Direct Synthesis of 2-Formylpyrrolidines, 2-Pyrrolidinones and 2-Dihydrofuranones Via Aerobic Copper-Catalyzed Aminooxygenation and Dioxygenation of 4-Pentenylsulfonamides and 4-Pentenylalcohols

Tomasz Wdowik, Sherry R. Chemler*

Department of Chemistry, Natural Sciences Complex, State University of New York at Buffalo, Buffalo, NY 14260

schemler@buffalo.edu

Supporting Information:
Experimental Procedures and Characterization of New Compounds

Table of Contents
General Information.........................................................................................................................................S-3
Materials. ......................................................................................................................................................S-3
(R)-4-Methyl-N-(1-(methylthio)hept-6-en-3-yl)benzenesulfonamide (1n).................................S-4
(R)-N-(1-(Benzyloxy)hex-5-en-2-yl)-4-methylbenzenesulfonamide (1o).................................S-5
N-(1-(Furan-3-yl)pent-4-en-1-yl)-4-methylbenzenesulfonamide (1r).................................S-5
Catalytic Aminooxygenation/Dioxygenation/C-C Bond Cleavage Reactions Towards 2-Pyrrolidinones, 2-Dihydrofuranones, 2 Formylpyrrolidines, and 2-Ketopyrrolidine.....S-6
Optimization of the Reaction Conditions .................................................................................................S-6
Synthesis of 2-Pyrrolidinones (Table 2) .................................................................................................S-8
Representative Procedure (Table 2, Conditions A): (S)-5-Methyl-1-tosylpyrrolidin-2-one (3b) ..................................................................................................................................................S-8
5-(But-3-en-1-yl)-1-tosylpyrrolidin-2-one (3c) ..........................................................................................S-9
5-Phenyl-1-tosylpyrrolidin-2-one (3d) .....................................................................................................S-9
4-Allyl-1-tosylpyrrolidin-2-one (3e) ..........................................................................................................S-10
4-(4-Chlorophenyl)-1-tosylpyrrolidin-2-one (3f) ....................................................................................S-10
4,4-Dimethyl-1-tosylpyrrolidin-2-one (3a) ..............................................................................................S-11
4,4-Dimethyl-1-(4-nitrophenyl)pyrrolidin-2-one (3g) ............................................................................S-11
4,4-Dimethyl-1-(methylsulfonyl)pyrrolidin-2-one (3h) ..........................................................................S-12
1-((3,5-Di-tert-butyl-4-methoxyphenyl)sulfonyl)-4,4-dimethylpyrrolidin-2-one (3i) .................S-12
3-Benzyl-1-tosylpyrrolidin-2-one (3j) .....................................................................................................S-13
Synthesis of 2-Dihydrofuranones (Table 3) ............................................................................................S-14
References (Table 3, Conditions B): 4-phenyldihydrofuran-2(3H)-one (5e) S-14
5,5-Diphenyldihydrofuran-2(3H)-one (5a) S-15
3,3-Dimethylisobenzofuran-1(3H)-one (5b) S-15

