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Chiral Rhodium(III) Complex-Catalyzed Cascade Michael-Alkylation Reactions: Enantioselective Synthesis of Cyclopropanes

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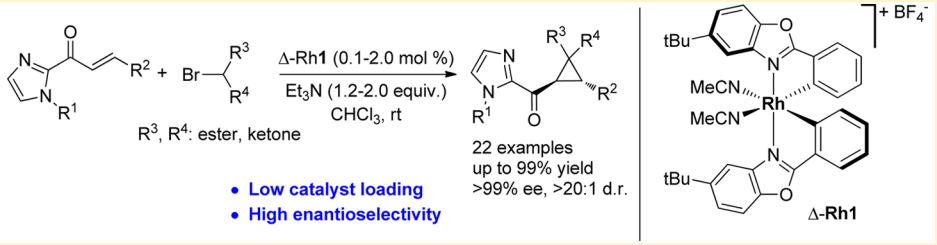
Supporting Information



ABSTRACT: Chiral Rh(III) complex catalyzed highly efficient enantioselective cyclopropanation of α,β-unsaturated 2-acyl imidazoles or pyridine with 2-bromomalonate is developed to generate corresponding multisubstituted cyclopropanes in 70−99% yields with 93→99% enantioselectivity. The proficiency of the process is also demonstrated in gram scale reaction maintaining same reactivity and selectivity level in lower catalyst loading. Moreover, the developed methodology is applicable in challenging synthesis of biscyclopropane scaffold with 97% ee in a single operation.

The cyclopropane moieties are one of the ubiquitous subunit in a diverse range of natural products and bioactive compounds.[1] Additionally, due to their unique combination of rigidness with inherent electrophilic reactivity, cyclopropane rings can serve as key intermediates for many useful synthetic transformations, such as ring-opening, cycloaddition, and rearrangement reactions.[2] Therefore, over the past few decades a considerable attention has been devoted toward the construction of enantiomerically enriched substituted cyclopropanes.[3] The enantioselective Simmons−Smith reaction[3f,4] and organometallic catalysis[5] have been intensively investigated with relatively electron-rich olefinic substrates for the synthesis of optically active cyclopropanes. Complimentarily, the catalytic asymmetric Michael-initiated ring-closure (MIRC) reaction[6] has been recognized as an attractive approach for cyclopropanation of electron-deficient alkenes with ylides[7,8] or alkyl halides.[9,10] Organocatalysts were proven as a powerful catalytic system for such transformation in terms of diastereo- and enantioselectivity, but limited with relatively large catalyst loading (usually 10−20 mol%), long reaction time, and narrow substrate scope. However, as compared to the widely used organocatalysts, employment of chiral Lewis acid catalyst for catalytic asymmetric MIRC reaction on electron-deficient alkenes system is limited.[8a,10] This was probably due to the coordination of Michael donor (malonates or β-keto esters) to a chiral complex in a bidentate chelating manner, which resulted in either difficulty in controlling the facial selectivity of the Michael acceptor or deactivation of Lewis acid center by formation of stable coordinate complex. To address these formidable challenges, development of an efficient and selective chiral Lewis acid complex for enantioselective cyclopropanation is highly desirable. Herein, we report a catalytic asymmetric cyclopropanation of α,β-unsaturated 2-acyl imidazoles with 2-bromomalonates promoted by chiral Rh(III) complex.[11]

The initial experiment was performed with α,β-unsaturated 2-acyl imidazole **1a** and diethyl 2-bromomalonate **2a** in the presence of chiral Lewis acid **Δ-Rh1** (2.0 mol%) as catalyst and Et_3N (2.0 equiv) as acid scavenger in 1,2-dichloroethane (DCE) at room temperature (Table 1). To our delight, the reaction was completed within 2 h to give cyclopropanation product **3a** as the single product in 99% yield with >20:1 dr and 96% ee (entry 1). A brief survey of chiral Lewis acids revealed that the activity of Rh(III) complex is superior to its isostructural iridium congener, which might be due to the weaker *N*-metal coordinate bond of acetonitrile ligand in **Δ-Rh1** compared to **Δ-Ir1**, and consequently faster ligand exchange kinetic which permits higher turnover frequency and turnover number (entry 1−3).[11a] This hypothesis was indirectly evidenced by the next round of catalysts investigation. **Δ-Rh2** or **Δ-Rh3** with electron-withdrawing group (CF_3) on R^1 or R^2 position (Figure 1) has stronger MeCN-Rh bond than **Δ-Rh1**, which caused dramatically decrease in reaction rate (entries 5 and 6) (for a single-crystal structure of **Δ-Rh2**, see the Supporting Information). Screening of various solvents showed that reactions performed in less polar halogenated solvents, such as DCE and $CHCl_3$, gave better results in terms of reaction rate and enantioselectivity (entries 7−9). Whereas,

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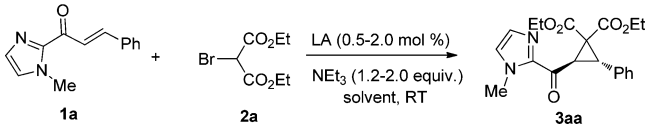
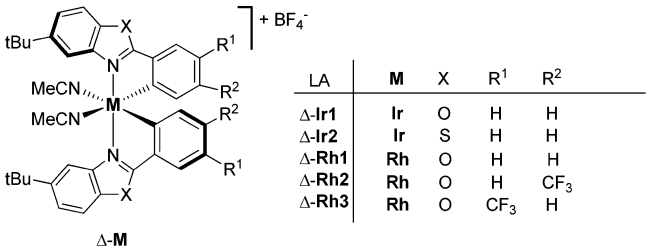
Table 1. Optimization of the Reaction Conditions[a]



entry	LA (mol%)	solvent	t (h)	yield (%)[b]	ee (%)[c]	d.r.[d]
1	Δ-**Rh1**	DCE	2	99	96	> 20:1
2	Δ-**Ir1**	DCE	24	n.r.		
3	Δ-**Ir2**	DCE	24	n.r.		
4		DCE	48	n.r.		
5	Δ-**Rh2**	DCE	48	46	95	> 20:1
6	Δ-**Rh3**	DCE	48	94	90	> 20:1
7	Δ-**Rh1**	Toluene	35	99	87	> 20:1
8	Δ-**Rh1**	THF	40	99	90	> 20:1
9	Δ-**Rh1**	$CHCl_3$	2	99	97	> 20:1
10[e]	Δ-**Rh1**	$CHCl_3$	3	99	> 99	> 20:1
11[f]	Δ-**Rh1**	$CHCl_3$	34	96	98	> 20:1
12[e,f,g]	Δ-**Rh1**	$CHCl_3$	4	99	> 99	> 20:1

[a]Reaction conditions: **1a** (0.3 mmol), **2a** (0.6 mmol), LA (2 mol%), Et_3N (0.6 mmol), solvent (0.6 mL). [b]Isolated yields. [c]Determined by chiral HPLC analysis. [d]Determined by ^1H NMR analysis of the crude reaction mixture. [e]0.5 mol% of Δ-**Rh1**. [f]1.2 equiv of **2a**, 1.2 equiv of Et_3N. [g]**1a** (1.0 M).



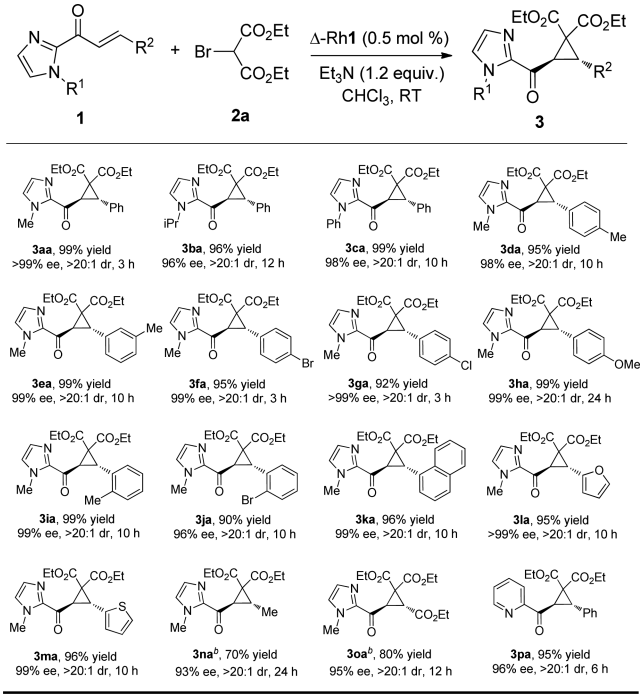
LA	M	X	R^1	R^2
Δ-**Ir1**	Ir	O	H	H
Δ-**Ir2**	Ir	S	H	H
Δ-**Rh1**	Rh	O	H	H
Δ-**Rh2**	Rh	O	H	CF_3
Δ-**Rh3**	Rh	O	CF_3	H

Figure 1. Chiral Lewis acid complexes investigated for enantioselective cyclopropanation reaction.

among different bases screened, Et_3N was found to be the optimal one (for details, see the Supporting Information).[12] Further decreasing the catalyst loading to 0.5 mol% under similar reaction condition still afforded **3aa** in high yield and excellent enantioselectivity within 3 h (99% yield, > 99% ee, entry 10). Nevertheless, lowering of diethyl 2-bromomalonate **2a** and Et_3N loading to 1.2 equiv resulted in longer reaction time (34 h) (entry 11). However, increased concentration of **1a** to 1.0 mol/L revealed the completion of reaction within 4 h with 99% yield and ee >99% (entry 12).

