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Efficient Preparation of New Rhodium- and Iridium-[Bis(oxazolinyl)-3,5-dimethylphenyl] Complexes by C–H Bond Activation: Applications in Asymmetric Synthesis

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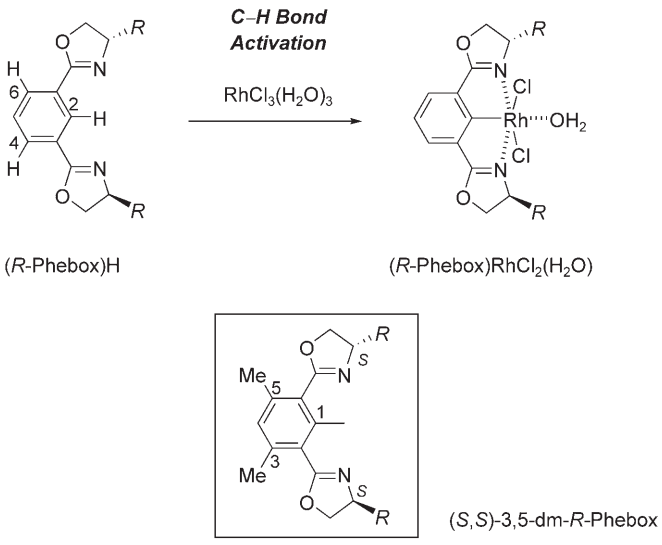
Abstract: The bis(oxazolinyl)-3,5-dimethylphenylrhodium and -iridium complexes were synthesized in high yields by an efficient C–H bond activation method with 4,6-dimethyl-1,3-bis(oxazolinyl)benzene derivatives. The catalytic activity of the complexes was examined for the asymmetric conjugate reduction of (*E*)-ethyl 3-phenylbut-2-enoate and the asymmetric reductive aldol reaction of *tert*-butyl acrylate and benzaldehyde. It was found that the rhodium complex of 3,5-dmPhebox showed the higher catalytic activity, whereas the corresponding iridium complexes proved to be less active.

Keywords: asymmetric catalysis; bisoxazoline; C–H bond activation; iridium; rhodium

Introduction

We have reported that bis(oxazolinylphenyl)rhodium complexes, (Phebox)Rh, show highly efficient catalytic activity in the asymmetric conjugate reduction of α,β-unsaturated carbonyl compounds and the asymmetric reductive aldol reaction of acrylates and aldehydes.[1,2] As a catalyst precursor (*R*-Phebox)$RhCl_2(H_2O)$ was conveniently prepared by a C–H bond activation method with 1,3-bis(oxazolinyl)benzene, (*R*-Phebox)H, and rhodium trichloride in methanol solution (Scheme 1). However, the yields of the desired complexes turned out to be relatively low or around middle range up to *ca.* 50%.[1a] In spite of efforts to improve the efficiency by employing several modifications, such as addition of appropriate bases, choice of solvents, and reaction temperature, etc., we could not find any better solution. Although we also attempted several transmetallation routes with (*R*-Phebox)$SnMe_3$, the yields have not been improved.[3] Hypothetically, we thought that C–H bond activation at the undesired 4- or 6-position of (*R*-Phebox)H might decrease the yields. In this context, Richards et al. observed a similar phenomenon of C–H bond activation at position 4 in the reaction of (Phebox)H and $Pd(OAc)_2$.[4] Finally, we decided that two methyl groups should be introduced into the benzene skeleton of Phebox, starting from the corresponding isophthalic acid. This modification has been shown in some cases in preparation of pincer complexes.[5] In addition, we disclose here two asymmetric catalyses in order to illustrate the catalytic activity of the obtained 3,5-dimethyl-Phebox complexes.

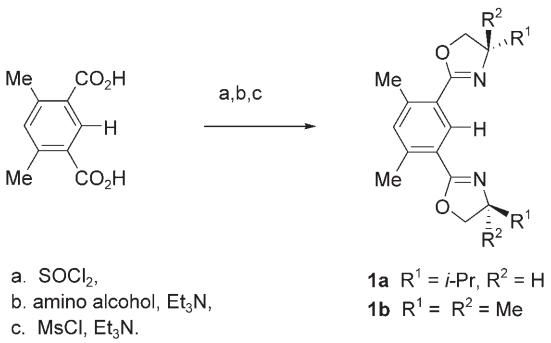


Scheme 1.