Synthesis of 2-Formylpyrrolidines and 2-Ketopyrrolidine (Table 4) S-16
Representative Procedure (Table 4, Conditions A): (2S,5S)-5-Methyl-1-tosylpyrrolidine-2-carbaldehyde (2b). S-16
4,4-Dimethyl-1-tosylpyrrolidine-2-carbaldehyde (2a) S-17
(±)-cis-5-(But-3-en-1-yl)-1-tosylpyrrolidine-2-carbaldehyde (2c) S-18
(±)-cis-5-Phenyl-1-tosylpyrrolidine-2-carbaldehyde (2d) S-18
4-Allyl-1-tosylpyrrolidine-2-carbaldehyde (2e) S-19
4-(4-Chlorophenyl)-1-tosylpyrrolidine-2-carbaldehyde (2f) S-19
4,4-Dimethyl-1-((4-nitrophenyl)sulfonyl)pyrrolidine-2-carbaldehyde (2g) S-20
1-((3,5-Di-tert-buty1-4-methoxyphenyl)sulfonyl)-4,4-dimethylpyrrolidine-2-carbaldehyde (2i) S-21
(±)-trans-3-Benzyl-1-tosylpyrrolidine-2-carbaldehyde (2j) S-21
(2S,5R)-5-Isopropyl-1-tosylpyrrolidine-2-carbaldehyde (2k) S-22
(2S,5R)-5-(tert-Butyl)-1-tosylpyrrolidine-2-carbaldehyde (2l) S-23
(2S,5R)-5-Benzyl-1-tosylpyrrolidine-2-carbaldehyde (2m) S-23
(2S,5R)-5-(2-(Methylthio)ethyl)-1-tosylpyrrolidine-2-carbaldehyde (2n) S-24
(2S,5R)-5-((Benzyloxy)methyl)-1-tosylpyrrolidine-2-carbaldehyde (2o) S-24
(2S,5R)-5-(((tert-Butyl(dimethyl)silyl)oxy)methyl)-1-tosylpyrrolidine-2-carbaldehyde (2p) S-25
(2R,5R)-5-Butyl-1-tosylpyrrolidine-2-carbaldehyde (2q) S-26
Gram scale synthesis of (2R,5R)-5-butyl-1-tosylpyrrolidine-2-carbaldehyde (2q) S-26
(±)-cis-5-(Furan-3-yl)-1-tosylpyrrolidine-2-carbaldehyde (2r) S-27
4-Phenyl-1-tosylpyrrolidine-2-carbaldehyde (2s) S-27
(±)-trans-3-Phenyl-1-tosylpyrrolidine-2-carbaldehyde (2t) S-28
1-Tosylindoline-2-carbaldehyde (2u) S-28
(4,4-Dimethyl-1-tosylpyrrolidin-2-yl)(phenyl)methanone (2v) S-29

Kinetics Studies (Figure 1) S-30
Labeling Studies (Scheme 4) S-32
4,4-Dimethyl-1-tosylpyrrolidin-2-[^18]O]one (3a') S-32
Enantioselective Synthesis of 2-Formylpyrrolidine S-35
References S-37
General Information.
Analytical thin-layer chromatography (TLC) of all reactions was performed on silica gel 60 F254 TLC plates. Visualization was performed with UV light (254 nm), or iodine, or standard potassium permanganate solution or vanillin spray reagent followed by heating. Purification of reaction products was executed by flash column chromatography using silica gel 60 (230-400 mesh).
All nuclear magnetic resonance (NMR) data were collected using a Varian Inova-500, Varian Inova-400, or Varian Mercury-300 spectrometers. All chemical shifts are reported in ppm and were referenced to residual solvent peaks (\(^1\)H NMR: CDCl\(_3\) \(\delta = 7.26\) ppm, \(^{13}\)C NMR: CDCl\(_3\) \(\delta = 77.00\) ppm, CD\(_2\)Cl\(_2\) \(\delta = 54.24\) ppm). Multiplicities are abbreviated as follows: singlet (s), broad singlet (bs), doublet (d), triplet (t), quartet (q), pentet (p), multiplet (m).
Infrared spectra were recorded using a Nicolet-Impact 420 FTIR spectrometer or a PerkinElmer Spectrum Two spectrometer using the attenuated total reflectance attachment (ATR). Wavenumbers in inverse centimeters (cm\(^{-1}\)) are reported for characteristic peaks.
High resolution mass spectra were obtained at SUNY Buffalo’s mass spectrometry facility on a ThermoFinnigan MAT95XL high resolution magnetic sector mass spectrometer and Bruker Daltonics SolariX 12 Tesla FTICR mass spectrometer. All EI and ESI data are reported as either [M]+, [M + H]+, or [M + Na]+.
Optical rotations were obtained using a Rudolph Autopol 1 polarimeter fitted with a micro cell with a 100 mm path length.
Melting points were measured with a Mel-Temp melting point apparatus and are uncorrected.
Materials.
Solvents were used as received from the supplier unless otherwise noted. Tetrahydrofuran, diethyl ether, dichloromethane and toluene were dried using a commercial alumina column solvent purification system purchased from Contour Glass Co (Irvine, California). \(\alpha,\alpha,\alpha\)-Trifluorotoluene was dried with potassium carbonate and phosphorus pentoxide following by distillation over phosphorus pentoxide prior to use. Xylenes were distilled over calcium hydride prior to use.
Reagent grade, 97% copper(I) chloride, and extra pure, 99% copper(I) cyanide were used out of the bottle as supplied.
Bisoxazoline ligand, 4,5-dihydro-2-(2-(4,5-dihydrooxazol-2-yl)propan-2-yl)oxazole (L), was synthesized using our previously reported procedure.\(^1\)
Substrates 1a,\(^{2,3,4}\) 1b,\(^{5,6,7}\) 1c,\(^{8}\) 1d,\(^{9,10}\) 1e,\(^{11,12}\) 1f,\(^{13,14}\) 1g,\(^{2,3,4}\) 1h,\(^{2,3,4}\) 1i,\(^{15}\) 1j,\(^{11}\) 1k,\(^{5,6,7}\) 1l,\(^{5,6,7}\) 1m,\(^{16}\) 1p,\(^{7,17,18}\) 1q,\(^{8}\) 1s,\(^{19}\) 1t,\(^{20,21,22}\) 1u,\(^{2,3,4}\) 4a,\(^{23}\) 4b,\(^{24}\) 4b',\(^{25}\) 4e,\(^{26,27}\) were prepared as previously reported.
Previously unknown compound 1n was synthesized following the reported protocol, i.e. by opening known aziridine \(^5\) (that was obtained from L-methionine \(^5,6\) ) with allyl magnesium chloride:\(^7\)

