Supporting Information

Highly Regio- and Enantioselective Heck Reaction of N-methoxycarbonyl-2-pyrroline with Planar Chiral Diphosphine- oxazoline Ferrocenyl Ligands

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General information:

Unless otherwise stated, all ^1H NMR spectra were recorded on a Varian Mercury 300 spectrometer in CDCl_3 and the chemical shifts were referenced to CHCl_3 ($\delta = 7.27$ ppm). ^{31}P NMR spectra were recorded on a Varian Mercury 300 spectrometer (125MHz) and the chemical shifts were referenced to external 85% H_3PO_4 . Optical rotation was measured by a Perkin-Elmer 241 MC polarimeter with a thermally jacketed 10 cm cell at 20°C (concentration C given as g/100 mL). IR spectra were recorded in KBr and measured in cm^{-1} , using a Shimadzu IR-440 infrared spectrophotometer. Mass spectra and high-resolution mass spectra were taken by using HP5989A and Finnigan Mat mass spectrometers respectively. Melting points are uncorrected.

All reactions were performed under a dry argon atmosphere; Benzene and toluene freshly distilled from sodium under argon atmosphere. 1,2-Dichloroethane, DMF were distilled from CaH_2 under argon atmosphere. N-methoxycarbonyl-2-pyrroline (**1**), liquid aryltriflates (**2**) and even other reagents purchased commercially were distilled under argon atmosphere before using.

Analytical data for Ligands 5: (The detail procedure for the synthesis of these ligands, see: reference 1.)

(S,Sp)-5a: Mp: 70°C; $[\alpha]_D^{20} = -54^\circ$ (c, 1.5, CHCl₃); ¹H NMR (CDCl₃) δ = 0.64 (d, J = 6.8 Hz, 3H), 0.80 (d, J = 6.8 Hz, 3H), 1.63 (m, 1H), 3.44 (m, 1H), 3.70 (t, J = 8.2 Hz, 3H), 3.80-3.91 (m, 1H), 3.96 (m, 1H), 4.18-4.30 (m, 3H), 4.48-4.51 (m, 2H), 4.92 (t, J = 1.2 Hz, 1H), 7.18-7.48 (m, 20H); ³¹P NMR (CDCl₃) δ = -16.49 (s, 1P), -17.28 (s, 1P). MS (EI) m/z (%): 666 (M⁺, 100), 480 (70.40), 393 (38.65), 183 (39.60). IR (KBr, cm⁻¹): 2955, 1658, 1478, 1433, 1026, 980, 741, 695, 498. Anal. Calcd. for C₄₀H₃₇FeNOP₂: C, 72.19; H, 5.60; N, 2.11. Found: C, 72.10; H, 5.60; N, 1.94.

(S,Sp)-5b: M.p: 69 °C; $[\alpha]_D^{20} = -10.7^\circ$ (c, 1.52, CHCl₃); ¹H NMR (CDCl₃/TMS): δ 2.24 (dd, J = 9.2 Hz, 1H), 3.02 (dd, J = 13.6 Hz, 1H), 3.50 (m, 1H), 3.55 (t, J = 7.9 Hz, 1H), 3.97 (m, 1H), 4.13 (t, J = 8.4 Hz, 1H), 4.25 (m, 3H), 4.50 (m, 2H), 4.85 (m, 1H), 7.10-7.50 (m, 25H); ³¹P NMR (CDCl₃): δ -16.49 (s, 1P), -17.38 (s, 1P). MS (EI) m/z (%): 713 (M⁺, 100.00), 714 (M⁺+1, 44.21), 636 (17.12), 622 (28.15), 529 (18.22), 528 (50.38), 518 (16.22), 464 (38.12); IR (KBr, cm⁻¹): 3065, 1656, 1478, 1434, 1163, 1027, 982, 831, 742, 696; Anal. Calcd. for C₄₄H₃₇ONP₂Fe (713): C, 74.06; H, 5.23; N, 1.96; Found: C, 74.01; H, 5.37; N, 2.11.

