Supporting Information

Axially Chiral Biaryl Diols (BAMOLs) Catalyze Highly Enantioselective Hetero— Diels-Alder Reactions Through Hydrogen Bonding

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EXPERIMENTAL PROCEDURES and CHARACTERIZATION DATA

General Experimental. All reactions were carried out in oven- or flame-dried glassware under an inert atmosphere of nitrogen or argon. (E)-1-dimethylamino-3-*tert*-butyldimethylsiloxy-1,3-butadiene was synthesized by literature methods and distilled prior to use. All liquid aldehydes were distilled prior to use. All solid aldehydes were recrystallized prior to use. Pd(OAc)₂ (Strem), 1,3-bis(diphenylphosphino)propane (dppp) (Aldrich), and carbon monoxide (Aldrich) were used as received. Acetyl chloride was distilled from *N,N*-dimethylaniline just prior to use. PhCH₃, CH₂Cl₂, and diisopropylethylamine were distilled over CaH₂ under an atmosphere of argon. Methanol was distilled over magnesium turnings under an atmosphere of argon. Dimethyl sulfoxide was distilled over CaH₂ under vacuum and stored under argon. Carbonylations were conducted in a Fisher-Porter apparatus. ¹H and ¹³C NMR were recorded at 500 MHz and 125 MHz respectively on a Bruker DRX-500 spectrometer. Proton chemical shifts were internally referenced to the residual proton resonance in CDCl₃ (δ 7.26). Carbon chemical shifts were internally referenced to the deuterated solvent signals in CDCl₃ (δ 77.00). Infrared spectra were obtained on a Nicolet 20 SXB FT-IR spectrometer. Melting points are uncorrected and were measured on a Fisher-Johns melting point apparatus. TLCs were run on Whatman Partisil K6F thin layer chromatography plates (250 μm, 60 Å). Silica gel (60 Å, 230-400 mesh) was obtained from Silicycle and used as received. All enantiomeric excesses were determined by Chiral High-performance liquid chromatography (HPLC) and were run on a Varian

ProStar Series equipped with a variable wavelength detector using Diacel chiral stationary columns fitted with a guard column. Optical rotations were measured on a JASCO DIP-1000 digital polarimeter. Absolute stereochemistry of dihydropyranones were assigned from literature optical rotations, otherwise stereochemistry was tentatively assigned.

(R)-2,2'-bis(trifluoromethanesulfonate)-5,5',6,6',7,7',8,8'-octahydro-1,1'-binaphthyl

The title compound was prepared from the corresponding commercially available diol (Aldrich) following a procedure for triflation of (S)-BINOL.¹

Representative procedure for synthesis of (R)-2,2'-bis(carbomethoxy)-5,5',6,6',7,7',8,8'-octahydro-1,1'-binaphthyl²

Bistriflate (2.20 g, 3.94 mmol), methanol (7.98 mL, 197 mmol, 50 equiv.) and diisopropylethylamine (3.02 mL, 17.33 mmol, 4.4 equiv.) were dissolved in 19.7 mL of dimethyl sulfoxide. This homogeneous solution was transferred via cannula to a Fisher-Porter flask charged with Pd(OAc)₂ (0.133 g, 0.59 mmol, 0.15 equiv.), dppp (0.244 g, 0.59 mmol, 0.15 equiv.) and a stir bar under an atmosphere of argon. The vessel was then sealed and quickly cycled three times between a vacuum and an atmosphere of CO. The CO pressure in the flask was increased to 1.5 atm and partially immersed in an 80° C oil bath. The reaction was followed by TLC at roughly 24 h intervals following the release of pressure and removal from heat. After complete consumption of all starting

