry 15 in Table 2). The general procedure was followed with **1c** (196 mg, 1.00 mmol) and 3-(hydroxymethyl)phenylboronic acid (**2i**) (167 mg, 1.10 mmol). The crude product was purified by flash column chromatography (EtOAc/hexane) to give **3m** (209 mg, 92%) as pale yellow solid: mp 48 $^\circ\text{C}$; ^1H NMR (400 MHz, CDCl_3 , TMS) δ 1.63 (br t, J = 4.9 Hz, 1H), 3.78 (s, 3H), 3.92 (s, 2H), 4.65 (d, J = 4.9 Hz, 2H), 6.83 (d, J = 8.6 Hz, 2H), 7.08–7.13 (m, 3H), 7.19 (d, J = 7.9 Hz, 2H), 7.27 (t, J = 7.7 Hz, 1H); ^{13}C $\{^1\text{H}\}$ NMR (100 MHz, CDCl_3) δ 41.0, 55.2, 65.4, 113.9, 124.7, 127.4, 128.1, 128.7, 129.8, 133.1, 141.0, 142.0, 158.0; IR (thin film) 3406 cm^{-1} ; Anal. Calcd for $\text{C}_{15}\text{H}_{16}\text{O}_2$: C, 78.92; H, 7.06. Found: C, 78.75; H, 7.06.

3-Benzyl-1-nitrobenzene⁵ (3n) (Entry 16 in Table 2). The general procedure was followed with **1a** (167 mg, 1.01 mmol) and 3-nitrophenylboronic acid (**2j**) (183 mg, 1.10 mmol) in the presence of 2 mol % DPPPEnt–palladium catalyst. The crude product was purified by flash column chromatography (EtOAc/hexane) to give **3n** (178 mg, 83%) as yellow oil: ^1H NMR (400 MHz, CDCl_3 , TMS) δ 4.08 (s, 2H), 7.18 (d, J = 7.1 Hz, 2H), 7.24 (t, J = 7.3 Hz, 1H), 7.32 (t, J = 7.3 Hz, 2H), 7.41–7.47 (m, 1H), 7.51 (d, J = 7.6 Hz, 1H), 8.04–8.08 (m, 2H); ^{13}C $\{^1\text{H}\}$ NMR (100 MHz, CDCl_3) δ 41.5, 121.3, 123.7, 126.7, 128.8, 128.9, 129.3, 135.0, 139.3, 143.2, 148.4.

(*E*)-3-(4-Methoxyphenyl)-1-phenyl-1-propene⁹ (3o) (Entry 17 in Table 2). The general procedure was followed with **1c** (196 mg, 1.00 mmol) and (*E*)-2-phenylethenylboronic acid (**2k**) (163 mg, 1.10 mmol). The crude product was purified by flash column chromatography (EtOAc/hexane) to give **3o** (183 mg, 82%) as yellow oil: ^1H NMR (400 MHz, CDCl_3 , TMS) δ 3.48 (d, J = 6.5 Hz, 2H), 3.79 (s, 3H), 6.33 (dt, J = 15.7, 6.5 Hz, 1H), 6.43 (d, J = 15.8 Hz, 1H), 6.85 (d, J = 8.6 Hz, 2H), 7.15 (d, J = 8.6 Hz, 2H), 7.19 (t, J = 7.3 Hz, 1H), 7.28 (t, J = 7.4 Hz, 2H), 7.35 (d, J = 7.4 Hz, 2H); ^{13}C $\{^1\text{H}\}$ NMR (100 MHz, CDCl_3) δ 38.4, 55.3, 113.9, 126.1, 127.0, 128.5, 129.6, 129.7, 130.7, 132.2, 137.5, 158.1.