(S,Sp)-5c: Mp: 70 °C; $[\alpha]_D^{20} = -130.5^\circ$ (c, 1.485, CHCl₃); ¹H NMR (CDCl₃) δ = 0.75 (s, 9H), 3.43 (s, 1 H), 3.75 (dt, J = 39.0, 8.1 Hz, 2H), 3.94 (t, J = 1.5 Hz, 1H), 4.13-4.21 (m, 3H), 4.26 (t, J = 1.6 Hz, 1H), 4.49 (t, J = 1.7 Hz, 1H), 4.89 (s, 1H), 7.10-7.40 (m, 20H); ³¹P NMR (CDCl₃) δ = -17.24 (s, 1P), -17.47 (s, 1P). MS (EI) m/z (%): 679 (M⁺, 100), 680 (M+1, 44.33), 622 (34.59). IR (KBr, cm⁻¹): 2953, 1662, 1479, 1434, 1164, 1141, 1027, 979, 831, 742, 702, 696, 501. Anal. Calc. For C₄₁H₃₉FeNOP₂: C, 72.47; H, 5.78; N, 2.06. Found: C, 72.39; H, 5.77; N, 2.24.

(S,Sp)-5d: M.p. 130 °C; $[\alpha]_D^{20} = -41^\circ$ (c, 1.53, CHCl₃); ¹H NMR (CDCl₃/TMS): δ 1.59 (s, 1H), 3.51-3.52 (m, 1H), 3.75 (t, J = 8.2 Hz, 1H), 4.01 (t, J = 1.4 Hz, 1H), 4.22 (t, J = 2.5 Hz, 1H), 4.30 (t, J = 1.6 Hz, 1H), 4.53 (t, J = 1.7 Hz, 1H), 4.63 (t, J = 9.7 Hz, 1H), 4.96-4.97 (m, 1H), 5.04 (q, J = 9.6 Hz, 1H), 6.90-6.92 (m, 2H), 7.20-7.45 (m, 23H); ³¹P NMR

(CDCl₃): δ -16.70 (s, 1P), -17.49 (s, 1P). MS (EI) m/z (%): 699 (M⁺, 100.00), 700 (M⁺+1, 44.08), 595 (25.19), 519 (17.13), 518 (48.91), 515 (26.59), 514 (70.75), 498 (17.74); IR (cm⁻¹): 3065, 2895, 1656, 1477, 1434, 1138, 1027, 986, 742, 696, 496; Anal. Calcd. for C₄₃H₃₅ONP₂Fe (699): C, 73.83; H, 5.04; N, 2.00; Found: C, 73.76; H, 5.29; N, 2.27.

(S,Rp)-5a: M.p. 69 °C; $[\alpha]_D^{25} = 161^\circ$ (c 0.16, CHCl₃); ¹H NMR (300 MHz, CDCl₃/TMS): δ 0.61 (d, $J = 6.2$ Hz, 6 H), 1.55 (m, 1 H), 3.47 (m, 1 H), 3.85-4.05 (m, 4 H), 4.16 (t, $J = 2.5$ Hz, 1 H), 4.26 (m, 1 H), 4.50 (t, $J = 1.8$ Hz, 2 H), 4.87 (m, 1 H), 7.1-7.50 (m, 20 H); MS (EI) m/z (%): 666 (M⁺, 100.0), 623 (22.60), 588 (19.73), 518 (19.21), 480 (42.40), 305 (19.43), 171 (24.81). IR (KBr, cm⁻¹): 2955, 1657, 1478, 1433, 1027, 981, 742, 695, 487. Anal. Calcd. For C₄₀H₃₇NOP₂Fe: C, 72.19; H, 5.60, N, 2.11; Found: C, 72.14; H, 5.80; N, 2.22.

Typical experimental procedure for Asymmetric Heck Reactions: Palladium species (50 μ mol), diphosphine-oxazoline ferrocenyl ligand (0.1 mmol) and solvent (5 mL) were placed under Ar in an Schlenk tube with a magnetic stirring bar. After reacting for 30 minutes, aryl triflate (1 mmol) and *n*-tridecane (20 mg) (an internal GC standard) were added, followed by the addition of *N*-methoxycarbonyl-2-pyrroline **1** (638 mg, 5 mmol) and *i*-Pr₂NEt (base, 2 mmol). The mixture was stirred at 80°C under Ar until the reaction was complete according to GC analysis. The reaction mixture was diluted with additional EtOAc (20 mL) and the resulting red suspension was extracted with sat. Na₂CO₃ (3 $\times$ 10 mL) solution. The combined organic solution was dried with Na₂SO₄, and then concentrated to give a red oil, which was purified by flash chromatography on silica gel (petroleum ether: ethyl acetate = 6:1) to afford **3** and **4** as colorless oil. The ee values were determined by chiral HPLC. Absolute configuration of products was assigned through comparison of the sign of specific rotations with literature data.²