With the optimized reaction conditions in hand (Table 1, entry 12), we further investigated the generality of MIRC process using a variety of *α,β*-unsaturated 2-acyl imidazoles **1** and diethyl *α*-bromomalonate **2a** (Table 2). The bulkiness of the substituents at the imidazole (R^1) ring did not have any influence on enantioselectivity and yields as evidenced by the fact that sterically hindered isopropyl and phenyl group (**1b** and **1c**) containing imidazoles also gave quantitative yields of corresponding cyclopropanes (**3ba** and **3ca**) with 96% and 98% ee, respectively. The *α,β*-unsaturated 2-acyl imidazoles **1d**−**1h** bearing aromatic residues with different substitution patterns and electronic properties were well tolerated in this reaction condition resulting the corresponding cyclopropanation products in 90−99% yields with excellent enantioselectivity [electron neutral (**1d**, **1e**), withdrawing (**1f**, **1g**), donating (**1h**)]. Nevertheless, electron donor substituted *α,β*-unsaturated

Table 2. Enantioselective Cyclopropanation of *α,β*-Unsaturated 2-Acyl Imidazoles 1 with Diethyl *α*-Bromomalonate 2a Catalyzed by Δ-Rh1[a]



[a]Reaction conditions: **1a** (0.3 mmol), **2a** (0.36 mmol), Δ-**Rh1** (0.5 mol%), NEt_3 (0.36 mmol), $CHCl_3$ (0.3 mL), all yields were of isolated products based on **1**. Enantiomeric excess were determined via HPLC analysis on a chiral stationary phase. d.r. values were determined by ^1H NMR analysis of the crude reaction mixture. [b]2.0 mol% of Δ-**Rh1** was employed, 50 °C.

2-acyl imidazole **1h** required a slightly longer reaction time. Notably, the orthosubstituted substrates (**1i**, **1j**, **1k**) were also compatible to afford the desired products in good yields (90−99%) and excellent ee (96−99%). Moreover, heterocycle substituted *α,β*-unsaturated 2-acyl imidazoles (**1l**, **1m**) worked well in optimal reaction conditions to give desired product in 95% yield, > 99% ee (**3la**) and 96% yield, 99% ee (**3ma**), respectively. In addition to aromatic substituents, the aliphatic variants of *α,β*-unsaturated 2-acyl imidazole (Me, CO_2Et) were also investigated to get the corresponding products **3na** and **3oa** with excellent enantioselectivities, albeit with 2 mol% of catalyst loading and higher temperature. Furthermore, substrate which can coordinate to metal (Rh) center in bidentate fashion, such as *α,β*-unsaturated 2-acylpyridine **1p**, was also reacted to afford the desired adduct in 95% yield with 96% ee. Our catalytic system appears to match or even surpass the best reported asymmetric cyclopropanation of *α,β*-unsaturated compounds with bromomalonates in terms of yield, enantioselectivity, catalyst loading, and the scope of substrates.[9]

The absolute configuration of product **3ka** is determined and confirmed by a single-crystal X-ray analysis (Figure 2, for details, see the Supporting Information).[13]

Then, we evaluated the scope of the *α*-bromomalonates (Table 3). To our delight, we found that the efficiency and enantioselectivity were not affected with increased size of the ester group (iPr and Bn), good yields and excellent enatioselectivity were obtained (**3ab**, 98%, 98% ee; **3ac**, 99%, 97% ee), which obviously were superior to other reported methods.[9c,d,g] Surprisingly, *tert*-butyl 2-bromomalonate **2d**,

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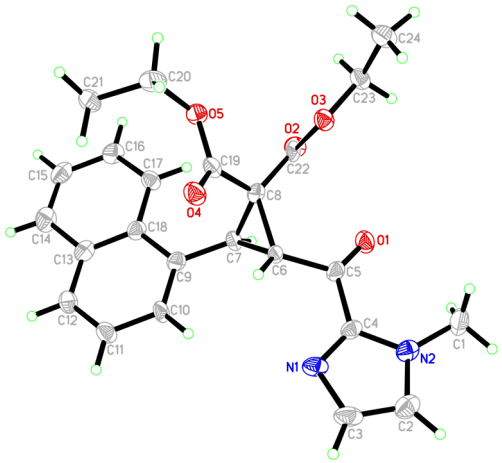
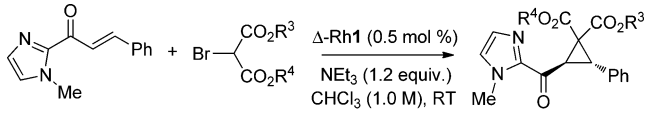
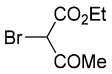


Figure 2. X-ray derived ORTEP of **3ka** with thermal ellipsoids shown at the 35% probability level.

Table 3. Enantioselective Cyclopropanation of α,β-Unsaturated 2-Acyl Imidazole 1a with α-Bromomalonates 2a–2f[a]



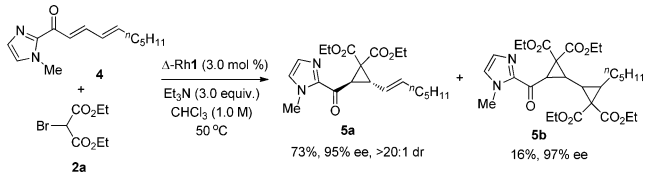
entry	R^3, R^4	3	t (h)	yield (%)[b]	ee (%)[c]	d.r.[d]
1	Et, Et	**3aa**	3	99	>99	>20:1
2	*i*Pr, *i*Pr	**3ab**	16	98	98	>20:1
3	Bn, Bn	**3ac**	16	99	97	>20:1
4[e]	*t*Bu, *t*Bu	**3ad**	24	95	95	>20:1
5[e]	Et, *t*Bu	**3ae**	12	99	94	1.5:1
6[e]		**3af**	16	80	>99	4:1

[a]Reaction conditions: **1a** (0.3 mmol), **2a** (0.36 mmol), **Δ-Rh1** (0.5 mol%), NEt_3 (0.36 mmol), $CHCl_3$ (0.3 mL). [b]Isolated yields. [c]Determined by chiral HPLC analysis. [d]Determined by ^1H NMR analysis of the crude reaction mixture. [e]2.0 mol% of **Δ-Rh1**, 50 °C.

which could not be tolerated in other approach, worked well in our catalytic system to give desired product **3ad** in 95% yield with 95% ee. In addition to symmetrical α-bromomalonates, the unsymmetrical substrates were also examined, resulting in corresponding cyclopropanes in good yield with excellent ee values, albeit poor to moderate dr were obtained (**3ae**, 1.5:1; **3af**, 4:1).

To demonstrate the potential application of this methodology, we attempted to construct structurally and functionally complex biscyclopropane skeleton (Scheme 1). Pleasingly, in the presence of 3.0 mol% of **Δ-Rh1** and 3.0 equiv of Et_3N, the reaction of conjugated diene **4** with **2a** occurred to afford desired biscyclopropane **5b** in 16% yield with 97% ee.[14] However, vinylcyclopropane **5a** was obtained predominately in 73% yield with 95% ee. These observations indicated that the

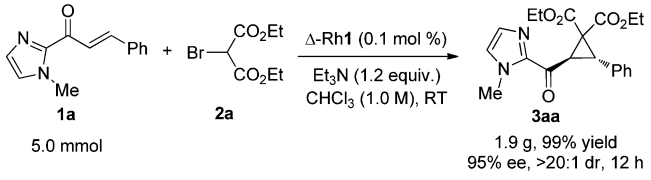
Scheme 1. One Step Enantioselective Synthesis of Biscyclopropane 5b



first nucleophilic attack of diethyl α-bromomalonate **2a** was happened prior to β-postion than δ-position of **4**, which caused formation of vinylcyclopropane **5a** as major product.

To further explore the practicality of the current methodology, a gram-scale synthesis of **3aa** was carried out. Remarkably, by employing as low as 0.1 mol% of **Δ-Rh1** (4.2 mg/0.005 mmol), the reaction of **1a** on a 5.0 mmol scale (1.06 g) with **2a** could be completed in 12 h, delivering the cyclopropanation product **3aa** in 99% yield (990 catalyst turnovers) with 95% ee (Scheme 2).