material (48 – 72 h) the reaction was purged with nitrogen and cooled to room temperature. The contents were transferred to a flask for removal of a majority of excess solvents *in vacuo*. The reduced mixture was diluted with ethyl acetate (40 mL), washed with water (3 x 10 mL), saturated NaCl solution (10 mL), and dried over anhydrous MgSO₄. The filtered solution was concentrated *in vacuo* and purified by flash column chromatography (5:1 hexanes:EtOAc) to afford a white solid (1.250 g, 83 %). $[\alpha]_D^{27} = -1.6^\circ$ (*c* 1.0, CHCl₃); ¹H NMR (CDCl₃, 500 MHz) δ 7.75 (2H, d, *J* = 8.0 Hz), 7.12 (2H, d, *J* = 8.0 Hz), 3.56 (6H, s), 2.86 (4H, m), 2.17 (2H, ddd, *J* = 13.0, 6.0, 6.0 Hz), 1.99 (2H, ddd, *J* = 12.0, 6.0, 6.0 Hz), 1.74 (4H, m), 1.65 (4H, m); ¹³C NMR (CDCl₃, 125 MHz) δ 167.42, 141.76, 141.56, 135.25, 127.91, 127.00, 126.46, 51.52, 30.30, 27.29, 23.14, 22.49; IR (film) ν 2933, 1733, 1717, 1700, 1684, 1653, 1559, 1540, 1506, 1457, 1436, 1294, 1277, 1257, 1190, 1129 cm⁻¹.

Representative procedure for the synthesis of 3a and 3b:

(R)-2,2'-bis(hydroxybis(4-fluoro-3,5-diethylphenyl)methyl)-5,5',6,6',7,7',8,8'-octahydro-1,1'-binaphthyl (3b)

A solution of *n*-BuLi in hexanes (1.6 M, 6.25 mL, 10.00 mmol) was added slowly to a solution of 5-bromo-1,3-diethyl-2-fluoro-benzene³ (2.29 g, 9.91 mmol) in THF (40 mL) at –78 °C. The resulting reaction mixture was stirred at –78 °C for 30 min. prior to the slow addition of a THF solution (20 mL) of diester (757 mg, 2.00 mmol). The reaction mixture was stirred for 1 h at –78 °C followed by 1 hour at –10 °C, and then quenched with a slow addition of a saturated NaHCO₃ solution (60 mL). The mixture was extracted with diethyl ether (2 x 40 mL). The combined organic layers were washed with saturated NaCl solution (150 mL), dried over anhydrous Na₂SO₄, and concentrated *in vacuo*. The resulting crude material was purified by flash column chromatography on silica gel (99:1 hexanes:Et₂O) to afford the title compound as a white solid (1.33 g, 72 %).

(R)-2,2'-bis(hydroxybis(4-flouro-3,5-dimethylphenyl)methyl)-5,5',6,6',7,7',8,8'-octahydro-1,1'-binaphthyl (3a)

Isolated as a white powder; $[\alpha]_D^{30} = +101.6^\circ$ (c 1.0, CHCl_3); ^1H NMR (CDCl_3 500 MHz) δ 6.92 (2H, d, $J = 8.0$ Hz), 6.83 (2H, dd, $J = 6.0, 6.0$ Hz), 6.77 (2H, d, $J = 8.0$ Hz), 2.67 (2H, ddd, $J = 16.0, 6.0, 6.0$), 2.56 (2H, ddd, $J = 16.0, 7.0, 7.0$ Hz), 2.18 (24H, d, $J = 14.5$ Hz), 1.51-1.41 (2H, m), 1.41-1.31 (2H, m), 1.18-1.08 (2H, m) 0.98-0.88 (2H, ddd, $J = 5.5, 5.5, 9.0$ Hz), 0.77-0.67 (2H, m); ^{13}C NMR (CDCl_3 , 126 MHz) δ 159.84 (d, $J = 24.0$ Hz), 157.90 (d, $J = 24.0$ Hz), 144.16 (d, $J = 4.0$ Hz), 140.28, 139.19 (d, $J = 4.0$ Hz), 137.73, 136.84, 136.66, 129.22 (d, $J = 5.0$ Hz), 128.84, 128.58, 127.94 (d, $J = 5.0$ Hz), 127.37, 123.38 (d, $J = 18.0$ Hz), , 123.20 (d, $J = 18.0$ Hz), 83.43, 29.80, 29.70, 26.91, 22.64, 22.35, 14.90 (dd, $J = 12.5, 4.0$ Hz); IR (film) ν 3534, 3490, 3419, 2928, 2860, 1489, 1457, 1436, 1380, 1310, 1264, 1209, 1138, 1127, 1061, 973, 907, 882, 842 cm^{-1} .