Results and Discussion

Preparation of Ligands

3,5-Dimethyl-*R*-Phebox ligands **1a** and **1b** were readily synthesized in three steps by chlorination of 4,6-dimethylisophthalic acid in thionyl chloride, condensa-

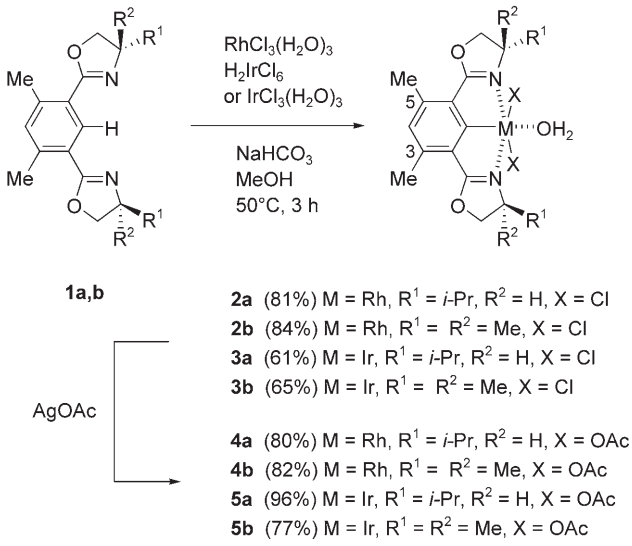


Scheme 2.

tion with β-amino alcohol, and oxazoline formation with methanesulfonyl chloride and triethylamine (Scheme 2).

Preparation of Complexes

Heating of a mixture of chiral ligand **1a** or non-chiral **1b**, $RhCl_3(H_2O)_3$, and $NaHCO_3$ in methanol gave the corresponding chloride complexes (3,5-dm-*ip*Phebox)$RhCl_2(H_2O)$ **2a** (81%) and (3,5-dm-*dm*Phebox)$RhCl_2(H_2O)$ **2b** (84%), respectively (Scheme 3). The yields were greatly improved, comparing to that (56%) for (*ip*Phebox)$RhCl_2(H_2O)$ previously reported by us.[1] In addition, although we could not synthesize so far the corresponding iridium complex by the C–H bond activation reaction with (*ip*Phebox)H and $H_2IrCl_6(H_2O)_6$, the iridium complexes **3a** and **3b** were fortunately obtained albeit in a middle range of 61% and 65%, respectively. Thus, the C–H bond activation at the desired position was realized efficiently by introduction of the two methyl groups at the neighboring positions of the oxazoline substitutents. The chloride complexes could, in turn, be converted to the acetate complexes **4** and **5** by treatment with an excess of silver acetate in high yields (77–96%).



Scheme 3.

Structure Analysis

The molecular structures of **2b** and **3b** could be analyzed by X-ray crystallography to show their C_{2v} symmetrical forms (Figure 1). Phebox skeletons meridianally bind to the rhodium atom and the iridium atom with an Rh–C bond length of 1.91 Å and an Ir–C bond length of 1.93 Å, respectively. The bond angles of N–Rh–N and N–Ir–N are 159.79° and 158.52, respectively. The rhodium complex has thus slightly shorter metal–C bond and wider N,N bite angle compared to the iridium complex.

Application to Asymmetric Catalysis

Asymmetric Conjugate Reduction of α,β-Unsaturated Ester

(*E*)-Ethyl 3-phenylbut-2-enoate (**6**) was selected as a probe substrate (Scheme 4). The catalytic reduction of the ester **6** was carried out with 1 mol% of the chiral acetate complexes **4a** and **5a** in combination with diethoxymethylsilane (1.5 equivs.) in toluene solution at 50°C, respectively. The reaction with the rhodium complex **4a** was complete within half an hour. After hydrolysis, the reduction product **7** was obtained in 90% yield with 96% *ee* (*R*) (Table 1, run 1). Thus, the rhodium catalyst **4a** proved to be an active catalyst and kept the enantioselectivity, compared to that previously reported for the non-3,5-dimethyl-substituted one; 96%, 96% *ee* (*R*).[1a] On the other hand, the iridium complex **5a** was first examined but proved to show a slightly lower catalytic activity compared to the rhodium one. The reaction took a longer time at 50°C to give the product **7** in 63–64% yield with 56–72% *ee* (runs 2 and 4).