Scheme 2. Gram Scale Reaction



The proposed mechanism of chiral Rh (III) catalyzed Michael–Alkylation process is depicted in Figure 3. The 2-

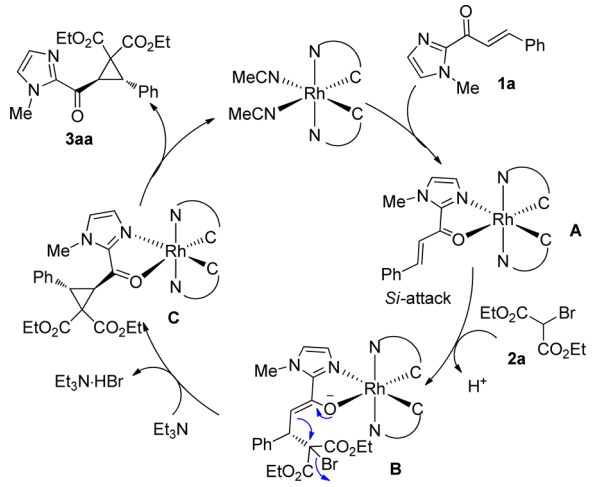


Figure 3. Proposed mechanism for chiral Rh (III) catalyzed enantioselective cyclopropanation reaction.

acyl imidazole substrate **1a** is activated by the rhodium catalyst through bidentate *N,O*-coordination (intermediate **A**). Excellent shielding of the *Re*-face of the intermediate **A** by the bulky *t*-Bu group of achiral ligand of rhodium complex leads to *Si*-facial nucleophilic addition by diethyl α-bromomalonate **2a**, resulting the enolate anion (intermediate **B**). Next, intermediate **B** undergoes an intramolecular nucleophilic substitution i.e., cyclization to afford the coordinated intermediate **C** with cyclopropane skeleton. The desired product **3aa** is released from the coordinated intermediate **C** by ligand exchange with **1a** and a new catalytic cycle is initiated.

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In summary, we have developed a highly efficient chiral Rh(III) complex catalyzed enantioselective cyclopropanation of α,β-unsaturated 2-acyl imidazoles or pyridine **1** with readily available bromomalonate **2**. Multisubstituted cyclopropanes **3** were constructed in good yields (70−99%) with excellent enantioselectivity (93→99% ee). Notably, this catalytic system exhibits outstanding advantages in terms of reactivity and selectivity, as the fact that cyclopropane **3aa** (99% yield, 95% ee) can be achieved on gram scale by using as low as 0.1 mol% of Rh(III) complex. Moreover, structurally complex biscyclopropane **5b** can be constructed with excellent enantioselectivity (97% ee) in a single step, albeit only 16% yield was obtained.

EXPERIMENTAL SECTION

All reactions were performed in Schlenk tubes under an atmosphere of argon using oven-dried glassware. Commercially obtained reagents were used without further purification, unless otherwise noted. Chloroform was distilled over P_2O_5 and stored over 3 Å type molecular sieves. THF and toluene were distilled freshly before use over sodium and benzophenone. Dichloromethane (DCM) and 1,2-dichloroethane (DCE) were distilled from CaH_2. Reactions were checked for completion by TLC analysis and plates were visualized with short-wave UV light (254 nm). The ^{1}H and ^{13}C NMR spectra were obtained in $CDCl_3$ or CD_2Cl_2 using a NMR spectrometer at 400 and 100 MHz, respectively. Chemical shifts are reported in parts per million (δ value) calibrated against the residual solvent peak. Signal patterns are indicated as follows: s, singlet; d, doublet; t, triplet; q, quartet; m, multiplet. Coupling constants (J) are given in hertz (Hz). HPLC analyses of the compounds were done using IA-IF columns using hexane and isopropanol as eluent. The infrared spectra were recorded on IR spectrometer as KBr pellets, with absorption reported in cm^{-1}. High-resolution mass spectra were recorded on TOF LC/MS Mass Spectrometry. **Δ-Rh1**, **Δ-Ir1**, **Δ-Ir2**,[11a] α,β-unsaturated 2-acyl imidazoles **1** and **4**,[15] α-bromomalonate **2b−2f**[16] were prepared according to procedure reported previously. **L2** and **L3** were prepared according to the literature.[11a]

Procedure for Synthesis of Catalyst Δ-Rh2 and Δ-Rh3. **L** (1.31 g, 4.1 mmol) was added to $RhCl_3{\cdot}3H_2O$ (526.6 mg, 2.0 mmol) in a mixture of 2-ethoxyethanol and water (3:1, 92 mL). The reaction mixture was heated at 120 °C for 24 h under argon atmosphere. The resulting precipitate was collected by filtration, washed with methanol, and dried to obtain the product *dimer*-**2** and *dimer*-**3**.

Dimer-**2**: Yellow solid, 544.5 mg, 35% yield. ^{1}H NMR (400 MHz, $CDCl_3$) δ = 8.18 (d, J = 1.6 Hz, 4H), 7.73 (d, J = 7.9 Hz, 4H), 7.28−7.25 (m, 4H), 7.21−7.18 (m, 8H), 6.4 (s, 4H), 1.25 (s, 36H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ = 169.1 (q, J = 3.4 Hz), 164.4, 164.0, 149.3, 147.6, 138.3, 133.9, 131.4 (q, J = 30.7 Hz), 129.8 (q, J = 3.8 Hz), 124.7, 124.0, 123.4 (q, J = 271.9 Hz), 119.9 (q, J = 3.9 Hz), 115.1, 110.3, 35.1, 31.5. ^{19}F NMR (376 MHz, $CDCl_3$) δ = −63.4. IR (KBr): ν (cm^{-1}) 3088, 3087, 3051, 2962, 2905, 2869, 1613, 1599, 1580, 1524, 1463, 1428, 1388, 1366, 1314, 1273, 1255, 1129, 1094, 1083, 1070, 1038, 933, 887, 825, 807, 791, 762, 703. HRMS (ESI, m/z) calcd for $C_{72}H_{60}ClF_{12}N_4O_4Rh_2$ [M-Cl]$^+$: 1513.2216, found: 1513.2202.

Dimer-**3**: Yellow solid, 389.3 mg, 25% yield. ^{1}H NMR (400 MHz, $CDCl_3$) δ = 8.32 (s, 4H), 7.85 (s, 4H), 7.26−7.22 (m, 8H), 7.00−6.98 (m, 4H), 6.27−6.25 (m, 4H), 1.24 (s, 36H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ = 169.1, 169.0 (q, J = 37.8 Hz), 149.3, 147.5, 138.6, 133.6, 130.8, 126.9 (q, J = 4.4 Hz), 125.5 (q, J = 32.6 Hz), 124.2, 124.1 (q, J = 270.0 Hz), 121.3 (q, J = 3.0 Hz), 115.4, 110.2, 35.1, 31.5. ^{19}F NMR (376 MHz, $CDCl_3$) δ = −62.3. IR (KBr): ν (cm^{-1}) 2963, 2926, 2872, 2856, 1620, 1604, 1482, 1455, 1421, 1374, 1326, 1317, 1287, 1262, 1251, 1190, 1169, 1127, 1087, 1073, 1023, 942, 895, 848, 807, 705, 651. HRMS (ESI, m/z) calcd for $C_{72}H_{60}ClF_{12}N_4O_4Rh_2$ [M-Cl]$^+$: 1513.2216, found: 1513.2200.

To a solution of NaOMe (16.2 mg, 0.30 mmol) in methanol (16.0 mL), *D*-proline (34.5 mg, 0.30 mmol) was added in one portion. The mixture was stirred for 10 min, to which a suspension of dimer (232.3 mg, 0.15 mmol) was added. The mixture was stirred and heated at 50 °C for 12 h. After the mixture cooled to room temperature, CH_2Cl_2 (16.0 mL) was added. The reaction mixture was stirred for a further 12 h. The solvent was removed *in vacuo*. The residue was purified by flash chromatography on silica gel (EtOAc/DCM = 1:5) to obtain the product Δ-(***R***)-**2** or Δ-(***R***)-**3**.

Δ-(***R***)-**2**: Yellow solid, 45.2 mg, 35% yield. ^{1}H NMR (400 MHz, $CDCl_3$) δ = 8.14 (d, J = 1.1 Hz, 1H), 7.90−7.82 (m, 2H), 7.73−7.62 (m, 4H), 7.31−7.25 (m, 3H), 6.94 (s, 1H), 6.53 (s, 1H), 4.25−4.20 (m, 1H), 4.02−3.96 (m, 1H), 2.77−2.75 (m, 1H), 2.24−2.19 (m, 2H), 2.05−1.95 (m, 1H), 1.68−1.49 (m, 2H), 1.42(s, 9H), 1.38 (s, 9H). ^{13}C NMR (CD_2Cl_2, 100 MHz): δ = 180.0, 171.0, 169.9, 166.4 (q, J = 30.1 Hz), 165.1 (q, J = 31.6 Hz), 151.4, 150.8, 148.6, 137.8, 137.2, 134.1, 133.9, 131.5 (q, J = 31.3 Hz), 131.4 (q, J = 31.0 Hz), 130.9 (q, J = 3.5 Hz), 129.9 (q, J = 4.0 Hz), 125.6, 125.4, 124.7, 124.6, 123.7 (q, J = 271.7 Hz), 120.3 (q, J = 2.8 Hz), 119.8 (q, J = 3.3 Hz), 115.3, 112.1, 111.2, 110.9, 63.9, 49.2, 35.3, 35.1, 31.3, 29.7, 29.6, 26.5. ^{19}F NMR (376 MHz, $CDCl_3$) δ = −63.0, −63.3. IR (KBr): ν (cm^{-1}) 2964, 2927, 2872, 2851, 1612, 1581, 1481, 1462, 1388, 1314, 1254, 1166, 1127, 1069, 1037, 933, 888, 826, 810, 703. HRMS (ESI, m/z) calcd for $C_{41}H_{38}F_6N_3NaO_4Rh$ [M+Na]$^+$: 876.1714, found: 876.1715.

