

Supporting Information

**Pd-catalyzed 5-*endo-trig*-type cyclization of  $\beta,\gamma$ -unsaturated carbonyl compounds: An efficient ring closing reaction to give  $\gamma$ -butenolides and 3-pyrrolin-2-ones**

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### General information:

$^1\text{H}$  and  $^{13}\text{C}$  NMR spectra were recorded with JEOL JNM-EX270 ( $^1\text{H}$  NMR, 270 MHz;  $^{13}\text{C}$  NMR, 67.7 MHz).  $^1\text{H}$  NMR spectra are reported as follows: chemical shift in ppm ( $\delta$ ) relative to the chemical shift of  $\text{CDCl}_3$  at 7.26 ppm, integration, multiplicities (s = singlet, d = doublet, t = triplet, q = quadruplet, m = multiplet), and coupling constants (Hz).  $^{13}\text{C}$  NMR spectra reported in ppm ( $\delta$ ) relative to the central line of triplet for  $\text{CDCl}_3$  at 77 ppm. IR spectral data were obtained on PERKIN ELMER 2000 FTIR; absorption bands are reported in  $\text{cm}^{-1}$ . ESI/TOF mass spectra were obtained with JMS-T100LC. HRMS spectra were obtained with JEOL MStation JMS-700. Elemental analysis was performed on PERKIN-ELMER 2400. Column chromatography was carried out by  $\text{SiO}_2$  60 N (spherical, neutral, 40–100  $\mu\text{m}$ , KANTO Chemical Co.). Analytical thin layer chromatography (TLC) was performed on 0.2 mm pre-coated plate  $\text{SiO}_2$  60  $\text{F}_{254}$  (Merck). All manipulations were conducted under an argon atmosphere using standard Schlenk techniques.

### Materials:

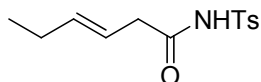
Unless otherwise noted, all materials were obtained from commercial suppliers. Freshly distilled THF and DCM were used (THF was distilled from sodium/benzophenone and DCM was distilled over  $\text{CaH}_2$ ). (*E*)-3-hexenoic acid (**1a**), (*E*)-3-pentenoic acid (**1b**), (*E*)-3-heptenoic acid (**1c**), (*E*)-3-decenoic acid (**1d**), (*E*)-3-octenoic acid and (*E*)-4-phenyl-but-3-enoic acid were commercially available. Carboxylic acids **1a–d** as starting materials for the reaction were used without any purification. Substrates (*E*)-5-phenyl-3-pentenoic acid (**1e**) and (*E*)-5-methyl-3-hexenoic acid (**1f**) were synthesized by the  $\text{SiO}_2$ -catalyzed Knoevenagel condensation between the corresponding aldehyde and malonic acid using a microwave oven (kitchen type, National NE-M310Z).<sup>1</sup> (*E*)-4-Phenoxy-3-butenic acid (**1g**) was synthesized following the reported procedure.<sup>2</sup> Methylation<sup>3</sup> of **1a** afforded (*E*)-2-methyl-3-hexenoic acid (**1h**). Cyclohex-1-enyl acetic acid was synthesized starting from cyclohex-1-enyl acetonitrile.<sup>4</sup>

### General procedure for the synthesis of alkenamides:<sup>5</sup>

The corresponding carboxylic acid precursor (5 mmol) was taken in a flask and to this was added 1 equivalent of *p*-toluenesulfonyl isocyanate. The mixture was dissolved in dry THF under argon atmosphere using argon filled balloon and then stirred at room temperature for 10 min.  $\text{Et}_3\text{N}$  (1 equivalent, 5 mmol, 0.7 mL) was added drop-wise to the reaction mixture via a syringe. After stirring for 3h at room temperature, the solution was diluted with EtOAc (15 mL) and washed with 1N HCl then with brine. After drying with  $\text{Na}_2\text{SO}_4$ , the organic phase was concentrated and purified by flash silica gel column chromatography [hexane to hexane/EtOAc (9/1)] to give alkenamides **7**.

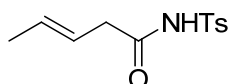
**Analytical data of the alkenamides:**

**(*E*)-*N*-Tosyl-3-hexenamide (7a):**



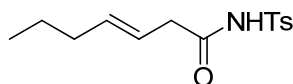
This compound was obtained in 57% yield as colorless solid according to the general procedure described for the synthesis of alkenamides.  $^1\text{H}$  NMR (270 MHz,  $\text{CDCl}_3$ )  $\delta$  0.93 (t,  $J$  = 7.6 Hz, 3H), 1.95–2.06 (m, 2H), 2.41 (s, 3H), 2.95 (d,  $J$  = 7.0 Hz, 2H), 5.32–5.43 (m, 1H), 5.56–5.66 (m, 1H), 7.31 (d,  $J$  = 8.1 Hz, 2H), 7.92 (d,  $J$  = 8.1 Hz, 2H), 8.66 (br s, 1H).  $^{13}\text{C}$  NMR (67.7 MHz,  $\text{CDCl}_3$ )  $\delta$  13.2, 21.6, 25.4, 40.1, 118.9, 128.1, 129.3, 135.3, 138.5, 144.8, 169.5. IR (KBr) 3092, 1683, 1599, 1456, 1346, 1260, 1160, 1092  $\text{cm}^{-1}$ . ESI/TOF mass 290 ( $\text{M}+\text{Na}$ ) $^+$ . Anal. Calcd for  $\text{C}_{13}\text{H}_{17}\text{NO}_3\text{S}$ : C, 58.40; H, 6.41; N, 5.24. Found: C, 58.47; H, 6.42; N, 5.20.

