Macromolecular Effect: Synthesis of a Ferrocenylmethlyphosphine-Containing Polymer as Highly Efficient Ligands for Room Temperature Palladium-Catalyzed Suzuki Cross Coupling Reactions of Aryl Chlorides

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General: NMR spectra were recorded on Varian 200 MHz or 600 MHz spectrometers. EI Mass measurement was carried out by CUNY-Hunter mass center. Elemental analysis was carried out by AtlanticMicro Analysis, Inc. Gel permeation chromatography measurement was carried out by using Waters GPC with polystyrene standards in THF. Et₂O and THF were dried with sodium/benzophenone. Pd(OAc)₂, phenyl bionic acid, potassium fluoride and diphenylphosphine (10% w. in hexanes) were purchase from Strem and used directly. Other chemical reagents were purchase from Aldrich and used directly.

Synthesis and characterization of 5:

To a mixture of 1,3,5-tribromobenzene (6.28 g, 20.0 mmol) in Et₂O (140 ml) at -75°C was added *n*-BuLi (12.5 mL, 1.6 M in hexanes, 20.0 mmol) under N₂. After stirring at -75 °C for 45 min, a solution of ferrocenecarbaldehyde (4.28 g, 20 mmol) in THF (6ml) was added to the mixture. The mixture was warmed to room temperature in 4 hr. H₂O was added and the mixture was extracted with Et₂O. The organic layer was washed with brine and the solvent was evaporated under vacuum. Flash chromatography on silica gel (hexanes: Et₂O = 100 : 0 to 100 : 20) gave **5** as a yellow solid. 7.66 g (85.1% yield). ¹H NMR (200 MHz, CDCl₃) δ 7.521 (t, *J* = 1.8 Hz, 1H), 7.450 (d, *J* = 1.8 Hz, 2H), 5.330(d, *J* = 3.0 Hz, 1H), 4.230(s, 5H), 4.199(m, 3H), 4.148(m, 1H), 2.540 (d, *J* = 3.0 Hz, 1H). ¹³C NMR (50 MHz, CDCl₃) δ 147.30, 133.04, 128.22, 122.88, 93.70, 70.88, 68.75, 68.68, 67.75, 65.73. MS *m/z*: 449 (M⁺); 433 (100). Anal. calcd. for C₁₇H₁₄Br₂FeO: C, 45.36; H, 3.13. Found: C, 45.50; H, 3.14.

Synthesis and characterization of polymer 7

To a mixture of dibromide **5** (1.350 g, 3.0 mmol.) and diboronic acid **6** (1.120 g, 3.06 mmol.) in 2M K₂CO₃/ THF (20 ml/20 ml) was added Pd(PPh₃)₄ (0.060 mg) under N₂. The mixture was refluxed for 24 h and bromobenzene was added to cap the end group. After another

12 h refluxing, the reaction mixture was cooled to room temperature and extracted with CH_2Cl_2 . After washing with brine, the solvent was evaporated by using a rota-evaporator. The residue was redissolved in CH_2Cl_2 and precipitated from MeOH. The solid was collected by filtration. The dissolution-precipitation-filtration procedure was repeated three times. After drying under vacuum, polymer **7** was obtained in 93% yield (1.58 g). GPC (polystyrenes standards): $M_w = 6800$, $M_n = 2800$ (PDI = 2.43). ^1H NMR (200 MHz, CDCl_3) δ 7.687 (br.s, 1H), 7.652 (br.s, 2H), 7.530 (s), 7.035 (2, 2H), 6.922 (s), 5.569 (d, $J = 3.2$ Hz, 0.82H), 5.458 (d, $J = 3.2$ Hz, 0.18 H), 3.337 (m, 2), 4.258 (s, 5H), 4.181 (s, 2H), 3.902 (br. T, $J = 6.0$ Hz, 4H), 2.510 (d, $J = 3.0$ Hz, 0.2H), 2.468 (d, $J = 3.0$ Hz, 0.8H), 1.67 (m, 4H), 1.226 (m, 12H), 0.824 (t, $J = 7.2$ Hz, 6H). ^{13}C NMR (50 MHz, CDCl_3) δ 150.26, 142.30, 138.02, 130.67, 126.36, 116.26, 94.25, 69.62, 68.46, 68.06, 67.98, 67.53, 66.12, 31.54, 29.41, 25.81, 22.57, 14.07. Anal. calcd for $(\text{C}_{35}\text{H}_{42}\text{FeO}_3)_n$: C, 74.20; H, 7.47. Found: C, 72.37; H 7.19. The relative large difference between the theoretical value and the experimental one is believed to be caused by the end groups as can be seen clearly from the ^1H NMR.