Δ-(***R***)-**3**: Yellow solid, 52.0 mg, 40% yield. ^{1}H NMR (400 MHz, $CDCl_3$) δ = 8.15 (d, J = 1.4 Hz, 1H), 8.01 (s, 1H), 7.97 (s, 1H), 7.74−7.68 (m, 2H), 7.65−7.61 (m, 2H), 7.27−7.26 (m, 1H), 7.16−7.11 (m, 2H), 6.87 (d, J = 8.0 Hz, 1H), 6.51 (d, J = 8.0 Hz, 1H), 4.28−4.22 (m, 1H), 4.09−4.03 (m, 1H), 2.80−2.74 (m, 1H), 2.30−2.13 (m, 2H), 2.03−1.95 (m, 1H), 1.70−1.66 (m, 2H), 1.42 (s, 9H), 1.39 (s, 9H). ^{13}C NMR (CD_2Cl_2, 100 MHz): δ = 180.1, 171.7 (q, J = 29.7 Hz), 171.1, 170.9 (q, J = 28.6 Hz) 170.0 (q, J = 3.8 Hz), 151.4, 150.7, 148.6, 137.9, 137.2, 135.3, 134.3, 131.1, 130.9, 126.8 (q, J = 33.8 Hz), 125.4 (q, J = 32.6 Hz), 125.8 (q, J = 32.6 Hz), 124.4 (q, J = 270.0 Hz), 124.7, 122.0 (q, J = 3.8 Hz) 121.7 (q, J = 3.6 Hz), 115.2, 112.1, 111.1, 110.9, 63.8, 49.3, 35.3, 35.1, 31.4, 31.3, 29.7, 26.7. ^{19}F NMR (376 MHz, $CDCl_3$) δ = −62.4, −62.5. IR (KBr): ν (cm^{-1}) 2964, 2969, 2872, 1617, 1606, 1541, 1483, 1451, 1420, 1375, 1326, 1318, 1286, 1251, 1189, 1169, 1125, 1071, 1024, 943, 899, 848, 831, 811, 706, 653. HRMS (ESI, m/z) calcd for $C_{41}H_{38}F_6N_3NaO_4Rh$ [M+Na]$^+$: 876.1714, found: 876.1708.

A suspension of the rhodium auxiliary complex Δ-(***R***)-**2** or Δ-(***R***)-**3** (239.0 mg, 0.28 mmol) and NH_4BF_4 (294.0 mg, 2.80 mmol) in acetonitrile (56.0 mL) was heated at 50 °C for 24 h under argon in the dark. Then the solvent was removed under reduced pressure and the product was subjected to flash silica gel chromatography (100% CH_2Cl_2 to CH_2Cl_2/CH_3CN = 15:1) to give the catalysts**Δ-Rh2** or **Δ-Rh3**.

Δ-Rh2: 126.4 mg, 49% yield, pale yellow solid;$[\alpha]_D^{25}$ = −176.6 (c = 0.5, $CHCl_3$). ^{1}H NMR (CD_2Cl_2, 400 MHz,) δ = 7.92−7.89 (m, 4H), 7.83−7.74 (m, 4H), 7.37 (d, J = 7.8, 4H), 6.56 (s, 2H), 2.35 (s, 6H), 1.46 (s, 18H). ^{13}C NMR (CD_2Cl_2, 100 MHz): δ = 167.4 (q, J = 3.7 Hz), 156.7, 156.4, 148.9, 146.1, 134.7, 131.2, 129.9 (q, J = 31.3 Hz), 126.5 (q, J = 3.6 Hz), 123.4, 120.9 (q, J = 271.8 Hz), 120.0 (q, J = 2.6 Hz), 119.1 (q, J = 3.7 Hz), 110.8, 109.4, 32.9, 28.9, 0.9. ^{19}F NMR (376 MHz, $CDCl_3$) δ = −63.1, −63.2, −63.2. IR (KBr): ν (cm^{-1}) 2964, 2926, 2855, 1620, 1604, 1483, 1455, 1421, 1374, 1326, 1317, 1287, 1251, 1190, 1169, 1126, 1084, 1072, 1022, 942, 896, 848, 827, 808, 757, 706, 651. HRMS (ESI, m/z) calcd for $C_{40}H_{36}F_6N_4O_2Rh$ [M-BF_4]$^+$: 821.1792, found: 821.1799.

Δ-Rh3[13]: 132.3 mg, 52% yield, pale yellow solid; $[\alpha]_D^{25}$ = −90.82 (c = 0.5, $CHCl_3$). ^{1}H NMR (400 MHz, CD_2Cl_2) δ = 8.01 (s, 2H), 7.92 (d, J = 1.1 Hz, 2H), 7.83−7.75 (m, 4H), 7.17 (d, J = 8.12 Hz, 2H), 6.55 (d, J = 8.12 Hz, 2H), 2.36 (s, 6H), 1.47 (s, 18H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ = 167.4 (q, J = 3.8 Hz), 162.0 (q, J = 31.1 Hz), 148.8, 146.0, 134.8, 131.1, 128.3, 125.2 (q, J = 2.2 Hz), 124.5 (q, J = 32.8 Hz), 123.3, 121.6 (q, J = 270.0 Hz), 120.0 (q, J = 2.6 Hz), 119.6 (q, J = 3.6 Hz), 110.8, 109.3, 32.9, 28.9, 0.9. ^{19}F NMR (376 MHz, $CDCl_3$) δ = −62.5, −62.6, −62.6. IR (KBr): ν (cm^{-1}) 2964, 2925, 2872, 2853, 1482, 1465, 1390, 1366, 1314, 1272, 1254, 1166, 1126, 1084, 1070, 1037, 933, 887, 827, 809, 703. HRMS (ESI, m/z) calcd for $C_{40}H_{36}F_6N_4O_2Rh$ [M-BF_4]$^+$: 821.1792, found: 821.1794.

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General Procedure for Chiral Rh(III) Complex Catalyzed Enantioselective Cyclopropantion Reaction. To an oven-dried 25 mL Schlenk tube equipped with a stir bar, **Δ-Rh1** (0.5 mol% or 2.0 mol%) was added along with α,β-unsaturated 2-acyl imidazole **1** (0.3 mmol) and $CHCl_3$ (0.3 mL). After being stirred at room temperature for 5 min, α-bromomalonate **2** (1.2 equiv or 2.0 equiv) was added at room temperature followed by NEt_3 (1.2 equiv or 2.0 equiv). The reaction was stirring at the room temperature until consumption of the 2-acyl imidazole as monitored by thin layer chromatography. The solution directly purified by silica gel column chromatography (EtOAc/Petroleum ether = 1:3) to afford cyclopropanes **3**.

Spectra Data of Product 3. *(2R,3S)-Diethyl 2-(1-Methyl-1H-imidazole-2-carbonyl)-3-phenylcyclopropane-1,1-dicarboxylate (**3aa**).* Colorless oil, 111 mg, 99% yield, 99.6% ee, $[\alpha]_D^{25}$ = +6.1 (c = 1.0, $CHCl_3$). The ee was determined by HPLC (Chiralpak column IA, λ = 254 nm, hexane/*i*-PrOH = 70/30, flow rate 1.0 mL/min, t_{major} = 6.78 min, t_{minor} = 11.77 min). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.34 (d, *J* = 7.2 Hz, 2H), 7.23−7.14 (m, 4H), 7.04 (s, 1H), 4.77 (d, *J* = 7.5 Hz, 1H), 4.26−4.15 (m, 2H), 3.91 (s, 3H), 3.90−3.79 (m, 2H), 3.66 (d, *J* = 7.5 Hz, 1H), 1.20 (t, *J* = 7.1 Hz, 3H), 0.83 (t, *J* = 7.1 Hz, 3H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ = 184.9, 165.5, 164.5, 142.2, 132.7, 129.1, 127.9, 127.2, 126.7, 126.5, 60.7, 60.6, 45.2, 36.4, 35.1, 33.5, 24.3, 13.0, 12.7. IR (KBr): ν (cm^{-1}) 2981, 1735, 1670, 1431, 1262, 1213, 1185, 1157, 1107, 1015, 918, 878, 854, 783, 698. HRMS (ESI, *m*/*z*) calcd for $C_{20}H_{22}N_2NaO_5$ $[M+Na]^+$: 393.1421, found: 393.1421.

*(2R,3S)-Diethyl 2-(1-Isopropyl-1H-imidazole-2-carbonyl)-3-phenylcyclopropane-1,1-dicarboxylate (**3ba**).* Colorless oil, 117 mg, 96% yield, 96% ee, $[\alpha]_D^{25}$ = +15.8 (c = 1.0, $CHCl_3$). The ee was determined by HPLC (Chiralpak column IC, λ = 254 nm, hexane/*i*-PrOH = 80/20, flow rate 1.0 mL/min, t_{major} = 12.40 min, t_{minor} = 10.94 min). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.43 (d, *J* = 7.2 Hz, 2H), 7.35 (s, 1H), 7.31−7.22 (m, 4H), 5.57−5.47 (m, 1H), 4.92 (d, *J* = 7.5 Hz, 1H), 4.34−4.21 (m, 2H), 4.01−3.87 (m, 2H), 3.75 (d, *J* = 7.5 Hz, 1H), 1.45−1.41 (m, 6H), 1.27 (t, *J* = 7.1 Hz, 3H), 0.91 (t, *J* = 7.1 Hz, 3H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ = 185.9, 166.5, 165.6, 142.5, 133.8, 130.6, 129.0, 128.2, 127.5, 122.0, 61.7, 61.6, 49.3, 46.3, 37.3, 35.1, 23.7, 23.4, 14.1, 13.7. IR (KBr): ν (cm^{-1}) 2982, 2937, 1737, 1670, 1429, 1392, 1283, 1252, 1214, 1184, 1107, 1011, 918, 877, 853, 782, 735, 698. HRMS (ESI, *m*/*z*) calcd for $C_{22}H_{27}N_2O_5$ $[M+H]^+$: 399.1914, found: 399.1912.