Asymmetric Reductive Aldol Reaction

The asymmetric coupling reaction of benzaldehyde and *tert*-butyl acrylate was then examined with **4a** and **5a** (Scheme 5). The catalytic reaction was carried out with 1 mol% of the chiral acetate complexes **4a** and **5a** in combination with diethoxymethylsilane (1.6 equivs.) in toluene solution at 50°C, respectively. The rhodium complex **4a** exhibited a high activity to give the reductive aldol product **8** in 98% yield, 95:5 of *anti*:*syn*, and 92% *ee* for **8*anti*** (Table 2, run 1). Ethyl

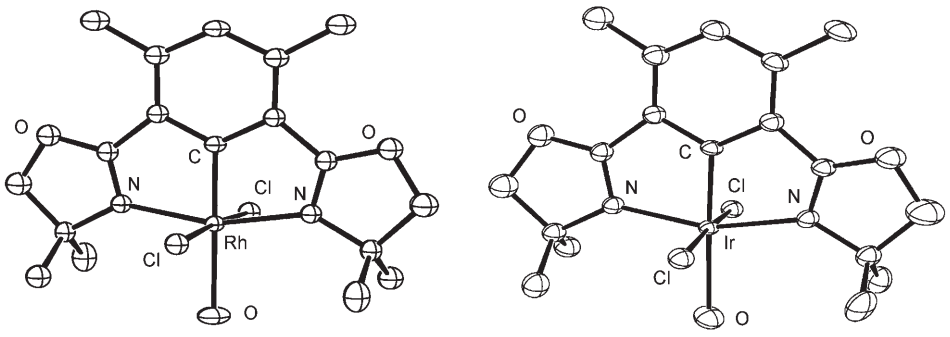


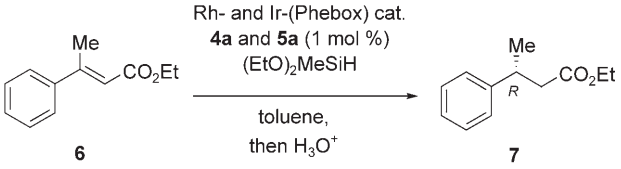
Figure 1. X-ray analysis of the complex **2b** and **3b**. Selected bond lengths [Å] and angles [°]: **2b**, Rh–C 1.913, Rh–O 2.234, N–Rh–N 159.79; **3b**, Ir–C 1.930, Ir–O 2.243, N–Ir–N 158.52.

Table 1. Asymmetric conjugate reduction of (*E*)-ethyl 3-phenylbut-2-enoate with Rh- and Ir-(Phebox) catalysts.[a]

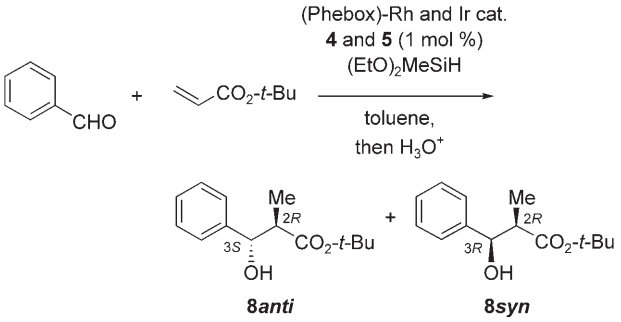
Run	Catalyst	Temperature/Time [°C/h]	Yield of **7** [%]	% ee
1	**4a**	50/0.5	90	96
2	**5a**	50/6.0	64	56
3	**5a**	reflux/6.0	33	14[b]
4[c]	**5a**	50/10	63	72

[a] Ester **6** (1.0 mmol), cat. (0.01 mmol), silane (1.5 mmol), toluene (2.0 mL).
[b] (*S*).
[c] Ester (1.0 mmol), cat. (0.02 mmol), silane (3.0 mmol), toluene (2.0 mL).

acetate can also be used as a solvent rather than THF (runs 2 and 3). On the other hand, the iridium complex **5a** can also catalyze the reaction but gives a low yield of 19% with a slightly lower stereoselectivity (run 5). An increase of the catalyst loading (2.5 mol%) and a higher temperature did not improved the yield and selectivity (runs 6 and 7). It is worthy of



Scheme 4.



Scheme 5.