\[
\begin{align*}
\text{O} & \quad \text{TsCl} \quad \text{DIPEA} \quad \text{NaOH} \\
\text{HO} & \quad \text{NHTs} \\
\text{S} & \quad \text{HO} \quad \text{NHTs} \\
\text{amine} & \quad \text{LAH} \\
\text{1n} & \quad \text{PPh\textsubscript{3}} \quad \text{DEAD} \\
\text{THF} & \quad 0 \degree C \quad \text{r.t.} \\
\text{S} & \quad \text{NHTs}
\end{align*}
\]

(R)-4-Methyl-N-(1-(methylthio)hept-6-en-3-yl)benzenesulfonamide (1n)

To a solution of (S)-2-(2-(methylthio)ethyl)-1-tosylaziridine (173.5 mg, 0.64 mmol) in tetrahydrofuran (4.5 mL) under argon at 0 \degree C was added dropwise 1.7M solution of allyl magnesium chloride in tetrahydrofuran (1.5 mL, 2.56 mmol, 4 equiv.). The mixture was allowed to warm up to r.t. overnight. Next, the mixture was quenched with aqueous saturated solution of ammonium chloride and extracted with diethyl ether (2x) and ethyl acetate (2x). Combined organic layers were washed with brine, dried over magnesium sulfate and chromatographed on silica gel (elution: ethyl acetate/hexanes 0\%–12\%–16\%) to afford 1n (158.1 mg) in 79\% yield as a colorless oil.

\([\alpha]_{D}^{26} +0.59 \text{ (c 1.12, CHCl}_3\text{)}\).

\(^1\text{H NMR}\) (300 MHz, CDCl\(_3\)) \(\delta\) 7.76 (d, \(J = 8.3\) Hz, 2H), 7.29 (d, \(J = 7.9\) Hz, 2H), 5.64 (ddt, \(J = 18.1, 9.3, 6.6\) Hz, 1H), 4.99-4.65 (m+br. s, 2H+1H), 3.44-3.31 (m, 1H), 2.42 (s, 3H), 2.40-2.24 (m, 2H), 2.08-1.84 (s+m, 3H+2H), 1.76-1.39 (m, 4H).

\(^{13}\text{C NMR}\) (75 MHz, CDCl\(_3\)) \(\delta\) 143.3, 138.2, 137.4, 129.6, 127.0, 115.2, 52.9, 34.2, 34.0, 30.1, 29.5, 21.5, 15.3.

IR: 3281, 2918, 1427, 1321, 1154, 1093, 814, 663, 576, 549 cm\(^{-1}\).

