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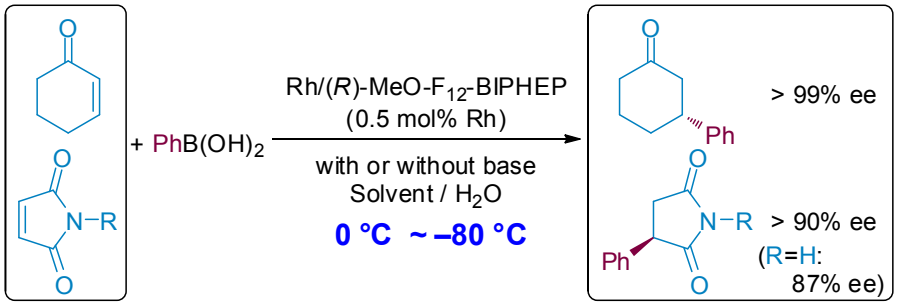


Abstract

Rhodium-catalyzed asymmetric 1,4-addition of arylboronic acids to α,β-unsaturated carbonyl compounds was achieved at temperatures below 0 °C using a

Rh/MeO-F_{12}-BIPHEP catalyst. The reaction of cyclohexenone or *N*-R maleimide with arylboronic acids proceeded even at −80 °C in the presence of the Rh catalyst. In the latter case, high enantioselectivity was observed because a low-temperature method was used, regardless of the type of substituent on maleimide.

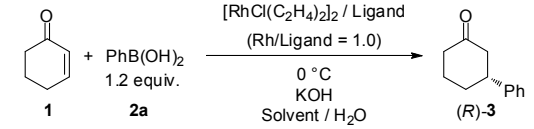
Rhodium-catalyzed asymmetric 1,4-addition of arylboronic acids to α,β-unsaturated carbonyl compounds is one of the most attractive catalytic reactions. Over 150 papers have been reported since 1998 on this reaction,[1,2] and that has been used for the asymmetric synthesis of several bio-active compounds.[3] Initially, the reaction was performed using 3 mol% of a Rh/BINAP catalyst at 100 °C.[1a] In 2003, a chiral diene ligand was reported as an excellent ligand[4] that made room temperature reactions possible. Since then, the reaction at room temperature has been reported using many rhodium catalysts ligated with chiral dienes, chiral sulfoxides, and chiral phosphoramidites.[5] On the other hand, we explored uniquely "highly electron-poor chiral diphosphine ligands",[6] and first demonstrated that they significantly accelerate reactions with Rh catalysts at room temperature and above. Although many types of

chiral Rh catalysts have been reported, including our catalysts, to our knowledge, Rh-catalyzed asymmetric 1,4-addition of arylboronic acid below 0 °C has not yet been attained.[7] This is quite a contrast to a Cu-catalyzed asymmetric 1,4-addition of dialkyl zinc, which was usually preformed below 0 °C.[8] In general, low-temperature conditions often improve the stereoselectivity of catalytic reactions, but at the same time, decrease the catalytic activity. To extend the range of applications of Rh-catalyzed asymmetric 1,4-additions, we, therefore, developed a catalyst that is active at 0 °C and below.

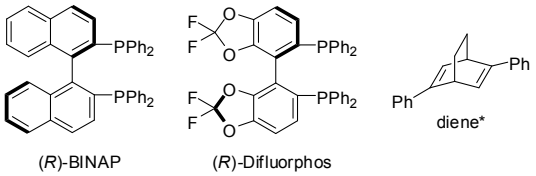
The asymmetric 1,4-additions of $PhB(OH)_2$ (**2a**) to cyclohexenone (**1**) at 0 °C was first evaluated to test the performance of different catalytic systems (Table 1). The reaction using 1.5 mol% $[RhCl(C_2H_4)_2]_2$ (3.0 mol% Rh) as the catalyst precursor and (*R*)-BINAP as the ligand (ligand/Rh = 1.0) in the presence of an aqueous KOH solution in toluene or 1,4-dioxane for 3 h gave no or minor amounts of the desired product (*R*)-**3** (entries 1, 2). The BINAP ligand was effective for this reaction in 1,4-dioxane at 35 °C.[9] Nonetheless, it is an ineffective ligand for low-temperature 1,4-addition. The use of electron-poor (*R*)-difluorphos[10] gave similar results (entries 3, 4). Although the reaction using Hayashi's chiral diene ((1*R*,4*R*)-2,5-diphenylbicyclo[2,2,2]octa-2,5-diene, diene*)[11] did not proceed in toluene (entry 5), the product was obtained in 1,4-dioxane

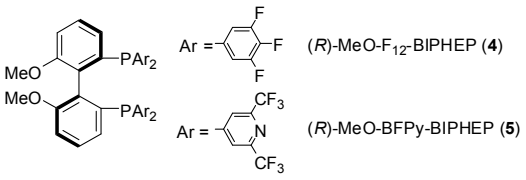
in good yield (80%) with high enantioselectivity (97% ee) for 1.5 h (entry 6). However, the reaction using 0.5 mol% Rh/diene* provided only 19% yield of (*R*)-**3** (entry 7). In contrast, highly electron-poor (*R*)-MeO-F_{12}-BIPHEP ((*R*)-**4**), which we previously developed,[6a,6b] significantly increased the activity of the rhodium catalyst in toluene at 0 °C. The reaction using the Rh catalyst (0.5 mol%) with (*R*)-**4** was completed in 1.5 h and afforded (*R*)-**3** with >99% ee. (entry 8). Although the more electron-poor (*R*)-MeO-BFPy-BIPHEP[6c] ((*R*)-**5**)-ligated Rh catalyst also showed high catalytic activity (entry 9, 75% yield), 14% yield of the 1,2-,1,4- adduct was simultaneously obtained as a side product.[12] The ligand screening thus highlighted that the (*R*)-**4** ligand is appropriate for low-temperature 1,4-addition.

Table 1 Asymmetric 1,4-addition of **2a** to **1** at 0 °C [a]



Ligand:





Entry	(*R*)-Ligand	Rh (%)	Solvent	Time (h)	Yield (%)	Ee (%)[b]
1	BINAP	3.0	Toluene	3	0	-
2	BINAP	3.0	Dioxane	3	5	99
3	Difluorphos	3.0	Toluene	3	0	-
4	Difluorphos	3.0	Dioxane	3	6	97
5	diene*	3.0	Toluene	3	0	-
6	diene*	3.0	Dioxane	1.5	80	97
7	diene*	0.5	Dioxane	1.5	19	97
8	**4**	0.5	Toluene	1.5	98	99.6
9	**5**	0.5	Toluene	1.5	75	96

[a] Reactions were carried out with **1** (0.52 mmol), **2a** (0.62 mmol), KOH (0.10 mmol) in the presence of Rh catalyst in solvent (0.35 mL) and H_2O (0.3 mL) at 0 °C. [b] Determined by HPLC analysis.

