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Three-Hindered Quadrant Phosphine Ligands with an Aromatic Ring Backbone for the Rhodium-Catalyzed Asymmetric Hydrogenation of Functionalized Alkenes

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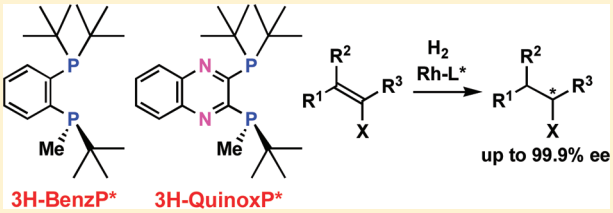
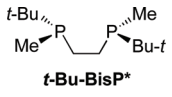
Supporting Information

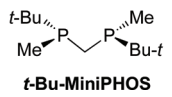
ABSTRACT: The three-hindered quadrant phosphine ligands (*R*)-1-*tert*-butylmethylphosphino-2-(di-*tert*-butylphosphino)-benzene ((*R*)-3H-BenzP*) and (*R*)-2-*tert*-butylmethylphosphino-3-(di-*tert*-butylphosphino)quinoxaline ((*R*)-3H-QuinoxP*) exhibited good to excellent enantioselectivities in the rhodium-catalyzed asymmetric hydrogenation of selected dehydroamino acid derivatives, enamides, and ethenephosphonates.



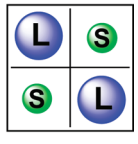
Despite the development of numerous chiral phosphine ligands, there remains a need for highly efficient and operationally convenient ligands in the field of asymmetric metal catalysis.[1] In our previous studies of the synthesis and application of new P-stereogenic phosphine ligands, we described the preparation of (*S*,*S*)-1,2-bis(*tert*-butylmethylphosphino)ethane (*t*-Bu-BisP*) and (*R*,*R*)-bis(*tert*-butylmethylphosphino)methane (*t*-Bu-MiniPHOS).[2−4] These ligands were designed based on a "quadrant diagram" concept,[5] with the expectation that the two bulky *tert*-butyl groups of the metal complexes would occupy the diagonal quadrants and the two methyl groups would be located in the other quadrants. Single crystal X-ray analysis of the rhodium complexes clearly revealed typical C_2-symmetric two-hindered quadrant catalyst structures. As expected, the catalysts provided high enantioselectivities in the rhodium-catalyzed asymmetric hydrogenation of functionalized alkenes.[2−4]



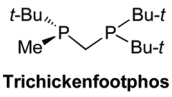
t-Bu-BisP*



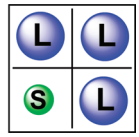
t-Bu-MiniPHOS



In 2004, Hoge et al. described the preparation of the enantiopure di-*tert*-butylphosphino(*tert*-butylmethylphosphino)-methane (Trichickenfootphos), a C_1-symmetric three-hindered quadrant diphosphine ligand, demonstrating its utility as a chiral ligand in the context of rhodium-catalyzed asymmetric hydrogenation toward the production of useful optically active compounds.[6,7] Thereafter, several new three-hindered quadrant phosphine ligands were prepared and successfully utilized in rhodium-catalyzed asymmetric hydrogenation reactions.[8−11] All of these ligands consisted of a bis(dialkylphosphino)methane molecular framework that formed four-membered metal complexes. To our knowledge, the use of three-hindered quadrant ligands to form five-membered chelates has not yet been reported.[12,13]



Trichickenfootphos



We recently reported the preparation of the C_2-symmetric P-stereogenic phosphine ligands 1,2-bis(*tert*-butylmethylphosphino)benzene (BenzP*) and 2,3-bis(*tert*-butylmethylphosphino)-quinoxaline (QuinoxP*).[14−16] These ligands exhibited excellent enantioselectivities and high catalytic activities in the rhodium-catalyzed asymmetric hydrogenation of various functionalized alkenes. Notably, the ligands were air-stable crystalline solids and were useful in the production of several chiral pharmaceutical ingredients with an amino acid or a secondary amine component. These results prompted us to study the enantioinduction properties of the rhodium complexes of three-hindered quadrant phosphine ligands, such as 1-(*tert*-butylmethylphosphino)-2-(di-*tert*-butylphosphino)benzene (3H-BenzP*)[17,18] and 2-(*tert*-butylmethylphosphino)-3-(di-*tert*-butylphosphino)quinoxaline (3H-QuinoxP*).