Table 2. Asymmetric reductive aldol reaction of *tert*-butyl acrylate and benzaldehyde with (Phebox)-Rh and Ir catalysts.[a]

Run	Catalyst	Temperature/Time [°C/h]	Yield of **8** [%]	ratio of *anti:syn*	% *ee* *anti*	*syn*
1	**4a**	50/0.5	98	95:5	92	7
2[b]	**4a**	50/0.5	74	89:11	88	9
3[c]	**4a**	50/0.5	99	95:5	91	8
4	**4b**	50/0.5	94	96:4	-	-
5	**5a**	50/6.0	19	93:7	89	16
6[d]	**5a**	50/2.0	23	93:7	90	8
7	**5a**	90/1.0	48	91:9	89	4
8	**5b**	50/2.0	56	96:4	-	-

[a] Benzaldehyde (1.0 mmol), cat. (0.01 mmol), *tert*-butyl acrylate (1.5 mmol), silane (1.6 mmol), toluene (3.0 mL).
[b] THF (3.0 mL) as a solvent.
[c] EtOAc (3.0 mL) as a solvent.
[d] Benzaldehyde (0.2 mmol), cat. (0.01 mmol), *tert*-butyl acrylate (0.6 mmol), silane (0.62 mmol), toluene (2.0 mL).

note that the non-chiral complexes **4b** and **5b** were also employed as catalysts and showed a similar *anti*-selectivity of 96:4, respectively.

Conclusions

We have synthesized 3,5-dimethyl-substituted Phebox derivatives and their rhodium and iridium complexes. The structures were clarified by X-ray analysis. The rhodium complexes were examined as catalysts for the asymmetric conjugate reduction and the asymmetric reductive aldol reaction and revealed high efficiency and selectivity. In addition, the corresponding iridium complexes were obtained, but the reactions resulted in a lower efficiency than the rhodium ones.

Experimental Section

General Remarks

^{1}H and ^{13}C NMR spectra were obtained at 25 °C on a Varian Mercury 300 spectrometer. ^{1}H NMR chemical shifts are reported in δ units, in ppm relative to the singlet at 7.26 ppm for chloroform. ^{13}C NMR spectra are reported in terms of chemical shift (δ, ppm) relative to the triplet at $\delta =$ 77.0 ppm for $CDCl_3$ as an internal standard. Infrared spectra were recorded on a JASCO FT/IR-230 spectrometer. Absolute toluene and hydrosilane were purchased from TCI. Column chromatography was performed with a silica gel column (Merck silica gel 60). 4,6-Dimethylisophthalic acid was prepared by the reported method.[6]

Synthesis of Ligands

(4,6-dm-*ip*Phebox)H (1a): To a suspension of 4,6-dimethylisophthalic acid (971 mg, 5.0 mmol) in toluene (5 mL) was slowly added thionyl chloride (3.0 mL). The mixture was refluxed for 5 h and then excess thionyl chloride was removed under reduced pressure to give 4,6-dimethylisophthaloyl chloride, which was used in next step without further purification.

A solution of 4,6-dimethylisophthaloyl chloride in THF (10 mL) was slowly added to a solution of L-valinol (1.03 g, 10.0 mmol) and triethylamine (20 mL) in THF (30 mL) at 0 °C. The mixture was stirred at room temperature for 2 h. Methanesulfonyl chloride (2.0 mL, 26 mmol) was added at 0 °C, and then the mixture was stirred at room temperature for 14 h. Formation of the product **1a** was monitored by TLC examination; $R_f = 0.7$ (ethyl acetate/hexane = 3:1). At 0 °C, aqueous potassium carbonate (1 N, *ca.* 50 mL) was added and the mixture was extracted with ethyl acetate. The organic layer was washed with saturated brine, was dried over magnesium sulfate, and was concentrated. The crude product was purified by column chromatography on silica gel (ethyl acetate/hexane 1:3) to give **1a** as a colorless solid; yield: 1.29 g (3.91 mmol, 78 %); mp 38–39 °C; $[\alpha]_D^{23}$: −155.1 (*c* 1.00, $CHCl_3$). ^{1}H NMR (300 MHz, $CDCl_3$): $\delta = 0.93$ (d, $J_{H,H} = 6.9$ Hz, 6H), 1.02 (d, $J_{H,H} = 6.6$ Hz, 6H), 1.83 (m, 2H), 2.59 (s, 6H), 4.03–4.15 (m, 4H), 4.26–4.38 (m, 2H), 7.11 (s, 1H), 8.20 (s, 1H); ^{13}C{^{1}H} NMR (75 MHz, $CDCl_3$): $\delta = 18.3$, 18.9, 21.7, 32.9, 69.2, 73.2, 124.7, 131.0, 134.0, 140.9, 162.8; IR (KBr): $\nu = 2961$, 892, 1647, 1558, 1468, 1366, 1067 cm^{-1}; anal. calcd. for $C_{20}H_{28}N_2O_2$: C 73.14, H 8.59, N 8.51; found: C 73.11, H 8.75, N 8.53.

