Asymmetric Reductive Ring-Opening of Bicyclic Olefins Catalyzed by Palladium and Nickel Complexes

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Supporting Information

General Procedure for the Palladium-Catalyzed Reductive Ring-Opening

Reaction: A 50-mL round bottom side-arm flask was charged with Pd[(*R*)-binap]Cl₂ (0.025 mmol) and zinc powder (2.50 mmol). The system was evacuated and purged with nitrogen gas three times. To the flask was added freshly distilled toluene (2.0 mL) via a syringe and the mixture was stirred for 20 min. Organic acid **2** (1.50 mmol) was then added and the reaction mixture was further stirred at room temperature for 1 h. 7-Oxabenzonorbornadiene **1** (0.50 mmol) in toluene (1.0 mL) was introduced and the reaction was allowed to run for the specified time as shown in Table 2. The solution was then stirred in air for 15 min and was filtered through a short Celite and silica gel pad and washed with dichloromethane several times. The filtrate was concentrated and the residue was purified on a silica-gel column using a hexane-ethyl acetate mixture as eluent to afford the desired product **3**. The enantiomeric excess was determined by HPLC analysis using a chiral column.

General Procedure for the Nickel-Catalyzed Reductive Ring-Opening

Reaction: A 50-mL round bottom side-arm flask was charged with Ni[(*S*)-binap]I₂ (0.025 mmol), zinc powder (2.50 mmol) and oxabenzonorbornadiene **1** (0.50 mmol). The system was evacuated and purged with nitrogen three times and freshly distilled acetonitrile (3.0 mL) was added via a syringe. The reaction mixture was stirred for 10 min and acid **2** (1.50 mmol) was added. The reaction was allowed to run for the specified time as shown in Table 2. The solution was then stirred in air for 15 min and then filtered through a short Celite and silica gel pad and washed with dichloromethane several times. The filtrate was concentrated and the residue was purified on a silica-gel column using a hexane-ethyl acetate mixture as eluent to afford the desired product **3**. The enantiomeric excess was determined by HPLC analysis using a chiral column as indicated below.

(1S)-1,2-dihydro-1-naphthalenol (3a): Method 1: A flask was charged with Pd[(*R*)-binap]Cl₂ (0.020 g, 0.025 mmol) and Zn (0.163 g, 2.50 mmol). The system was evacuated and purged with N₂ three times and freshly distilled toluene (2.0 mL) was added via a syringe. To the flask was added freshly distilled toluene (3.0 mL) via a syringe and the mixture was stirred for 20 min. valproic acid (CH₃CH₂CH₂)₂CHCOOH (0.23 mL, 2.5 mmol) was then added and the reaction mixture was further stirred at room temperature for 1 h. 7-Oxabenzonorbornadiene **1a** (0.072 g, 0.50 mmol) in toluene (1.0 mL) was introduced and the reaction was further allowed to run for 2 h. Compound **3a** was isolated in (0.651 g) 89 % yield and the R_f value is 0.21 (hexane : EA = 4 : 1). The ee was determined to be 90% using HPLC analysis on a chiral OBH column. Retention times in *n*-hexane : *i*-PrOH = 9 : 1 were 12.6 min (minor) and 13.8 min (major) (0.5 mL/min).

(1R)-1,2-dihydro-1-naphthalenol¹⁻³ (3a): Method 2: A flask was charged with 7-oxabenzonorbornadiene **1a** (0.072 g, 0.50 mmol), Ni[(*S*)-binap]I₂ (0.023 g, 0.025 mmol), Zn (0.163 g, 2.50 mmol). The system was evacuated and purged with N₂ three times and freshly distilled acetonitrile (3 mL) was added via a syringe. After 10-min stirring of the mixture, *t*-butyl acetic acid (CH₃)₃CCH₂COOH (0.19 mL, 1.50 mmol) was added and the reaction was allowed to run for 2 h. Compound **3a** was isolated in (0.0637 g) 87 % yield and the R_f value is 0.21 (hexane : EA = 4 : 1). The ee was determined to be 77 % using HPLC analysis on a chiral OBH column. ([α]_D +37) Retention times in *n*-hexane : *i*-PrOH = 9 : 1 were 12.6 min (major) and 13.8 min (minor) (0.5 mL/min).

¹H NMR (400 MHz, CDCl₃): δ 1.8 (1H, s, br), 2.5 (2H, m), 4.78 (1H, dd, *J* = 12 HZ,

8.0 Hz), 6.0 (1H, m), 6.56 (1H, d, $J = 8$ Hz), 7.13 (1H, dd, $J = 8$ Hz, 4Hz), 7.25 (2H, m), 7.37 (1H, d, $J = 8.0$ Hz); ^{13}C NMR (75 MHz, CDCl_3): δ 32.5, 67.6, 125.3, 125.7, 126.5, 126.9, 127.1, 127.5, 127.8, 128.4.