(R)-2,2'-bis(hydroxybis(4-flouro-3,5-dimethylphenyl)methyl)-5,5',6,6',7,7',8,8'-octahydro-1,1'-binaphthyl

Isolated as a white powder; $[\alpha]_D^{30} = +83.1^\circ$ (c 1.0, CHCl_3); ^1H NMR (CDCl_3 500 MHz) δ 6.90 (6H, d, $J = 7.0$ Hz), 6.86 (4H, d, $J = 7.0$ Hz), 6.71 (2H, d, $J = 8.0$ Hz), 4.20 (s, 2H), 2.66-2.48 (20H, m) 1.48-1.40 (2H, m), 1.40-1.30 (4H, m), 1.12 (24H, dt, $J = 11.5, 7.5$ Hz), 0.93 (1H, t, $J = 16.5$ Hz), 0.90 (1H, t, $J = 16.5$ Hz), 0.77-0.67 (2H, m); ^{13}C NMR (CDCl_3 , 125 MHz) δ 159.14 (d, $J = 26.5$ Hz) 157.20 (d, $J = 26.5$ Hz), 144.33 (d, $J = 3.5$ Hz), 139.45 (d, $J = 3.5$ Hz), 140.55, 137.47, 136.67 (d, $J = 2.5$ Hz), 129.44 (d, $J = 6.0$

Hz), 129.31 (d, $J = 6.0$ Hz), 128.97, 128.76, 128.16, 127.76 (d, $J = 5.0$ Hz), 127.28, 126.59 (d, $J = 5.0$ Hz), 125.23, 119.52, 83.59, 29.58, 26.80, 22.28, 22.54, 22.46 (d, $J = 2.6, 8.5$ Hz), 22.28, 14.53 (d, $J = 39.0$ Hz); IR (film) ν 3536, 3495, 2968, 2935, 2875, 1477, 1464, 1375, 1286, 1202, 1137, 1072, 907, 887, 839, 783, 734 cm^{-1} .

General Procedure for Enantioselective Hetero Diels-Alder Reactions (Table 1)

To a solution of the aldehyde (1.0 mmol) and either diol **3a** or **3b** (0.1 mmol) in PhCH_3 (0.5 mL) at either -40 or -80 $^{\circ}\text{C}$ (temp of cooling bath) was added (*E*)-1-dimethylamino-3-*tert*-butyldimethylsiloxy-1,3-butadiene (**1**) (0.5 mmol) dropwise (5-10 sec). The reaction was maintained at the temperature for the specified time indicated in Table 1. The reaction was then brought to -78 $^{\circ}\text{C}$ (dry ice/acetone) prior to dilution with CH_2Cl_2 (1.0 mL) and subsequent addition of acetyl chloride (1.0 mmol). This was allowed to stir for 30 min at -78 $^{\circ}\text{C}$ before transferring the crude mixture directly on top of a silica gel column and eluting with hexanes/ethyl acetate to afford the desired dihydropyranone.

2,3-Dihydro-2-methyl-4*H*-pyran-4-one (**4a**)

Isolated as a clear, pale yellow oil: 97% ee [Chiralcel AD-H, hexane:*i*-propanol = 99:1, 1.0 mL/min, t_R (major) 23.6 min, t_R (minor) 27.7 min]; $[\alpha]_D^{29} = -148.2^{\circ}$ (c 1.0, CHCl_3); ^1H NMR (CDCl_3 , 500 MHz) δ 7.35 (1H, d, $J = 6.0$ Hz), 5.41 (1H, dd, $J = 6.0, 1.0$ Hz), 4.55 (1H, m), 2.51 (1H, dd, $J = 16.5, 13.0$ Hz), 2.44 (1H, ddd, $J = 4.0, 1.0, 0.5$), 1.46 (1H, d, $J = 6.5$ Hz); ^{13}C NMR (CDCl_3 , 125 MHz) δ 192.7, 163.3, 106.8, 75.9, 43.4, 20.3; IR (film) ν 2981, 2937, 2902, 1684, 1675, 1594, 1576, 1457, 1406, 1287, 1230, 1190, 1111, 1050, 937, 877, 824, 790 cm^{-1} .