**(*E*)-*N*-Tosyl-3-pentenamide (7b):**



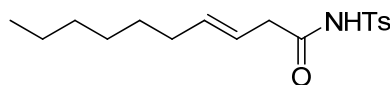
75% yield as colorless solid.  $^1\text{H}$  NMR (270 MHz,  $\text{CDCl}_3$ )  $\delta$  1.64 (d,  $J$  = 5.9 Hz, 3H), 2.41 (s, 3H), 2.94 (d,  $J$  = 6.7 Hz, 2H), 5.34–5.44 (m, 1H), 5.50–5.63 (m, 1H), 7.30 (d,  $J$  = 8.4 Hz, 2H), 7.92 (d,  $J$  = 8.1 Hz, 2H), 8.88 (br s, 1H).  $^{13}\text{C}$  NMR (67.7 MHz,  $\text{CDCl}_3$ )  $\delta$  18.0, 21.7, 40.3, 121.1, 128.2, 129.4, 132.1, 135.3, 145.0, 169.3. IR (KBr) 3246, 1722, 1595, 1434, 1340, 1246, 1164  $\text{cm}^{-1}$ . ESI/TOF mass 276 ( $\text{M}+\text{Na}$ ) $^+$ . Anal. Calcd for  $\text{C}_{12}\text{H}_{15}\text{NO}_3\text{S}$ : C, 56.90; H, 5.97; N, 5.53. Found: C, 56.57; H, 5.94; N, 5.34.

**(*E*)-*N*-Tosyl-3-heptenamide (7c):**



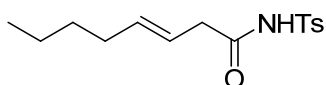
75% yield as colorless crystalline solid.  $^1\text{H}$  NMR (270 MHz,  $\text{CDCl}_3$ )  $\delta$  0.85 (t,  $J$  = 7.3 Hz, 3H), 1.28–1.42 (m, 2H), 1.94–2.02 (m, 2H), 2.42 (s, 3H), 2.95 (d,  $J$  = 6.7 Hz, 2H), 5.33–5.43 (m, 1H), 5.53–5.64 (m, 1H), 7.31 (d,  $J$  = 8.4 Hz, 2H), 7.92 (d,  $J$  = 8.4 Hz, 2H), 8.44 (br s, 1H).  $^{13}\text{C}$  NMR (67.7 MHz,  $\text{CDCl}_3$ )  $\delta$  13.6, 21.7, 22.1, 34.5, 40.2, 120.0, 128.2, 129.4, 135.3, 137.1, 144.9, 169.3. IR (KBr) 3114, 2927, 1683, 1597, 1464, 1352, 1166, 1087  $\text{cm}^{-1}$ . ESI/TOF 304 ( $\text{M}+\text{Na}$ ) $^+$ . Anal. Calcd for  $\text{C}_{14}\text{H}_{19}\text{NO}_3\text{S}$ : C, 59.76; H, 6.81; N, 4.98. Found: C, 60.05; H, 6.91; N, 4.81.

**(*E*)-*N*-Tosyl-3-decenamide (7d):**



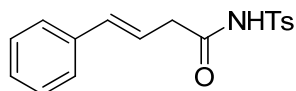
78% yield as colorless semi-solid.  $^1\text{H}$  NMR (270 MHz,  $\text{CDCl}_3$ )  $\delta$  0.85 (t,  $J = 6.5$  Hz, 3H), 1.21–1.29 (m, 8H), 1.94–2.03 (m, 2H), 2.41 (s, 3H), 2.95 (d,  $J = 7.0$  Hz, 2H), 5.31–5.42 (m, 1H), 5.51–5.62 (m, 1H), 7.31 (d,  $J = 8.6$  Hz, 2H), 7.92 (d,  $J = 8.4$  Hz, 2H), 8.73 (br s, 1H).  $^{13}\text{C}$  NMR (67.7 MHz,  $\text{CDCl}_3$ )  $\delta$  14.1, 21.7, 22.6, 28.8, 28.9, 31.7, 32.5, 40.4, 119.8, 128.3, 129.4, 135.3, 137.8, 145.0, 169.1. IR (KBr) 3307, 1738, 1731, 1714, 1456, 1446, 1435, 1338, 1172, 1089  $\text{cm}^{-1}$ . ESI/TOF mass Calcd for  $\text{C}_{17}\text{H}_{25}\text{NO}_3\text{S}$  ( $\text{M}+\text{Na}$ ) $^+$  346.1453, found 346.0959. Anal. Calcd for  $\text{C}_{17}\text{H}_{25}\text{NO}_3\text{S}$ : C, 63.13; H, 7.79; N, 4.33. Found: C, 62.85; H, 8.07; N, 4.15.