(4,6-dm-*dm*Phebox)H (1b): The preparation procedure of **1b** is similar to that of **1a**. Yield: 1.23 g (4.11 mmol, 82 %); colorless solid; mp: 143–144 °C. ^{1}H NMR (300 MHz, $CDCl_3$): $\delta = 1.35$ (s, 12H), 2.54 (s, 6H), 4.03 (s, 6H), 7.03 (s, 1H), 8.13 (s, 1H); ^{13}C{^{1}H} NMR (75 MHz, $CDCl_3$): $\delta =$ 21.36, 28.55, 67.94, 78.41, 125.0, 131.1, 133.8, 140.6, 161.8; IR (KBr): $\nu = 2967$, 2890, 1640, 1441, 1351, 1310, 1188, 1051, 1011 cm^{-1}; anal. calcd. for $C_{18}H_{24}N_2O_2$: C 71.97, H 8.05, N 9.33; found: C 71.93, H 8.14, N 9.34.

Synthesis of Rh and Ir Complexes

(3,5-dm-*ip*Phebox)RhCl$_2$(H$_2$O) (2a): $RhCl_3 \cdot 3H_2O$ (289 mg, 1.10 mmol), **1a** (328 mg, 1.00 mmol) and sodium bicarbonate (84 mg, 1.1 mmol) were placed in a 100 mL flask. After addition of methanol (20 mL) and H_2O (2 mL), the mixture was stirred at 60 °C for 1 h. The concentrated residue was passed through a silica gel column with ethyl acetate/hexane (2:1) as eluent to give **2a** as a brown solid; yield: 422 mg (0.81 mmol, 81 %); mp 320 °C (dec). ^{1}H NMR (300 MHz, $CDCl_3$): $\delta = 0.93$ (d, $J_{H,H} = 6.9$ Hz, 6H), 0.95 (d, $J_{H,H} =$ 6.9 Hz, 6H), 2.42 (m, 2H), 2.58 (s, 6H), 2.83 (br, 2H), 4.23 (m, 2H), 4.63–4.73 (m, 4H), 6.78 (s, 1H); ^{13}C{^{1}H} NMR (75 MHz, $CDCl_3$): $\delta = 15.26$, 19.20, 19.58, 29.27, 66.50, 70.83, 127.5, 128.4, 141.2, 127.9, 128.1, 140.8, 171.4 (d, $J_{Rh,C} =$ 3.5 Hz), 181.4 (d, $J_{Rh,C} = 24.5$ Hz); IR (KBr): $\nu = 3455$, 2954, 1614, 1485, 1385, 944 cm^{-1}; anal. calcd. for $C_{20}H_{29}Cl_2N_2O_3Rh$: C 46.26, H 5.63, N 5.39; found: C 46.08, H 5.63, N 5.14.

(3,5-dm-*dm*Phebox)RhCl$_2$(H$_2$O) (2b): The preparation procedure of **2b** was similar to that of **2a** but a different eluent (ethyl acetate/chloroform = 2:1) was used for column chromatography. Yield: 413 mg, (0.84 mmol, 84 %); brown solid; mp 339 °C (dec). ^{1}H NMR (300 MHz, $CDCl_3$): $\delta =$ 1.54 (s, 12H), 2.58 (s, 6H), 3.59 (br, 2H, H_2O), 4.48 (s, 4H), 6.74 (s, 1H); ^{13}C{^{1}H} NMR (75 MHz, $CDCl_3$): $\delta = 19.17$, 27.64, 65.17, 82.05, 127.9, 128.1, 140.8, 169.9 (d, $J_{Rh,C} =$ 3.4 Hz), 181.8 (d, $J_{Rh,C} = 23.9$ Hz); IR (KBr): $\nu = 3408$, 2977, 1602, 1487, 1455, 1381, 954 cm^{-1}; anal. calcd. for $C_{18}H_{25}Cl_2N_2O_3Rh \cdot (H_2O)$: C 42.45, H 5.34, N 5.50; found: C 42.76, H 5.04, N 5.21.

(3,5-dm-*ip*Phebox)IrCl$_2$(H$_2$O) (3a): $IrCl_6H_2 \cdot 6H_2O$ (570 mg, 1.11 mmol), **1a** (328 mg, 1.0 mmol) and sodium bicarbonate (277 mg, 3.30 mmol) were placed in a 100 mL flask. After addition of 2-propanol (40 mL), the mixture was refluxed for 10 h. The concentrated residue was purified by column chromatography on silica gel with ethyl acetate/hexane (2:1) as eluent to give **3a** as a yellow solid; in yield: 371 mg (0.61 mmol, 61 %); mp 204 °C (dec). ^{1}H NMR (300 MHz, $CDCl_3$): $\delta = 0.95$ (d, $J_{H,H} = 6.6$ Hz, 6H), 0.98 (d, $J_{H,H} = 6.9$ Hz, 6H), 2.43 (m, 2H), 2.62 (s, 6H), 4.19 (m, 2H), 4.73–4.86 (m, 4H), 6.63 (s, 1H); ^{13}C{^{1}H} NMR (75 MHz, $CDCl_3$): $\delta = 15.34$, 18.85, 19.58, 29.02, 67.10, 70.85, 125.8,