The ligand 3H-BenzP*, with an *R*-configuration, was prepared according to the procedures described in the literature.[17] The ligand was obtained as a colorless oil and was immediately converted into its cationic rhodium complex **1** by the usual means (Scheme 1).

Another ligand with a quinoxaline backbone was prepared in high yield from 2,3-dichloroquinoxaline via the intermediate **2** (Scheme 2). This ligand, (*R*)-3H-QuinoxP*, was an air-stable crystalline solid that formed the rhodium complex **3** without the need for special precautions.

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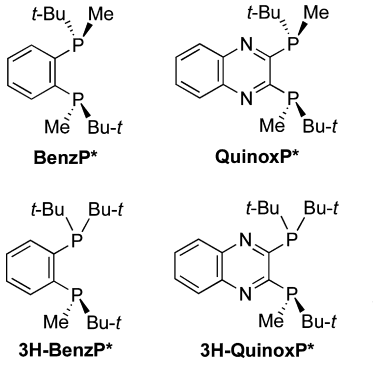
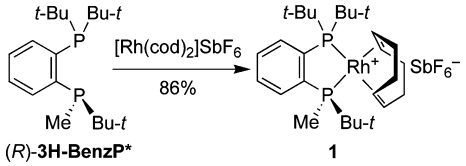
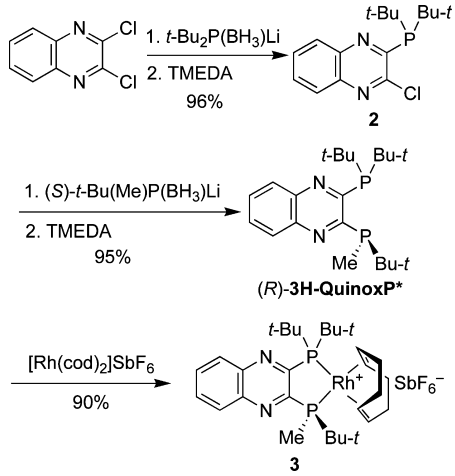


Scheme 1. Preparation of Rhodium Complex 1



Scheme 2. Preparation of (*R*)-3H-QuinoxP* and Its Rhodium Complex 3



The enantioinduction capabilities of the rhodium catalysts **1** and **3** were evaluated with respect to the hydrogenation of representative dehydroamino acid derivatives, enamides, and ethenephosphonates. The results are summarized in Table 1.

The hydrogenation of several α-dehydroamino acid derivatives (**4a**–**f**) provided largely varied results, depending on the substrate and the catalyst. Typical benchmark substrates, such as α-acetamidocinnamic acid derivatives and methyl 2-acetamidoacrylate (**4a**–**d**), afforded very high ee values of up to 99.9% (entries 1–8), but the ee values were slightly lower than those obtained through the use of BenzP* and QuinoxP*.[16] In contrast, remarkably lower enantioselectivities were observed in the reactions of 2-furyl and β-dimethyl-substituted compounds (entries 9–12).

