Suzuki-Miyaura Coupling Catalyzed by Polymer Incarcerated Palladium (PI Pd), a Highly Active, Recoverable and Reusable Pd Catalyst

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General:

Tetramethylsilane ($\delta = 0$) was used as an internal standard for ^1H NMR and CDCl_3 ($\delta = 77.0$) for ^{13}C NMR. The structures of the known compounds were confirmed by comparison

with commercially available compounds or data shown in literature.

Preparation of PI Pd (1)

Copolymer (1.00 g) was dissolved in tetrahydrofuran (20 mL) at room temperature, and to this solution was added tetrakis(triphenylphosphine)palladium(0) (0.10 g) as a core. The mixture was stirred for 24 h at this temperature. Hexane (30 mL) was slowly added at 0 °C. Coacervates were found to envelope the core dispersed in the medium. The mixture was left to stand at room temperature for 12 h, and the catalyst capsules were then washed with hexane several times and dried at room temperature for 24 h. Next, the catalyst capsules were stirred at 120 °C for 2 h to cross-link the capsules. The cross-linked catalyst was then washed with tetrahydrofuran several times and dried at room temperature for 24 h to give PI Pd (**1**, 545 mg, 0.15 mmol/g, 96 % of palladium metal was loaded).

Determination of loading of the palladium

PI Pd (**1**, 50.0 mg) was placed in 50 mL-test tube and then added sulfuric acid (1.0 mL). The mixture was heated at 180 °C for 30 min. After cooling to room temperature, nitric acid (0.5 mL) was added and further heated at 180 °C to decompose the polymer. After cooling to room temperature, water (5 mL) was added and heated at 180 °C again to dissolve completely. The solution was adjusted to 10 mL by water and then measured the amount of Pd metal by fluorescence X-ray (XRF) analysis to determine the loading of palladium.

A typical experimental procedure for the Suzuki-Miyaura coupling

2-Methylbiphenyl¹ (Table 4, entry 1): 2-Bromotoluene (**2**, 0.5 mmol), phenylboronic acid (**3**, 0.75 mmol), P(*o*-MeOC₆H₄)₃ (0.025 mmol), PI Pd (0.025 mmol, 5 mol%), and K₃PO₄ (1.0 mmol) were combined in toluene-H₂O (4/1) (5 mL). The mixture was stirred

for 2 h under reflux conditions. After hexane was added to quench the reaction, the catalyst was collected by filtration and washed with THF, water, and MeOH, and then was dried and reused. The solvents of the filtrate were removed under reduced pressure, MeCN was added to the residue, and insoluble inorganic salts were removed by filtration. After removal of the solvent, the volume of the residue was adjusted to 5 mL using MeCN to give a sample of XRF analysis for the measurement of leaching of the palladium. The sample solution after measurement of the leaching was evaporated and the residual crude product was purified by preparative thin-layer chromatography (PTLC) to afford 2-methylbiphenyl (88 %). ^1H NMR (CDCl_3) δ = 2.26 (s, 3H), 7.21-7.42 (m, 9H); ^{13}C NMR (CDCl_3 , 300 MHz) δ = 20.4, 125.7, 126.7, 127.2, 128.0, 129.2, 129.8, 130.3, 135.3, 141.9, 141.9.

2,6-Dimethylbiphenyl² (Table 4, entry 2): ^1H NMR (CDCl_3 , 400 MHz) δ = 2.02 (s, 6H), 7.08-7.58 (m, 8H).

2-Methyl-4'-tert-butylbiphenyl² (Table 4, entry 3): ^1H NMR (CDCl_3 , 400 MHz) δ = 1.36 (s, 9H), 2.29 (s, 3H), 7.20-7.30 (m, 6H), 7.42 (d, 2H, J = 8.3 Hz); ^{13}C NMR (CDCl_3 , 400 MHz) δ = 20.5, 31.4, 34.5, 124.9, 125.7, 127.0, 128.8, 129.9, 130.3, 135.4, 139.0, 141.9, 149.5.

4-Methoxybiphenyl¹ (Table 4, entry 4): ^1H NMR (CDCl_3 , 400 MHz) δ = 3.85 (s, 3H), 6.98 (d, 2H, J = 8.4 Hz), 7.30 (t, 1H, J = 6.8 Hz), 7.41 (t, 2H, J = 8.0 Hz), 7.54 (t, 4H, J = 8.0 Hz); ^{13}C NMR (CDCl_3 , 400 MHz) δ = 55.3, 114.2, 126.6, 126.7, 128.1, 128.7, 133.7, 140.8, 159.1.

4-*o*-Tolylpyridine³ (Table 4, entry 5): ^1H NMR (CDCl_3 , 400 MHz) δ = 2.27 (s, 3H), 7.19-7.33 (m, 6H), 8.65 (d, 2H, J = 6.1 Hz); ^{13}C NMR (CDCl_3 , 400 MHz) δ = 20.2, 124.2, 126.0, 128.3, 129.2, 130.6, 134.9, 138.9, 149.3, 149.9.

Biphenyl-2-ol⁴ (Table 4, entry 6): ^1H NMR (CDCl_3 , 300 MHz) δ = 5.26 (s, 1H), 6.95-

6.98 (m, 2H), 7.21-7.27 (m, 2H), 7.34-7.41 (m, 1H), 7.43-7.47 (m, 4H); ^{13}C NMR (CDCl_3 , 300 MHz) δ = 115.8, 120.8, 127.8, 128.1, 129.1, 129.1, 129.2, 130.2, 137.1, 152.4.