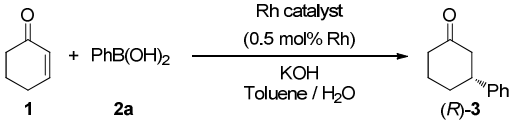
Next, the performance of the Rh/(*R*)-**4** catalyst for reactions below 0 °C was evaluated (Table 2). Not surprisingly, when the reaction was performed in the presence of 0.25 mol% of $[RhCl(C_2H_4)_2]_2$ and 0.5 mol% of (*R*)-**4** with KOH at −40 °C, a longer reaction time was required, with the desired product (*R*)-**3** obtained in 90% yield for 12 h using 2.0 equiv. of $PhB(OH)_2$ (entry 1). Notably, the reaction proceeded even at −80 °C to

give 85% yield of (*R*)-**3** for 24 h (entry 2). At −40 and −80 °C, the water layer turned into ice powder, which was roiled in toluene. Nevertheless, H_2O is crucial for this catalytic reaction. When the reaction was performed without H_2O using $[RhOH\{(R)\text{-}\mathbf{4}\}]_2$ as an active catalytic species,[9] only 17% of (*R*)-**3** was obtained at −40 °C (entry 3), suggesting that H_2O acts not only to convert $[RhCl\{(R)\text{-}\mathbf{4}\}]_2$ to $[RhOH\{(R)\text{-}\mathbf{4}\}]_2$ but also as a hydrolysis agent in the catalytic cycle.[9]

In general, the advantage of low-temperature reactions is the improvement of stereoselectivity. However, no improvement in enantioselectivity was observed when the reaction temperature was decreased (Table 2 entries 1, 2), because the ee at 20 °C (99.6% ee, Table 1 entry 4) had already reached the detection limits by HPLC analysis. The advantage of the low-temperature reaction was demonstrated in the reaction using $[RhOH(cod)]_2$ as the catalyst precursor. Although the reaction of $[RhOH(cod)]_2$ with chiral phosphine ligands readily proceeds to form the active species $[RhOH(phosphine)]_2$ without the addition of a base such as KOH,[9] use of this complex as a catalyst precursor *in situ* has been avoided except in a few cases.[7a,13] The liberated COD ligand, generated during ligand exchange, cannot be removed by distillation, and trace amounts of highly active $[RhOH(cod)]_2$[14] regenerated by equilibrium form racemic **3** to decrease enantioselectivity.[15] When the reaction of **1** with **2a** in toluene using 0.25

mol% $[RhOH(cod)]_2$ with 0.5 mol% (*R*)-**4** (0.5 mol% Rh, (*R*)-**4**/Rh = 1.0) at 20 °C was performed, the enantioselectivity of (*R*)-**3** was slightly decreased to 98.0% ee (entry 5). Under the same conditions without (*R*)-**4**, 17% racemic **3** was obtained using $[RhOH(cod)]_2$ (entry 6), suggesting that $[RhOH(cod)]_2$ reduced the enantioselectivity of the reaction with $[RhOH(cod)]_2$/(*R*)-**4** as the catalytic system. However, the catalytic activity of $[RhOH(cod)]_2$ was largely reduced at 0 °C and below compared with that at 20 °C (entries 8, 10, 12). Therefore, a decrease in the enantioselectivity of (*R*)-**3** using $[RhOH(cod)]_2$/(*R*)-**4** was not observed from 0 to −80 °C (entries 7, 9, 11).

Table 2 Asymmetric 1,4-addition at low temperature [a]



1 **2a** (*R*)-**3**

Entry	Rh catalyst	Temp (°C)	Time (h)	Yield (%)[a]	Ee (%)[b]
1[e]	$[RhCl(C_2H_4)_2]_2$/(*R*)-**4**	-40	12	90	99.6
2[f]	$[RhCl(C_2H_4)_2]_2$/(*R*)-**4**	-80	24	85	99.6
3[c,d,e]	$[RhOH\{(R)\text{-}4\}]_2$	-40	12	17	99.5
4[g]	$[RhCl(C_2H_4)_2]_2$/(*R*)-**4**	20	1	99	99.6
5[c,g]	$[RhOH(cod)]_2$/(*R*)-**4**	20	1	99	98.0
6[c,g]	$[RhOH(cod)]_2$	20	1	17	-
7[c,h]	$[RhOH(cod)]_2$/(*R*)-**4**	0	1.5	98	99.5
8[c,h]	$[RhOH(cod)]_2$	0	1.5	6	-
9[c,e]	$[RhOH(cod)]_2$/(*R*)-**4**	-40	12	87	99.7
10[c,e]	$[RhOH(cod)]_2$	-40	12	4	-
11[c,f]	$[RhOH(cod)]_2$/(*R*)-**4**	-80	24	84	99.6
12[c,f]	$[RhOH(cod)]_2$	-80	24	2	-

[a] Unless otherwise noted, reactions were carried out with **1** (0.52 mmol), **2a**, KOH (0.10 mmol) in the presence of rhodium complex (1.3 μmol) and (*R*)-**4** (2.6 μmol) in toluene (0.35 mL) and H_2O (0.3 mL). [b] Determined by HPLC analysis. [c] Without KOH. [d] Without H_2O. [e] 2.0 equiv. of **2a**. [f] 3.0 equiv. of **2a**. [g] 1.05 equiv. of **2a**. [h] 1.2 equiv. of **2a**.

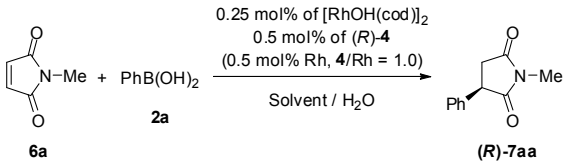
Next, we demonstrated an improvement in the enantioselectivity of asymmetric

1,4-addition to *N*-R maleimides using the Rh/(*R*)-**4** catalyst under low-temperature conditions. Asymmetric 1,4-addition of arylboronic acids to *N*-R maleimides has been reported by several researchers[16] because resulting products, i.e., chiral substituted succinimides, have potential as bioactive compounds.[17] The enantioselectivity of the reaction is significantly affected by the substituent (R group) on the nitrogen atom in the maleimide. A comparison of previously reported enantioselectivities for asymmetric 1,4-addition reactions using *N*-Me and *N*-Bn maleimides is presented in Figure S1 (see Supporting Information). It can be seen in the figure that no catalysts yielded more than 90% ee succinimides using both *N*-Me and *N*-Bn maleimides. Furthermore, the *N*-R maleimides were relatively less reactive substrates for the Rh-catalyzed 1,4-addition; thus, a comparatively large amount of catalyst and a high reaction temperature were required. In other words, performing low-temperature reactions using the known catalyst systems are very difficult.