1. When Pd(OAc)₂ and **(S,Sp)-5a** were used as catalyst in the phenylation of *N*-methoxycarbonyl-2-pyrroline in toluene, a ratio of 96:4 (**3a:4a**) was obtained with a conversion of 81% after 4 days, and product **3a** was isolated by flash chromatography on silica gel in 75% yield (152.3 mg) and 78% ee.

2. When Pd(OAc)₂ and **(S,Rp)-5a** were used as catalyst in the phenylation of *N*-methoxycarbonyl-2-pyrroline in toluene, a ratio of 80:20 (**3a:4a**) was obtained with a conversion of 95% after 4 days, and product **3a** was isolated by flash chromatography on silica gel in 70% yield (142.2 mg) and 40% ee.
3. When Pd(OAc)₂ and **(S,Sp)-5b** were used as catalyst in the phenylation of *N*-methoxycarbonyl-2-pyrroline in toluene, a ratio of 91:9 (**3a:4a**) was obtained with a conversion of 83% after 4 days, and product **3a** was isolated by flash chromatography on silica gel in 67% yield (136 mg) and 97% ee.
4. When Pd(OAc)₂ and **(S,Sp)-5c** were used as catalyst in the phenylation of *N*-methoxycarbonyl-2-pyrroline in toluene, a ratio of 93:7 (**3a:4a**) was obtained with a conversion of 75% after 3 days, and product **3a** was isolated by flash chromatography on silica gel in 63% yield (128 mg) and 98% ee.
5. When Pd(OAc)₂ and **(S,Sp)-5d** were used as catalyst in the phenylation of *N*-methoxycarbonyl-2-pyrroline in toluene, a ratio of 94:6 (**3a:4a**) was obtained with a conversion of 73% after 4 days, and product **3a** was isolated by flash chromatography on silica gel in 58% yield (117 mg) and 62% ee.
6. When Pd(OAc)₂ and **(S,Sp)-5b** were used as catalyst in the naphthylation of *N*-methoxycarbonyl-2-pyrroline in toluene, a ratio of 75:25 (**3b:4b**) was obtained with a conversion of 60% after 4 days, and product **3b** was isolated by flash chromatography on silica gel in 39% yield (98 mg) and 53% ee.
7. When Pd(OAc)₂ and **(S,Sp)-5c** were used as catalyst in the naphthylation of *N*-methoxycarbonyl-2-pyrroline in toluene, a ratio of 85:15 (**3b:4b**) was obtained with a conversion of 84% after 4 days, and product **3b** was isolated by flash chromatography on silica gel in 67% yield (170 mg) and 66% ee.
8. When Pd(OAc)₂ and **(S,Sp)-5c** were used as catalyst in the naphthylation of *N*-methoxycarbonyl-2-pyrroline in benzene, a ratio of 90:10 (**3b:4b**) was obtained with a conversion of 76% after 4 days, and product **3b** was isolated by flash chromatography on silica gel in 62% yield (156 mg) and 79% ee.
9. When Pd(OAc)₂ and **(S,Sp)-5c** were used as catalyst in the Arylation of *N*-methoxycarbonyl-2-pyrroline with 4-methoxyl-phenyl triflate (**2c**) in Benzene, a ratio of 98:2 (**3c:4c**) was obtained with a conversion of 75% after 4 days, and