1,4-Dibenzylbenzene¹⁰ (6) (Scheme 1). The general procedure was followed with dicarbonate **4** (129 mg, 0.507 mmol) and **2a** (147 mg, 1.21 mmol) in the presence of potassium carbonate (332 mg, 2.40 mmol) and DPPPEnt–palladium catalyst (10 μmol). The crude product was purified by flash column chromatography (EtOAc/hexane) to give **6** (103 mg, 79%) as colorless solid: ^1H NMR (400

MHz, CDCl₃, TMS) δ 3.94 (s, 4H), 7.10 (s, 4H), 7.16–7.22 (m, 6H), 7.25–7.31 (m, 4H); ¹³C {¹H} NMR (100 MHz, CDCl₃) δ 41.5, 126.0, 128.4, 128.9, 129.0, 138.8, 141.2.

1,3-Dibenzylbenzene¹¹ (7) (Scheme 1). The general procedure was followed with dicarbonate **5** (127 mg, 0.500 mmol) and **2a** (146 mg, 1.20 mmol) in the presence of potassium carbonate (333 mg, 2.41 mmol) and DPPent–palladium catalyst (10 μ mol). The crude product was purified by flash column chromatography (EtOAc/hexane) to give **6** (115 mg, 89%) as colorless solid: ¹H NMR (400 MHz, CDCl₃, TMS) δ 3.94 (s, 4H), 6.99–7.06 (m, 3H), 7.14–7.23 (m, 7H), 7.24–7.30 (m, 4H); ¹³C {¹H} NMR (100 MHz, CDCl₃) δ 41.9, 126.0, 126.7, 128.4, 128.5, 128.9, 129.6, 141.1, 141.2.

Estimation of Relative Reactivities among Benzylic Carbonates 1a, 1c, and 1d. General procedure of competitive experiments is as follows. Under nitrogen atmosphere, two benzylic carbonates (0.30 mmol each) were added to a suspension of **2a** (24 mg, 0.20 mmol), potassium carbonate (55 mg, 0.40 mmol), [Pd(η^3 -C₃H₅)Cl]₂ (1.8 mg, 5.0 μ mol), 1,5-bis(diphenylphosphino)pentane (4.4 mg, 10 μ mol), and naphthalene (10 mg, internal standard for GC analysis) in DMF (1.0 ml). When a benzylic carbonate was solid, DMF (1.0 ml) was added to a mixture of all solid materials. The suspension was stirred at 80 °C. After 3 h, yields of two diarylmethanes were determined by GC versus a calibrated internal standard (average of two runs).

The results of each competitive experiment were summarized in Table S-1.

Table S-1. Estimation of Relative Reactivities among **1a**, **1c**, and **1d**.

Entry	R ¹ (1)	R ² (1')	GC yield (3), %	GC yield (3'), %
1	H (1a)	MeO (1c)	27 (3a)	37 (3c)
2	H (1a)	CF ₃ (1d)	14 (3a)	51 (3d)
3	MeO (1c)	CF ₃ (1d)	18 (3c)	46 (3d)

Estimation of Relative Reactivities among Arylboronic Acids 2a, 2b, and 2c. General procedure of competitive experiments is as follows. Under nitrogen atmosphere, **1a** (33 mg, 0.20 mmol) was added to a suspension of two arylboronic acids (0.30 mmol each), potassium carbonate (166 mg, 1.20 mmol), [Pd(η^3 -C₃H₅)Cl]₂ (1.8 mg, 5.0 μ mol), 1,5-bis(diphenylphosphino)pentane (4.4 mg, 10 μ mol), and naphthalene (10 mg, internal standard for GC analysis) in DMF (1.0 ml). The suspension was stirred at 80 °C. After 3 h, yields of two diarylmethanes were determined by GC versus a calibrated internal standard (average of two runs).

The results of each competitive experiment were summarized in Table S-2.

Table S-2. Estimation of Relative Reactivities among **2a**, **2b**, and **2c**.

Entry	R^1 (2)	R^2 (2')	GC yield (3), %	GC yield (3'), %
1	H (2a)	MeO (2b)	34 (3a)	33 (3c)
2	H (2a)	CF_3 (2c)	23 (3a)	47 (3d)
3	MeO (2b)	CF_3 (2c)	24 (3c)	48 (3d)

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Figure S-1. ¹H (upper) and ¹³C (lower) NMR spectra of **3k**.