**(E)-N-Tosyl-3-octenamide (7e):**



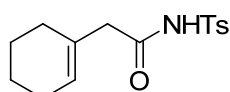
85% yield as colorless semi-solid.  $^1\text{H}$  NMR (270 MHz,  $\text{CDCl}_3$ )  $\delta$  0.82 (t,  $J = 7.0$  Hz, 3H), 1.16–1.31 (m, 4H), 1.91–1.98 (m, 2H), 2.39 (s, 3H), 2.95 (d,  $J = 6.7$  Hz, 2H), 5.31–5.42 (m, 1H), 5.47–5.58 (m, 1H), 7.29 (d,  $J = 8.6$  Hz, 2H), 7.92 (d,  $J = 8.4$  Hz, 2H), 9.11 (br s, 1H).  $^{13}\text{C}$  NMR (67.7 MHz,  $\text{CDCl}_3$ )  $\delta$  13.8, 21.6, 22.1, 31.0, 32.1, 40.1, 119.8, 128.1, 129.3, 135.3, 137.1, 144.8, 169.5. IR (KBr) 3306, 2872, 1728, 1598, 1435, 1338, 1172, 1088  $\text{cm}^{-1}$ . ESI/TOF mass Calcd for  $\text{C}_{15}\text{H}_{21}\text{NO}_3\text{S}$  ( $\text{M}+\text{Na}$ ) $^+$  318.1140, found 318.0671. Anal. Calcd for  $\text{C}_{15}\text{H}_{21}\text{NO}_3\text{S}$ : C, 60.99; H, 7.17; N, 4.74. Found: C, 60.53; H, 7.03; N, 4.52.

**(E)-N-Tosyl-4-phenyl-but-3-enamide (7f):**



70% yield as colorless solid.  $^1\text{H}$  NMR (270 MHz,  $\text{CDCl}_3$ )  $\delta$  2.38 (s, 3H), 3.19 (d,  $J = 6.7$  Hz, 2H), 6.08–6.19 (m, 1H), 6.41 (d,  $J = 15.9$  Hz, 1H), 7.21–7.28 (m, 7H), 7.94 (d,  $J = 8.4$  Hz, 2H), 9.26 (br s, 1H).  $^{13}\text{C}$  NMR (67.7 MHz,  $\text{CDCl}_3$ )  $\delta$  21.7, 40.4, 119.6, 126.2, 127.7, 128.2, 128.3, 129.5, 135.1, 135.2, 136.1, 145.0, 169.0. IR (KBr) 3358, 1687, 1596, 1452, 1349, 1246, 1172, 1091  $\text{cm}^{-1}$ . ESI/TOF mass Calcd for  $\text{C}_{17}\text{H}_{17}\text{NO}_3\text{S}$  ( $\text{M}+\text{Na}$ ) $^+$  338.0827, found 338.0379. Anal. Calcd for  $\text{C}_{17}\text{H}_{17}\text{NO}_3\text{S}$ : C, 64.74; H, 5.43; N, 4.44. Found: C, 64.45; H, 5.40; N, 4.58.

**N-Tosyl-(2-cyclohex-1-enyl)acetamide (7g):<sup>6</sup>**

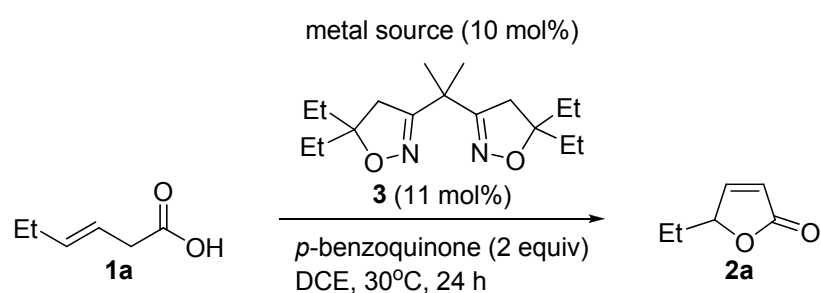


75% yield as colorless solid.  $^1\text{H}$  NMR (270 MHz,  $\text{CDCl}_3$ )  $\delta$  1.54–1.58 (m, 4H), 1.77 (br m, 2H), 2.02 (br

m, 2H), 2.42 (s, 3H), 2.85 (s, 2H), 5.60 (br s, 1H), 7.31 (d,  $J = 8.6$  Hz, 2H), 7.91 (d,  $J = 8.1$  Hz, 2H), 8.12 (br s, 1H).  $^{13}\text{C}$  NMR (67.7 MHz,  $\text{CDCl}_3$ )  $\delta$  21.68, 21.71, 22.5, 25.3, 28.1, 46.3, 128.1, 128.2, 129.4, 130.5, 135.3, 144.9, 168.9. IR (KBr) 3322, 1695, 1682, 1668, 1471, 1456, 1435, 1348, 1163, 1088  $\text{cm}^{-1}$ . ESI/TOF mass 316 ( $\text{M}+\text{Na}$ ) $^+$ . Anal. Calcd for  $\text{C}_{15}\text{H}_{19}\text{NO}_3\text{S}$ : C, 61.41; H, 6.53; N, 4.77. Found: C, 61.27; H, 6.61; N, 4.56.