- product **3c** was isolated by flash chromatography on silica gel in 69% yield (153 mg) and 90% ee.
10. When Pd(OAc)₂ and **(S,Sp)-5c** were used as catalyst in the Arylation of *N*-methoxycarbonyl-2-pyrroline with 4-fluoro-phenyl triflate (**2d**) in Benzene, a ratio of 98:2 (**3d:4d**) was obtained with a conversion of 85% after 4 days, and product **3b** was isolated by flash chromatography on silica gel in 76% yield (168 mg) and 97% ee.
 11. When Pd(OAc)₂ and **(S,Sp)-5c** were used as catalyst in the phenylation of *N*-methoxycarbonyl-2-pyrroline in Benzene, a ratio of 95:5 (**3a:4a**) was obtained with a conversion of 78% after 3 days, and product **3a** was isolated by flash chromatography on silica gel in 68% yield (138 mg) and 98% ee.
 12. When [Pd₂(dba)₃-dba] and **(S,Sp)-5c** were used as catalyst in the phenylation of *N*-methoxycarbonyl-2-pyrroline in Benzene, a ratio of 31:69 (**3a:4a**) was obtained with a conversion of 93% after 3 days, and product **4a** was isolated by flash chromatography on silica gel in 60% yield (122 mg) and 11% ee.
 13. When Pd(OAc)₂ and **(S,Sp)-5c** were used as catalyst in the phenylation of *N*-methoxycarbonyl-2-pyrroline in DMF, a ratio of 75:25 (**3a:4a**) was obtained with a conversion of 92% after 3 days, and product **3a** was isolated by flash chromatography on silica gel in 52% yield (105.5 mg) and 99% ee.
 14. When Pd(OAc)₂ and **(S,Sp)-5c** were used as catalyst in the phenylation of *N*-methoxycarbonyl-2-pyrroline in 1,2-dichloroethane, a ratio of 42:58 (**3a:4a**) was obtained with a conversion of 93% after 3 days, and product **4a** was isolated by flash chromatography on silica gel in 47% yield (95.5mg) and 29% ee.
 15. When [Pd₂(dba)₃-dba] and **(S,Sp)-5c** were used as catalyst in the phenylation of *N*-methoxycarbonyl-2-pyrroline in 1,2-dichloroethane, a ratio of 34:66 (**3a:4a**) was obtained with a conversion of 85% after 2 days, and product **4a** was isolated by flash chromatography on silica gel in 53% yield (107 mg) and 18% ee.

2-Phenyl-2,5-dihydro-pyrrole-1-carboxylic acid methyl ester (**3a**):

^1H NMR (300MHz, CDCl_3/TMS): δ 3.62 (d, $J = 32.3$ Hz, 3H), 4.31 (m, 1H), 4.43 (m, 1H), 5.50 (ddd, $J = 27.0, 4.7, 2.3$ Hz, 1H), 5.72-5.80 (m, 1H), 5.88-5.92 (m, 1H), 7.20-7.39 (m, 5H).

MS (EI) m/z (%): 203 (M^+ , 51.2), 188 (92.4), 171 (37.3), 144 (55.9), 126 (100.0), 115 (46.6), 91 (17.16), 77 (16.38), 67 (25.28), 59 (17.0).

HPLC for **3a**: Chiralcel OD-H, Flow rate: 0.5 mL / min, *n*-hexane / *i*-PrOH = 95 / 5, $\lambda = 220$ nm, $t_R = 13.9$ min (S), $t_R = 14.8$ min (R).

GC for tracing reaction (PE-XL, EC-5 (Altech); 30 m $\times$ 0.32 mm, 100°C-250°C, N_2 : 16 psi): $t_R = 3.3$ min (**2a**), $t_R = 7.6$ min (*n*-tridecane), $t_R = 21.0$ min (**4a**), $t_R = 21.9$ min (**3a**).

2-Naphthalen-2-yl-2,5-dihydro-pyrrole-1-carboxylic acid methyl ester (**3b**):

^1H NMR (300 MHz, CDCl_3/TMS): δ 3.54 (s, 1.5H), 3.67 (s, 1.5H), 4.45 (dm, 2H), 5.71 (dm, 1H), 5.82 (dm, 1H), 5.98 (m, 1H), 7.28-7.88 (m, 7H).

MS (EI) m/z (%): 253 (M^+ , 100), 254 ($\text{M}+1$, 18.47), 194 (18.83), 165 (34.23), 152 (11.55).

IR (cm^{-1}) 2991, 2954, 2898, 2865, 1699, 1454, 1381, 1201, 1114, 977, 869, 829, 785, 775, 692, 483.

HRMS. Calcd for $\text{C}_{16}\text{H}_{15}\text{NO}_2$ (**3b**): 253.110238; Found: 253.11147.