The enantioinduction capabilities of the catalysts **1** and **3** toward both (*E*)- and (*Z*)-β-dehydroamino acid esters were of particular interest because most previous studies reported that the (*E*)-isomers gave rise to higher enantioselectivities than the (*Z*)-isomers.[19] Hydrogenation of the model substrates **4g** and **4h** afforded high ee values of 95% (entries 14–16), except for the hydrogenation of **4g** with **1** (entry 13). These results suggested that the three-hindered catalysts **1** and **3** were readily applicable to (*Z*)-derivatives as well. The catalysts were then tested using other (*Z*)-β-dehydroamino acid ester substrates having an alkyl or an aryl substituent at the β-position (entries 17–28). The substrates possessing a *n*-propyl group or an isopropyl group were hydrogenated in good to high enantioselectivities (entries 17–20). It is noted that the isopropyl derivative **4j** underwent hydrogenation under 10 atm H_2 in the presence of **1** to furnish the product with 94.4% ee. The β-aryl-substituted β-dehydroamino acid esters were also hydrogenated to give the corresponding products with good to high enantiomeric excesses (entries 21–28). Notably, compound **4n** was converted with a high enantioselectivity into a key intermediate for the synthesis of the VLA-4 antagonist S9059.[20]

Entries 29–42 show the hydrogenation results of prochiral enamides. In a series of α-aryl-substituted enamides, the catalyst **3**, with a less electron-rich ligand 3H-QuinoxP*, gave remarkably higher enantioselectivities than the catalyst **1**, with an electron-rich ligand 3H-BenzP*, except for the hydrogenation of the phenyl-substituted enamide **4o**. Hydrogenation of the *tert*-butyl-substituted enamide **4t** provided very low enantioselectivities (9 and 15%) (entries 39 and 40). These results sharply contrasted with those obtained through the use of the C_2-symmetric BenzP* and QuinoxP*, which gave 96.6 and 99.0% ee, respectively.[16] On the other hand, a β-keto enamide **4u** was hydrogenated into the corresponding product with considerably high enantiomeric excesses (entries 41 and 42), though the ee values are not comparable to the highest ones reported previously.[21]

The enantioselective hydrogenation of enol phosphonates and enamido phosphonates provides an efficient approach to the synthesis of optically active amino and hydroxy phosphoric acids, which are of widespread utility as pharmaceuticals and agrochemicals.[22] Our results (95.6–98.4% ee) for the hydrogenation of the model substrates **4v** and **4w** were comparable to the highest enantioselectivities reported previously, suggesting that the catalysts **1** and **3** may be useful for the hydrogenation of similar ethenephosphonates.

In conclusion, rhodium complexes of the three-hindered quadrant phosphine ligands (*R*)-1-*tert*-butylmethylphosphino-2-(di-*tert*-butylphosphino)benzene ((*R*)-3H-BenzP*) and (*R*)-2-*tert*-butylmethylphosphino-3-(di-*tert*-butylphosphino)-quinoxaline ((*R*)-3H-QuinoxP*) were prepared, and their catalytic performances were evaluated with respect to the hydrogenation of representative dehydroamino acid derivatives, enamides, and ethenephosphonates. The enantioselectivities varied widely, depending on the substrate and catalyst; however, the results were promising and indicated that the catalysts are potentially useful in the asymmetric hydrogenation of other prochiral substrates.

EXPERIMENTAL SECTION

General Methods. All anaerobic and moisture-sensitive manipulations were conducted using standard Schlenk techniques under argon. ^{1}H NMR, ^{13}C NMR, and ^{31}P NMR spectra were obtained at 500, 125, and 200 MHz, respectively. Anhydrous tetrahydrofuran, diethyl ether, and dichloromethane were used as received from commercial suppliers.