*(2S,3R)-Diethyl 2-phenyl-3-(1-phenyl-1H-imidazole-2-carbonyl)-cyclopropane-1,1-dicarboxylate (**3ca**).* Colorless oil, 129 mg, 99% yield, 98% ee, $[\alpha]_D^{25}$ = +27.5 (c = 1.0, $CHCl_3$). The ee was determined by HPLC (Chiralpak column IA, λ = 254 nm, hexane/*i*-PrOH = 70/30, flow rate 1.0 mL/min, t_{major} = 6.88 min, t_{minor} = 8.95 min). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.43−7.38 (m, 6H), 7.30−7.21 (m, 6H), 4.87 (d, *J* = 7.5 Hz, 1H), 4.22−4.10 (m, 2H), 4.00−3.87 (m, 2H), 3.68 (d, *J* = 7.5 Hz, 1H), 1.18 (t, *J* = 7.1 Hz, 3H), 0.92 (t, *J* = 7.1 Hz, 3H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ = 184.5, 166.2, 165.6, 143.2, 138.1, 133.7, 130.6, 129.0, 128.9, 128.8, 128.2, 127.7, 127.5, 125.9, 61.7, 46.5, 37.2, 34.7, 14.0, 13.7. IR (KBr): ν (cm^{-1}) 2982, 1736, 1680, 1493, 1423, 1396, 1302, 1288, 1253, 1213, 1185, 1108, 1022, 984, 876, 769, 696. HRMS (ESI, *m*/*z*) calcd for $C_{25}H_{25}N_2O_5$ $[M+H]^+$: 433.1758, found:433.1757.

*(2R,3S)-Diethyl 2-(1-Methyl-1H-imidazole-2-carbonyl)-3-(p-tolyl)-cyclopropane-1,1-dicarboxylate (**3da**).* Colorless oil, 109 mg, 95% yield, 98% ee, $[\alpha]_D^{25}$ = +6.7 (c = 1.0, $CHCl_3$). The ee was determined by HPLC (Chiralpak column IA, λ = 254 nm, hexane/*i*-PrOH = 70/30, flow rate 1.0 mL/min, t_{major} = 6.95 min, t_{minor} = 17.81 min). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.29−7.25 (m, 3H), 7.12−7.08 (m, 3H), 4.82 (d, *J* = 7.6 Hz, 1H), 4.33−4.21 (m, 2H), 3.97 (s, 3H), 4.02−3.88 (m, 2H), 3.70 (d, *J* = 7.5 Hz, 1H), 2.30 (s, 3H), 1.27 (t, *J* = 7.1 Hz, 3H), 0.95 (t, *J* = 7.1 Hz, 3H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ = 186.0, 166.5, 165.6, 143.2, 137.1, 130.6, 130.0, 128.9, 128.8, 127.8, 61.7, 46.3, 37.2, 36.1, 34.6, 21.1, 14.0, 13.8. IR (KBr): ν (cm^{-1}) 2983, 1737, 1670, 1518, 1434, 1396, 1369, 1262, 1212, 1180, 1159, 1107, 1019, 919, 882, 853, 811. HRMS (ESI, *m*/*z*) calcd for $C_{21}H_{24}N_2NaO_5$ $[M+Na]^+$: 407.1577, found: 407.1576.

*(2R,3S)-Diethyl 2-(1-Methyl-1H-imidazole-2-carbonyl)-3-(m-tolyl)cyclopropane-1,1-dicarboxylate (**3ea**).* Colorless oil, 113.8 mg, 99% yield, 99% ee, $[\alpha]_D^{25}$ = +12.9 (c = 1.0, $CHCl_3$). The ee was determined by HPLC (Chiralpak column IA, λ = 254 nm, hexane/*i*-PrOH = 70/30, flow rate 1.0 mL/min, t_{major} = 6.01 min, t_{minor} = 8.43 min). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.26−7.25 (m, 1H), 7.20−7.15 (m, 3H), 7.12 (s, 1H), 7.05−7.03 (m, 1H), 4.82 (d, *J* = 7.5 Hz, 1H), 4.33−4.22 (m, 2H), 3.98 (s, 3H), 4.01−3.88 (m, 2H), 3.71−3.69 (d, *J* = 7.5 Hz, 1H), 2.31 (s, 3H), 1.27 (t, *J* = 7.1 Hz, 3H), 0.92 (t, *J* = 7.1 Hz, 3H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ = 186.0, 166.5, 165.6, 143.2, 137.8, 133.6, 130.1, 129.6, 128.3, 128.1, 127.8, 125.9, 61.7, 61.6, 46.3, 37.4, 36.1, 34.6, 21.3, 14.1, 13.7. IR (KBr): ν (cm^{-1}) 2982, 1736, 1670, 1416, 1397, 1368, 1334, 1268, 1239, 1200, 1157, 1109, 1019, 919, 861, 787, 698. HRMS (ESI, *m*/*z*) calcd for $C_{21}H_{24}N_2NaO_5$ $[M+Na]^+$: 407.1577, found: 407.1579.

*(2S,3R)-Diethyl 2-(4-Bromophenyl)-3-(1-methyl-1H-imidazole-2-carbonyl)cyclopropane-1,1-dicarboxylate (**3fa**).* Colorless oil, 128 mg, 95% yield, 99% ee, $[\alpha]_D^{25}$ = +34.5 (c = 1.0, $CHCl_3$). The ee was determined by HPLC (Chiralpak column IA, λ = 254 nm, hexane/*i*-PrOH = 70/30, flow rate 1.0 mL/min, t_{major} = 7.16 min, t_{minor} = 13.32 min). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.43−7.41 (m, 2H), 7.30−7.27 (m, 3H), 7.12 (s, 1H), 4.80 (d, *J* = 7.5 Hz, 1H), 4.34−4.22 (m, 2H), 4.05−3.90 (m, 2H), 3.99 (s, 3H), 3.65 (d, *J* = 7.5 Hz, 1H), 1.27 (t, *J* = 7.1 Hz, 3H), 0.98 (t, *J* = 7.1 Hz, 3H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ = 185.5, 166.2, 165.4, 143.2, 132.8, 131.3, 130.7, 130.2, 127.8, 121.6, 61.9, 61.8, 46.0, 36.6, 36.1, 34.6, 14.0, 13.9. IR (KBr): ν (cm^{-1}) 3456, 2982, 1735, 1671, 1492, 1433, 1405, 1391, 1334, 1261, 1213, 1184, 1157, 1110, 1012, 919, 881, 851, 814, 777, 691. HRMS (ESI, *m*/*z*) calcd for $C_{20}H_{21}BrN_2NaO_5$ $[M+Na]^+$: 471.0526, found: 471.0528.

*(2S,3R)-Diethyl 2-(4-Chlorophenyl)-3-(1-methyl-1H-imidazole-2-carbonyl)cyclopropane-1,1-dicarboxylate (**3ga**).* Colorless oil, 112 mg, 92% yield, 99.2% ee, $[\alpha]_D^{25}$ = +15.6 (c = 1.0, $CHCl_3$). The ee was determined by HPLC (Chiralpak column IA, λ = 254 nm, hexane/*i*-PrOH = 70/30, flow rate 1.0 mL/min, t_{major} = 6.92 min, t_{minor} = 12.70 min). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.36−7.34 (m, 2H), 7.29−7.25 (m, 3H), 7.13 (s, 1H), 4.81 (d, *J* = 7.5 Hz, 1H), 4.34−4.21 (m, 2H), 4.05−3.90 (m, 2H), 3.99 (s, 3H), 3.67 (d, *J* = 7.5 Hz, 1H), 1.28 (t, *J* = 7.1 Hz, 3H), 0.98 (t, *J* = 7.1 Hz, 3H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ = 185.6, 166.2, 165.4, 143.2, 133.4, 132.3, 130.4, 130.2, 128.4, 127.8, 61.9, 61.8, 46.1, 36.6, 36.1, 34.6, 14.0, 13.8. IR (KBr): ν (cm^{-1}) 3457, 1982, 1735, 1671, 1495, 1434, 1408, 1393, 1368, 1334, 1261, 1185, 1158, 1100, 1014, 919, 882, 852, 816, 780, 694. HRMS (ESI, *m*/*z*) calcd for $C_{20}H_{21}ClN_2NaO_5$ $[M+Na]^+$: 427.1031, found: 427.1030.