Synthesis and characterization of polymer 1

To a solution of polymer **7** (0.679 g, 1.2 mmol.) in HOAc/ CH_2Cl_2 (10 ml/4 ml) was added HPPH₂ (8 mL, 10% in hexanes) under N_2 . The mixture was stirred at room temperature for 15 h. The solvents were evaporated under vacuum. The residue was dissolved in CH_2Cl_2 (2 ml, N_2 degassed) and precipitated from MeOH (15 ml, N_2 degassed). The process was repeated four more times. The precipitation was collected by filtration under air. After drying under vacuum, polymer **1** was obtained as a yellow solid (0.760 g, 86.4% yield). GPC (polystyrenes standards): $M_w = 7700$, $M_n = 3100$ (PDI = 2.49). ^1H NMR (200 MHz, CDCl_3) δ 7.776 (m, 6H), 7.203-7.398 (m, 20H), 7.040 (br.s.) 4.405 (m, 2H), 3.985 (m, 4H), 3.877 (br.s, 5H), 3.543 (br.s, 2H), 1.746 (m, 4H), 1.355 (m, 4H), 1.262 (m, 8H), 0.835 (m, 6H). ^{13}C NMR (50 MHz, CDCl_3) δ 150.62, 138.30, 135.08, 134.68, 133.66, 133.31, 131.22, 128.08, 127.97, 116.81, 70.09, 68.70, 58.00, 56.40, 31.90, 29.84, 26.15, 22.89, 14.36 (observed complexity due to P-C splitting). ^{31}P NMR (81 MHz, CDCl_3 , H_3PO_4 as standard) δ 1.779, 2.502 (minor peak). Anal. calcd. for $(\text{C}_{47}\text{H}_{51}\text{FeO}_2\text{P})_n$: C, 76.83; H, 7.00; Found: C, 75.67; H, 6.84. The relative large difference between the theoretical value and the experimental one is also believed to be caused by the end groups which can be seen from ^{31}P NMR.

Synthesis and characterization of monophosphine 2

At room temperature, to a solution of **4** (0.290 g, 1.0 mmol) in HOAc (4 ml, degassed with N_2) was added HPPH₂ (4 mL, 10% in hexanes) under N_2 . The solution turned from reddish

yellow to yellow immediately and a precipitation was observed within 5 minutes. The mixture was stirred at room temperature for 6 h. The solid was collected by filtration and washing with MeOH. After drying under vacuum, **2** was obtained as a yellow solid (0.382 g, 83% yield). ^1H NMR (200 MHz, CDCl_3) δ 7.472 (m, 2H), 7.268(m, 1H), 7.355(m, 2H), 4.560(d, J = 6.6 Hz, 1H), 4.150(m, 1H), 4.050(m, 1H), 3.840(m, 1H), 3.761(m, 5H), 3.442(m, 1H). ^{13}C NMR (50 MHz, CD_3COCD_3) δ 142.50, 137.60, 138.04, 134.76, 133.50, 129.80, 129.00, 128.4(m), 126.60, 90.5, 69.89, 68.66, 68.37, 67.76, 66.69, 47.2 (observed complexity due to P-C splitting). ^{31}P NMR (81 MHz, CDCl_3 , H_3PO_4 as standard) δ 4.83. MS m/z : 461(M^+ + 1); 275 (M^+ - PPh_2 , 100). Anal. calcd. for $\text{C}_{29}\text{H}_{25}\text{FeP}$: C, 75.67; H, 5.47. Found: C, 75.84; H 5.57.