126.6, 140.9, 162.8, 176.9; IR (KBr): $\nu = 3361$, 2921, 1603, 1485, 1384, 1332, 1218 cm^{-1}; anal. calcd. for $C_{20}H_{29}Cl_2IrN_2O_3 \cdot 0.5(C_4H_8O_2)$: C 40.49, H 5.10, N 4.29; found: C 40.64, H 5.07, N 4.24.

(3,5-dm-*dm*Phebox)IrCl$_2$(H$_2$O) (3b): The preparation procedure of **3b** was similar to that of **3a**; Yield: 375 mg (0.65 mmol, 65%). Complex **3b** was also obtained by the reaction of $IrCl_3 \cdot 3\ H_2O$ (389 mg, 1.10 mmol) with **1b** (300 mg, 1.00 mmol) in the presence of $NaHCO_3$ (92 mg, 1.1 mmol); yield: 63%; yellow solid; mp 356°C (dec). ^{1}H NMR (300 MHz, $CDCl_3$): $\delta = 1.58$ (s, 12H), 2.63 (s, 6H), 3.22 (br, 2H, H_2O), 4.59 (s, 4H), 6.59 (s, 1H); $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$): $\delta = 18.84$, 27.87, 65.90, 82.02, 126.31, 126.33, 140.7, 161.4, 175.6; IR (KBr): $\nu = 3567$, 2976, 2918, 1605, 1544, 1487, 1455, 1400, 1382, 1336, 1217, 1057, 1022, 955, 845 cm^{-1}; anal. calcd. for $C_{18}H_{25}Cl_2IrN_2O_3$ (580.53): C 37.24, H 4.34, N 4.83; found: C 36.92, H 4.38, N 4.57.

(3,5-dm-*ip*Phebox)Rh(OAc)$_2$(H$_2$O) (4a): The complex **3a** (260 mg, 0.50 mmol) and silver acetate (334 mg, 2.00 mmol) were placed in a 50 mL flask. After addition of CH_2Cl_2 (5 mL), the mixture was stirred at room temperature for 24 h. After removal of the solvent under reduced pressure, the residue was purified by column chromatography on silica gel with ethyl acetate/methanol (5:1) to give **4a** as a yellow solid; yield: 224 mg (0.40 mmol, 80%); mp 225°C (dec). ^{1}H NMR (300 MHz, $CDCl_3$): $\delta = 0.66$ (d, $J_{H,H} = 6.9$ Hz, 6H), 0.92 (d, $J_{H,H} = 7.2$ Hz, 6H), 1.65 (s, 6H), 2.48 (m, 2H), 2.58 (s, 6H), 4.31 (m, 2H), 4.58–4.67 (m, 4H), 5,99 (br, 2H), 6.78 (s, 1H); $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$): $\delta =$ 14.15, 19.02, 19.22, 23.97, 28.97, 66.88, 70.48, 127.7, 128.3, 140.4, 172.3 (d, $J_{Rh,H} = 4.0$ Hz), 182.0 (d, $J_{Rh,H} = 1.7$ Hz), 190.2 (d, $J_{Rh,H} = 24.5$ Hz); IR (KBr): $\nu = 3411$, 2956, 2874, 1605, 1483, 1383, 1324, 1245, 1223, 1073, 1020, 936, 692 cm^{-1}; anal. calcd. for $C_{24}H_{35}N_2O_7Rh$: C 50.89, H 6.23, N 4.95; found: C 50.36, H 6.23, N 4.75.

(3,5-dm-*dm*Phebox)Rh(OAc)$_2$(H$_2$O) (4b): Yield: 221 mg (0.41 mmol, 82%); yellow solid; mp 290°C (dec). ^{1}H NMR (300 MHz, $CDCl_3$): $\delta = 1.45$ (s, 12H), 1.68 (s, 6H), 2.61 (s, 6H), 4.48 (s, 4H), 4.97 (br, 2H, H2O), 6.77 (s, 1H); $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$): $\delta = 19.12$, 23.73, 27.07, 64.69, 82.13, 127.9, 128.2, 140.5, 171.1 ($J_{Rh,C} = 4.0$ Hz), 189.7 ($J_{Rh,C} =$ 25.1 Hz); IR (KBr): $\nu = 3395$, 2971, 2925, 1599, 1483, 1456, 1380, 1324, 1252, 1213, 1051, 1016, 950 cm^{-1}; anal. calcd. for $C_{22}H_{31}N_2O_7Rh$: C 49.08, H 5.80, N 5.20; found: C 49.13, H 5.72, N 5.23.