(*S*)-2,3-Dihydro-2-*n*-propyl-4*H*-pyran-4-one (**4b**)⁴

Isolated as a clear, pale yellow oil: 94% ee [Chiralcel OD-H, hexane:*i*-propanol = 99:1, 0.5 mL/min, t_R (major) 23.5 min, t_R (minor) 26.5 min]; $[\alpha]_D^{28} = -78.4^\circ$ (c 1.0, CHCl_3); ^1H NMR (CDCl_3 , 500 MHz) δ 7.32 (1H, d, $J = 6.0$ Hz), 5.36 (1H, dd, $J = 6.0, 1.0$ Hz), 4.37 (1H, m), 2.47 (1H, dd, $J = 16.0, 12.5$ Hz), 2.38 (1H, ddd, $J = 16.5, 4.0, 1.0$ Hz), 1.77 (1H, m), 1.61 (1H, m), 1.44 (2H, m), 0.93 (3H, t, $J = 7.5$ Hz); ^{13}C NMR (CDCl_3 , 125 MHz) δ 192.8, 163.3, 106.9, 79.3, 41.8, 36.4, 18.0, 13.7; IR (film) ν 2962, 2931, 2874, 1683, 1596, 1457, 1407, 1274, 1218, 1037, 917, 790 cm^{-1} .

(S)-2,3-dihydro-2-phenethyl-4H-pyran-4-one (4c)⁵

Isolated as a clear, pale yellow oil: 95% ee [Chiralcel OD-H, hexane:*i*-propanol = 90:10, 1.0 mL/min, t_R (major) 17.9 min, t_R (minor) 28.8 min]; $[\alpha]_D^{28} = -102.2^\circ$ (c 1.0, CHCl_3); ^1H NMR (CDCl_3 , 500 MHz) δ 7.39 (1H, d, $J = 6.0$ Hz), 7.30 (2H, t, $J = 7.5$ Hz), 7.21 (3H, m), 5.42 (1H, dd, $J = 6.0, 1.0$ Hz), 4.40 (1H, ddd, $J = 13.0, 8.0, 4.0$ Hz), 2.84 (1H, m), 2.76 (1H, m), 2.54 (1H, dd, $J = 16.5, 14.5$ Hz), 2.38 (1H, ddd, $J = 17.0, 3.0, 0.5$ Hz), 2.20-2.13 (1H, m), 1.99-1.92 (1H, m); ^{13}C NMR (CDCl_3 , 125 MHz) δ 192.41, 163.12, 140.63, 128.57, 128.36, 126.23, 107.08, 78.45, 41.83, 36.04, 30.95; IR (film) ν 3026, 2926, 2865, 1675, 1594, 1456, 1406, 1269, 1225, 1196, 1043, 1016, 752, 700 cm^{-1} .

2,3-dihydro-2-(2-(phenylthio)ethyl)-4H-pyran-4-one (4d)

Isolated as a clear, colorless oil: 94% ee [Chiralcel AD-H, hexane:*i*-propanol = 80:20, 0.5 mL/min, t_R (major) 13.6 min, t_R (minor) 14.4 min]; $[\alpha]_D^{28} = -113.8^\circ$ (c 1.0, CHCl_3); ^1H

NMR (CDCl₃, 500 MHz) δ 7.40-7.18 (6H, m), 5.41 (1H, d, J = 6.0 Hz), 4.60 (1H, ddd, J = 16.5, 8.0, 3.5 Hz), 3.18-3.10 (1H, m), 3.09-3.00 (1H, m), 2.53 (1H, dd, J = 16.5, 14.0 Hz), 2.42 (1H, dd, J = 16.5, 3.0 Hz), 2.20-2.10 (1H, m), 1.97-1.88 (1H, m); ¹³C NMR (CDCl₃, 125 MHz) δ 191.99, 162.85, 135.37, 129.61, 129.04, 126.42, 107.23, 77.61, 41.67, 33.92, 29.08; IR (film) ν 3056, 2926, 1676, 1596, 1481, 1484, 1405, 1276, 1233, 1213, 1193, 1043, 1025, 1013, 793, 741, 691 cm⁻¹.