(*R*)-1-(*tert*-Butylmethylphosphino)-2-(di-*tert*-butylphosphino)benzene(1,5-cyclooctadiene)rhodium(I) Hexafluoroantimonate (1). A solution of (*R*)-1-(*tert*-butylmethylphosphino)-2-(di-*tert*-butylphosphino)benzene (64.9 mg, 0.200 mmol) in dichloromethane (1 mL) was added dropwise to a solution of $[Rh(cod)_2]SbF_6$ (101.0 mg, 0.182 mmol) in dichloromethane (5 mL) at 0 °C under argon. After stirring at room temperature for 1 h, the solution was concentrated under reduced pressure to 0.5 mL, followed

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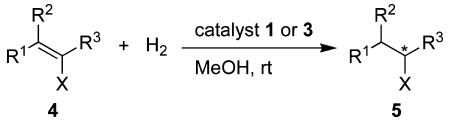
Table 1. Asymmetric Hydrogenation of Functionalized Alkenes Using [Rh((*R*)-3H-BenzP*)(cod)]SbF_6 (1) or [Rh((*R*)-3H-QuinoxP*)(cod)]SbF_6 (3)



entry[a,b]	substrate	catalyst	S/C	H_2 (atm)	product	ee (%) (config.)
1	**4a**: R^1 = Ph, R^2 = H, R^3 = CO_2Me, X = NHAc	**1**	1000	3	**5a**	99.2 (*R*)
2	**4a**: R^1 = Ph, R^2 = H, R^3 = CO_2Me, X = NHAc	**3**	1000	3	**5a**	98.4 (*R*)
3	**4b**: R^1 = Ph, R^2 = H, R^3 = CO_2H, X = NHAc	**1**	1000	3	**5b**	91.6 (*R*)[c]
4	**4b**: R^1 = Ph, R^2 = H, R^3 = CO_2H, X = NHAc	**3**	1000	3	**5b**	97.6 (*R*)[c]
5	**4c**: R^1 = 3-FC_6H_4, R^2 = H, R^3 = CO_2H, X = NHAc	**1**	1000	3	**5c**	97.7 (*R*)[c]
6	**4c**: R^1 = 3-FC_6H_4, R^2 = H, R^3 = CO_2H, X = NHAc	**3**	1000	3	**5c**	97.1 (*R*)[c]
7	**4d**: R^1 = R^2 = H, R^3 = CO_2Me, X = NHAc	**1**	1000	3	**5d**	93.6 (*R*)
8	**4d**: R^1 = R^2 = H, R^3 = CO_2Me, X = NHAc	**3**	1000	3	**5d**	99.9 (*R*)
9[d]	**4e**: R^1 = 2-Furyl, R^2 = H, R^3 = CO_2Me, X = NHCbz	**1**	200	4	**5e**	76 (*R*)[e]
10[d]	**4e**: R^1 = 2-Furyl, R^2 = H, R^3 = CO_2Me, X = NHCbz	**3**	200	4	**5e**	84 (*R*)
11[d]	**4f**: R^1 = R^2 = Me, R^3 = CO_2Me, X = NHAc	**1**	200	3	**5f**	64 (*S*)
12[d]	**4f**: R^1 = R^2 = Me, R^3 = CO_2Me, X = NHAc	**3**	200	3	**5f**	40 (*S*)
13	**4g**: R^1 = H, R^2 = CO_2Me, R^3 = Me, X = NHAc	**1**	1000	3	**5g**	86 (*R*)
14	**4g**: R^1 = H, R^2 = CO_2Me, R^3 = Me, X = NHAc	**3**	1000	3	**5g**	94.5 (*R*)
15	**4h**: R^1 = CO_2Me, R^2 = H, R^3 = Me, X = NHAc	**1**	1000	3	**5h**	94.8 (*R*)
16	**4h**: R^1 = CO_2Me, R^2 = H, R^3 = Me, X = NHAc	**3**	1000	3	**5h**	95.0 (*R*)
17	**4i**: R^1 = CO_2Me, R^2 = H, R^3 = Pr, X = NHAc	**1**	1000	5	**5i**	92.1 (*R*)
18	**4i**: R^1 = CO_2Me, R^2 = H, R^3 = Pr, X = NHAc	**3**	1000	5	**5i**	90 (*R*)