### The effects of reaction conditions:

**Table S1.** The effect of metal source on the reaction of **1a** when using ligand **3**



| Entry | Metal source                                       | Yield of <b>2a</b> (%) <sup>a</sup> |
|-------|----------------------------------------------------|-------------------------------------|
| 1     | $\text{Pd}(\text{OAc})_2$                          | 75 (40) <sup>b</sup>                |
| 2     | $\text{Pd}(\text{OCOCF}_3)_2$                      | 2                                   |
| 3     | $\text{Pd}(\text{acac})_2$                         | 67                                  |
| 4     | $\text{PdCl}_2(\text{CH}_3\text{CN})_2$            | Trace                               |
| 5     | $\text{PdCl}_2$                                    | Trace                               |
| 6     | $\text{Pd}(\text{hfacac})_2$                       | Trace                               |
| 7     | $\text{Pd}(\text{CH}_3\text{CN})_4(\text{BF}_4)_2$ | no reaction                         |
| 8     | $\text{Pd}_2(\text{dba})_3 \cdot \text{CHCl}_3$    | no reaction                         |
| 9     | $\text{Ni}(\text{acac})_2$                         | no reaction                         |
| 10    | $\text{Cu}(\text{OAc})_2$                          | no reaction                         |
| 11    | $\text{AgOTf}$                                     | no reaction                         |
| 12    | $\text{Rh}_2(\text{OAc})_4$                        | no reaction                         |

<sup>a</sup>

Determined by  $^1\text{H}$  NMR. <sup>b</sup> 5 mol% of catalyst.

**Table S2.** The effect of solvent and additive on the reaction of **1a** when using ligand **3**

| $\text{Pd(OAc)}_2$ (10 mol%)<br>$\textbf{3}$ (11 mol%)<br>$\textbf{1a} \xrightarrow[\text{solvents, 30}^\circ\text{C, 24 h}]{\text{p-benzoquinone (2 equiv) additive (2 equiv)}} \textbf{2a}$ |         |                                 |                                     |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------|---------------------------------|-------------------------------------|
| Entry                                                                                                                                                                                         | Solvent | Additive (2 equiv)              | Yield of <b>2a</b> (%) <sup>a</sup> |
| 1                                                                                                                                                                                             | DCE     | none                            | 75                                  |
| 2                                                                                                                                                                                             | DCM     | none                            | 40                                  |
| 3                                                                                                                                                                                             | THF     | none                            | 66                                  |
| 4                                                                                                                                                                                             | acetone | none                            | 59                                  |
| 5                                                                                                                                                                                             | MeOH    | none                            | no reaction                         |
| 6                                                                                                                                                                                             | DCM     | Na <sub>2</sub> CO <sub>3</sub> | trace                               |
| 7                                                                                                                                                                                             | DCM     | NaOAc                           | trace                               |
| 8                                                                                                                                                                                             | DCM     | Cs <sub>2</sub> CO <sub>3</sub> | trace                               |
| 9                                                                                                                                                                                             | DCM     | K <sub>2</sub> CO <sub>3</sub>  | trace                               |
| 10                                                                                                                                                                                            | DCM     | NEt <sub>3</sub>                | trace                               |

<sup>a</sup> Determined by <sup>1</sup>H NMR.

#### General procedure for synthesis of $\gamma$ -butenolides:

A mixture of (*P\*,R\*,R\**)-*i*-Pr-SPRIX ( $\pm$ )-**4** (6.2 mg, 0.0165 mmol, 11 mol %) and Pd(OAc)<sub>2</sub> (3.4 mg, 0.015 mmol, 10 mol %) in DCE (2 mL) was stirred at 30 °C for 2 h under an argon atmosphere in a Schlenk tube. To this solution were added *p*-benzoquinone (32.4 mg, 0.3 mmol, 2 equiv) and substrate **1a** (17.1 mg, 0.15 mmol) via a syringe. The reaction mixture was stirred at 30 °C and the reaction course was monitored by TLC as well as <sup>1</sup>H NMR spectroscopy. After 12 h, the reaction mixture was filtered through a short column of SiO<sub>2</sub> using ethyl acetate as an eluent, and the resulting filtrate was concentrated. The residue was purified by flash SiO<sub>2</sub> column chromatography (sample loaded after adsorption in small amounts of SiO<sub>2</sub> and eluted with hexane/acetone; 99/1 to 96/4) to afford the corresponding  $\gamma$ -butenolide, 5-ethyl-2(5*H*)-furanone **2a** (15.8 mg, 94%).