Synthesis and characterization of monomer **3**

(a) To a mixture of dibromide **5** (0.675 g, 1.5 mmol) and **8**¹ (1.063 g, 3.3 mmol) in 2M K_2CO_3 / THF (10 ml/10 ml) was added $\text{Pd(PPh}_3)_4$ (0.050 mg) under N_2 . The mixture was refluxed for 24 h. After cooling to room temperature, the reaction mixture was extracted with Et_2O . The organic layer was washed with brine and the solvent was evaporated under vacuum. Flash chromatography on silica gel (hexanes: Et_2O = 100 : 0 to 100 : 20) gave **9** as a yellow oil. 7.66 g (85.1% yield). ^1H NMR (200 MHz, CDCl_3) δ 7.607 (m, 1H), 7.573(m, 2H), 6.943 (d, J = 2.8 Hz, 2H), 6.891(d, J = 8.8 Hz, 2H), 6.805(dd, J = 8.8, 2.8 Hz, 2H), 5.529(d, J = 3.2 Hz, 2H), 4.300(m, 1H), 4.260(m, 1H), 4.224 (s, 5H), 4.160(m, 2H), 3.919 (t, J = 6.6 Hz, 4H), 3.843(t, J = 6.6 Hz, 4H), 2.425 (d, J = 3.2 Hz, 1H), 1.718(m, 4H), 1.334(m, 12H), 0.895 (t, J = 6.8 Hz, 6H), 0.831 (t, J = 6.6 Hz, 6H). ^{13}C NMR (50 MHz, CD_3COCD_3) δ 153.68, 150.48, 144.72, 138.05, 132.14, 129.49, 126.41, 117.18, 114.55, 113.93, 72.33, 69.29, 68.73, 68.32, 67.60, 67.54, 67.23, 66.50, 31.71, 29.50, 26.06, 25.86, 22.65, 22.61, 13.76, 13.67. MS m/z : 843(M^+); 827 (M^+ - H_2O , 100). Anal. calcd. for $\text{C}_{53}\text{H}_{72}\text{FeO}_5$: C, 75.34; H, 8.59. Found: C, 75.26; H 8.65.

(b) To a solution of **9** (0.500 g, 0.6 mmol) in HOAc (6 ml) was added HPPH_2 (3 mL, 10% in hexanes) under N_2 . The mixture was stirred at room temperature for 3 h and heated to 60°C for 30 min. The solvents were evaporated under vacuum. The residue was dissolved in CH_2Cl_2 (2 ml, N_2 degassed) and MeOH (5 ml, N_2 degassed). Removal of CH_2Cl_2 by vacuum and MeOH by decanting yielded a precipitation. This process was repeated four times. After drying undervacuum, a yellow was obtained (0.420g, 70% yield). ^1H NMR (200 MHz, CDCl_3) δ 7.611 (m, 2H), 7.571(m, 1H), 7.355(m, 2H), 7.249(m, 4H), 7.137(br.s, 4H), 6.876(m, 2H), 6.804(m, 2H), 4.349(m, 12H), 4.016(m, 1H), 3.937(m, 4H), 3.837(m, 2H), 3.807(br.s, 5H), 3.486(m, 1H), 1.776(m, 4H), 1.648(m, 4H), 1.344(m, 8H), 1.200(m, 8H), 0.908(br.s, 6H), 0.812(br.s, 6H). ^{13}C NMR (50 MHz, CD_3COCD_3) δ 153.39, 150.40, 138.04, 134.67, 133.23, 133.12, 132.58, 129.46, 128.77, 127.80, 117.47, 114.87, 113.77, 69.89, 69.67, 68.66, 68.37, 67.76, 66.09, 31.56, 29.41, 25.75, 22.53, 13.96 (observed complexity due to P-C splitting). ^{31}P NMR (81 MHz, CDCl_3 , H_3PO_4 as standard) δ 1.809. MS m/z : 1012(M^+); 827 (M^+ - PPh_2 , 100). Anal. calcd for $\text{C}_{65}\text{H}_{81}\text{FeO}_4\text{P}$: C, 77.06; H, 8.06. Found: C, 77.39; H 8.10.

General procedure for the room temperature 1/Pd(0)-catalyzed Suzuki cross-coupling reaction of aryl chlorides with arylboronic acids

To a vial containing **1** (0.036 g, 0.05 mmol), Pd(OAc)₂ (0.011g, 0.05mmol), arylboronic acid (1.5 equiv.), KF (3.0 equiv.) was added THF (2.0 mL). After the mixture was stirred at room temperature for ca. 5 min, aryl chloride was added (1.0 equiv). The resultant was allowed to stir at room temperature for 48 - 60 h. The reaction was quenched with water and extracted with diethyl ether. The organic layer was washed with brine. Evaporation of solvents and purification of the residue by column chromatography on silica gel with Et₂O/hexane afforded the biphenyl products.

References:

1. Huang, W.-S.; Hu, Q. -S.; Pu, L. *J. Org. Chem.* **1999**, *64*, 7940.