Electronic Supplementary Information for Dalton Transactions

Supporting information of

Controllable synthesis of P-chiral 1,2- and 1,3-diphosphines *via* asymmetric Diels-Alder reactions involving functionalized allylic phosphines as dienophiles

Mingjun Yuan, Sumod A. Pullarkat, Crystal Huixian Yeong, Yongxin Li, Deepa Krishnan, and Pak-Hing Leung*

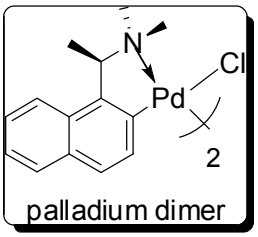
Division of Chemistry & Biological Chemistry, School of Physical & Mathematical Sciences,

Nanyang Technological University, Singapore 637371, Singapore

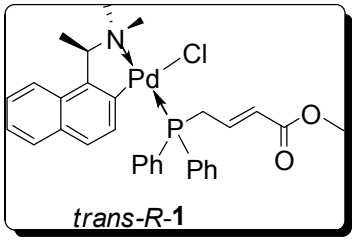
General methods

All air-sensitive manipulations were performed under a positive pressure of argon using a standard Schlenk line. Solvents were dried and degassed prior to use when necessary. NMR spectra were recorded at 25 ºC on a Bruker ACF 300 spectrometer. Optical rotations were measured on the specified solution in a 0.1 dm cell at 20 ºC with a Perkin-Elmer 341 polarimeter. Melting points were measured using the SRS Optimelt Automated Melting Point System, SRS MPA100.

Preparation of allylic phosphine palladium complex *R*-1.

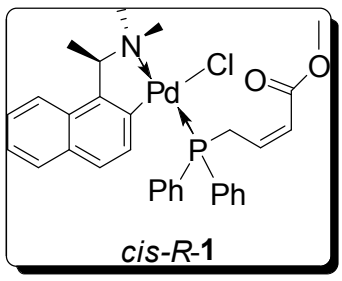


Sodium diphenylphosphide generated from diphenylphosphine (0.5 g, 2.68 mmol) in THF (25 mL) solution was cooled to 0 ºC and bromoacetaldehyde dimethyl acetal (0.45 g, 2.68 mmol) in THF (5 mL) was added dropwise over 10 min, the resulting mixture was stirred for 1h. To the solution 4 N HCl (10 mL) was then added and stirred for 10 h at room temperature. Subsequently the pH of the solution was adjusted with sodium carbonate to 9~10. The mixture was then extracted with ethyl acetate (3 × 20 mL). To the organic layer methyl (triphenylphosphoranylidene)-acetate (1.35 g, 4.03 mmol)) was added. After being stirred for 3 h at room temperature, palladium dimer (0.87 g, 1.28 mmol) was added to the mixture and stirred for another 1 h. Upon removal of the solvent, the complex *R*-**1** was isolated by chromatography on silica as a pale yellow powder (*cis*-*R*-**1**, 0.35 g 22%; *trans*-*R*-**1**, 1.02 g 64%).