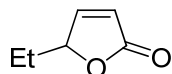
#### General procedure for synthesis of 3-pyrrolin-2-ones:

A mixture of (*P\*,R\*,R\**)-*i*-Pr-SPRIX ( $\pm$ )-**4** (6.2 mg, 0.0165 mmol, 11 mol %) and Pd(OAc)<sub>2</sub> (3.4 mg, 0.015 mmol, 10 mol %) in CH<sub>2</sub>Cl<sub>2</sub> (2 mL) was stirred at 30 °C for 2 h under an argon atmosphere in

a Schlenk test tube. To this solution were added *p*-benzoquinone (32.4 mg, 0.3 mmol, 2 equiv) and substrate (*E*)-*N*-tosyl-3-heptenamide (**7c**, 42.2 mg, 0.15 mmol). The reaction mixture was stirred at 30 °C and the reaction course was monitored by TLC. The mixture was filtered through a short column of SiO<sub>2</sub> using ethyl acetate as an eluent, and the resulting filtrate was concentrated. The residue was purified by flash silica gel column chromatography (sample loaded after adsorption in small amounts of silica gel and eluted with hexane/acetone; 98/2 to 90/10) to afford the corresponding *N*-tosyl-5-propyl-3-pyrrolin-2-one (**8c**, 40.6 mg, 97%).

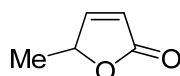
#### Analytical data of the products

##### 5-Ethyl-2(5*H*)-furanone (**2a**):<sup>7</sup>



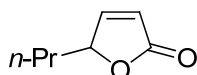
<sup>1</sup>H NMR (270 MHz, CDCl<sub>3</sub>) δ 0.99 (t, *J* = 7.4 Hz, 3H), 1.90–1.63 (m, 2H), 5.01–4.96 (m, 1H), 6.10 (dd, *J* = 2.2, 5.7 Hz, 1H), 7.42 (dd, *J* = 0.8, 5.7 Hz, 1H). <sup>13</sup>C NMR (67.7 MHz, CDCl<sub>3</sub>) δ 9.1, 26.4, 84.3, 121.7, 155.7, 173.0.

##### 5-Methyl-2(5*H*)-furanone (**2b**):<sup>7</sup>



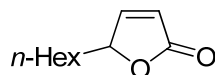
<sup>1</sup>H NMR (270 MHz, CDCl<sub>3</sub>) δ 1.45 (d, *J* = 6.7 Hz, 3H), 5.18–5.10 (m, 1H), 6.10 (dd, *J* = 1.9, 5.7 Hz, 1H), 7.46 (dd, *J* = 1.3, 5.7 Hz, 1H). <sup>13</sup>C NMR (67.7 MHz, CDCl<sub>3</sub>) δ 18.9, 79.6, 121.2, 157.2, 172.8.

##### 5-Propyl-2(5*H*)-furanone (**2c**):<sup>7</sup>



<sup>1</sup>H NMR (270 MHz, CDCl<sub>3</sub>) δ 0.97 (t, *J* = 7.3 Hz, 3H), 1.51–1.41 (m, 2H), 1.74–1.61 (m, 2H), 5.04–4.99 (m, 1H), 6.10 (dd, *J* = 1.9, 5.7 Hz, 1H), 7.45 (dd, *J* = 1.3, 5.7 Hz, 1H). <sup>13</sup>C NMR (67.7 MHz, CDCl<sub>3</sub>) δ 13.8, 18.4, 35.2, 83.2, 121.4, 156.1, 172.9.

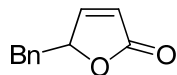
##### 5-Hexyl-2(5*H*)-furanone (**2d**):<sup>7</sup>



<sup>1</sup>H NMR (270 MHz, CDCl<sub>3</sub>) δ 0.85 (t, *J* = 7.0 Hz, 3H), 1.47–1.26 (m, 8H), 1.81–1.57 (m, 2H), 5.03–4.98 (m, 1H), 6.07 (dd, *J* = 1.9, 5.7 Hz, 1H), 7.42 (dd, *J* = 1.4, 5.9 Hz, 1H). <sup>13</sup>C NMR (67.7 MHz,

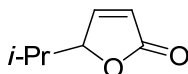
CDCl<sub>3</sub>)  $\delta$  14.1, 22.6, 25.0, 29.0, 31.6, 33.2, 83.4, 121.4, 156.1, 173.0.

**5-Benzyl-2(5*H*)-furanone (2e):**<sup>8</sup>



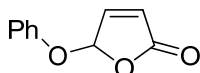
<sup>1</sup>H NMR (270 MHz, CDCl<sub>3</sub>)  $\delta$  2.95 (dd,  $J$  = 7.0, 13.0 Hz, 1H), 3.15 (dd,  $J$  = 6.2, 13.0 Hz, 1H), 5.22 (t,  $J$  = 6.7 Hz, 1H), 6.07 (dd,  $J$  = 1.6, 5.7 Hz, 1H), 7.45–7.15 (m, 6H). <sup>13</sup>C NMR (67.7 MHz, CDCl<sub>3</sub>)  $\delta$  39.6, 83.4, 121.9, 127.2, 128.6, 129.2, 134.7, 155.4, 172.6.