(1R)-5,8-Dimethyl-1,2-dihydro-1-naphthalenol⁴ (3b): $\text{Ni}[(S)\text{-binap}]\text{I}_2$ (0.023 g, 0.025 mmol), **1b** (0.0860 g, 0.50 mmol), Zn (0.163 g, 2.50 mmol), CH_3CN (3.0 mL) and $(\text{CH}_3)_3\text{CCH}_2\text{COOH}$ (0.19 mL, 1.50 mmol) was stirred at 25 °C for 4 h (see the general procedure). Compound **3b** was isolated in (0.0746 g) 86 % and the R_f value is 0.3 (hexane : EA = 4 : 1). The enantiomeric excess was determined to be 71 % using HPLC analysis on a chiral OD column. Retention times in *n*-hexane : *i*-PrOH = 9 : 1 were 10.7 min (minor) and 11.4 min (major) (0.5 mL/min). ^1H NMR (300 MHz, CDCl_3): δ 1.74 (br, 1 H, OH), 2.32 (s, 3 H), 2.39 (s, 3 H), 2.52-2.53 (m, 1 H), 2.74 (m, 1 H), 4.91 (br, 1 H), 6.01 (t, $J = 9.5$ Hz, 1 H), 6.78 (d, $J = 9.5$ Hz, 1 H), 7.00 (d, $J = 7.2$ Hz, 1H), 7.08 (d, $J = 7.2$ Hz, 1H). ^{13}C NMR (75 MHz, CDCl_3): δ 18.16 (q), 18.89 (q), 32.15 (t), 62.99 (d), 123.95 (d), 124.56 (d), 129.40 (d), 130.00 (d), 130.38 (s), 131.57 (s), 133.39 (s), 133.49 (s); IR (neat): 3388, 2943, 1688, 1449, 1381, 1261, 1050, 805 cm^{-1} ; EI-MS m/z (rel intensity): 174 (M^+ , 0.1), 158 ($\text{M}-\text{H}_2\text{O}^+$, 100); HRMS Calcd for $\text{C}_{12}\text{H}_{14}\text{O}$: 174.1045; Found 174.1050.

Methyl N-[(1S)-1, 2-dihydro-1-naphthalenyl]carbamate (3d): A flask was charged with $\text{Pd}[(R)\text{-binap}]\text{Cl}_2$ (0.020 g, 0.025 mmol), Zn (0.163 g, 2.50 mmol). The system

was evacuated and purged with nitrogen gas three times and freshly distilled toluene (2.0 mL) was added via a syringe. After 20-min stirring, acid (CH₃CH₂CH₂)₂CHCOOH (0.23 mL, 2.50 mmol) was added and the reaction mixture was stirred at room temperature for 1 h. Subsequently, **1d** (0.100 g, 0.50 mmol) in toluene (1.0 mL) was introduced and the reaction was further allowed to run for 3 h. Compound **3d** was isolated in 84% and the ee was determined to be 80 % using HPLC analysis on a chiral OD column. Retention times in *n*-hexane : *i*-PrOH = 9 : 1 were 10.3 min (major) and 13.5 min (minor) (0.5 mL/min). mp 64-65 °C; ¹H NMR (300 MHz, CDCl₃): δ 2.48-2.51 (br, 2 H), 3.64 (s, 3 H), 4.91 (br, 1 H), 5.19 (br, 1 H), 5.94-5.98 (dt, *J* = 9.5 Hz, *J* = 4.1 Hz, 1 H), 6.52 (d, *J* = 9.5 Hz, 1 H), 7.07 (d, *J* = 6.5 Hz, 1 H), 7.20-7.32 (m, 3 H); ¹³C NMR (75 MHz, CDCl₃): δ 47.64, 48.03, 51.99, 125.54, 126.43, 126.94, 127.61, 127.78, 128.04, 133.01, 134.54, 156.29; IR (neat): 3314, 2954, 1701, 1504, 1235, 1051, 942, 771, 689 cm⁻¹; EI-MS *m/z* (rel intensity): 203 (M⁺, 5), 129 (M-NHCOOMe⁺, 100); HRMS Calcd for C₁₂H₁₃NO₂: 203.1031; Found 203.1031.