trans-R-**1**

trans-R-**1** (1.02 g), $[\alpha]_D$ = – 45.9° (*c* 1.7, CH_2Cl_2). Mp: 195.5–197 ºC. Anal. Calcd for $C_{31}H_{33}ClNO_2PPd$: C, 59.6; H, 5.3; N, 2.2. Found: C, 59.5; H, 5.5; N, 2.3. ^{31}P NMR ($CDCl_3$, 121 MHz): δ 33.2 (s). ^{1}H NMR ($CDCl_3$, 300 MHz): δ 2.04 (d, 3H, J_{HH} = 6.3 Hz, CH*Me*), 2.68 (s, 3H, N*Me*), 2.99 (d, 3H, J_{PH} = 3.4 Hz, N*Me*), 3.29 (m, 1H, J_{HH} = 9.0 Hz, J_{HH} = 12.5 Hz, J_{PH} = 14.0 Hz, PCH′*H*), 3.66 (s, 3H, CO_2*Me*), 3.88 (m, 1H, J_{HH} = 6.5 Hz, J_{HH} = 12.5 Hz, J_{PH} = 12.9 Hz, PC*H*′H), 4.33 (qn, 1H, J_{HH} = J_{PH} = 6.2 Hz, C*H*CH_3), 5.63 (dd, 1H, J_{HH} = 15.7 Hz, J_{PH} = 4.6 Hz, C*H*CO_2Me), 6.62 (dd, 1H, J_{HH} = 8.5 Hz, J_{PH} = 6.3 Hz, Ar), 6.94 (d, 1H, J_{HH} = 8.5 Hz, Ar), 7.12-8.07 (m, 15H, Ar and CH_2C*H*). ^{13}C NMR ($CDCl_3$): δ 23.6 (s), 35.6 (d, J_{PC} = 29.5 Hz), 48.5 (s), 51.2 (d, J_{PC} = 3.0 Hz), 51.6 (s), 73.2 (d, J_{PC} = 3.2 Hz), 123.4 (s), 124.3 (s), 124.8 (d, J_{PC} = 8.3 Hz), 124.9 (d, J_{PC} = 8.8 Hz), 125.9 (s), 128.4 (d, J_{PC} = 10.5 Hz), 128.8 (s), 128.9 (s), 129.1 (d, J_{PC} = 10.5 Hz), 129.6 (d, J_{PC} = 44.3 Hz), 129.7 (d, J_{PC} = 44.8 Hz), 131.0 (d, J_{PC} = 2.4 Hz), 131.2 (s), 131.5 (d, J_{PC} = 2.4 Hz), 133.9 (d, J_{PC} = 10.8 Hz), 134.3 (d, J_{PC} = 11.8 Hz), 135.6 (d, J_{PC} = 12.1 Hz), 142.3 (d, J_{PC} = 4.5 Hz), 149.2 (d, J_{PC} = 2.1 Hz), 150.2 (s), 166.3 (d, J_{PC} = 2.8 Hz).

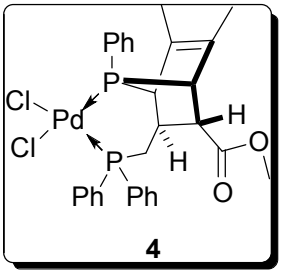


cis-R-**1**

cis-R-**1** (0.35 g), $[\alpha]_D$ = +110.5° (*c* 1.5, CH_2Cl_2). Mp: 193–195 ºC. Anal. Calcd for $C_{31}H_{33}ClNO_2PPd$: C, 59.6; H, 5.3; N, 2.2. Found: C, 59.6; H, 5.4; N, 2.4. ^{31}P NMR ($CDCl_3$， 121 MHz): δ 33.7 (s). ^{1}H NMR (CD_2Cl_2, 300 MHz): δ 2.03 (d, 3H, J_{HH} = 6.4 Hz, CH*Me*), 2.67 (d, 3H,

J_{HH} = 1.6 Hz, N*Me*), 2.96 (d, 3H, J_{PH} = 3.5 Hz, N*Me*), 3.36 (s, CO_2*Me*), 4.02 (m, 1H, J_{HH} = 6.5 Hz, J_{HH} = 12.2 Hz, PCH′*H*), 4.30 (m, 1H, PC*H*′H), 4.36 (qn, 1H, J_{HH} = J_{PH} = 6.2 Hz, C*H*CH_3), 5.81 (dd, 1H, J_{HH} = 11.5 Hz, J_{PH} = 4.9 Hz, C*H*CO_2Me), 6.64 (dd, 1H, J_{HH} = 8.5 Hz, J_{PH} = 6.5 Hz, Ar), 6.84 (m, 1H, PCH_2C*H*), 6.90 (d, 1H, J_{HH} = 8.5 Hz, Ar), 7.16-8.17 (m, 14H, Ar). ^{13}C NMR (CD_2Cl_2): δ 23.6 (s), 31.5 (d, J_{PC} = 31.3 Hz), 48.1 (d, J_{PC} = 2.6 Hz), 50.7 (s), 50.8 (d, J_{PC} = 3.1 Hz), 72.8 (d, J_{PC} = 3.3 Hz), 121.9 (d, J_{PC} = 11.5 Hz), 123.3 (s), 124.1 (s), 124.4 (d, J_{PC} = 5.7 Hz), 125.6 (s), 127.7 (d, J_{PC} = 10.6 Hz), 128.4 (s), 128.7 (s), 128.8 (d, J_{PC} = 10.5 Hz), 129.7 (d, J_{PC} = 44.7 Hz), 130.0 (d, J_{PC} = 45.3 Hz), 130.4 (d, J_{PC} = 2.5 Hz), 131.0 (s), 131.2 (d, J_{PC} = 2.4 Hz), 133.8 (d, J_{PC} = 11.1 Hz), 134.5 (d, J_{PC} = 12.1 Hz), 135.7 (d, J_{PC} = 12.1 Hz), 142.4 (d, J_{PC} = 2.8 Hz), 149.3 (d, J_{PC} = 2.1 Hz), 150.1 (s), 165.9 (d, J_{PC} = 3.5 Hz).