The reaction of *N*-Me maleimide (**6a**) with **2a** was performed in the presence of the Rh/(*R*)-**4** catalyst (0.5 mol% Rh) at 30 °C for 1 h (Table 3). The complex $[RhOH(cod)]_2$ was used as the catalyst precursor because the complex without (*R*)-**4** showed slightly lower catalytic activity for the reaction of **6a** with **2a**, and the enantioselectivity using

the $[RhCl(C_2H_4)]_2$/(*R*)-**4** catalytic system with KOH was identical to that of $[RhOH(cod)]_2$/(*R*)-**4** (entries 2,3 vs. 1). In this reaction, it was found that the solvent influenced the enantioselectivity. Using Et_2O as the solvent afforded higher enantioselectivity (87% ee) of (*R*)-**7aa** compared with that obtained in toluene, 1,4-dioxane, CH_2Cl_2, and THF (entry 1 vs. 4–7). When the reaction temperature was decreased to 0 or −10 °C in Et_2O, the enantioselectivity of (*R*)-**7aa** was improved to 90% or 92% ee, respectively (entries 8 and 9). Improvement in the enantioselectivity at decreased reaction temperature is due to the common "low-temperature effect", because the $[RhOH(cod)]_2$ precursor complex has very little catalytic activity in this reaction, as mentioned above (entry 2). Although lowering the reaction temperature even further (−40 °C) did not improve the enantioselectivity (entry 10), over 90% ee could be achieved using only 0.5 mol% Rh/(*R*)-**4** catalyst.

Table 3 Asymmetric 1,4-addition of **2a** to *N*-Me-maleimide(**6a**) [a]



6a **2a** (***R***)-**7aa**

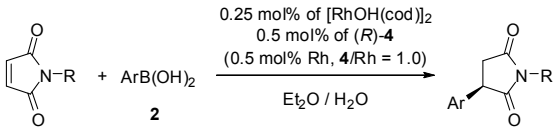
Entry	**2a** (equiv.)	Solvent	Temp (°C)	Time (h)	Yield (%)	Ee (%)[b]
1	2.0	Et_2O	30	1	99	87
2[c]	2.0	Et_2O	30	1	6	-
3[d]	2.0	Et_2O	30	1	98	87
4	2.0	Toluene	30	1	96	72
5	2.0	1,4-dioxane	30	1	98	78
6	2.0	CH_2Cl_2	30	1	86	69
7	2.0	THF	30	1	98	71
8	3.0	Et_2O	0	1	96	90
9	5.0	Et_2O	-10	3	94	92
10	5.0	Et_2O	-40	10	95	92

[a] Unless otherwise noted, reactions were carried out with **6a** (1.04 mmol), **2a** in the presence of $[RhOH(cod)]_2$ (2.6 μmol) and (*R*)-**4** (5.3 μmol) in solvent (2 mL) and H_2O (0.3 mL). [b] Determined by HPLC analysis. [c] Without (*R*)-**4**. [d] Using 0.25 mol% of $[RhCl(C_2H_4)_2]_2$ and 0.5 mol% of (*R*)-**4** with KOH.

To further explore the scope of the reaction, the asymmetric 1,4-addition of other arylboronic acids bearing electron-donating or -withdrawing substituents (**2**) to *N*-Me maleimide (**6a**) was performed at 0 °C or −10 °C (Table 4). Although the reaction of arylboronic acids required longer reaction times as compared with that of **2a**, the yields and enantioselectivities of product **7** were over 90%, even when only 0.5 mol% Rh/(*R*)-**4** was used (entries 1–8). Thus, it can be concluded that the low-temperature reaction using the Rh/(*R*)-**4** catalyst is effective for the 1,4-addition of arylboronic acids

to *N*-R maleimides. When the asymmetric 1,4-addition of **2a** to *N*-R maleimide (R = Bn (**6b**), Cy (**6c**), or Ph (**6d**)) was performed at −10 °C, the products **7ba–7da** were obtained in over 90% ee (entries 9–11). Notably, substrates **6c** and **6d** gave almost enantiomerically pure products.

Table 4 Asymmetric 1,4-addition of arylboronic acids (**2**) to *N*-R maleimide(**6**) [a]



Entry	**6** of R	**2** of Ar	Temp (°C)	Time (h)	Yield (%)	Ee (%)[b]
1[c]	Me (**a**)	2-F-C_6H_4 (**b**)	0	24	99 (**7ab**)	91 (-)
2[c]	Me (**a**)	2-MeO-C_6H_4 (**c**)	0	36	97 (**7ac**)	95 (-)
3[c]	Me (**a**)	3-F-C_6H_4 (**d**)	0	36	99 (**7ad**)	91 (*R*)
4[d]	Me (**a**)	3-Cl-C_6H_4 (**e**)	0	48	98 (**7ae**)	92 (*R*)
5[d]	Me (**a**)	3-MeO-C_6H_4 (**f**)	-10	24	96 (**7af**)	94 (*R*)
6[c]	Me (**a**)	3-Me-C_6H_4 (**g**)	-10	5	92 (**7ag**)	94 (*R*)
7[d]	Me (**a**)	3,5-$(CH_3)_2$-C_6H_3 (**h**)	0	48	98 (**7ah**)	94 (-)
8[d]	Me (**a**)	4-F-C_6H_4 (**i**)	0	48	98 (**7ai**)	95 (*R*)
9[e]	Bn (**b**)	Ph (**a**)	-10	3	95 (**7ba**)	95 (*R*)
10[f]	Cy (**c**)	Ph (**a**)	-10	5	96 (**7ca**)	99 (*R*)
11[c]	Ph (**d**)	Ph (**a**)	-10	4	95 (**7da**)	99 (*R*)
12[c]	H (**e**)	Ph (**a**)	-10	3	10 (**7ea**)	-
13[c]	H (**e**)	Ph (**a**)	-10	3	96 (**7ea**)	84 (*R*)
14[c]	H (**e**)	Ph (**a**)	-50	24	94 (**7ea**)	87 (*R*)
15[c]	H (**e**)	Ph (**a**)	-80	24	70 (**7ea**)	87 (*R*)

[a] Unless otherwise noted, reactions were carried out with **6** (1.04 mmol), **2** in the presence of $[RhOH(cod)]_2$ (2.6 μmol) and (*R*)-**4** (5.3 μmol) in diethyl ether (2 mL) and H_2O (0.3 mL). [b] Determined by HPLC analysis. [c] 5.0 equiv. of **2**. [d] 8.0 equiv. of **2**. [e] 3.0 equiv. of **2**. [f] 4.0 equiv. of **2**.