*(2S,3R)-Diethyl 2-(4-Methoxyphenyl)-3-(1-methyl-1H-imidazole-2-carbonyl)cyclopropane-1,1-dicarboxylate (**3ha**).* Yellowish oil, 120 mg, 99% yield, 99% ee, $[\alpha]_D^{25}$ = +5.0 (c = 1.0, $CHCl_3$). The ee was determined by HPLC (Chiralpak column IA, λ = 254 nm, hexane/*i*-PrOH = 70/30, flow rate 1.0 mL/min, t_{major} = 6.16 min, t_{minor} = 21.42 min). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.34−7.30 (m, 2H), 7.26 (d, *J* = 0.8 Hz, 1H), 7.11 (s, 1H), 6.84−6.80 (m, 2H), 4.80 (d, *J* = 7.6 Hz, 1H), 4.33−4.21 (m, 2H), 4.03−3.89 (m, 2H), 3.98 (s, 3H), 3.77 (s, 3H), 3.67 (d, *J* = 7.6 Hz, 1H), 1.27 (t, *J* = 7.1 Hz, 3H), 0.97 (t, *J* = 7.2 Hz, 3H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ = 186.0, 166.6, 165.6, 159.0, 143.3, 130.1, 130.0, 127.7, 125.7, 113.6, 61.7, 55.2, 46.3, 36.9, 36.1, 34.8, 14.0, 13.8. IR (KBr): ν (cm^{-1}) 3110, 2982, 2938, 2838, 1736, 1670, 1613, 1582, 1517, 1396, 1369, 1257, 1214, 1177, 1106, 1031, 919, 883, 851, 824, 776. HRMS (ESI, *m*/*z*) calcd for $C_{21}H_{24}N_2NaO_6$ $[M+Na]^+$: 423.1527, found: 423.1530.

*(2R,3S)-Diethyl 2-(1-Methyl-1H-imidazole-2-carbonyl)-3-(o-tolyl)-cyclopropane-1,1-dicarboxylate (**3ia**).* Colorless oil, 114 mg, 99% yield, 99% ee, $[\alpha]_D^{25}$ = −8.9 (c = 1.0, $CHCl_3$). The ee was determined by HPLC (Chiralpak column IA, λ = 254 nm, hexane/*i*-PrOH = 70/30, flow rate 1.0 mL/min, t_{major} = 5.49 min, t_{minor} = 9.56 min). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.38−7.33 (m, 1H), 7.27 (m, 1H), 7.19−7.12 (m, 4H), 4.93 (d, *J* = 7.6 Hz, 1H), 4.35−4.23 (m, 2H), 3.99 (s, 3H), 3.96−3.84 (m, 2H), 3.65 (d, *J* = 7.6 Hz, 1H), 2.47 (s, 3H), 1.28 (t, *J* = 7.1 Hz, 3H), 0.86 (t, *J* = 7.1 Hz, 3H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ = 186.1, 166.6, 165.7, 143.3, 138.5, 131.9, 130.1, 129.8, 128.9, 127.8, 127.7, 125.5, 61.7, 61.6, 45.8, 37.0, 36.1, 34.3, 19.4, 14.0, 13.6. IR (KBr): ν (cm^{-1}) 2982, 1737, 1670, 1427, 1396, 1369, 1335, 1260, 1158, 1105, 1015, 919, 883, 781, 739, 685. HRMS (ESI, *m*/*z*) calcd for $C_{21}H_{24}N_2NaO_5$ $[M+Na]^+$: 407.1577, found: 407.1578.

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J. Org. Chem. 2017, 82, 796−803

*(2R,3R)-Diethyl 2-(2-Bromophenyl)-3-(1-methyl-1H-imidazole-2-carbonyl)cyclopropane-1,1-dicarboxylate (**3ja**).* Yellowish oil, 123.7 mg, 90% yield, 96% ee, $[\alpha]_D^{25}$ = +4.5 (c = 1.0, $CHCl_3$). The ee was determined by HPLC (Chiralpak column IA, λ = 254 nm, hexane/*i*-PrOH = 70/30, flow rate 1.0 mL/min, t_{major} = 6.28 min, t_{minor} = 12.24 min). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.55−7.52 (m, 1H), 7.46−7.44 (m, 1H), 7.29−7.25 (m, 2H), 7.15−7.11 (m, 2H), 4.83 (d, *J* = 7.6 Hz, 1H), 4.32 (q, *J* = 7.2 Hz, 2H), 4.06−3.93 (m, 2H), 4.00 (s, 3H), 3.74 (d, *J* = 7.6 Hz, 1H), 1.28 (t, *J* = 7.1 Hz, 3H), 0.97 (t, *J* = 7.1 Hz, 3H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ = 185.5, 165.9, 165.7, 143.3, 133.9, 132.6, 131.0, 130.1, 129.1, 127.7, 127.0, 125.5, 61.8, 61.6, 45.7, 38.3, 36.1, 35.4, 14.0, 13.7. IR (KBr): ν (cm^{-1}) 2982, 1733, 1671, 1429, 1397, 1369, 1334, 1283, 1257, 1214, 1187, 1158, 1106, 1025, 919, 883, 859, 779, 750, 691. HRMS (ESI, *m*/*z*) calcd for $C_{20}H_{21}BrN_2NaO_5$ $[M+Na]^+$: 471.0526, found: 471.0525.

*(2R,3S)-Diethyl 2-(1-Methyl-1H-imidazole-2-carbonyl)-3-(naphthalen-1-yl)cyclopropane-1,1-dicarboxylate (**3ka**).* White solid, 120 mg, 95% yield, 99% ee, mp = 96−99 °C; $[\alpha]_D^{25}$ = +7.3 (c = 1.0, $CHCl_3$). The ee was determined by HPLC (Chiralpak column IA, λ = 254 nm, hexane/*i*-PrOH = 70/30, flow rate 1.0 mL/min, t_{major} = 6.27 min, t_{minor} = 16.71 min). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 8.60 (d, *J* = 8.8 Hz, 1H), 7.82 (d, *J* = 8.0 Hz, 1H), 7.77 (d, *J* = 8.4 Hz, 1H), 7.63 (d, *J* = 7.2 Hz, 1H), 7.59−7.55 (m, 1H), 7.49−7.40 (m, 2H), 7.30 (d, *J* = 0.3 Hz, 1H), 7.13 (s, 1H), 5.05 (d, *J* = 7.2 Hz, 1H), 4.43−4.31 (m, 2H), 4.08 (d, *J* = 7.2 Hz, 1H), 4.01 (s, 3H), 3.73−3.58 (m, 2H), 1.34 (t, *J* = 7.1 Hz, 3H), 0.50 (t, *J* = 7.2 Hz, 3H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ = 186.1, 166.9, 165.5, 143.3, 133.4, 132.9, 130.2, 130.1, 128.3, 128.2, 127.8, 126.9, 126.4, 125.9, 125.1, 124.6, 61.8, 61.4, 45.9, 36.6, 36.2, 34.6, 14.1, 13.3. IR (KBr): ν (cm^{-1}) 3048, 2981, 1735, 1670, 1597, 1510, 1429, 1405, 1369, 1329, 1272, 1255, 1197, 1158, 1111, 1021, 919, 885, 861, 802, 779. HRMS (ESI, *m*/*z*) calcd for $C_{24}H_{24}N_2NaO_5$ $[M+Na]^+$: 443.1577, found: 443.1580.

*(2R,3R)-Diethyl 2-(Furan-2-yl)-3-(1-methyl-1H-imidazole-2-carbonyl)cyclopropane-1,1-dicarboxylate (**3la**).* Colorless oil, 102.7 mg, 95% yield, 99.2% ee, $[\alpha]_D^{25}$ = −53.9 (c = 1.0, $CHCl_3$). The ee was determined by HPLC (Chiralpak column IA, λ = 254 nm, hexane/*i*-PrOH = 70/30, flow rate 1.0 mL/min, t_{major} = 7.13 min, t_{minor} = 9.91 min). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.32 (t, *J* = 1.2 Hz, 1H), 7.24 (d, *J* = 0.8 Hz, 1H), 7.12 (s, 1H), 6.30 (d, *J* = 1.4 Hz, 2H), 4.73 (d, *J* = 7.3 Hz, 1H), 4.31−4.19 (m, 2H), 4.16−4.03 (m, 2H), 3.98 (s, 3H), 3.63 (d, *J* = 7.3 Hz, 1H), 1.25 (t, *J* = 7.1 Hz, 3H), 1.11 (t, *J* = 7.1 Hz, 3H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ = 185.0, 165.7, 165.2, 148.1, 143.1, 142.1, 130.2, 127.8, 110.5, 108.6, 62.0, 61.9, 45.5, 36.1, 34.6, 29.7, 14.0, 13.8. IR (KBr): ν (cm^{-1}) 3118, 2983, 1738, 1671, 1508, 1465, 1403, 1370, 1260, 1201, 1157, 1107, 1016, 919, 864, 742. HRMS (ESI, *m*/*z*) calcd for $C_{18}H_{20}N_2NaO_6$ $[M+Na]^+$: 383.1214, found: 383.1216.