**5-Isopropyl-2(5*H*)-furanone (2f):**<sup>7</sup>



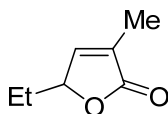
<sup>1</sup>H NMR (270 MHz, CDCl<sub>3</sub>)  $\delta$  0.93 (d,  $J$  = 6.7 Hz, 6H), 2.06–1.89 (m, 1H), 4.80–4.76 (m, 1H), 6.08 (dd,  $J$  = 1.9, 5.7 Hz, 1H), 7.39 (dd,  $J$  = 1.3, 5.7 Hz, 1H). <sup>13</sup>C NMR (67.7 MHz, CDCl<sub>3</sub>)  $\delta$  17.7, 17.9, 31.7, 87.9, 122.2, 154.7, 172.9.

**5-Phenoxy-2(5*H*)-furanone (2g):**



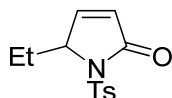
<sup>1</sup>H NMR (270 MHz, CDCl<sub>3</sub>)  $\delta$  6.34 (dd,  $J$  = 1.3, 5.7 Hz, 1H), 6.42 (t,  $J$  = 1.3 Hz, 1H), 7.41–7.09 (m, 6H). <sup>13</sup>C NMR (67.7 MHz, CDCl<sub>3</sub>)  $\delta$  100.7, 116.9, 123.7, 125.2, 129.7, 149.6, 156.1, 169.7. IR (KBr) 3113, 1790, 1760, 1592, 1494, 1366, 1221, 1158, 1082, 1017 cm<sup>-1</sup>. HRMS (EI) Calcd for C<sub>10</sub>H<sub>9</sub>O<sub>3</sub> (M+H<sup>+</sup>) 177.0551. Found 177.0539; HRMS(FAB) Calcd for C<sub>10</sub>H<sub>9</sub>O<sub>3</sub> (M+H<sup>+</sup>) 177.0551. Found 177.0564.

**5-Ethyl-3-methyl-2(5*H*)-furanone (2h):**<sup>9</sup>



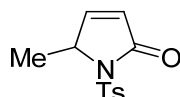
<sup>1</sup>H NMR (270 MHz, CDCl<sub>3</sub>)  $\delta$  0.99 (t,  $J$  = 7.3 Hz, 3H), 1.82–1.62 (m, 2H), 1.92 (t,  $J$  = 1.6 Hz, 3H), 4.90–4.78 (m, 1H), 7.05–7.01 (m, 1H). <sup>13</sup>C NMR (67.7 MHz, CDCl<sub>3</sub>)  $\delta$  9.2, 10.7, 26.7, 82.1, 130.1, 148.2, 174.1.

**N-Tosyl-5-ethyl-3-pyrrolin-2-one (8a):**



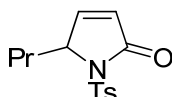
$^1\text{H}$  NMR (270 MHz,  $\text{CDCl}_3$ )  $\delta$  0.76 (t,  $J = 7.6$  Hz, 3H), 1.97–2.21 (m, 2H), 2.41 (s, 3H), 4.81–4.87 (m, 1H), 6.01 (dd,  $J = 1.6, 6.2$  Hz, 1H), 7.14 (dd,  $J = 1.9, 5.9$  Hz, 1H), 7.30 (d,  $J = 8.6$  Hz, 2H), 7.94 (d,  $J = 8.6$  Hz, 2H).  $^{13}\text{C}$  NMR (67.7 MHz,  $\text{CDCl}_3$ )  $\delta$  7.9, 21.7, 25.1, 65.3, 125.9, 127.9, 129.5, 135.8, 144.8, 151.4, 168.9. IR (KBr) 2974, 2882, 1728, 1599, 1455, 1361, 1169, 1091, 1001  $\text{cm}^{-1}$ . ESI/TOF mass 288 ( $\text{M}+\text{Na}$ ) $^+$ . Anal. Calcd for  $\text{C}_{13}\text{H}_{15}\text{NO}_3\text{S}$ : C, 58.85; H, 5.70; N, 5.28. Found: C, 58.81; H, 5.65; N, 5.17.

***N*-Tosyl-5-methyl-3-pyrrolidin-2-one (8b):**<sup>10</sup>



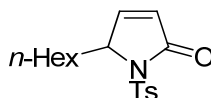
$^1\text{H}$  NMR (270 MHz,  $\text{CDCl}_3$ )  $\delta$  1.57 (d,  $J = 6.7$  Hz, 3H), 2.41 (s, 3H), 4.81–4.90 (m, 1H), 5.96 (dd,  $J = 1.6, 5.9$  Hz, 1H), 7.11 (dd,  $J = 1.9, 5.9$  Hz, 1H), 7.30 (d,  $J = 8.6$  Hz, 2H), 7.94 (d,  $J = 8.6$  Hz, 2H).  $^{13}\text{C}$  NMR (67.7 MHz,  $\text{CDCl}_3$ )  $\delta$  19.1, 21.7, 60.5, 124.9, 127.9, 129.5, 136.0, 144.8, 153.1, 168.4. IR (KBr) 2939, 1722, 1596, 1493, 1455, 1353, 1293, 1168, 1090, 1005  $\text{cm}^{-1}$ . ESI/TOF mass 274 ( $\text{M}+\text{Na}$ ) $^+$ . Anal. Calcd for  $\text{C}_{12}\text{H}_{13}\text{NO}_3\text{S}$ : C, 57.35; H, 5.21; N, 5.57. Found: C, 56.83; H, 5.03; N, 5.31.