2-(3-(3,4-dihydro-4-oxo-2H-pyran-2-yl)propyl)isoindoline-1,3-dione (4e)

Isolated as a yellow oil: 92% ee [Chiralcel OD-H, hexane:*i*-propanol = 50:50, 0.5 mL/min, t_R (minor) = 19.6 min, t_R (major) = 21.4 min]; $[\alpha]_D^{29}$ = -74.6° (*c* 1.0, CHCl₃); ¹H NMR (CDCl₃, 500 MHz) δ 7.85 (2H, dd, J = 5.5, 3.0 Hz), 7.73 (2H, dd, J = 5.5, 3.0 Hz), 7.32 (1H, d, J = 6.0 Hz), 5.39 (1H, d, J = 6.0 Hz), 4.44 (1H, m), 3.75 (t, 1H, J = 7.0 Hz), 2.51 (1H, dd, J = 16.5, 14.0 Hz), 2.41 (1H, dd, J = 16.5, 3.0 Hz), 1.98-1.88 (1H, m), 1.88-1.78 (1H, m), 1.76-1.68 (1H, m); ¹³C NMR (CDCl₃, 125 MHz) δ 192.31, 168.36, 163.04, 134.03, 131.99, 123.28, 107.08, 78.78, 41.80, 37.40, 31.64, 24.13; IR (film) ν 2938, 1771, 1709, 1675, 1594, 1399, 1363, 1272, 1218, 1046, 720 cm⁻¹.

2,3-dihydro-2-(prop-1-ynyl)-4H-pyran-4-one (4f)

Isolated as a pale, yellow solid: 98% ee [Chiralcel AD-H, hexane:*i*-propanol = 95:5, 0.5 mL/min, t_R (major) 22.4 min, t_R (minor) 26.2 min]; $[\alpha]_D^{29}$ = -248.7° (*c* 1.0, CHCl₃); m.p. = 51-53 °C (CHCl₃); ¹H NMR (CDCl₃, 500 MHz) δ 7.30 (1H, d, J = 6.0 Hz), 5.46 (1H, d, J = 6.0 Hz), 5.15 (1H, ddd, J = 9.0, 5.0, 2.0 Hz), 2.79-2.67 (1H, m), 1.89 (3H, J = 2.0 Hz); ¹³C NMR (CDCl₃, 125 MHz) δ 190.81, 161.92, 107.55, 84.84, 74.34, 69.28, 42.60,

3.63; IR (film) ν 2921, 2252, 1683, 1597, 1402, 1363, 1268, 1222, 1035, 979, 929, 843, 794 cm^{-1} .

2,3-Dihydro-2-*iso*-butyl-4*H*-pyran-4-one (4g)

Isolated as a clear, pale yellow oil: 94% ee [Chiralcel OD-H, hexane:*i*-propanol = 80:20, 0.5 mL/min, t_R (major) 8.9 min, t_R (minor) 9.7 min]; $[\alpha]_D^{28} = -97.4^\circ$ (c 1.0, CHCl_3); ^1H NMR (CDCl_3 , 500 MHz) δ 7.34 (1H, d, $J = 6.0$ Hz), 5.39 (1H, dd, $J = 6.0, 1.0$ Hz), 4.47 (1H, m), 2.49 (1H, dd, $J = 17.0$ Hz, 13.5 Hz), 2.42 (1H, ddd, $J = 17.0, 4.0, 0.5$ Hz), 1.82 (2H, m), 1.42 (1H, m), 0.95 (6H, d, $J = 6.5$ Hz); ^{13}C NMR (CDCl_3 , 125 MHz) δ 192.7, 163.3, 106.9, 78.0, 43.4, 42.3, 24.09, 22.9, 22.1; IR (film) ν 2959, 2930, 2872, 1683, 1596, 1469, 1407, 1275, 1219, 1178, 1038, 905, 815, 788 cm^{-1} .