4-Nitrobiphenyl² (Table 4, entry 7): ^1H NMR (CDCl_3 , 400 MHz) δ = 7.42-7.51 (m, 3H), 7.61 (d, 2H, J = 7.8 Hz), 7.72 (d, 2H, J = 8.5 Hz), 8.27 (d, 2H, J = 8.5 Hz); ^{13}C NMR (CDCl_3 , 400 MHz) δ = 124.0, 127.3, 127.7, 128.9, 129.1, 138.7, 147.0, 147.5.

4-Cyano-2'-methylbiphenyl¹ (Table 4, entry 8): ^1H NMR (CDCl_3 , 400 MHz) δ = 2.25 (s, 3H), 7.19 (d, 1H, J = 7.1 Hz), 7.25-7.33 (m, 3H), 7.44 (d, 2H, J = 8.0 Hz), 7.71 (d, 2H, J = 7.8 Hz); ^{13}C NMR (CDCl_3 , 400 MHz) δ = 20.3, 110.7, 118.9, 126.1, 128.3, 129.4, 130.0, 130.6, 131.9, 135.0, 140.0, 146.8.

4-Carbomethoxy-2'-methylbiphenyl⁵ (Table 4, entry 9): ^1H NMR (CDCl_3 , 400 MHz) δ = 2.25 (s, 3H), 3.92 (s, 3H), 7.19-7.26 (m, 4H), 7.38 (d, 2H, J = 8.1 Hz), 8.08 (d, 2H, J = 8.1 Hz); ^{13}C NMR (CDCl_3 , 400 MHz) δ = 20.3, 52.0, 125.8, 127.7, 128.5, 129.2, 129.3, 129.4, 130.4, 135.0, 140.8, 146.7, 166.9.

4-Acetylbiphenyl² (Table 4, entry 10): ^1H NMR (CDCl_3 , 400 MHz) δ = 2.60 (s, 3H), 7.35-7.46 (m, 3H), 7.58-7.66 (m, 4H), 8.00 (d, 2H, J = 8.6 Hz); ^{13}C NMR (CDCl_3 , 400 MHz) δ = 26.5, 127.1, 127.1, 128.1, 128.8, 128.8, 135.7, 139.7, 145.6, 197.6.

2-Methyl-3-phenyl-2-cyclopentenone⁶ (Table 4, entry 11): ^1H NMR (CDCl_3 , 400 MHz) δ = 1.96 (s, 3H), 2.51-2.54 (m, 2H), 2.89-2.91 (m, 2H), 7.39-7.53 (m, 5H).

4-Methoxy-2'-methylbiphenyl⁵ (Table 4, entry 12): ^1H NMR (CDCl_3 , 300 MHz) δ = 2.27 (s, 3H), 3.83 (s, 3H), 6.94 (d, 2H, J = 8.8 Hz), 7.19-7.25 (m, 6H); ^{13}C NMR (CDCl_3 , 300 MHz) δ = 20.5, 55.2, 113.5, 125.7, 126.9, 129.9, 130.2, 130.3, 134.4, 135.4, 141.5, 158.5.

4-Acetyl-2'-methylbiphenyl⁵ (Table 4, entry 13): ^1H NMR (CDCl_3 , 300 MHz) δ = 2.26 (s, 3H), 2.63 (s, 3H), 7.20-7.29 (m, 4H), 7.41 (d, 2H, J = 8.6 Hz), 8.00 (d, 2H, J = 8.6 Hz); ^{13}C NMR (CDCl_3 , 300 MHz) δ = 20.3, 26.5, 125.8, 127.8, 128.1, 129.4, 129.4, 130.4, 135.0, 135.5, 140.6, 146.9, 197.7.

The coupling reaction of hindered substrates

2,6,2'-Trimethylbiphenyl⁷ (Table 5, entry 2): 2-bromo-*m*-xylene (0.5 mmol), 2-methylphenylboronic acid (0.75 mmol), 2-dicyclohexylphosphinobiphenyl² (0.025 mmol), Pd (1, 0.025 mmol, 5 mol%), and K₃PO₄ (1.0 mmol) were combined in toluene-H₂O (4/1) (5 mL). The mixture was stirred for 2 h under reflux condition. After hexane was added to quench the reaction, the catalyst was collected by filtration and washed with THF, H₂O, and MeOH, and then dried. The solvent of the filtrate was removed under reduced pressure, and the crude product was purified by preparative thin-layer chromatography (PTLC) to afford 2,6,2'-trimethylbiphenyl (71 %). ¹H NMR (CDCl₃, 300 MHz) δ = 1.94 (s, 6H), 1.96 (s, 3H), 6.99-7.02 (m, 1H), 7.08-7.30 (m, 6H).

2-Acetyl-2'-methylbiphenyl⁸ (Table 5, entry 4): ¹H NMR (CDCl₃, 300 MHz) δ = 1.97 (s, 3H), 2.13 (s, 3H), 7.11 (d, 1H, *J* = 7.5 Hz), 7.19-7.30 (m, 4H), 7.39-7.53 (m, 2H), 7.68 (dd, 1H, *J* = 1.5, 7.5 Hz); ¹³C NMR (CDCl₃, 300 MHz) δ = 20.1, 29.7, 125.8, 127.3, 128.0, 128.1, 129.5, 130.2, 130.6, 130.8, 135.5, 140.2, 140.4, 140.7, 203.0.

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