Synthesis of Dichloro Complex 4: Asymmetric Diels-Alder reaction between *trans-R*-1 and DMPP

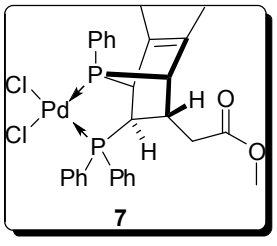


4

A solution of *trans-R*-**1** (0.60g, 0.96 mmol) in dichloromethane (20 mL) was treated with silver perchlorate (0.43g, 1.92 mmol) in water (5 mL). The mixture was stirred for 30 min at room temperature. After the removal of AgCl precipitate, the organic layer was washed with H_2O (3 × 15 mL), dried over $MgSO_4$, and subsequently treated with DMPP (0.18 g, 0.96 mmol). The solution was stirred for 30 days at room temperature yield the six-membered chelate complexes (**3a** and **3b**, δ: –2.3, 106.5, J_{PP} = 57.0 Hz; 24.0, 95.3, J_{PP} = 57.0 Hz) and five-membered chelate complexes (**6a** and **6b**, δ: 27.1, 127.8, J_{PP} = 39.0 Hz; 52.7, 126.0, J_{PP} = 40.1 Hz) in the ratio of 7:1.

The mixture was not isolated and was treated with concentrated hydrochloric acid (5 mL) for 4 h at room temperature, washed with water (3×20 mL), dried over $MgSO_4$. Chromatography on silica gel eluting with ethyl acetate-hexanes yielded the dichloro complex **4** (0.43, 68%) and **7** (0.06, 9%). Dichloro complex **4** could be crystallized from chloroform-diethyl ether as pale yellow prisms. $[\alpha]_D = -107.1°$ (*c* 0.8, CH_2Cl_2). Mp: 268–270 ºC. Anal. Calcd for $C_{29}H_{30}Cl_2O_2P_2Pd$: C, 53.6; H, 4.6. Found: C, 53.3; H, 4.8. ^{31}P NMR (CD_2Cl_2, 121 MHz): δ 16.5 (d, J_{PP} = 19.8 Hz), 99.2 (d, J_{PP} = 19.8 Hz). ^{1}H NMR (CD_2Cl_2, 300 MHz): δ 1.29 (s, 3H, C=C*Me*), 1.58 (s, 3H, C=C*Me*), 2.28 (br, s, 1H, PC*H*), 3.00 (m, 1H, J_{HH} = 8.0 Hz, PC*H*′H), 3.02 (d, 1H, J_{PH} = 6.7 Hz, PC*H*), 3.40 (m, 1H, PCH′*H*), 3.77 (s, 3H, CO_2*Me*), 4.02 (q, 1H, J_{PH} = J_{HH} =2.2 Hz, C*H*CO_2Me), 4.55 (br, 1H, PCH_2C*H*), 7.23–8.22 (m, 15H, Ar). ^{13}C NMR (CD_2Cl_2): δ 14.0 (d, J_{PC} = 1.7 Hz), 14.7 (d, J_{PC} = 3.0 Hz), 33.6 (dd, J_{PC} = 3.1 Hz, J_{PC} = 32.7 Hz), 38.3 (d, J_{PC} = 19.7 Hz), 46.6 (dd, J_{PC} = 17.6 Hz, J_{PC} = 30.5 Hz), 51.4 (d, J_{PC} = 27.1 Hz), 52.3 (d, J_{PC} = 37.9 Hz), 52.4 (s), 125.9 (d, J_{PC} = 53.4 Hz), 128.1 (d, J_{PC} = 5.1 Hz), 128.2 (d, J_{PC} = 4.1 Hz), 128.7 (dd, J_{PC} = 2.7 Hz, J_{PC} = 52.7 Hz), 129.9 (d, J_{PC} = 11.3 Hz), 130.2 (d, J_{PC} = 58.7 Hz), 130.8 (d, J_{PC} = 3.2 Hz), 131.3 (d, J_{PC} = 2.8 Hz), 132.3 (s), 132.4 (d, J_{PC} = 1.6 Hz), 132.6 (s), 133.2 (d, J_{PC} = 2.6 Hz), 135.1 (d, J_{PC} = 12.6 Hz), 136.4 (br s), 171.8 (d, J_{PC} = 21.2 Hz).