***N*-Tosyl-5-propyl-3-pyrrolidin-2-one (8c):**



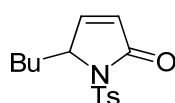
$^1\text{H}$  NMR (270 MHz,  $\text{CDCl}_3$ )  $\delta$  0.89 (t,  $J = 7.0$  Hz, 3H), 1.10–1.23 (m, 2H), 1.79–1.93 (m, 1H), 2.06–2.19 (m, 1H), 2.41 (s, 3H), 4.82–4.86 (m, 1H), 5.98 (dd,  $J = 1.6, 6.2$  Hz, 1H), 7.16 (dd,  $J = 2.2, 6.2$  Hz, 1H), 7.30 (d,  $J = 8.1$  Hz, 2H), 7.94 (d,  $J = 8.4$  Hz, 2H).  $^{13}\text{C}$  NMR (67.7 MHz,  $\text{CDCl}_3$ )  $\delta$  13.9, 17.3, 21.7, 34.2, 64.5, 125.5, 127.8, 129.4, 135.9, 144.7, 151.7, 168.7. IR (KBr) 2960, 1720, 1597, 1355, 1169, 1089  $\text{cm}^{-1}$ . ESI/TOF mass 302 ( $\text{M}+\text{Na}$ ) $^+$ . Anal. Calcd for  $\text{C}_{14}\text{H}_{17}\text{NO}_3\text{S}$ : C, 60.19; H, 6.13; N, 5.01. Found: C, 60.28; H, 6.26; N, 4.79.

***N*-Tosyl-5-hexyl-3-pyrrolidin-2-one (8d):**



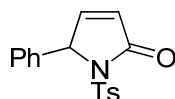
$^1\text{H}$  NMR (270 MHz,  $\text{CDCl}_3$ )  $\delta$  0.83 (t,  $J$  = 6.5 Hz, 3H), 1.02–1.23 (m, 8H), 1.80–1.94 (m, 1H), 2.06–2.20 (m, 1H), 2.39 (s, 3H), 4.83–4.85 (m, 1H), 5.98 (dd,  $J$  = 0.8, 6.2 Hz, 1H), 7.16 (dd,  $J$  = 1.3, 6.2 Hz, 1H), 7.29 (d,  $J$  = 8.1 Hz, 2H), 7.93 (d,  $J$  = 8.1 Hz, 2H).  $^{13}\text{C}$  NMR (67.7 MHz,  $\text{CDCl}_3$ )  $\delta$  14.1, 21.7, 22.5, 23.7, 29.0, 31.6, 32.0, 64.6, 125.5, 127.8, 129.4, 135.9, 144.7, 151.8, 168.8. IR (KBr) 2922, 1722, 1716, 1599, 1471, 1360, 1170, 1092, 1078, 1006  $\text{cm}^{-1}$ . ESI/TOF mass 344 ( $\text{M}+\text{Na}$ ) $^+$ . Anal. Calcd for  $\text{C}_{17}\text{H}_{23}\text{NO}_3\text{S}$ : C, 63.52; H, 7.21; N, 4.36. Found: C, 63.88; H, 7.18; N, 4.07.

***N*-Tosyl-5-butyl-3-pyrrolin-2-one (8e):**



$^1\text{H}$  NMR (270 MHz,  $\text{CDCl}_3$ )  $\delta$  0.82 (t,  $J$  = 7.0 Hz, 3H), 1.02–1.32 (m, 4H), 1.81–1.95 (m, 1H), 2.06–2.19 (m, 1H), 2.40 (s, 3H), 4.82–4.85 (m, 1H), 5.98 (dd,  $J$  = 1.6, 5.9 Hz, 1H), 7.16 (dd,  $J$  = 1.9, 6.2 Hz, 1H), 7.29 (d,  $J$  = 8.4 Hz, 2H), 7.93 (d,  $J$  = 8.4 Hz, 2H).  $^{13}\text{C}$  NMR (67.7 MHz,  $\text{CDCl}_3$ )  $\delta$  13.9, 21.7, 22.5, 25.8, 31.8, 64.5, 125.6, 127.8, 129.4, 135.9, 144.8, 151.8, 168.8. IR (KBr) 2960, 1728, 1594, 1360, 1169, 1089  $\text{cm}^{-1}$ . ESI/TOF mass 316 ( $\text{M}+\text{Na}$ ) $^+$ . Anal. Calcd for  $\text{C}_{15}\text{H}_{19}\text{NO}_3\text{S}$ : C, 61.41; H, 6.53; N, 4.77. Found: C, 61.52; H, 6.79; N, 4.56.