Finally, the asymmetric 1,4-additon of **2a** to *N*-H maleimide (**6e**) was performed. This substrate **6e** has been reported as being inactive for Rh-catalyzed asymmetric 1,4-additions.[16i] Although the reaction using the Rh/(*R*)-**4** catalyst (0.5 mol%) at −10 °C for 3 h gave only 10% yield of the desired product **7ea** (entry 12), the use of 3.0 mol%

catalyst afforded **7ea** in 96% yield with 84% ee (entry 13). When the reaction temperature was decreased to −50 °C, the enantioselectivity of **7ea** increased to 87% ee (entry 14); further improvement in the ee was not observed at −80 °C (entry 15). Although the enantioselectivity did not reach 90% ee, this result is the first successful example of Rh-catalyzed asymmetric 1,4-additon of arylboronic acid to *N*-H maleimide.[18]

In conclusion, we demonstrated the first example of Rh-catalyzed asymmetric 1,4-addition below 0 °C. The electron-poor (*R*)-**4** ligand highly activates Rh catalysts for asymmetric 1,4-additions, and the catalysts retain their activity at reaction temperatures as low as −80 °C for improving enantioselectivities. Thus, the Rh/(*R*)-**4** catalyst will be useful for the asymmetric synthesis of several bioactive compounds by asymmetric 1,4-addition reactions under low-temperature conditions.

Experimental Section

General information. All reactions were carried out under an argon atmosphere with dry solvents under anhydrous conditions, unless otherwise noted. All solvents were purchased as dehydrated grade and then were stored in Schlenk tubes under an argon

atmosphere. Chiral ligands, BINAP, difluorphos, and diene* were purchased and used without further purification. Reagents were purchased at the highest commercial quality and used without further purification, unless otherwise noted. Preparative column chromatography was carried out by using silica gel (BW-127 ZH, 100－270 mesh). ^{1}H NMR and ^{13}C NMR spectra were measured at 400 MHz and 101 MHz, respectively, and chemical shifts are given relative to tetramethylsilane (TMS). ^{19}F NMR spectra were measured at 376 MHz, and chemical shifts are given relative to CCl_3F using C_6F_6 as secondary reference (–162.9 ppm).

General procedure for the 1,4-addition of phenylboronic acid (2a) to 2-cyclohexen-1-one (1).

A 20 mL Schlenk flask was flushed with argon and charged with (*R*)-**4** (2.05 mg, 2.6 μmol), $[RhCl(C_2H_4)_2]_2$ (0.50 mg, 1.3 μmol), potassium hydroxide (5.6 mg, 0.10 mmol), deoxygenated 1,4-dioxane (0.3 mL) and deoxygenated water (0.1 mL). The mixture was stirred at room temperature for 15 minutes, and then the solvent was removed under reduced pressure. After addition of phenylboronic acid (**2a**) (76.0 mg, 0.62 mmol), 2-cyclohexen-1-one (**1**) (50 μL, 0.52 mmol), deoxygenated toluene (0.35 mL), and deoxygenated water (0.3 mL), the resulting mixture was stirred at 0 °C for 1.5 hours and

then sat. $NaHCO_3$ aq. was added. After extraction with ethyl acetate, the organic layer was dried over $MgSO_4$, filtrated with suction, and then concentrated under reduced pressure. The residue was purified by silica gel column chromatography (hexane/EtOAc = 5/1) to give (*R*)-3-phenylcyclohexanone (**3**)[9] as a colorless oil (88.7 mg, 98% yield, 99.6% ee). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.74 – 1.93 (m, 2H), 2.05 – 2.20 (m, 2H), 2.33 – 2.64 (m, 4H), 2.96 – 3.07 (m, 1H), 7.21 – 7.27 (m, 3H), 7.31 – 7.36 (m, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ = 25.4, 32.6, 41.0, 44.6, 48.8, 126.4, 126,5, 128.5, 144.2, 210.9. IR (neat): 3061, 3028, 2937, 2866, 1713, 1603, 1497, 1452, 1421, 1344, 1315, 1250, 1223, 1030, 756, 700, 538 cm^{-1}. $[\alpha]_D^{28.1}$ = +19.8 (*c* 1.0, $CHCl_3$). HPLC (Daicel Chiralcel OD-3, detected at 254 nm, hexane/2-propanol = 99/1, flow rate = 0.7 mL/min): t_R of (*S*)-**3**; 27.6 min. (0.2%), t_R of (*R*)-**3**; 29.8 min. (99.8%).

General procedure for the 1,4-addition of arylboronic acid (2) to maleimides (6)

Procedure for the 1,4-addition of phenylboronic acid (2a) to *N*-methylmaleimide (6a) to obtain (*R*)-1-methyl-3-phenyl-2,5-pyrrolidinedione (7aa).[16b]

A 20 mL Schlenk flask was flushed with argon and charged with (*R*)-**4** (4.2 mg, 5.3 μmol), $[RhOH(cod)]_2$ (1.2 mg, 2.6 μmol) and deoxygenated dichloromethane (0.5 mL). The mixture was stirred at room temperature for 10 minutes, and then the solvent was

removed under reduced pressure. After addition of phenylboronic acid (**2a**) (635 mg, 5.20 mmol), *N*-methylmaleimide (**6a**) (116 mg, 1.04 mmol), deoxygenated diethyl ether (2.0 mL), and deoxygenated water (0.3 mL), the resulting mixture was stirred at -10 °C for 3 hours. and then sat. $NaHCO_3$ aq. was added. After extraction with ethyl acetate, the organic layer was dried over $MgSO_4$, filtrated with suction, and then concentrated under reduced pressure. The residue was purified by silica gel column chromatography (hexane/acetone = 3/1) to give 184 mg of **7aa** (94% yield, 92% ee) as a white solid. M.p. = 72 – 73 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ 2.83 (dd, ^2J = 18.5 Hz, ^3J = 4.7 Hz, 1H), 3.07 (s, 3H), 3.11 (dd, ^2J = 18.5 Hz, ^3J = 9.6 Hz, 1H), 4.03 (dd, ^3J = 9.6 Hz and 4.7 Hz, 1H), 7.20 – 7.24 (m, 2H), 7.29 – 7.64 (m, 1H), 7.34 – 7.40 (m, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 25.3, 37.2, 46.1, 127.5, 128.1, 129.3, 137.2, 176.4, 177.9. IR (KBr): 3441, 3032, 2937, 1774, 1693, 1433, 1383, 1279, 1121, 951, 810, 752, 704, 648 cm^{-1}. $[\alpha]_D^{21.4}$ = -83.7 (*c* 1.01, $CHCl_3$) {lit[16b] $[\alpha]_D^{20}$ = +67.7 (*c* 1.08, $CHCl_3$) for (*S*)-enantiomer, 88% ee}. HPLC (Daicel Chiralcel AD-H, detected at 254 nm, hexane/2-propanol = 9/1, flow rate = 1.0 mL/min): t_R of (*R*)-**7aa**; 12.7 min. (96%), t_R of (*S*)-**7aa**; 15.2 min. (4%).