Synthesis of Dichloro Complex 7: Asymmetric Diels-Alder reaction between *cis*-*R*-1 and DMPP



7

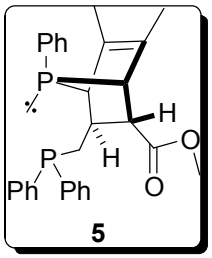
By following the same procedure as described for the synthesis of complex **4**. *cis*-*R*-**1** (0.30g,

0.48 mmol), after the removal of the chloro ligand using silver perchlorate (0.20g, 0.88 mmol), was treated with DMPP (0.09 g, 0.48 mmol) at room temperature for 12 days. The reaction only gave the regioisomers **6a** and **6b** and the 121 MHz ^{31}P NMR spectrum showed a pairs of doublets at δ (27.1, 127.8, J_{PP} = 39.0 Hz), and (52.7, 126.0, J_{PP} = 40.1 Hz). Treatment a dichloromethane solution (8 mL) of regioisomers **6a** and **6b** with concentrated hydrochloric acid (4 mL) for 4 h at room temperature, purification by column chromatography, upon crystallized from dichloromethane-diethyl ether, the dichloro complex **7** was isolated as pale yellow prisms (0.25g, 81%). $[\alpha]_D = -60.7°$ (*c* 0.6, CH_2Cl_2). Mp: 281–283 ºC. Anal. Calcd for $C_{29}H_{30}Cl_2O_2P_2Pd$: C, 53.6; H, 4.6. Found: C, 53.4; H, 4.9. ^{31}P NMR (CD_2Cl_2, 121 MHz): δ 34.2 (d, J_{PP} = 5.2 Hz), 133.4 (d, J_{PP} = 5.2 Hz). ^{1}H NMR (CD_2Cl_2, 300 MHz): δ 1.59 (s, 3H, C=C*Me*), 1.60 (s, 3H, C=C*Me*), 1.91 (dd, 1H, J_{HH} = 5.7 Hz, J_{HH} = 15.3 Hz, CHCH′*H*), 2.15 (dd, 1H, J_{HH} = 9.8 Hz, J_{HH} = 15.3 Hz, CHC*H*′H), 2.69 (dd, 1H, J_{PH} = 7.3 Hz, J_{PH} = 50.3 Hz, PPh_2CH), 3.17 (br m, 1H, PC*H*), 3.30 (br m, 1H, C*H*CH_2), 3.47 (s, 3H, CO_2Me), 3.60 (br, 1H, PC*H*), 7.40–8.30 (m, 15H, Ar). ^{13}C NMR (CD_2Cl_2): δ 14.8 (br s), 15.7 (d, J_{PC} = 3.3 Hz), 37.4 (t, J_{PC} = J_{PC} = 34.6 Hz), 37.5 (t, J_{PC} = J_{PC} = 8.0 Hz), 39.8 (dd, J_{PC} = 7.3 Hz, J_{PC} = 21.7 Hz), 51.4 (d, J_{PC} = 30.0 Hz), 51.8 (s), 55.4 (dd, J_{PC} = 16.0 Hz, J_{PC} = 34.3 Hz), 124.9 (d, J_{PC} = 48.6 Hz), 125.7 (d, J_{PC} = 47.2 Hz), 126.4 (d, J_{PC} = 53.2 Hz), 128.3 (d, J_{PC} = 11.2 Hz), 128.7 (d, J_{PC} = 11.4 Hz), 129.6 (d, J_{PC} = 10.8 Hz), 131.7 (d, J_{PC} = 2.8 Hz), 132.2 (d, J_{PC} = 2.7 Hz), 132.3 (dd, J_{PC} = 2.0 Hz, J_{PC} = 19.6 Hz), 132.5 (s), 132.6 (d, J_{PC} = 6.8 Hz), 134.0 (d, J_{PC} = 10.6 Hz), 134.8 (d, J_{PC} = 2.1 Hz), 134.9 (d, J_{PC} = 10.7 Hz), 170.4 (s).