Methyl N-[-1,4-dimethyl-1,2-dihydro-1-naphthalenyl]carbamate (3e): **1e** (0.114 g, 0.50 mmol), PdCl₂[(*R*)-binap] (0.0200 g, 0.0250 mmol), Zn (0.163 g, 2.50 mmol), toluene (3.0 mL) and (CH₃)₃CCH₂COOH (0.19 mL, 1.50 mmol) at 25 °C for 12 h. The compound **3e** was isolated in 79 % yield (0.0914 g) and the *R_f* is 0.39 (hexane : EA = 4 : 1). The ee was determined to be 27 % using HPLC analysis on a chiral OD column. Retention times in *n*-hexane : *i*-PrOH = 9 : 1 were 15.1 min (major) and 15.7 min (minor) (0.5 mL/min). ¹H NMR (300 MHz, CDCl₃): δ 1.62 (s, 3 H), 2.06 (s, 3 H),

2.29 (d, $J = 17.0$ Hz, 1 H), 3.08 (d, $J = 17.0$ Hz, 1 H), 3.59 (s, 3 H), 5.06 (br, 1 H), 5.76 (br, 1 H), 7.24-7.27 (m, 3 H), 7.43-7.44 (m, 1 H); ^{13}C NMR (75 MHz, CDCl_3): δ 19.29 (q), 26.62 (q), 35.87 (t), 51.57 (s), 54.16 (q), 122.93 (d), 123.71 (d), 123.87 (d), 127.34, 127.42 (d), 131.64 (s), 134.21 (s), 139.57 (s), 155.23 (s); IR (neat): 3374, 2966, 1707, 1494, 1247, 1080, 934, 809, 752 cm^{-1} ; EI-MS m/z (rel intensity): 231 (M^+ , 3.0), 172 (M-COOMe^+ , 100); HRMS Calcd for $\text{C}_{14}\text{H}_{16}\text{NO}_2$: 231.1260; Found 231.1271.

N-[(1R)-1,2-dihydro-1-naphthalenyl]-4-methyl-1-benzenesulfonamide (3f): **1f** (0.148 g, 0.50 mmol), $\text{PdCl}_2[(R)\text{-BINAP}]$ (0.020 g, 0.025 mmol), Zn (0.163 g, 2.50 mmol), toluene (3.0 mL) and $(\text{CH}_3)_3\text{CCH}_2\text{COOH}$ (0.19 mL, 1.50 mmol) at 25 $^\circ\text{C}$ for 12 h. The compound **3f** was isolated in 82 % yield (0.1226 g) and the R_f value is 0.25 (hexane : EA = 2 : 1). The ee was determined to be 71 % using HPLC analysis on a chiral OD column. Retention times in n -hexane : i -PrOH = 9 : 1 were 22.9 min (major) and 24.1 min (minor) (0.5 mL/min). ^1H NMR (300 MHz, CDCl_3): δ 2.41 (s, 5 H), 4.46 (m, 1 H), 5.08 (d, $J = 8.4$ Hz, 1 H), 5.86 (dd, $J = 9.5$ Hz, $J = 4.7$ Hz, 1 H), 6.47 (d, $J = 9.5$ Hz, 1 H), 6.91-6.94 (m, 1 H), 7.00-7.06 (m, 2 H), 7.19 (t, $J = 7.3$ Hz, 1 H), 7.26 (d, $J = 7.8$ Hz, 2 H), 7.70 (d, $J = 7.8$ Hz, 2 H); ^{13}C NMR (75 MHz, CDCl_3): δ 21.43, 30.84, 50.91, 125.19, 126.45, 126.80, 126.94, 127.49, 127.78, 128.26, 129.55, 132.99, 133.37, 138.02, 143.17; IR (neat): 3279, 3044, 2938, 1598, 1488, 1425, 1319, 1157, 1088, 931, 815, 667 cm^{-1} ; EI-MS m/z (rel intensity): 299 (M^+ , 7), 297 (M-H_2^+ , 35), 144 ($\text{M-SO}_2\text{-}p\text{-CH}_3\text{-Ph}^+$, 85), 115 (100); HRMS Calcd for $\text{C}_{17}\text{H}_{17}\text{O}_2\text{SN}$: 299.0981; Found 299.0967.