(*S*)-2-Cyclohexyl-2,3-dihydro-4*H*-pyran-4-one (4h)⁴

Isolated as a clear, colorless oil: 84% ee [Chiralcel OD-H, hexane:*i*-propanol = 95:5, 0.3 mL/min, t_R (major) 24.7 min, t_R (minor) 26.9 min]; $[\alpha]_D^{28} = -127.2^\circ$ (c 1.0, CHCl_3); ^1H NMR (CDCl_3 , 500 MHz) δ 7.36 (1H, d, $J = 6.0$ Hz), 5.38 (1H, dd, $J = 6.0, 1.0$ Hz), 4.16 (1H, ddd, $J = 14.5, 5.5, 3.0$ Hz), 2.54 (1H, dd, $J = 16.5, 14.5$ Hz), 2.38 (1H, ddd, $J = 16.5, 3.0, 1.0$ Hz), 1.91 – 1.84 (1H, m), 1.83 – 1.75 (2H, m), 1.74 – 1.62 (3H, m), 1.31 – 1.00 (5H, m); ^{13}C NMR (CDCl_3 , 125 MHz) δ 193.30, 163.59, 106.79, 83.55, 41.34, 39.07, 28.11, 27.99, 26.19, 25.83, 25.76; IR (film) ν 2928, 2854, 1681, 1596, 1450, 1407, 1278, 1240, 1215, 1038, 993, 910, 793 cm^{-1} .

(*S*)-2,3-Dihydro-2-phenyl-4*H*-pyran-4-one (4i)⁶

Isolated as a clear, colorless oil: >98% ee [Chiralcel OD-H, hexane:*i*-propanol = 90:10, 0.9 mL/min, t_R (major) 12.9 min, t_R (minor) 15.0 min]; $[\alpha]_D^{28} = -100.8^\circ$ (c 1.0, CHCl_3); ^1H NMR (CDCl_3 , 500 MHz) δ 7.59 (1H, d, $J = 6.5$ Hz), 7.43 (5H, m), 5.54 (1H, dd, $J = 6.5, 1.0$ Hz), 5.43 (1H, dd, $J = 14.0, 4.5$ Hz), 2.92 (1H, dd, $J = 17.0, 14.0$ Hz), 2.67 (1H, ddd, $J = 17.0, 4.5, 1.0$ Hz); ^{13}C NMR (CDCl_3 , 125 MHz) δ 192.2, 163.2, 137.8, 128.9, 128.8, 126.1, 107.4, 81.1, 43.4; IR (film) ν 1676, 1595, 1403, 1270, 1227, 1209, 1038, 933, 758, 698 cm^{-1} .

2,3-Dihydro-2-(3-Methoxyphenyl)-4*H*-pyran-4-one (4j)

Isolated as a clear, colorless oil: 98% ee [Chiralcel OD-H, hexane:*i*-propanol = 90:10, 0.5 mL/min, t_R (major) 33.1 min, t_R (minor) 42.5 min]; $[\alpha]_D^{28} = -99.7^\circ$ (c 1.0, CHCl_3); ^1H NMR (CDCl_3 , 500 MHz) δ 7.48 (1H, d, $J = 6.0$ Hz), 7.33 (1H, t, $J = 8.0$ Hz); 6.99-6.89 (3H, m); 5.52 (1H, d, $J = 6.0$ Hz); 5.40 (1H, dd, $J = 14.5, 3.0$ Hz); 3.83 (3H, s); 2.89 (1H, dd, $J = 16.5, 14.5$ Hz); 2.66 (1H, dd, $J = 17.0, 2.5$ Hz); ^{13}C NMR (CDCl_3 , 125 MHz) δ 192.05, 163.095, 159.88, 139.36, 129.93, 118.19, 114.20, 111.76, 107.37, 80.93, 55.29, 43.42; IR (film) ν 1675, 1591, 1491, 1457, 1437, 1402, 1269, 1222, 1038, 782 cm^{-1} .

2,3-dihydro-2-(2-nitrophenyl)-4*H*-pyran-4-one (4k)

Isolated as a clear, pale yellow oil: 98% ee [Chiralcel AD-H, hexane:*i*-propanol = 90:10, 0.5 mL/min, t_R (major) 46.4 min, t_R (minor) 51.3 min]; $[\alpha]_D^{29} = -82.5^\circ$ (c 1.0, CHCl_3); ^1H

NMR (CDCl₃, 500 MHz) δ 8.01 (1H, dd, J = 22.4, 8.0 Hz), 7.82 (1H, d, J = 8.0 Hz), 7.73 (1H, t, J = 7.5 Hz), 7.54 (1H, t, 1H, J = 7.5 Hz), 7.47 (1H, d, J = 6.0 Hz), 6.04 (1H, dd, J = 14.0, 3.0 Hz), 5.56 (1H, d, J = 6.0 Hz), 2.95 (1H, dd, J = 17.0, 2.5 Hz), 2.75 (1H, dd, J = 17.0, 14.0 Hz); ¹³C NMR (CDCl₃, 125 MHz) δ 190.78, 162.55, 147.14, 134.01, 133.80, 129.47, 128.04, 124.89, 107.85, 77.13, 43.06; IR (Film) ν 1683, 1596, 1578, 1526, 1402, 1347, 1269, 1226, 1039, 994, 931, 852, 790, 747 cm⁻¹.