***N*-Tosyl-5-phenyl-3-pyrrolin-2-one (8f):**



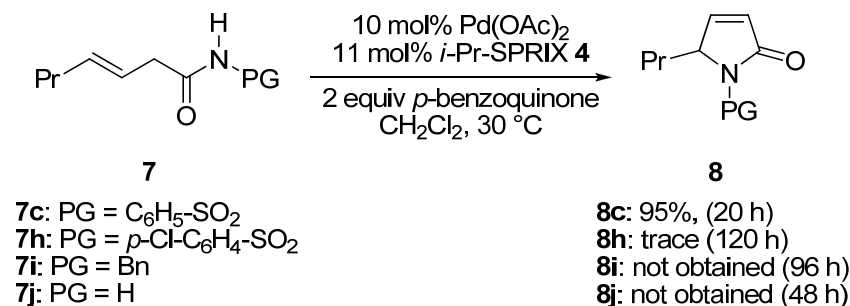
$^1\text{H}$  NMR (270 MHz,  $\text{CDCl}_3$ )  $\delta$  2.29 (s, 3H), 5.74–5.76 (m, 1H), 6.06 (dd,  $J$  = 1.3, 6.2 Hz, 1H), 7.02–7.08 (m, 5H), 7.19–7.30 (m, 3H), 7.34 (d,  $J$  = 8.1 Hz, 2H).  $^{13}\text{C}$  NMR (67.7 MHz,  $\text{CDCl}_3$ )  $\delta$  21.7, 67.4, 124.8, 127.7, 127.8, 128.7, 128.9, 129.1, 133.3, 135.6, 144.5, 151.0, 168.5. IR (KBr) 3096, 1738, 1732, 1596, 1456, 1357, 1295, 1166, 1090, 1073  $\text{cm}^{-1}$ . ESI/TOF mass 336 ( $\text{M}+\text{Na}$ ) $^+$ . Anal. Calcd for  $\text{C}_{17}\text{H}_{15}\text{NO}_3\text{S}$ : C, 65.16; H, 4.82; N, 4.47. Found: C, 65.01; H, 4.68; N, 4.33.

**Synthesis of (*E*)-2,2-dideuterio-hex-3-enoic acid (1a-d):**

Diisopropylamine (0.48 mL, 2 equiv) in THF (10 mL) was cooled to  $-20\text{ }^{\circ}\text{C}$ . To this solution was added slowly 2.0 M solution of *n*-BuLi in THF (1.7 mL, 2 equiv). After stirring for 30 min, a solution of (*E*)-3-hexenoic acid (**1a**, 196 mg, 1.7 mmol) in THF (1 mL) was added dropwise via syringe. The reaction mixture became deep yellow in color. After 30 min, it was quenched with  $\text{D}_2\text{O}$  (0.75 mL) and then allowed to warm at rt. The mixture was neutralized with 2N HCl and extracted with ethyl acetate

(30 mL  $\times$  3) then dried with Na<sub>2</sub>SO<sub>4</sub>. Filtration followed by solvent evaporation gave **1a-d** in quantitative yield (197 mg, 43% D at  $\alpha$ -position). The procedure was repeated once again to obtain **1a-d** labeled with 81% D. Analytical data: <sup>1</sup>H NMR (270 MHz, CDCl<sub>3</sub>)  $\delta$  0.96 (t,  $J$  = 7.3 Hz, 3H), 2.11–2.01 (m, 2H), 3.03 (s, 0.36H), 5.69–5.46 (m, 2H).

#### The effect of *N*-protecting group on the reaction



#### Ee values of products **2** when using optically pure Pd-*i*Pr-SPRIX complex

| Entry <sup>a</sup> | Substrate                  | Product   | Ee of <b>2</b> (%) <sup>d</sup> |
|--------------------|----------------------------|-----------|---------------------------------|
|                    |                            |           |                                 |
| 1 <sup>b</sup>     | <b>1b:</b> R = Me          | <b>2b</b> | 50                              |
| 2                  | <b>1c:</b> R = Pr          | <b>2c</b> | 52                              |
| 3                  | <b>1e:</b> R = Bn          | <b>2e</b> | 52                              |
| 4 <sup>b</sup>     | <b>1f:</b> R = <i>i</i> Pr | <b>2f</b> | 50                              |
| 5 <sup>c</sup>     | <b>1g:</b> R = OPn         | <b>2g</b> | 28                              |
| 6                  |                            |           | 4                               |
|                    | <b>1h</b>                  | <b>2h</b> |                                 |

<sup>a</sup> Reaction conditions: Pd(OAc)<sub>2</sub> (10 mol %), (*P,R,R*)-**4** (11 mol %), *p*-benzoquinone (2 equiv.), DCE, 30 °C, 24 h. <sup>b</sup> DCM. <sup>c</sup> 75 °C. <sup>d</sup> Determined by HPLC (Chiralcel OB-H;  $\lambda$  220 nm, hexane/IPA=9/1)

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