(3,5-dm-*ip*Phebox)Ir(OAc)$_2$(H$_2$O) (5a): The complex **3a** (304 mg, 0.50 mmol) and silver acetate (501 mg, 3.00 mmol) were placed in a 50 mL flask. After addition of THF (10 mL), the mixture was stirred at 60°C for 12 h. After removal of the solvent under reduced pressure, the residue was purified by column chromatography on silica gel with ethyl acetate/methanol (10:1) to give **5a** as a yellow solid; yield: 315 mg (0.48 mmol, 96%); mp: 216°C (dec). ^{1}H NMR (300 MHz, $CDCl_3$): $\delta = 0.71$ (d, $J_{H,H} = 6.6$ Hz, 6H), 0.95 (d, $J_{H,H} = 7.2$ Hz, 6H), 1.68 (s, 6H), 2.52 (m, 2H), 2.65 (s, 6H), 4.28 (m, 2H), 4.68–4.79 (m, 4H), 6.63 (s, 1H), 6.72 (br, 2H); $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$): $\delta = 14.20$, 18.68, 19.30, 23.20, 28.89, 67.60, 70.54, 126.1, 126.5, 140.3, 171.3, 178.3, 183.1; IR (KBr): $\nu = 3435$, 2958, 2931, 2874, 1605, 1483, 1384, 1325, 1244, 1223, 1074, 1019, 934, 691 cm^{-1}; anal. calcd. for $C_{24}H_{35}IrN_2O_7$: C 43.96, H 5.38, N 4.27; found: C 43.85, H 5.32, N 4.10.

(3,5-dm-*dm*Phebox)Ir(OAc)$_2$(H$_2$O) (5b): Yield: 243 mg (0.39 mmol, 77%); yellow solid; mp 269°C (dec). ^{1}H NMR (300 MHz, $CDCl_3$): $\delta = 1.47$ (s, 12H), 1.67 (s, 6 h), 2.67 (s, 6H), 4.57 (s, 4H), 6.62 (s, 1H), 7.93 (br, 2H); $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$): $\delta = 18.70$, 23.51, 26.92, 65.20, 81.95, 126.1, 126.8, 140.2, 170.3, 177.2, 182.9; IR (KBr): $\nu = 3372$, 2929, 1645, 1600, 1464, 1380, 1327, 1212, 1050, 954 cm^{-1}; anal. calcd. for $C_{22}H_{31}IrN_2O_7$: C 42.10, H 4.98, N 4.46; found: C 41.85, H 4.79, N 4.12.

X-ray Crystallographic Determination

Single crystals suitable for X-ray analysis were obtained by recrystallization from dichloromethane/hexane at room temperature. A crystal was mounted on a quartz fiber, and diffraction data were collected in θ ranges at 173 K with a Bruker SMART APEX CCD diffractometer with graphite-monochromated $Mo_{K\alpha}$ radiation ($\lambda = 0.71073$ Å). An empirical absorption correction was applied by using SADABS. The structure was solved by direct method and refined by full-matrix least-square on F^2 by using SHELXTL. All non-hydrogen atoms were refined with anisotropic displacement parameters.