19	**4j**: R^1 = CO_2Et, R^2 = H, R^3 = *i*-Pr, X = NHAc	**1**	500	10	**5j**	94.4 (*S*)
20[f]	**4j**: R^1 = CO_2Et, R^2 = H, R^3 = *i*-Pr, X = NHAc	**3**	500	10	**5j**	72 (*S*)
21	**4k**: R^1 = CO_2Me, R^2 = H, R^3 = Ph, X = NHAc	**1**	1000	3	**5k**	96.8 (*S*)
22	**4k**: R^1 = CO_2Me, R^2 = H, R^3 = Ph, X = NHAc	**3**	1000	3	**5k**	91.4 (*S*)
23	**4l**: R^1 = CO_2Et, R^2 = H, R^3 = 4-$MeOC_6H_4$, X = NHAc	**1**	200	5	**5l**	96.4 (*S*)
24	**4l**: R^1 = CO_2Et, R^2 = H, R^3 = 4-$MeOC_6H_4$, X = NHAc	**3**	200	5	**5l**	92.6 (*S*)
25	**4m**: R^1 = CO_2Me, R^2 = H, R^3 = 3,5-$Cl_2C_6H_3$, X = NHAc	**1**	200	4	**5m**	76 (*S*)
26	**4m**: R^1 = CO_2Me, R^2 = H, R^3 = 3,5-$Cl_2C_6H_3$, X = NHAc	**3**	200	4	**5m**	89 (*S*)
27	**4n**: R^1 = CO_2Et, R^2 = H, R^3 = 3,4-$(MeO)_2C_6H_3$, X = NHAc	**1**	500	10	**5n**	94.1 (*S*)
28	**4n**: R^1 = CO_2Et, R^2 = H, R^3 = 3,4-$(MeO)_2C_6H_3$, X = NHAc	**3**	500	10	**5n**	92.8 (*S*)
29	**4o**: R^1 = R^2 = H, R^3 = Ph, X = NHAc	**1**	1000	3	**5o**	71 (*R*)
30	**4o**: R^1 = R^2 = H, R^3 = Ph, X = NHAc	**3**	1000	3	**5o**	71 (*S*)
31	**4p**: R^1 = R^2 = H, R^3 = 2-Naph, X = NHAc	**1**	1000	4	**5p**	43 (*R*)
32	**4p**: R^1 = R^2 = H, R^3 = 2-Naph, X = NHAc	**3**	1000	4	**5p**	96.4 (*R*)
33	**4q**: R^1 = R^2 = H, R^3 = 3-$AcOC_6H_4$, X = NHAc	**1**	1000	4	**5q**	58 (*R*)
34	**4q**: R^1 = R^2 = H, R^3 = 3-$AcOC_6H_4$, X = NHAc	**3**	200	4	**5q**	96.3 (*R*)
35	**4r**: R^1 = R^2 = H, R^3 = 4-$O_2NC_6H_4$, X = NHAc	**1**	1000	4	**5r**	92.8 (*R*)
36	**4r**: R^1 = R^2 = H, R^3 = 4-$O_2NC_6H_4$, X = NHAc	**3**	200	4	**5r**	98.6 (*R*)
37	**4s**: R^1 = R^2 = H, R^3 = 3,5-$(F_3C)_2C_6H_3$, X = NHAc	**1**	1000	4	**5s**	73 (*R*)
38	**4s**: R^1 = R^2 = H, R^3 = 3,5-$(F_3C)_2C_6H_3$, X = NHAc	**3**	1000	4	**5s**	96.1 (*R*)
39	**4t**: R^1 = R^2 = H, R^3 = *t*-Bu, X = NHAc	**1**	300	5	**5t**	9 (*S*)
40	**4t**: R^1 = R^2 = H, R^3 = *t*-Bu, X = NHAc	**3**	300	5	**5t**	15 (*S*)
41	**4u**: R^1 = PhCO, R^2 = H, R^3 = Me, X = NHAc	**1**	200	5	**5u**	89 (+)
42[g]	**4u**: R^1 = PhCO, R^2 = H, R^3 = Me, X = NHAc	**3**	200	5	**5u**	86 (+)
43	**4v**: R^1 = R^2 = H, R^3 = $P(O)(OMe)_2$, X = OBz	**1**	1000	5	**5v**	98.0 (*S*)
44	**4v**: R^1 = R^2 = H, R^3 = $P(O)(OMe)_2$, X = OBz	**3**	1000	5	**5v**	96.8 (*S*)
45	**4w**: R^1 = R^2 = H, R^3 = $P(O)(OEt)_2$, X = NHAc	**1**	200	4	**5w**	95.6 (*S*)
46	**4w**: R^1 = R^2 = H, R^3 = $P(O)(OEt)_2$, X = NHAc	**3**	200	4	**5w**	98.4 (*S*)