(-)-3-(2-Fluorophenyl)-1-methyl-2,5-pyrrolidinedione (7ab)

(-)-3-(2-Fluorophenyl)-1-methyl-2,5-pyrrolidinedione (**7ab**) was obtained from (*R*)-**4**

(0.53 mg, 0.66 μmol), $[RhOH(cod)]_2$ (0.15 mg, 0.33 μmol), *N*-methylmaleimide (**6a**) (14.4 mg, 0.13 mmol), 2-fluorophenylboronic acid (**2b**) (90.9 mg, 0.65 mmol), deoxygenated diethyl ether (0.4 mL), and deoxygenated water (0.1 mL) at 0 °C for 24 hours by the general procedure described above. White solid (26.4 mg, 99% yield, 91% ee). M.p. = 63 – 64 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ 2.77 (dd, ^2J = 18.4 Hz, ^3J = 5.3 Hz, 1H), 3.10 (s, 3H), 3.21 (dd, ^2J = 18.4 Hz, ^3J = 9.8 Hz, 1H), 4.12 (dd, ^3J = 9.8 Hz and 5.3 Hz, 1H), 7.06 – 7.17 (m, 2H), 7.19 – 7.25 (m, 1H), 7.28 – 7.35 (m, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 25.4, 36.8, 41.8, 116.2 (d, $^2J_{F\text{-}C}$ = 21.5 Hz), 124.8 (d, $^3J_{F\text{-}C}$ = 14.2 Hz), 126.8 (d, $^4J_{F\text{-}C}$ = 3.7 Hz), 130.1 (d, $^2J_{F\text{-}C}$ = 24.7 Hz), 130.2 (d, $^3J_{F\text{-}C}$ = 12.5 Hz), 160.9 (d, $^1J_{F\text{-}C}$ = 247 Hz), 176.0, 177.4 ^{19}F NMR (376 MHz, $CDCl_3$): -118.0 – -117.9 (m, 1F). IR (KBr): 3447, 3088, 2961, 2934, 1778, 1697, 1493, 1435, 1385, 1288, 1232, 1117, 1061, 953, 845, 762, 700, 638 cm^{-1}. $[\alpha]_D^{27.5}$ = -32.0 (*c* 1.04, $CHCl_3$). HPLC (Daicel Chiralcel AD-3, detected at 254 nm, hexane/2-propanol = 9/1, flow rate = 1.0 mL/min): t_R of (-)-**7ab**; 14.5 min. (95.5%), t_R of (+)-**7ab**; 17.8 min. (4.5%). Anal. calc. for $C_{11}H_{10}FNO_2$: C, 63.76; H, 4.86; N, 6.76. Found: C, 63.82; H, 4.64; N, 6.76.

(-)-3-(2-Methoxyphenyl)-1-methyl-2,5-pyrrolidinedione (7ac)

(-)-3-(2-Methoxyphenyl)-1-methyl-2,5-pyrrolidinedione (**7ac**) was obtained from (*R*)-**4**

(0.53 mg, 0.66 μmol), $[RhOH(cod)]_2$ (0.15 mg, 0.33 μmol), *N*-methylmaleimide (**6a**) (14.4 mg, 0.13 mmol), 2-methoxyphenylboronic acid (**2c**) (98.8 mg, 0.65 mmol), deoxygenated diethyl ether (0.4 mL), and deoxygenated water (0.1 mL) at 0 °C for 36 hours by the general procedure described above. White solid (27.6 mg, 97% yield, 95% ee). M.p. = 98 – 99 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ 2.75 (dd, ^2J = 18.2 Hz, ^3J = 5.1 Hz, 1H), 3.08 (s, 3H), 3.76 (dd, ^2J = 18.2 Hz, ^3J = 9.8 Hz, 1H), 3.75 (s, 3H), 3.94 (dd, ^3J = 9.8 Hz and 5.1 Hz, 1H), 6.82 – 6.89 (m, 1H), 6.92 – 6.97 (m, 1H), 7.16 – 7.19 (m, 1H), 7.27 – 7.33 (m, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 25.1, 36.5, 44.1, 55.6, 111.3, 121.1, 125.9, 129.6, 130.9, 157.0, 177.1, 178.9. IR (KBr): 3447, 3063, 2947, 2845, 1773, 1678, 1587, 1496, 1439, 1408, 1383, 1335, 1285, 1248, 1115, 1024, 951, 829, 802, 696, 644 cm^{-1}. $[\alpha]_D^{28.3}$ = -29.5 (*c* 1.11, $CHCl_3$). HPLC (Daicel Chiralcel AD-3, detected at 254 nm, hexane/2-propanol = 9/1, flow rate = 1.0 mL/min): t_R of (-)-**7ac**; 16.0 min. (97.5%), t_R of (+)-**7ac**; 19.7 min. (2.5%). Anal. calc. for $C_{12}H_{13}NO_3$: C, 65.74; H, 5.98; N, 6.39. Found: C, 65.90; H, 6.01; N, 6.32.

(*R*)-3-(3-Fluorophenyl)-1-methyl-2,5-pyrrolidinedione (7ad)[16i]

(*R*)-3-(3-Fluorophenyl)-1-methyl-2,5-pyrrolidinedione (**7ad**) was obtained from (*R*)-**4** (0.53 mg, 0.66 μmol), $[RhOH(cod)]_2$ (0.15 mg, 0.33 μmol), *N*-methylmaleimide (**6a**)

(14.4 mg, 0.13 mmol), 3-fluorophenylboronic acid (**2d**) (90.9 mg, 0.65 mmol), deoxygenated diethyl ether (0.4 mL), and deoxygenated water (0.1 mL) at 0 °C for 36 hours by the general procedure described above. White solid (26.4 mg, 99% yield, 91% ee). M.p. = 78 – 79 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ 2.82 (dd, ^{2}J = 18.4 Hz, ^{3}J = 4.9 Hz, 1H), 3.08 (s, 3H), 3.23 (dd, ^{2}J = 18.4 Hz, ^{3}J = 9.6 Hz, 1H), 4.04 (dd, ^{3}J = 9.6 Hz and 4.9 Hz, 1H), 6.94 – 6.98 (m, 1H), 6.98 – 7.06 (m, 2H), 7.31 – 7.38 (m, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 25.4, 37.0, 45.7 (d, $^{4}J_{F\text{-}C}$ = 1.5 Hz), 114.8 (d, $^{2}J_{F\text{-}C}$ = 22.4 Hz), 115.2 (d, $^{2}J_{F\text{-}C}$ = 21.7 Hz), 123.2 (d, $^{4}J_{F\text{-}C}$ = 3.0 Hz), 130.9 (d, $^{3}J_{F\text{-}C}$ = 8.22 Hz), 139.4 (d, $^{3}J_{F\text{-}C}$ = 7.5 Hz), 163.2 (d, $^{1}J_{F\text{-}C}$ = 248 Hz), 175.9, 177.3. ^{19}F NMR (376 MHz, $CDCl_3$): -112.8 – -112.7 (m, 1F). IR (KBr): 3441, 3076, 3020, 2939, 1776, 1678, 1614, 1589, 1487, 1437, 1376, 1362, 1140, 1119, 1049, 957, 901, 881, 878, 752, 696, 640 cm^{-1}. $[\alpha]_D^{24.8}$ = -62.2 (*c* 1.02, $CHCl_3$) {lit[16i] $[\alpha]_D^{25}$ = -57.1 (*c* 0.98, $CHCl_3$) for 89% ee}. HPLC (Daicel Chiralcel AD-3, detected at 254 nm, hexane/2-propanol = 9/1, flow rate = 0.7 mL/min): t_R of (*R*)-**7ad**; 22.0 min. (96%), t_R of (*S*)-**7ad**; 24.9 min. (4%).