Liberation of the 1,3-Diphosphine Ligand 5 and 8.

A solution of dichloro complex **4** (0.15 g, 0.23 mmol) in dichloromethane (8 mL) was stirred vigorously with aqueous KCN (0.8 g, 12.3 mmol) for 30 min. The organic layer was separated,

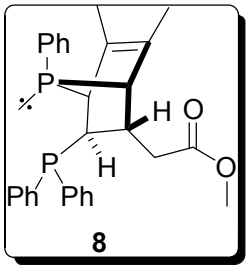
washed with water (3×10 mL), and dried with $MgSO_4$. The diphosphine ligand **5** was obtained as white solid upon removal of solvent under reduced pressure (0.10 g, 92%).



5

$[\alpha]_D = -18.1°$ (*c* 0.9, CH_2Cl_2). ^{31}P NMR ($CDCl_3$, 121 MHz): δ –18.6 (s), 104.6 (s). ^1H NMR ($CDCl_3$, 300 MHz): δ 1.40 (s, 3H, C=C*Me*), 1.42 (s, 3H, C=C*Me*), 2.41 (m, 1H, PCH_2CH), 2.60 (m, 1H, J_{HH} = 8.6 Hz, J_{HH} = 13.5 Hz, PC*H*′H), 2.74 (m, 1H, J_{HH} = 6.8 Hz, J_{HH} = 13.5 Hz, PCH′*H*), 2.78 (m, 1H, PC*H*), 3.12 (dt, 1H, J_{HH} = 2.2 Hz, J_{PH} = 11.0 Hz, PC*H*), 3.34 (m, 1H, J_{HH} = 2.4 Hz, J_{HH} =5.0 Hz, C*H*CO_2Me), 3.60 ((s, 3H, CO_2Me), 7.12–7.54 (m, 15H, Ar).

Similarly the diphosphine ligand **8** (0.07 g, 91%) was liberated from dichloro complex **7** (0.11 g, 0.17 mmol) as a white solid.



8

$[\alpha]_D = +124.3°$ (*c* 1.1, CH_2Cl_2). ^{31}P NMR ($CDCl_3$, 121 MHz): δ –7.5 (d, J_{PP} = 68.0 Hz), 104.7 (d, J_{PP} = 68.0 Hz). ^1H NMR ($CDCl_3$, 300 MHz): δ 1.20 (m, 1H, J_{HH} = 3.4 Hz, CHCH′*H*), 1.46 (s, 3H, C=C*Me*), 1.56 (s, 3H, C=C*Me*), 1.66 (dd, 1H, J_{HH} = 12.3 Hz, J_{HH} = 14.9 Hz, CHC*H*′H), 2.03 (dt, 1H, J_{PH} = J_{HH} = 5.2 Hz, J_{PH} = 18.7 Hz, PPh_2CH), 2.58 (br d, 1H, J_{PH} = 10.9 Hz, PC*H*), 2.87 (br d, 1H, J_{PH} = 11.0 Hz, PC*H*), 3.12 (m, 1H, C*H*CH_2), 3.51 (s, 3H, CO_2Me), 7.05–7.60 (m, 15H, Ar).