Dimethyl (1*R*,2*R*,6*R*)-6-Hydroxy-3-cyclohexene-1,2-dicarboxylate (5): **4** (0.106 g, 0.50 mmol), NiI₂[(*S*)-BINAP] (0.023 g, 0.025 mmol), Zn (0.163 g, 2.50 mmol), CH₃CN (3.0 mL) and (CH₃)₃CCH₂COOH (0.19 mL, 1.50 mmol) at 30 °C for 3 days. Compound **5** was isolated in (0.0674 g) 63 % and the valve R_f is 0.17 (hexane : EA = 4 : 1). The ee was determined to be 43% using HPLC analysis on a chiral OD column. Retention times in *n*-hexane : *i*-PrOH = 85 : 15 were 14.0 min (minor) and 14.6 min (major) (0.5 mL/min). ¹H NMR (400 MHz, CDCl₃): δ 2.00 (m, 1 H), 2.41-2.47 (m, 1 H), 2.64 (dd, *J* = 9.6 Hz, *J* = 5.6 Hz, 1 H), 3.62 (s, 3 H), 3.65 (s, 4 H), 4.08 (br, 1 H), 4.37 (td, *J* = 9.6 Hz, *J* = 5.6 Hz, 1 H), 5.68-5.69 (m, 2 H); ¹³C NMR (75 MHz, CDCl₃): δ 32.37 (t), 43.05 (d), 46.88 (d), 51.85 (q), 52.02 (q), 64.25 (d), 122.12 (d), 127.02 (d), 172.01 (s), 173.80 (s); IR (neat): 3454, 2953, 1732, 1437, 1216, 1044 cm⁻¹; EI-MS *m/z* (rel intensity): 358 (M⁺, 11), 323 (M-Cl⁺, 17), 322 (M-HCl⁺, 56), 305 (M-HCl-OH⁺, 8); HRMS Calcd for C₁₀H₁₄O₅: 214.0841; Found 214.0856.

Methyl 7-Oxo-6-oxabicyclo[3.2.1]oct-2-ene-8-carboxylate (7): **6** (0.106 g, 0.50 mmol), NiI₂[(*S*)-BINAP] (0.023 g, 0.025 mmol), Zn (0.163 g, 2.50 mmol), THF (3.0 mL), (CH₃)₃CCH₂COOH (0.19 mL, 1.50 mmol) at 25 °C for 3 days and compound **7** was isolated in (0.0774 g) in 85 % yield. The R_f value is 0.19 (hexane : EA = 3 : 2) and the ee was determined to be 53 % using HPLC analysis on a chiral OBH column (*n*-hexane : *i*-PrOH = 85 : 15). ¹H NMR (300 MHz, CDCl₃): δ 2.53-2.54 (m, 2 H), 2.88 (s, 1 H), 3.27 (d, *J* = 7.0 Hz, 1 H), 3.70 (s, 3 H), 4.97 (s, 1 H), 5.75 (d, *J* = 8.5 Hz, 1 H), 6.00 (t, *J* = 8.5 Hz, 1H). ¹³C NMR (75 MHz, CDCl₃): δ 32.83 (t), 39.93 (d), 49.24 (d), 52.54 (q), 77.51 (d), 125.10 (d), 127.25 (d), 170.93 (s), 174.95 (s); IR (neat):

2958, 2362, 1782, 1732, 1437, 1350, 1204, 1029 cm^{-1} ; EI-MS m/z (rel intensity): 182 (M^+ , 100), 181 ($M-1^+$, 41); HRMS Calcd for $\text{C}_9\text{H}_{10}\text{O}_4$: 182.0579; Found 182.0571.

(1R*,5R*,6R*)-6-Methoxy-5-(phenylsulfonyl)-3-cyclohexen-1-ol (9):

$\text{NiI}_2[(S)\text{-BINAP}]$ (0.023 g, 0.025 mmol), **8** (0.133 g, 0.50 mmol), Zn (0.163 g, 2.50 mmol), CH_3CN (3.0 mL) and $(\text{CH}_3)_3\text{CCH}_2\text{COOH}$ (0.19 mL, 1.50 mmol) at 25 °C for 12 h. Retention times of the racemic compound **9** in *n*-hexane : *i*-PrOH = 9 : 1 were 36.3 min and 42.2 min (0.5 mL/min). Compound **9** was isolated in (0.071 g) 53 % and the value R_f is 0.28 (hexane : EA = 1 : 1). mp 130-131 °C; ^1H NMR (300 MHz, CDCl_3): δ 2.29 (br, 3 H), 3.25 (s, 3H), 3.82 (t, $J = 4.2$ Hz, 1 H), 4.02 (br, 2 H), 5.70 (d, $J = 8.2$ Hz, 1 H), 5.97-5.99 (m, 1 H), 7.55-7.69 (m, 3 H), 7.91 (d, $J = 7.3$ Hz, 1 H); ^{13}C NMR (75 MHz, CDCl_3): 30.18, 57.01, 64.57, 65.23, 77.42, 116.30, 128.61, 129.02, 131.48, 133.77, 138.58; IR (neat): 3483, 2920, 1447, 1300, 1144, 1000, 761, 725, 635 cm^{-1} ; EI-MS m/z (rel intensity): 268 (M^+ , 69), 250 ($M-\text{H}_2\text{O}^+$, 11), 127 ($M-\text{SO}_2\text{Ph}^+$, 80); HRMS Calcd for $\text{C}_{13}\text{H}_{16}\text{SO}_4$: 268.0769; Found 268.0763.

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