(*R*)-3-(3-Chlorophenyl)-1-methyl-2,5-pyrrolidinedione (7ae)[16i]

(*R*)-3-(3-Chlorophenyl)-1-methyl-2,5-pyrrolidinedione (**7ae**) was obtained from (*R*)-**4** (0.53 mg, 0.66 μmol), $[RhOH(cod)]_2$ (0.15 mg, 0.33 μmol), *N*-methylmaleimide (**6a**)

(14.4 mg, 0.13 mmol), 3-chlorophenylboronic acid (**2e**) (163 mg, 1.04 mmol), deoxygenated diethyl ether (0.4 mL), and deoxygenated water (0.1 mL) at 0 °C for 48 hours by the general procedure described above. White solid (28.5 mg, 98% yield, 92% ee). M.p. = 89 – 90 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ 2.81 (dd, ^{2}J = 18.4 Hz, ^{3}J = 4.9 Hz, 1H), 3.08 (s, 3H), 3.22 (dd, ^{2}J = 18.4 Hz, ^{3}J = 9.6 Hz, 1H), 4.01 (dd, ^{3}J = 9.6 Hz and 4.9 Hz, 1H), 7.10 – 7.15 (m, 1H), 7.22 – 7.24 (m, 1H), 7.28 – 7.34 (m, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 25.4, 37.0, 45.6, 125.8, 127.8, 128.4, 130.6, 135.1, 139.0, 175.8, 177.2. IR (KBr): 3452, 3057, 2982, 2945, 1780, 1690, 1497, 1574, 1479, 1414, 1385, 1288, 1227, 1196, 1119, 1063, 1040, 959, 893, 804, 785, 687, 646, 631 cm^{-1}. $[\alpha]_D^{26.6}$ = -61.6 (*c* 1.04, $CHCl_3$) {lit[16i] $[\alpha]_D^{25}$ = -54.1 (*c* 1.09, $CHCl_3$) for 87% ee}. HPLC (Daicel Chiralcel AD-3, detected at 254 nm, hexane/2-propanol = 7/3, flow rate = 0.4 mL/min): t_R of (*S*)-**7ae**; 18.7 min. (96%), t_R of (*R*)-**7ae**; 20.2 min. (4%).

(*R*)-3-(3-Methoxyphenyl)-1-methyl-2,5-pyrrolidinedione (7af)[16i]

(*R*)-3-(3-Methoxyphenyl)-1-methyl-2,5-pyrrolidinedione (**7af**) was obtained from (*R*)-**4** (1.4 mg, 1.8 μmol), $[RhOH(cod)]_2$ (0.40 mg, 0.88 μmol), *N*-methylmaleimide (**6a**) (38.9 mg, 0.35 mmol), 3-methoxyphenylboronic acid (**2f**) (425 mg, 2.8 mmol), deoxygenated diethyl ether (0.7 mL), and deoxygenated water (0.1 mL) at -10 °C for 24 hours by the

general procedure described above. White solid (73.7 mg, 96% yield, 94% ee). M.p. = 75 – 76 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ 2.35 (s, 3H), 2.82 (dd, ^2J = 18.6 Hz, ^3J = 4.7 Hz, 1H), 3.08 (s, 3H), 3.20 (dd, ^2J = 18.6 Hz, ^3J = 9.6 Hz, 1H), 3.98 (dd, ^3J = 9.6 Hz and 4.7 Hz, 1H), 6.75 – 6.81 (m, 1H), 6.83 – 6.87 (m, 1H), 7.26 – 7.31 (m, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 25.4, 37.2, 46.1, 55.4, 113.2, 113.7, 119.6, 130.4, 138.7, 160.2, 176.4, 177.8. IR (KBr): 3443, 3063, 2947, 2839, 1776, 1678, 1597, 1494, 1435, 1383, 1325, 1252, 1176, 1121, 1065, 1036, 953, 889, 862, 878, 750, 633 cm^{-1}. $[\alpha]_D^{28.0}$ = -83.1 (*c* 1.06, $CHCl_3$) {lit[3] $[\alpha]_D^{25}$ = -47.7 (*c* 0.65, $CHCl_3$) for 90% ee}. HPLC (Daicel Chiralcel IA, detected at 254 nm, hexane/2-propanol, flow rate = 1.0 mL/min): t_R of (*S*)-**7af**; 26.1 min. (2.4%), t_R of (*R*)-**7af**; 29.3 min. (97.6%).

(*R*)-1-Methyl-3-(3-methylphenyl)- 2,5-pyrrolidinedione (7ag)[16i]

(*R*)-1-Methyl-3-(3-methylphenyl)- 2,5-pyrrolidinedione (**7ag**) was obtained from (*R*)-**4** (2.1 mg, 2.6 μmol), $[RhOH(cod)]_2$ (0.60 mg, 1.3 μmol), *N*-methylmaleimide (**6a**) (57.8 mg, 0.52 mmol), 3-methylphenylboronic acid (**2g**) (353 mg, 2.6 mmol), deoxygenated diethyl ether (1.0 mL), and deoxygenated water (0.15 mL) at -10 °C for 5 hours by the general procedure described above. White solid (97.2 mg, 92% yield, 94% ee). M.p. = 93 – 94 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ 2.35 (s, 3H), 2.82 (dd, ^2J = 18.6 Hz, ^3J = 4.7

Hz, 1H), 3.08 (s, 3H), 3.20 (dd, ^{2}J = 18.6 Hz, ^{3}J = 9.6 Hz, 1H), 3.98 (dd, ^{3}J = 9.6 Hz and 4.7 Hz, 1H), 6.95 – 7.02 (m, 2H), 7.11 – 7.14 (m, 1H), 7.23 – 7.28 (m, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 21.5, 25.4, 46.1, 124.5, 128.2, 128.9, 129.2, 137.2, 139.1, 176.5, 178.1. IR (KBr): 3443, 2949, 1776, 1682, 1493, 1433, 1387, 1288, 1121, 1061, 953, 818, 779, 752, 692, 650 cm^{-1}. $[\alpha]_D^{25.0}$ = -67.3 (*c* 1.02, $CHCl_3$) {lit[16i] $[\alpha]_D^{25}$ = -62.3 (*c* 1.06, $CHCl_3$) for 91% ee}. HPLC (Daicel Chiralcel AD-H, detected at 254 nm, hexane/2-propanol = 9/1, flow rate = 0.7 mL/min): t_R of (*R*)-**7ag**; 17.1 min. (97%), t_R of (*S*)-**7ag**; 20.0 min. (3%).