[a]All reactions were carried out in methanol at room temperature over 18 h, and the conditions were not optimized. [b]The reactions were completed under the conditions, unless otherwise noted. [c]The ee values were determined after conversion of the product into its methyl ester. [d]The hydrogenation was carried out in dichloromethane. [e]The hydrogenation in methanol provided the corresponding product with 47% ee. [f]Conversion of the reaction: 50%. [g]Conversion of the reaction: 42%.

by the addition of diethyl ether (5 mL). The precipitated solid was collected on a glass filter and washed with diethyl ether to afford orange microcrystals (120 mg, 86%): ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.21 (d, J = 14.9 Hz, 9H), 1.26 (d, J = 13.8 Hz, 9H), 1.46 (d, J = 13.7 Hz), 1.61 (d, J = 8.6 Hz), 2.16−2.24 (m, 3H), 2.24−2.32 (m, 1H), 2.42−2.51 (m, 2H), 2.68−2.75 (m, 2H), 4.47 (m, 1H), 5.45 (m, 1H), 5.57 (m, 1H), 6.45 (m, 1H), 7.68−7.75 (m, 2H), 7.76−7.75 (m, 1H), 8.13−8.17 (m, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 5.2 (d, J = 24.0 Hz), 26.0 (d, J = 24.0 Hz), 29.4 (s), 31.21 (s), 31.5 (s), 35.8 (d, J = 22.8 Hz), 37.4 (d, J = 28.8 Hz), 39.6 (d, J = 7.2 Hz), 41.8 (d, J = 14.4 Hz),

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95.1 (s), 100.0 (s), 100.6 (m), 109.1 (s), 131.5 (d, J = 23.9), 132.6 (d, J = 16.8 Hz), 134.2 (d, J = 15.6 Hz); ^{31}P NMR (202 MHz, $CDCl_3$) δ 59.3 (d, J = 149.8 Hz), 83.6 (d, J = 160.7 Hz); HRMS-TOF (m/z) [M − SbF_6 − C_8H_{12} (COD)]$^+$ calcd for $C_{19}H_{34}P_2Rh^+$, 427.1191; found, 427.1190.