HRMS (+ESI): exact mass calcd for C\(_{15}\)H\(_{24}\)NO\(_2\)S\(_2\) [M + H\(^+\)]: 314.1243, found: 314.1256.

Previously unknown compound 1o was synthesized by deprotection of 1p\(^{18}\) affording known alcohol that was protected with benzyl bromide following modified known protocol:\(^{28}\)
(R)-N-(1-(Benzyloxy)hex-5-en-2-yl)-4-methylbenzenesulfonamide (1o)
Sodium hydride (95%, 24.7 mg, 0.98 mmol) was added to a stirred solution of (R)-N-(1-hydroxyhex-5-en-2-yl)-4-methylbenzenesulfonamide (131.8 mg, 0.49 mmol) in dry THF (1 mL) at −40 ºC and the mixture was stirred for 30 min with warming to 0 ºC. To the above mixture at 0 ºC was added dropwise benzyl bromide (60 µL, 0.49 mmol) and the mixture was stirred for 2 h. After that time additional portion of sodium hydride (95%, 14.9 mg, 0.59 mmol) was added. The mixture was allowed to warm up to r.t. overnight. The reaction was quenched with aqueous saturated solution of ammonium chloride and stirred for 10 min at 0 ºC. The mixture was extracted with EtOAc and the extract was washed with brine twice and dried over magnesium sulfate. Concentration under reduced pressure gave a residue, which was purified by chromatography on silica gel (elution: ethyl acetate/hexanes) to afford 1o (136.1 mg) in 77% yield as a white solid.
mp 39-40 ºC.
\([\alpha]_{D}^{24} +16.2 \ (c \ 1.00, \text{CHCl}_3)\).
The NMR data are consistent with literature values reported for mixture of 1o and its enantiomer (racemic mixture).9
\(^1H\) NMR (300 MHz, CDCl\(_3\)) \(\delta\) 7.71 (d, \(J = 8.2 \text{ Hz}, 2\)H), 7.38-7.16 (m, 7H), 5.79-5.59 (m, 1H), 4.98-4.85 (m, 2H), 4.77 (d, \(J = 8.3 \text{ Hz}, 1\)H), 4.34 (s, 2H), 3.42-3.26 (m, 2H), 3.20 (dd, \(J = 9.2, 4.1 \text{ Hz}, 1\)H), 2.41 (s, 3H), 2.09-1.88 (m, 2H), 1.61 (q, \(J = 7.4 \text{ Hz}, 2\)H).
\(^{13}C\) NMR (75 MHz, CDCl\(_3\)) \(\delta\) 143.2, 138.1, 137.7, 137.6, 129.6, 128.4, 127.8, 127.6, 127.0, 115.2, 73.2, 70.9, 53.1, 31.8, 29.8, 21.5.
Previously unknown compound 1r was synthesized following the reported protocol\(^9,10\) via known N-tosylaldimine:\(^9\)

\(N\)-(1-(Furan-3-yl)pent-4-en-1-yl)-4-methylbenzenesulfonamide (1r)
\(N\)-(furan-3-ylmethylene)-4-methylbenzenesulfonamide (295.3 mg, 1.18 mmol) was added slowly to a solution of but-3-enylmagnesium bromide (freshly prepared from 5-bromo-1-butene and magnesium, ca. 3 mmol) in diethyl ether (6 mL) at 0 ºC. After 30 min, the reaction was quenched with aqueous saturated solution of ammonium chloride and extracted with diethyl ether. The combined organic layers were dried over sodium
sulfate, and concentrated to afford the crude compound that was purified by chromatography on silica gel (elution: ethyl acetate/hexanes) to afford 1r (308.7 mg) in 85% yield as a white solid.

mp 67-68 °C.

$^1$H NMR (300 MHz, CDCl$_3$) δ 7.61 (d, $J = 8.1$ Hz, 2H), 7.22-7.09 (m, 2H+1H), 6.09 (dd, $J = 3.2$, 1.9 Hz, 1H), 5.88 (d, $J = 3.3$ Hz, 1H), 5.81-5.61 (m, 1H), 5.06 (d, $J = 8.7$ Hz, 1H), 5.00-4.90 (m, 2H), 4.41 (q, $J = 7.6$ Hz, 1H), 2.37 (s, 3H), 2.05-1.94 (m, 2H), 1.92-1.80 (m, 2H).