(-)-3-(3,5-Dimethylphenyl)-1-methyl-2,5-pyrrolidinedione (7ah)

(-)-3-(3,5-Dimethylphenyl)-1-methyl-2,5-pyrrolidinedione (**7ah**) was obtained from (*R*)-**4** (0.53 mg, 0.66 μmol), $[RhOH(cod)]_2$ (0.15 mg, 0.33 μmol), *N*-methylmaleimide (**6a**) (14.4 mg, 0.13 mmol), 3,5-dimethylphenylboronic acid (**2h**) (156 mg, 1.04 mmol), deoxygenated diethyl ether (0.4 mL), and deoxygenated water (0.1 mL) at 0 °C for 48 hours by the general procedure described above. White solid (27.7 mg, 98% yield, 94% ee). M.p. = 100 – 102 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ 2.30 (s, 6H), 2.81 (dd, ^{2}J = 18.4 Hz, ^{3}J = 4.5 Hz, 1H), 3.08 (s, 3H), 3.18 (dd, ^{2}J = 18.4 Hz, ^{3}J = 9.6 Hz, 1H), 3.94 (dd, ^{3}J = 9.6 Hz and 4.5 Hz, 1H), 6.79 – 6.81 (m, 2H), 6.93 – 6.95 (m, 1H). ^{13}C NMR

(100 MHz, $CDCl_3$): δ 21.4, 25.4, 37.5, 46.1, 125.3, 129.8, 137.2, 139.0, 176.6, 178.2. IR (KBr): 2936, 2854, 1767, 1697, 1452, 1393, 1375, 1340, 1144, 750, 702, 652 cm^{-1}. $[\alpha]_D^{26.4}$ = -109.6 (*c* 0.68, $CHCl_3$). HPLC (Daicel Chiralcel AD-3, detected at 254 nm, hexane/2-propanol = 9/1, flow rate = 0.7 mL/min): t_R of (-)-**7ah**; 13.9 min. (97%), t_R of (+)-**7ah**; 16.0 min. (3%). Anal. calc. for $C_{13}H_{15}NO_2$: C, 71.87; H, 6.96; N, 6.45. Found: C, 72.01; H, 6.91; N, 6.36.

(*R*)-3-(4-Fluorophenyl)-1-methyl-2,5-pyrrolidinedione (7ai)[16i]

(*R*)-3-(4-Fluorophenyl)-1-methyl-2,5-pyrrolidinedione (**7ai**) was obtained from (*R*)-**4** (1.4 mg, 1.8 μmol), $[RhOH(cod)]_2$ (0.40 mg, 0.88 μmol), *N*-methylmaleimide (**6a**) (38.9 mg, 0.35 mmol), 4-fluorophenylboronic acid (**2i**) (392 mg, 2.80 mmol), deoxygenated diethyl ether (0.7 mL), and deoxygenated water (0.15 mL) at 0 °C for 48 hours by the general procedure described above. White solid (71.1 mg, 98% yield, 95% ee). M.p. = 100 – 101 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ .2.79 (dd, ^2J = 18.4 Hz, ^3J = 4.8 Hz, 1H), 3.09 (s, 3H), 3.21 (dd, ^2J = 18.4 Hz, ^3J = 9.6 Hz, 1H), 4.10 (dd, ^3J = 9.6 Hz and 4.8 Hz, 1H), 6.95 – 7.10 (m, 2H), 7.17 – 7.24 (m, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 25.4, 37.2, 45.3, 116.3 (d, $^2J_{F\text{-}C}$ = 21.2 Hz), 129.2 (d, $^3J_{F\text{-}C}$ = 8.2 Hz), 132.8 (d, $^4J_{F\text{-}C}$ = 3.8 Hz), 162.5 (d, $^1J_{F\text{-}C}$ = 248 Hz), 176.1, 177.7. ^{19}F NMR (376 MHz, $CDCl_3$): -121.0 – -120.6

(m, 1F). IR (KBr): 3442, 3068, 2955, 1776, 1693, 1601, 1514, 1437, 1404, 1352, 1288, 1221, 1155, 1123, 947, 854, 833, 692, 527 cm^{-1}. $[\alpha]_D^{26.6}$ = -65.1 (*c* 1.01, $CHCl_3$) {lit[16i] $[\alpha]_D^{25}$ = -57.8 (*c* 0.94, $CHCl_3$) for 87% ee}. HPLC (Daicel Chiralcel AD-3, detected at 254 nm, hexane/2-propanol = 9/1, flow rate = 1.0 mL/min): t_R of (*R*)-**7ai**; 14.8 min. (97.4%), t_R of (*S*)-**7ai**; 19.9 min. (2.6%).

(*R*)-1-Benzyl-3-phenyl-2,5-pyrrolidinedione (7ba)[16a]

(*R*)-1-Benzyl-3-phenyl-2,5-pyrrolidinedione (**7ba**) was obtained from (*R*)-**4** (4.2 mg, 5.3 μmol), $[RhOH(cod)]_2$ (1.2 mg, 2.6 μmol), *N*-benzylmaleimide (**6b**) (195 mg, 1.04 mmol), phenylboronic acid (**2a**) (380 mg, 3.12 mmol), deoxygenated diethyl ether (2.0 mL), and deoxygenated water (0.3 mL) at -10 °C for 3 hours by the general procedure described above. White solid (262 mg, 95% yield, 95% ee). M.p. = 59 – 60 °C. ^1H NMR (400 MHz, $CDCl_3$): δ 2.80 (dd, ^2J = 18.6 Hz, ^3J = 4.9 Hz, 1H), 3.18 (dd, ^2J = 18.6 Hz, ^3J = 9.6 Hz, 1H), 4.03 (dd, ^3J = 9.6 Hz and 4.9 Hz, 1H), 4.68 (d, ^2J = 14.1 Hz, 1H), 4.74 (d, ^2J = 14.1 Hz, 1H), 7.15 (d, ^3J = 7.2 Hz, 2H), 7.24 – 7.37 (m, 6H), 7.40 (d, ^3J = 7.2 Hz, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 37.3, 42.8, 46.0, 127.5, 128.0, 128.1, 128.8, 128.9, 129.3, 135.9, 137.3, 175.9, 177.5. IR (KBr): 3442, 3061, 3030, 2918, 1773, 1709, 1499, 1429, 1404, 1340, 1165, 932, 698, 646 cm^{-1}. $[\alpha]_D^{22.4}$ = -48.6 (*c* 1.06,

$CHCl_3$) {lit[16a] $[\alpha]_D^{20}$ = -33.7 (*c* 1.20, $CHCl_3$) for 88% ee}. HPLC (Daicel Chiralcel OD-H, detected at 254 nm, hexane/2-propanol = 9/1, flow rate = 1.0 mL/min): t_R of (*S*)-**7ba**; 23.3 min. (2.3%), t_R of (*R*)-**7ba**; 28.3 min. (97.7%).