Refinement details: **2b:** empirical formula; $C_{18}H_{25}Cl_2N_2O_3Rh \cdot (H_2O)$; M_r = 509.23; temperature 173(2) K; crystal system: orthorhombic; space group: *Ibca*; a = 8.5867(5), b = 16.7843(10), c = 29.3837(18) Å, V = 4234.8(4) Å^3, Z = 8, $\rho_{calcd.}$ = 1.597 Mg/m^3, μ = 1.084 mm^{-1}, $F(000)$ = 2080, crystal size = 0.25 × 0.15 × 0.10 mm^3, θ range = 1.39–27.48°; index ranges: $-11 \le h \le 10$, $-13 \le k \le 21$, $-33 \le l \le 38$; reflections collected 14252, independent reflections 2434 [R(int) = 0.0478], completeness to θ = 27.48°,100.0%; max/min transmission 1.000000/0.754755; data/restraints/parameters 2434/0/136; goodness-of-fit on F^2 0.983; final R indices [$I > 2\sigma(I)$]: R1 = 0.0284, wR2 = 0.0688; R indices (all data): R1 = 0.0379, wR2 = 0.0738; largest diff. peak/hole 0.953/−0.722 e·Å^{-3}; **3b:** empirical formula; $C_{18}H_{25}Cl_2IrN_2O_3 \cdot (H_2O)$; M_r = 598.52; temperature 173(2) K; crystal system: monoclinic; space group: $P2_1/n$; a = 8.8453(5), b = 8.4164(4), c = 27.7472(14) Å, β = 90.8520(10)°, V = 2065.43(18) Å^3, Z = 4, $\rho_{calcd.}$ = 1.925 Mg/m^3, μ = 6.749 mm^{-1}, $F(000)$ = 1168, crystal size = 0.40 × 0.30 × 0.20 mm^3, θ range = 1.47−27.52°; Index ranges: $-9 \le h \le 11$, $-9 \le k \le 10$, $-36 \le l \le 36$; reflections collected 14172, independent reflections 4750 [R(int) = 0.0911], completeness to θ = 27.52°, 99.9%; max/min transmission 1.000000/0.613727; data/restraints/parameters 4750/1/258; goodness-of-fit on F^2 1.068; final R indices [$I > 2\sigma(I)$]: R1 = 0.0286, wR2 = 0.0693; R indices (all data): R1 = 0.0308, wR2 = 0.0723; largest diff. peak/hole 1.805/−1.548 e·Å^{-3}.

Crystallographic data (excluding structure factors) for the structures reported in this paper have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication no. CCDC-297744 for **2b** and CCDC-297745 for **3b**. Copies of the data can be obtained free of charge on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK [fax.: (internat.) +44–1223/336–033; e-mail: deposit@ccdc.cam.ac.uk].

Conjugate Reduction of α,β-Unsaturated esters (Table 1, run 1)

To a mixture of the ester **6** (190 mg, 1.0 mmol) and the catalyst **4a** (5.4 mg, 0.01 mmol) in 2.0 mL of toluene was slowly added diethoxymethylsilane (201 mg, 1.5 mmol) at 50 °C. The mixture was stirred for 0.5 h and then treated with hydrochloric acid (1 N, 1 mL). After extraction with ethyl acetate and concentration, the residue was purified by silica gel column chromatography with ethyl acetate/hexane to give the product, ethyl (*R*)-3-phenylbutanoate (**7**) as a colorless oil; yield: 173 mg (0.90 mmol, 90 %). The *ee* was determined by chiral HPLC analysis [DAICEL CHRALCEL OB column, 0.5 mL min^{-1}, *i*-PrOH/hexane (1:99), R_t = 14.1 min (major), 16.8 min (minor)], 96 % *ee* for *R*. The NMR spectra were consistent with previously reported data; see ref.[1a]

Reductive Aldol Reaction (Table 2, run 1)

To a mixture of the rhodium complex **4a** (5.7 mg, 0.01 mmol) and benzaldehyde (106 mg, 1.0 mmol) in toluene (3.0 mL), *tert*-butyl acrylate (192 mg, 1.5 mmol) was added at 50 °C. Then, diethoxymethylsilane (215 mg, 1.6 mmol) was slowly added by a syringe. The mixture was stirred at 50 °C for 0.5 h. At 0 °C, the reaction was quenched by addition of aqueous HCl (4 N, 1 mL), MeOH (1 mL), and THF (1 mL). After stirring for 30 min, the mixture was extracted with ethyl acetate (3 × 5 mL). The combined organic layer was washed with aqueous $NaHCO_3$ (2 × 10 mL), and was dried over $MgSO_4$. After concentration, the residue was purified by silica gel column chromatography with hexane-ethyl acetate (20:1) as an eluent to give a mixture of the desired products **8*anti*** and **8*syn***; yield: 231 mg (0.98 mmol, 98 %). The *anti*:*syn* ratio was determined by ^{1}H NMR to be 95:5. The optical purity wad determined by HPLC analysis with DAICEL-CHIRALPAK AS-H (eluent: hexane/*i*-PrOH = 99:1, flow rate: 1.0 mL min^{-1}) to be 92 % *ee* (2*R*,3*S*) for *anti*; retention time: 8.9 min (*syn*, 2*R*,3*R*), 11.4 min (*anti*, 2*S*,3*R*), 13.4 min (*syn*, 2*S*,3*S*), 15.1 min (*anti*, 2*R*,3*S*). The NMR spectra were consistent with previously reported data; see Supporting Information of ref.[2]

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