2-(Di-*tert*-butylphosphino)-3-chloroquinoxaline (2). To a solution of di-*tert*-butylphosphine−borane (2.40 g, 15.0 mmol) in THF (30 mL) was added *n*-BuLi (9.4 mL of a 1.6 M hexane solution, 15.0 mmol) under argon at −5 °C. The resulting yellow-green solution was slowly added to a solution of 2,3-dichloroquinoxaline (1.99 g, 10.0 mmol) in THF (40 mL) over 10 min. After stirring for an additional 30 min, water (50 mL) was added, the organic layer was separated, and the aqueous layer was extracted with hexane (25 mL). The combined organic extracts were washed with water (25 mL × 2) and brine (50 mL), dried over Na_2SO_4, and evaporated to give a pasty oil. TMEDA (10 mL) and ethyl acetate (20 mL) were added, and the solution was kept for 2 h until the deboronation reaction had completed. The reaction mixture was diluted with ethyl acetate (30 mL) and washed successively with water, 5% aqueous HCl solution, water, and brine, followed by drying over Na_2SO_4. The solvent was removed on a rotary evaporator to give a yellow pasty oil, which was purified by silica gel column chromatography (hexane/ethyl acetate = 30/1) to afford 2-(di-*tert*-butylphosphino)-3-chloroquinoxaline as a yellow solid (2.98 g, 96%): mp 71−72 °C, R_f = 0.23 (silica gel, hexane/ethyl acetate = 30/1); ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.26 (d, J = 12.0 Hz, 18H), 7.71−7.79 (m, 2H), 7.95−8.00 (m, 1H), 8.10−8.15 (m, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 30.2 (d, J = 14.4 Hz), 34.4 (d, J = 22.8 Hz), 128.4, 129.5, 130.0, 131.4, 140.6, 141.2, 153.4 (d, J = 38.5 Hz), 160.9 (d, J = 34.9 Hz); ^{31}P NMR (202 MHz, $CDCl_3$) δ 26.5 (brs); HRMS-ESI (m/z) [M + H]$^+$ calcd for $C_{16}H_{23}ClN_2P^+$, 309.1287; found, 309.1270.

(*R*)-2-(*tert*-Butylmethylphosphino)-3-(di-*tert*-butylphosphino)quinoxaline ((*R*)-3H-QuinoxP*). To a solution of (*S*)-*tert*-butylmethylphosphine−borane (0.72 g, 6.1 mmol) in THF (5 mL) was added *n*-BuLi in hexane (3.8 mL of a 1.6 M hexane solution, 6.1 mmol) at 0 °C under argon. After stirring for 30 min, the solution was slowly added to a suspension of 2-di-*tert*-butylphosphino)-3-chloroquinoxaline (1.15 g, 3.7 mmol) in DMF (20 mL) at −5 °C, and stirring was continued for an additional 4 h at the same temperature. Water (40 mL) was added, and the mixture was extracted with ethyl acetate (40 mL × 2). The combined extracts were washed with brine (40 mL) and evaporated to give a yellow pasty oil, which was reacted with TMEDA (10 mL) in ethyl acetate (20 mL) for 1 h at room temperature. The reaction mixture was diluted with ethyl acetate (20 mL), and the solution was washed successively with water, a 6 M HCl solution, water, and brine, followed by drying over Na_2SO_4. The solvent was removed under reduced pressure, and the residue was purified by silica gel column chromatography using hexane/ethyl acetate = 30/1 as the eluent to afford (*R*)-2-(*tert*-butylmethylphosphino)-3-(di-*tert*-butylphosphino)quinoxaline (1.32 g, 95%) as a yellow solid. Pure compound was obtained by recrystallization from hot ethyl acetate/methanol (1/5): mp 165−167 °C. R_f = 0.20 (silica gel, hexane/ethyl acetate = 30/1); $[\alpha]^{25}_D$ −46.0 (*c* 0.5, EtOAc); ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.15 (d, J = 12.0 Hz, 9H), 1.19 (d, J = 11.5 Hz, 9H), 1.34 (d, J = 11.8 Hz, 9H), 1.41 (d, J = 5.5 Hz, 3H), 7.67−7.76 (m, 2H), 8.03−8.12 (m, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 6.7 (d, J = 8.4 Hz), 27.7 (d, J = 13.2 Hz), 30.5 (d, J = 13.2 Hz), 30.7 (d, J = 13.2 Hz), 31.3 (dd, J = 14.4, 2.4 Hz), 34.5 (dd, J = 24.0, 4.8 Hz), 35.3 (dd, J = 22.8, 2.4 Hz), 129.5, 129.6, 129.7, 129.8, 141.1, 141.2, 166.4 (t, J = 31.2 Hz), 167.5 (dd, J = 33.7, 28.8 Hz); ^{31}P NMR (202 MHz, $CDCl_3$,) δ −14.4 (dm, J = 107 Hz), 21.6 (dm, J = 107 Hz); HRMS-ESI (m/z) [M + H]$^+$ calcd for $C_{21}H_{35}N_2P_2^+$, 377.2275; found, 377.2299.