*(2R,3R)-Diethyl 2-(1-Methyl-1H-imidazole-2-carbonyl)-3-(thiophen-2-yl)cyclopropane-1,1-dicarboxylate (**3ma**).* Brown oil, 108.4 mg, 96% yield, 99% ee, $[\alpha]_D^{25}$ = −36.5 (c = 1.0, $CHCl_3$). The ee was determined by HPLC (Chiralpak column IA, λ = 254 nm, hexane/*i*-PrOH = 70/30, flow rate 1.0 mL/min, t_{major} = 6.91 min, t_{minor} = 11.27 min). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.26 (d, *J* = 0.8 Hz, 1H), 7.18 (dd, *J* = 5.1 Hz, *J* = 1.1 Hz, 1H), 7.11 (s, 1H), 7.06−7.05 (m, 1H), 6.93 (dd, *J* = 5.1 Hz, *J* = 3.6 Hz, 1H), 4.81 (d, *J* = 7.3 Hz, 1H), 4.32−4.20 (m, 2H), 4.10−3.99 (m, 2H), 3.98 (s, 3H), 3.77 (dd, *J* = 7.3 Hz, *J* = 0.9 Hz, 1H), 1.26 (t, *J* = 7.2 Hz, 3H), 1.05 (t, *J* = 7.2 Hz, 3H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ = 185.1, 166.0, 165.1, 143.2, 136.4, 130.2, 127.8, 127.2, 126.7, 125.2, 62.0, 61.8, 46.7, 36.2, 36.1, 31.8, 14.0, 13.8. IR (KBr): ν (cm^{-1}) 3110, 2982, 1736, 1670, 1448, 1421, 1396, 1369, 1285, 1258, 1202, 1158, 1108, 1013, 919, 871, 853. HRMS (ESI, *m*/*z*) calcd for $C_{18}H_{20}N_2NaO_5S$ $[M+Na]^+$: 399.0985, found: 399.0989.

*(2R,3R)-Diethyl 2-Methyl-3-(1-methyl-1H-imidazole-2-carbonyl)-cyclopropane-1,1-dicarboxylate (**3na**).* Yellowish oil, 64.7 mg, 70% yield, 93% ee, $[\alpha]_D^{25}$ = +7.6 (c = 1.0, $CHCl_3$). The ee was determined by HPLC (Chiralpak column IA, λ = 254 nm, hexane/*i*-PrOH = 70/30, flow rate 1.0 mL/min, t_{major} = 20.68 min, t_{minor} = 10.42 min). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.21 (s, 1H), 7.07 (s, 1H), 4.32−4.16 (m, 4H), 4.12 (d, *J* = 7.1 Hz, 1H), 3.95 (s, 3H), 2.51−2.45 (m, 1H), 1.34−1.21 (m, 9H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ = 186.6, 166.8, 166.7, 143.3, 129.8, 127.4, 61.9, 61.4, 45.2, 37.1, 36.1, 29.7, 28.9, 14.2, 14.0, 11.5. IR (KBr): ν (cm^{-1}) 2982, 2937, 1733, 1669, 1510, 1429, 1400, 1369, 1287, 1261, 1204, 1146, 1112, 1081, 1061, 1028, 919, 901, 861, 845, 784, 686. HRMS (ESI, *m*/*z*) calcd for $C_{15}H_{21}N_2O_5$ $[M+H]^+$: 309.1445, found: 309.1444.

*(2R,3R)-Triethyl 3-(1-Methyl-1H-imidazole-2-carbonyl)-cyclopropane-1,1,2-tricarboxylate (**3oa**).* Yellowish oil, 87.9 mg, 80% yield, 95% ee, $[\alpha]_D^{25}$ = +10.1 (c = 1.0, $CHCl_3$). The ee was determined by HPLC (Chiralpak column IC, λ = 254 nm, hexane/*i*-PrOH = 70/30, flow rate 1.0 mL/min, t_{major} = 40.17 min, t_{minor} = 25.72 min). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.24 (s, 1H), 7.10 (s, 1H), 4.56 (d, *J* = 7.0 Hz, 1H), 4.31−4.15 (m, 6H), 3.96 (s, 3H), 3.22 (d, *J* = 7.0 Hz, 1H), 1.30−1.21 (m, 9H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ = 183.8, 167.3, 165.0, 164.9, 142.9, 130.4, 127.9, 62.4, 62.1, 61.7, 44.3, 36.0, 34.9, 32.7, 14.0, 13.9. IR (KBr): ν (cm^{-1}) 2984, 2939, 1740, 1672, 1511, 1465, 1447, 1402, 1369, 1331, 1262, 1231, 1202, 1106, 1032, 1032, 917, 864, 791. HRMS (ESI, *m*/*z*) calcd for $C_{17}H_{22}N_2NaO_7$ $[M+Na]^+$: 389.1319, found: 389.1321.

*(2S,3R)-Diethyl 2-Phenyl-3-picolinoylcyclopropane-1,1-dicarboxylate (**3pa**).* Brown oil, 101.2 mg, 92% yield, 96% ee, $[\alpha]_D^{25}$ = +20.6 (c = 1.0, $CHCl_3$). The ee was determined by HPLC (Chiralpak column IC, λ = 254 nm, hexane/*i*-PrOH = 70/30, flow rate 1.0 mL/min, t_{major} = 10.18 min, t_{minor} = 7.32 min). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 8.82−8.80 (m, 1H), 8.07−8.05 (m, 1H), 7.88−7.84 (m, 1H), 7.54−7.51 (m, 1H), 7.44−7.42 (m, 2H), 7.33−7.23 (m, 3H), 5.10 (d, *J* = 7.6 Hz, 1H), 4.30−4.24 (m, 2H), 4.03−3.91 (m, 2H), 3.79 (d, *J* = 7.6 Hz, 1H), 1.26 (t, *J* = 7.2 Hz, 4H), 0.96 (t, *J* = 7.2 Hz, 3H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ = 195.7, 166.5, 165.7, 153.0, 149.4, 136.9, 133.9, 128.9, 128.2, 127.5, 122.1, 61.8, 61.7, 46.6, 38.0, 33.0, 14.0, 13.8. IR (KBr): ν (cm^{-1}) 2980, 2889, 1735, 1685, 1486, 1423, 1383, 1253, 1213, 1152, 1073, 817, 705. HRMS (ESI, *m*/*z*) calcd for $C_{21}H_{21}NNaO_5$ $[M+H]^+$: 390.1312, found: 390.1314.

*(2R,3S)-Diisopropyl 2-(1-Methyl-1H-imidazole-2-carbonyl)-3-phenylcyclopropane-1,1-dicarboxylate (**3ab**).* Yellowish oil, 117 mg, 99% yield, 98% ee, $[\alpha]_D^{25}$ = +3.5 (c = 1.0, $CHCl_3$). The ee was determined by HPLC (Chiralpak column IA, λ = 254 nm, hexane/*i*-PrOH = 70/30, flow rate 1.0 mL/min, t_{major} = 5.60 min, t_{minor} = 8.05 min). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.41−7.40 (m, 2H), 7.30−7.21 (m, 4H), 7.12 (m, 1H), 5.21−5.12 (m, 1H), 4.83 (d, *J* = 7.5 Hz, 1H), 4.81−4.75 (m, 1H), 3.98 (s, 3H), 3.72 (d, *J* = 7.5 Hz, 1H), 1.29 (d, *J* = 6.3 Hz, 3H), 1.20 (d, *J* = 6.3 Hz, 3H), 0.98−0.95 (m, 6H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ = 186.0, 165.9, 165.0, 143.3, 133.8, 130.1, 129.0, 128.1, 127.7, 127.4, 69.4, 69.0, 46.5, 37.2, 36.1, 34.4, 21.6, 21.5, 21.4, 21.1. IR (KBr): ν (cm^{-1}) 3113, 3063, 2983, 2938, 1733, 1671, 1433, 1399, 1375, 1291, 1263, 1218, 1184, 1097, 1027, 906, 870, 782, 699. HRMS (ESI, *m*/*z*) calcd for $C_{22}H_{27}N_2O_5$ $[M+H]^+$: 399.1914, found: 399.1915.

*(2R,3S)-Dibenzyl 2-(1-Methyl-1H-imidazole-2-carbonyl)-3-phenylcyclopropane-1,1-dicarboxylate (**3ac**).* Yellowish oil, 146.9 mg, 99% yield, 97% ee, $[\alpha]_D^{25}$ = −12.8 (c = 1.0, $CHCl_3$). The ee was determined by HPLC (Chiralpak column IA, λ = 254 nm, hexane/*i*-PrOH = 70/30, flow rate 1.0 mL/min, t_{major} = 11.53 min, t_{minor} = 35.95 min). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.37−7.34 (m, 2H), 7.27−7.18 (m, 12H), 7.04 (s, 1H), 6.99−6.97 (m, 2H), 5.27−5.17 (m, 2H), 4.94−4.85 (m, 3H), 3.85 (s, 3H), 3.80 (d, *J* = 7.6 Hz, 1H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ = 185.7, 166.4, 165.4, 143.2, 135.6, 135.1, 133.4, 130.2, 129.0, 128.4, 128.3, 128.3, 128.2, 128.1, 128.0, 127.8, 127.7, 67.5, 67.4, 46.1, 37.7, 36.1, 35.0. IR (KBr): ν (cm^{-1}) 3064, 3033, 2955, 1737, 1669, 1498, 1455, 1432, 1398, 1335, 1281, 1263, 1212, 1175, 1113, 1079, 1028, 1003, 905, 861, 738, 697. HRMS (ESI, *m*/*z*) calcd for $C_{30}H_{26}N_2NaO_5$ $[M+H]^+$: 517.1734, found: 517.1738.