$^{13}$C NMR (75 MHz, CDCl$_3$) δ 152.6, 143.0, 141.8, 137.6, 137.0, 129.3, 126.9, 115.6, 109.9, 106.9, 77.4, 77.0, 76.6, 51.2, 34.0, 29.7, 21.4.

IR: 3271, 2925, 1428, 1325, 1158, 1093, 1011, 915, 812, 735, 664 cm$^{-1}$.


All other commercially available starting materials and reagents were used out of the bottle as purchased from the supplier without further purification unless otherwise noted.

### Catalytic Aminooxygenation/Dioxygenation/C-C Bond Cleavage Reactions Towards 2-Pyrrolidinones, 2-Dihydrofuranones, 2 Formylpyrrolidines, and 2-Ketopyrrolidine

#### Optimization of the Reaction Conditions

<table>
<thead>
<tr>
<th>Entry</th>
<th>[Cu]</th>
<th>Temperature °C</th>
<th>Result$^a$</th>
<th>1a</th>
<th>2a</th>
<th>3a</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CuF$_2$</td>
<td>105</td>
<td>88</td>
<td>9</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Cu(OTf)$_2$</td>
<td>105</td>
<td>57</td>
<td>25</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Cu(OMe)$_2$</td>
<td>105</td>
<td>90</td>
<td>7</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>CuCl</td>
<td>105</td>
<td>0</td>
<td>20</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>CuI</td>
<td>105</td>
<td>41</td>
<td>0</td>
<td>59</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>CuBr</td>
<td>105</td>
<td>45</td>
<td>16</td>
<td>39</td>
<td></td>
</tr>
</tbody>
</table>
## Supporting Information

<table>
<thead>
<tr>
<th>Entry</th>
<th>Ligand (22 mol%) or base</th>
<th>Solvent (temperature)</th>
<th>Result&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>1a</td>
</tr>
<tr>
<td>1</td>
<td>–</td>
<td>PhCF₃ (105 °C)</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>–</td>
<td>PhCH₃ (105 °C)</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>–</td>
<td>PhCH₃ (120 °C)</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>–</td>
<td>DMF (105 °C)</td>
<td>18</td>
</tr>
<tr>
<td>5</td>
<td>–</td>
<td>Pyridine (105 °C)</td>
<td>53</td>
</tr>
<tr>
<td>6</td>
<td>–</td>
<td>AcOH (105 °C)</td>
<td>100</td>
</tr>
<tr>
<td>7</td>
<td>L</td>
<td>PhCF₃ (105 °C)</td>
<td>16</td>
</tr>
<tr>
<td>8</td>
<td>L</td>
<td>PhCH₃ (105 °C)</td>
<td>0</td>
</tr>
<tr>
<td>9&lt;sup&gt;b&lt;/sup&gt;</td>
<td>L</td>
<td>PhCH₃ (105 °C)</td>
<td>–</td>
</tr>
<tr>
<td>10</td>
<td>L</td>
<td>t-BuOH (80 °C)</td>
<td>67</td>
</tr>
<tr>
<td>11</td>
<td>L</td>
<td>MeCN (80 °C)</td>
<td>91</td>
</tr>
<tr>
<td>12&lt;sup&gt;c&lt;/sup&gt;</td>
<td>L+DABCO (40 mol%)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>PhCF₃ (120 °C)</td>
<td>9</td>
</tr>
<tr>
<td>13</td>
<td>Pyridine (49 mol%)</td>
<td>PhCF₃ (105 °C)</td>
<td>0</td>
</tr>
<tr>
<td>14</td>
<td>1,10-Phenanthroline</td>
<td>PhCF₃ (105 °C)</td>
<td>65</td>
</tr>
<tr>
<td>15</td>
<td>2,2'-Bipyridine</td>
<td>PhCF₃ (105 °C)</td>
<td>39</td>
</tr>
<tr>
<td>16</td>
<td>N,N-diethylsalicylamide</td>
<td>PhCF₃ (105 °C)</td>
<td>40</td>
</tr>
<tr>
<td>17</td>
<td>Pyridine N-oxide</td>
<td>PhCF₃ (105 °C)</td>
<td>0</td>
</tr>
</tbody>
</table>

<sup>a</sup> Relative ratio based on crude NMR; (isolated yield).