(*R*)-2-(*tert*-Butylmethylphosphino)-3-(di-*tert*-butylphosphino)quinoxaline(1,5-cyclooctadiene)rhodium(I) Hexafluoroantimonate (3). A solution of (*R*)-2-(*tert*-butylmethylphosphino)-3-(di-*tert*-butylphosphino)quinoxaline (39.4 mg, 0.105 mmol) in dichloromethane (1.5 mL) was added dropwise to a solution of $[Rh(cod)_2]SbF_6$ (55.5 mg, 0.100 mmol) in dichloromethane (2 mL) at 0 °C under argon. After stirring at room temperature for 30 min, the solution was concentrated under reduced pressure to 0.5 mL, followed by the addition of diethyl ether (3 mL). The precipitated solid was collected on a glass filter and washed with diethyl ether to give (*R*)-2-(*tert*-butylmethylphosphino)-3-(di-*tert*-butylphosphino)quinoxaline(1,5-cyclooctadiene)rhodium(I) hexafluoroantimonate (74 mg, 90%) as a brown microcrystalline solid: ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.26 (d, J = 14.9 Hz, 9H), 1.31 (d, J = 14.1 Hz, 9H), 1.55 (d, J = 14.3 Hz, 9H), 1.78 (d, J = 8.6 Hz, 3H), 2.16−2.38 (m, 4H), 2.44−2.60 (m, 2H), 2.66−2.84 (m, 2H), 4.65−4.75 (m, 1H), 5.56−5.66 (m, 1H), 5.66−5.72 (m, 1H), 6.51−6.61 (m, 1H), 7.96−8.10 (m, 2H), 8.22−8.35 (m, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 4.6 (d, J = 24.0 Hz), 26.2 (d, J = 16.8 Hz), 29.3 (d, J = 3.6 Hz), 30.8 (d, J = 4.8 Hz), 31.2 (d, J = 4.8 Hz), 35.7 (dd, J = 36.0, 3.6 Hz), 38.6 (d, J = 27.6 Hz), 40.4 (d, J = 8.4 Hz), 43.2 (d, J = 13.2 Hz), 85.2 (dd, J = 14.4, 7.2 Hz), 94.2 (dd, J = 12.0 Hz, 6.0 Hz), 102.5 (dd, J = 9.6, 3.6 Hz), 130.2, 108.8 (t, J = 6.0 Hz), 133.1, 141.4 (d, J = 8.4 Hz), 141.9 (d, J = 7.2 Hz), 155.8 (dd, J = 55.7, 45.7 Hz), 157.1 (dd, J = 49.3, 40.9 Hz); ^{31}P NMR (202 MHz, $CDCl_3$) δ 44.2 (d, J = 141 Hz), 62.3 (d, J = 122 Hz); HRMS-ESI (m/z) [M − SbF_6]$^+$ calcd for $C_{29}H_{46}N_2P_2Rh^+$, 587.2191; found, 587.2190.

General Procedure for Asymmetric Hydrogenation. The rhodium precatalyst (0.002 mmol), substrate (2 mmol), and a magnetic stir bar were introduced into a hydrogenation bottle. The system was then evacuated and filled with hydrogen. After repeating this operation several times, degassed methanol (5 mL) was added, and the hydrogen pressure was adjusted to 3 atm. After stirring for 18 h, the reaction mixture was evaporated under reduced pressure, and the residue was passed through a short column of silica gel using ethyl acetate/hexane (1:1) as the eluent to remove the rhodium catalyst. The solvent was removed under reduced pressure, and the product was dried under vacuum. The enantiomeric excess of the product was determined by HPLC or GC analysis using chiral columns.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Conditions for determining the enantiomeric excesses of the hydrogenation products and NMR spectra of the new compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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