(*R*)-1-Cyclohexyl-3-phenyl-2,5-pyrrolidinedione (7ca)[16a]

(*R*)-1-Cyclohexyl-3-phenyl-2,5-pyrrolidinedione (**7ca**) was obtained from (*R*)-**4** (4.2 mg, 5.3 μmol), $[RhOH(cod)]_2$ (1.2 mg, 2.6 μmol), *N*-cyclohexylmaleimide (**6c**) (186 mg, 1.04 mmol), phenylboronic acid (**2a**) (507 mg, 4.16 mmol), deoxygenated diethyl ether (2.0 mL), and deoxygenated water (0.3 mL) at -10 °C for 5 hours by the general procedure described above. White solid (260 mg, 96% yield, >99% ee). M.p. = 83 – 84 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.18 – 1.39 (m, 3H), 1.60 – 1.69 (m, 3H), 1.80 – 1.87 (m, 2H), 2.12 – 2.26 (m, 2H), 2.74 (dd, ^2J = 18.4 Hz, ^3J = 4.5 Hz, 1H), 3.13 (dd, ^2J = 18.4 Hz, ^3J = 9.6 Hz, 1H), 3.93 (dd, ^3J = 9.6 Hz and 4.5 Hz, 1H), 4.04 (tt, ^3J = 12.3 Hz and 3.9 Hz, 1H), 7.19 (d, ^3J = 7.2 Hz, 2H), 7.27 – 7.32 (m, 1H), 7.36 (t, ^3J = 7.2 Hz, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 25.1, 25.91, 25.93, 29.0, 37.2, 45.7, 52.1, 127.3, 127.9, 129.3, 137.9, 176.5, 177.9. IR (KBr): 3443, 2936, 2854, 1767, 1697, 1452, 1393, 1375, 1340, 1144, 750, 702, 652 cm^{-1}. $[\alpha]_D^{23.1}$ = -38.2 (*c* 1.01, $CHCl_3$) {lit[16a] $[\alpha]_D^{20}$ = -34.0 (*c* 0.82, $CHCl_3$) for 87% ee}. HPLC (Daicel Chiralcel OD-H, detected at 254 nm,

hexane/2-propanol = 9/1, flow rate = 1.0 mL/min): t_R of (*S*)-**7ca**; 13.5 min. (0%), t_R of (*R*)-**7ca**; 16.0 min. (100%).

(*R*)-1-Phenyl-3-phenyl-2,5-pyrrolidinedione (7da)[16b]

(*R*)-1-Phenyl-3-phenyl-2,5-pyrrolidinedione (**7da**) was obtained from (*R*)-**4** (4.2 mg, 5.3 μmol), $[RhOH(cod)]_2$ (1.2 mg, 2.6 μmol), *N*-cyclohexylmaleimide (**7d**) (180 mg, 1.04 mmol), phenylboronic acid (**2a**) (635 mg, 5.20 mmol), deoxygenated diethyl ether (2.0 mL), and deoxygenated water (0.3 mL) at -10 °C for 4 hours by the general procedure described above. White solid (248 mg, 95% yield, >99% ee). M.p. = 137 – 138 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ 2.98 (dd, ^2J = 18.6 Hz, ^3J = 4.7 Hz, 1H), 3.35 (dd, ^2J = 18.6 Hz, ^3J = 9.6 Hz, 1H), 4.17 (dd, ^3J = 9.6 Hz and 4.7 Hz, 1H), 7.27 – 7.50 (m, 10H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 37.4, 46.1, 126.6, 127.5, 128.2, 128.8, 129.3, 129.4, 132.0, 137.3, 175.3, 176.8. IR(KBr): 3442, 3057, 3028, 2941, 1776, 1705, 1499, 1456, 1387, 1178, 795, 758, 702 cm^{-1}. $[\alpha]_D^{23.5}$ = -12.5 (*c* 1.02, $CHCl_3$) {lit[16b] $[\alpha]_D^{20}$ = +10.6 (*c* 1.03, $CHCl_3$) for (*S*)-enantiomer, 90% ee}. HPLC (Daicel Chiralcel OD-H, detected at 254 nm, hexane/2-propanol = 9/1, flow rate = 1.0 mL/min): t_R of (*S*)-**7da**; 47.8 min. (0%), t_R of (*R*)-**7da**; 55.8 min. (100%).

(*R*)-3-Phenyl-2,5-pyrrolidinedione (7ea)[16b]

(*R*)-3-Phenyl-2,5-pyrrolidinedione (**7ea**) was obtained from (*R*)-**4** (5.3 mg, 6.6 μmol), $[RhOH(cod)]_2$ (1.5 mg, 3.3 μmol), maleimide (**6e**) (21.3 mg, 0.219 mmol), phenylboronic acid (**2a**) (134 mg, 1.10 mmol), deoxygenated diethyl ether (0.3 mL), and deoxygenated water (0.1 mL) at -50 °C for 24 hours by the general procedure described above. White solid (34.8 mg, 91% yield, 87% ee). M.p. = 88 – 89 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ 2.89 (dd, ^2J = 18.6 Hz, ^3J = 4.9 Hz, 1H), 3.26 (dd, ^2J = 18.6 Hz, ^3J = 9.6 Hz, 1H), 4.10 (dd, ^3J = 9.6 Hz and 4.9 Hz, 1H), 7.24 – 7.40 (m, 5H), 8.30 (br s, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 38.4, 47.5, 127.5, 128.3, 129.4, 136.7, 176.1, 177.9. IR(KBr): 3442, 3057, 3028, 2941, 1776, 1705, 1499, 1456, 1387, 1178, 795, 758, 702 cm^{-1}. $[\alpha]_D^{23.5}$ = -69.9 (*c* 1.00, EtOH) {lit[16b] $[\alpha]_D^{20}$ = +77.3 (*c* 0.84, EtOH) for (*S*)-enantiomer, 93% ee}. HPLC (Daicel Chiralcel OJ-H, detected at 254 nm, hexane/2-propanol = 2/1, flow rate = 0.6 mL/min): t_R of (*R*)-**7ea**; 38.8 min. (93.6%), t_R of (*S*)-**7ea**; 53.6 min. (6.4%).

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Supporting Information

Copies of ^{1}H NMR, ^{13}C NMR and HPLC data for all products. This material is available free of charge via the Internet at http://pubs.acs.org.

References and Footnotes

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