*(2R,3S)-Ditert-butyl 2-(1-methyl-1H-imidazole-2-carbonyl)-3-phenylcyclopropane-1,1-dicarboxylate (**3ad**).* White solid, 121.5 mg, 95% yield, 95% ee, mp = 97−100 °C; $[\alpha]_D^{25}$ = +6.9 (c = 1.0, $CHCl_3$). The ee was determined by HPLC (Chiralpak column IA, λ = 254 nm, hexane/*i*-PrOH = 70/30, flow rate 1.0 mL/min, t_{major} = 4.33 min, t_{minor} = 4.84 min). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.41−7.40 (m, 1H), 7.32−7.20 (m, 4H), 7.09 (s, 1H), 4.74 (d, *J* = 7.4 Hz, 1H), 3.99 (s, 3H), 3.66 (d, *J* = 7.4 Hz, 1H), 1.47 (s, 9H), 1.19 (s, 9H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ = 186.3, 165.4, 164.5, 143.4, 134.0, 130.0,

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J. Org. Chem. 2017, 82, 796−803

129.0, 128.0, 127.4, 127.3, 82.1, 81.5, 48.3, 36.9, 36.1, 34.2, 27.9, 27.7. IR (KBr): ν (cm^{-1}) 3118, 3069, 3008, 2978, 2934, 1745, 1727, 1671, 1604, 1476, 1449, 1429,1398, 1369, 1305, 1269, 1227, 1157, 1119, 1022, 986, 918, 874, 838, 782, 743, 700. HRMS (ESI, m/z) calcd for $C_{24}H_{31}N_2O_5$ $[M+H]^+$: 427.2227, found: 427.2226.

*(2R,3S)-1-tert-Butyl 1-ethyl 2-(1-Methyl-1H-imidazole-2-carbonyl)-3-phenylcyclopropane-1,1-dicarboxylate (**3ae**).* Yellowish oil, 118 mg, 99% yield, 94% ee, 1:1.5 dr, $[\alpha]_D^{25}$ = −13.5 (c = 1.0, $CHCl_3$). The ee was determined by HPLC (Chiralpak column IA, λ = 254 nm, hexane/*i*-PrOH = 70/30, flow rate 1.0 mL/min, $t_{major\text{-}1}$ = 17.36 min, $t_{minor\text{-}1}$ = 38.35 min, $t_{major\text{-}2}$ = 18.74 min, $t_{minor\text{-}2}$ = 22.24 min). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.43−7.38 (m, 2H), 7.33−7.22 (m, 4H), 7.11−7.10 (m, 1H), 4.79 (d, J = 7.4 Hz, 1H), 4.35−4.20 (m, 2H), 3.97 (s, 3H), 3.71 (d, J = 7.4 Hz, 1H), 1.29 (t, J = 7.1 Hz, 3H), 1.16 (s, 9H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ = 186.3, 186.0, 166.7, 165.8, 165.2, 164.3, 143.4, 133.9, 133.9, 130.1, 130.0, 129.1, 128.9, 128.1, 128.0, 127.6, 127.5, 127.4, 82.4, 81.8, 61.5, 47.4, 47.1, 37.3, 37.1, 36.1, 36.1, 34.6, 34.2, 27.8, 27.6, 14.2, 13.8. IR (KBr): ν (cm^{-1}) 2979, 1733, 1671, 1431, 1398, 1369, 1297, 1264, 1217, 1159, 1023, 918, 878, 843, 791, 698. HRMS (ESI, m/z) calcd for $C_{22}H_{27}N_2O_5$ $[M+H]^+$: 399.1914, found: 399.1913.

*(2R,3S)-Ethyl 1-Acetyl-2-(1-methyl-1H-imidazole-2-carbonyl)-3-phenylcyclopropanecarboxylate (**3af**).* Yellowish oil, 81.7 mg, 80% yield, 99% ee, 1:4 dr, $[\alpha]_D^{25}$ = −50.7 (c = 1.0, $CHCl_3$). The ee was determined by HPLC (Chiralpak column IC, λ = 254 nm, hexane/*i*-PrOH = 70/30, flow rate 1.0 mL/min, $t_{major\text{-}1}$ = 16.65 min, $t_{minor\text{-}1}$ = 10.50 min, $t_{major\text{-}2}$ = 19.13 min, $t_{minor\text{-}2}$ = 13.10 min). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.39 (m, 6H), 7.08 (s, 1H), 4.92 (d, J = 7.6 Hz, 1H), 4.34 (m, 2H), 3.98 (s, 3H), 3.79 (d, J = 7.7 Hz, 1H), 2.03 (s, 3H), 1.29 (t, J = 7.12 Hz, 3H). IR (KBr): ν (cm^{-1}) 2982, 2937, 1733, 1669, 1463, 1429, 1400, 1287, 1261, 1204, 1174, 1112, 1028, 845, 784. HRMS (ESI, m/z) calcd for $C_{19}H_{20}N_2NaO_4$ $[M+H]^+$: 363.1315, found: 363.1314.

Procedure for Synthesis of Biscyclopropane 5b. To an oven-dried 25 mL Schlenk tube equipped with a stir bar, Δ-**Rh1** (3.0 mol%) was added along with conjugated diene **4** (0.3 mmol) and $CHCl_3$ (0.3 mL). After being stirred at room temperature for 5 min, α-bromomalonate **2a** (0.9 mmol, 3 equiv) was added at room temperature followed by NEt_3 (0.9 mmol, 3.0 equiv). The reaction was stirring at the room temperature until consumption of **4** (monitored by thin layer chromatography). The solution directly purified by silica gel column chromatography (EtOAc/Petroleum ether = 1:3) to afford cyclopropane **5a** and biscyclopropane **5b**.

*(2R,3R)-Diethyl 2-((E)-Hept-1-en-1-yl)-3-(1-methyl-1H-imidazole-2-carbonyl)cyclopropane-1,1-dicarboxylate (**5a**).* Yelowish oil, 85.5 mg, 73% yield, 95% ee, $[\alpha]_D^{25}$ = +14.4 (c = 1.0, $CHCl_3$). The ee was determined by HPLC (Chiralpak column IC, λ = 254 nm, hexane/*i*-PrOH = 70/30, flow rate 1.0 mL/min, t_{major} = 12.75 min, t_{minor} = 8.35 min). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.21 (s, 1H), 7.07 (s, 1H), 5.90−5.83 (m, 1H), 5.40−5.34 (m, 1H), 4.38 (d, J = 7.0 Hz, 1H), 4.33−4.16 (m, 4H), 3.95 (s, 3H), 3.05 (dd, J = 7.0 Hz, J = 8.8 Hz, 1H), 2.02 (m, 2H), 1.29−1.22 (m, 6H), 0.87 (t, J = 6.6 Hz, 3H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ = 185.9, 166.4, 166.3, 143.3, 136.9, 129.9, 127.5, 122.5, 61.9, 61.5, 45.4, 36.7, 36.4, 36.1, 32.5, 31.3, 28.7, 22.5, 14.1, 14.0. IR (KBr): ν (cm^{-1}) 2959, 2930, 2858, 1735, 1669, 1465, 1400, 1369, 1278, 1199, 1157, 1102, 1027, 972, 918, 862, 780, 691. HRMS (ESI, m/z) calcd for $C_{21}H_{31}N_2O_5$ $[M+H]^+$: 391.2227, found: 391.2232.

*Tetraethyl 3-(1-Methyl-1H-imidazole-2-carbonyl)-3′-pentyl-[1,1′-bi(cyclopropane)]-2,2,2′,2′-tetracarboxylate (**5b**).* Yellowish oil, 26 mg, 16% yield, 97% ee, $[\alpha]_D^{25}$ = −18.2 (c = 1.0, $CHCl_3$). The ee was determined by HPLC (Chiralpak column IC, λ = 254 nm, hexane/*i*-PrOH = 70/30, flow rate 1.0 mL/min, t_{major} = 16.07 min, t_{minor} = 7.67 min). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.15 (m, 1H), 6.99 (s, 1H), 4.31 (d, J = 7.0 Hz, 1H), 4.27−4.02 (m, 4H), 3.86 (s, 3H), 2.22 (dd, J = 7.0 Hz, J = 8.0 Hz, 1H), 2.01 (m, 1H), 1.90 (m, 1H), 1.23−1.10 (m, 20H), 0.75 (t, J = 6.8 Hz, 3H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ = 185.5, 167.8, 167.7, 166.2, 165.8, 143.2, 130.0, 127.5, 62.2, 61.6, 61.4, 61.2, 44.5, 39.8, 36.1, 36.0, 32.9, 32.0, 31.4, 31.3, 30.2, 29.7, 29.4, 28.3, 27.4, 22.5, 14.1, 14.0, 13.9. IR (KBr): ν (cm^{-1}) 2960, 2934, 2860, 1732, 1669, 1466, 1415, 1369, 1298, 1263, 1201, 1157, 1029, 917, 861, 793, 738. HRMS (ESI, m/z) calcd for $C_{28}H_{41}N_2O_9$ $[M+H]^+$: 549.2807, found: 549.2805.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.6b02583.

Optimization of reaction condition and NMR and HPLC spectra (PDF)
Crystallographic data for **3ka** (CIF)
Crystallographic data for **Δ-Rh3** (CIF)

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Notes

The authors declare no competing financial interest.

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