HPLC for **3b**: Chiralcel OJ, Flow rate: 0.5 mL / min, *n*-hexane / *i*-PrOH = 80 / 20, $\lambda = 220$ nm, $t_R = 24.7$ min (R), $t_R = 31.2$ min (S).

GC for tracing reaction (PE-XL, EC-5 (Altech); 30 m $\times$ 0.32 mm, 100°C-250°C, N_2 : 16 psi): $t_R = 7.6$ min (*n*-tridecane), $t_R = 17.1$ min (**2b**), $t_R = 32.6$ min (**4b**), $t_R = 33.5$ min (**3b**).

2-(4-Methoxy-phenyl)-2,5-dihydro-pyrrole-1-carboxylic acid methyl ester (**3c**):

^1H NMR (300 MHz, CDCl_3/TMS): δ 3.57 (s, 1.5H), 3.66 (s, 1.5H), 3.78 (d, $J = 5.0$ Hz, 3H), 4.21-4.46 (m, 2H), 5.48 (ddd, $J = 27.9, 4.7, 2.3$ Hz, 1H), 5.74 (m, 1H), 5.91 (bd, $J = 6.2$ Hz, 1H), 6.85 (m, 2H), 7.13 (d, $J = 8.8$ Hz, 1H), 7.23 (dd, $J = 8.5, 1.8$ Hz, 1H).

MS (EI) m/z (%): 233 (M^+ , 85.63), 234 ($\text{M}+1$, 100.0), 131 (37.45), 103 (44.15), 77 (37.45).

IR (cm^{-1}) 2869, 1702, 1615, 1497, 1451, 1387, 1366, 1305, 1257, 1175, 1139, 1103, 1028, 919, 838, 739, 706, 618, 526.

HRMS. Calcd for $\text{C}_{13}\text{H}_{15}\text{NO}_3$ (**3c**): 233.10519; Found: 233.10080.

HPLC for **3c**: Chiralcel OD, Flow rate: 0.8 mL / min, *n*-hexane / *i*-PrOH = 93 / 7, $\lambda = 220$ nm, $t_R = 24.6$ min (S), $t_R = 26.9$ min (R).

GC for tracing reaction (PE-XL, EC-5 (Altech); 30 m $\times$ 0.32 mm, 100°C-250°C, N_2 : 16 psi): $t_R = 5.9$ min (**2c**), $t_R = 7.6$ min (*n*-tridecane), $t_R = 28.3$ min (**4c**), $t_R = 28.9$ min (**3c**).

2-(4-Fluoro-phenyl)-2,5-dihydro-pyrrole-1-carboxylic acid methyl ester (**3d**):

^1H NMR (300 MHz, CDCl_3/TMS): δ 3.57 (s, 1.5H), 3.67 (s, 1.5H), 4.32-4.48 (m, 2H), 5.49 (ddd, $J = 27.9, 4.7, 2.6$ Hz, 1H), 5.74 (m, 1H), 6.95-7.29 (m, 4H).

MS (EI) m/z (%): 221 (M^+ , 78.38), 206 (100.0), 189 (15.55), 162 (71.90), 133 (52.20), 126 (72.28).

IR (cm^{-1}) 3078, 2957, 2867, 1706, 1605, 1509, 1450, 1384, 1319, 1223, 1193, 1157, 1123, 1010, 979, 952, 834, 773, 686, 578, 554, 525.

HRMS. Calcd for $\text{C}_{12}\text{H}_{12}\text{NO}_2\text{F}$ (**3d**): 221.08521; Found: 221.08365.

HPLC for **3d**: Chiralcel OJ, Flow rate: 0.7 mL / min, *n*-hexane / *i*-PrOH = 90 / 10, $\lambda = 220$ nm, $t_R = 19.3$ min (R), $t_R = 37.8$ min (S).

GC for tracing reaction (PE-XL, EC-5 (Altech); 30 m $\times$ 0.32 mm, 100°C-250°C, N₂: 16 psi): t_R = 2.0 min (**2d**), t_R = 7.6 min (*n*-tridecane), t_R = 21.2 min (**4d**), t_R = 21.9 min (**3d**).

References:

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2. Ozawa, F.; Kubo A.; Hayashi, T.; *J. Organomet. Chem.* **1992**, 428, 267.