2,3-Dihydro-2-(1-naphthyl)-4H-pyran-4-one (4l)

Isolated as a pale, yellow oil: 97% ee [Chiralcel AS, hexane:*i*-propanol=80:20, 0.5 mL/min, t_R (major) 27.6 min, t_R (minor) 46.2 min]; $[\alpha]_D^{28}$ = +52.2° (c 1.0, CHCl₃); ¹H NMR (CDCl₃, 500 MHz) δ 7.98(1H, d, J = 8.0 Hz), 7.90 (1H, dd, J = 13.5, 8.0 Hz) 7.66 (1H, d, J = 7.0 Hz), 7.60 – 7.50 (4H, m), 6.18 (1H, dd, J = 14.0, 3.0 Hz), 5.62 (1H, d, J = 6.0 Hz), 3.08 (1H, dd, J = 17.0, 14.0 Hz), 2.87 (1H, dd, J = 17.0, 2.5 Hz); ¹³C NMR (CDCl₃, 125 MHz) δ 192.30, 163.35, 133.78, 133.21, 130.00, 129.50, 129.09, 126.73, 126.00, 125.25, 123.85, 122.55, 107.50, 78.41, 42.70; IR (film) ν 1676, 1591, 1403, 1272, 1223, 1037, 932, 800, 776 cm⁻¹.

(S)-2,3-Dihydro-2-(2-furyl)-4H-pyran-4-one (4m)⁴

Isolated as a pale yellow, crystalline solid: >99% ee [Chiralcel OD-H, hexane:*i*-propanol = 90:10, 0.5 mL/min, t_R (major) 23.8 min, t_R (minor) 25.8 min]; $[\alpha]_D^{29}$ = -310.1° (c 1.0, CHCl₃); m.p. = 67-69 °C (EtOAc/hexanes); ¹H NMR (CDCl₃, 500 MHz) δ 7.48 (1H, s), 7.36 (1H, d, J = 6.0 Hz), 6.46 (1H, d, J = 4.0 Hz), 6.41 (1H, dd, J = 3.0, 2.0), 5.51 (1H, dd, J = 6.0, 1.0 Hz), 5.48 (1H, dd, J = 13.0, 4.0 Hz) 3.08 (1H, dd, J = 17.0, 13.0 Hz), 2.72

(¹H, dd, *J* = 17.0, 3.5 Hz); ¹³C NMR (CDCl₃, 125 MHz) δ 191.21, 162.36, 149.96, 143.56, 110.52, 109.64, 107.33, 73.49, 39.48; IR (Film) ν 1676, 1595, 1403, 1273, 1227, 1209, 1037, 1015, 987, 910, 793, 749 cm⁻¹.

(1) Uozumi, Y.; Tanahashi, A.; Hayashi, T., *J. Org. Chem.* **1993**, *58*, 6826.

(2) (a) Kurz, L.; Lee, G.; Morgans, D., Jr.; Waldyke, M. J.; Ward, T., *Tetrahedron Lett.* **1990**, *31*, 6321. (b) Ohta, T.; Ito, M.; Inagaki, K.; Takaya, H., *Tetrahedron Lett.* **1993**, *34*, 1615.

(3) Meade, E. A.; Sznajdman, M.; Pollard, G. T.; Beauchamp, L. M.; Howard, J. L., *Eur. J. Med. Chem.* **1998**, *33*, 363.

(4) Corey, E. J.; Cywin, C. L.; Roper, T. D., *Tetrahedron Lett.* **1992**, *33*, 6907.

(5) Kezuka, S.; Mita, T.; Ohtsuki, N.; Ikeno, T.; Yamada, T., *Bull. Chem. Soc. Jpn.* **2001**, *74*, 1333.

(6) Bednarski, M.; Danishefsky, S., *J. Am. Chem. Soc.* **1986**, *108*, 7060.