<sup>b</sup> Reaction run in xylenes.

<sup>c</sup> Air bubbling instead of O₂ balloon.

<sup>d</sup> 15 mol% of CuCl and 17 mol% of ligand were used;

DABCO = 1,4-diazabicyclo[2.2.2]octane.
Synthesis of 2-Pyrrolidinones (Table 2)

\[
\begin{align*}
\text{Conditions A:} & \quad 1. \text{CuCl (20 mol%), PhCH}_3, 105 \, ^\circ\text{C}, 4 \, \text{Å MS; 2. + DABCO (40 mol%).} \\
\text{Conditions B:} & \quad 1. \text{CuCl (15 mol%), } \text{L (17 mol%), PhCF}_3, 120 \, ^\circ\text{C}, 4 \, \text{Å MS; 2. + DABCO (40 mol%).} \\
\text{Conditions C:} & \quad \text{CuCN (20 mol%), } \text{L (22 mol%), PhCH}_3, 120 \, ^\circ\text{C}, 4 \, \text{Å MS.} \\
\text{Conditions D:} & \quad 1. \text{CuCl (20 mol%), } \text{L (22 mol%), PhCF}_3, 105 \, ^\circ\text{C}, 4 \, \text{Å MS; 2. + DABCO (34 mol%).}
\end{align*}
\]

Representative Procedure (Table 2, Conditions A): (S)-5-Methyl-1-tosylpyrrolidin-2-one (3b)

Copper(I) chloride (3.9 mg, 0.039 mmol, 20 mol%) was placed in a dry 100 mL round bottom flask and dried under vacuum while gently heated with a heat gun. Next, the flask was back-filled with argon and toluene (1.9 mL), flame dried 4 Å molecular sieves (ca. 35 mg) and (S)-N-(hex-5-en-2-yl)-4-methylbenzenesulfonamide (48.3 mg, 0.19 mmol) were added. The argon atmosphere was replaced with oxygen. Next, the balloon with oxygen was attached to the flask through an inlet hose adapter and the mixture was stirred under oxygen (1 atm) at 105 °C (oil bath temperature). The progress of the reaction was monitored by TLC (eluent: ethyl acetate/hexanes 1:4 v/v) and after 6 hours no more starting material was observed. Next, DABCO (8.5 mg, 0.075 mmol, 40 mol%) was added and the stirring under oxygen at 105 °C was continued until the intermediate aldehyde disappeared based on TLC (after about 4 hours). After that time the mixture was filtered through a pad of Celite and the Celite was washed with dichloromethane and ethyl acetate. The crude product was purified by flash chromatography on silica gel (elution: ethyl acetate/hexanes 0%-20%) to afford 3b (29.1 mg) in 60% yield as a white solid.

The NMR data are consistent with reported literature values.\textsuperscript{29,30} 
\[
[a]^{27}_D +49.6 \, (c \, 1.50, \text{CH}_2\text{Cl}_2); \text{lit.}^{29} \, [\alpha]^{20}_D +55.9 \, (c \, 1.5, \text{CH}_2\text{Cl}_2).
\]

\(^1\text{H NMR (400 MHz, CDCl}_3\) δ 7.94 (d, \(J = 8.4 \, \text{Hz}, \, 2\text{H}), 7.32 (d, \(J = 7.8 \, \text{Hz}, \, 2\text{H}), 4.52 (dqq, \(J = 8.2, 6.4, 2.0 \, \text{Hz}, \, 1\text{H}), 2.55 (ddd, \(J = 16.9, 10.6, 8.8 \, \text{Hz}, \, 1\text{H}), 2.43 (s, \, 3\text{H}), 2.41-2.20 (m, \, 2\text{H}), 1.71 (ddddd, \(J = 11.7, 9.3, 3.3, 1.9 \, \text{Hz}, \, 1\text{H}), 1.46 (d, \(J = 6.4 \, \text{Hz}, \, 3\text{H}).
\]

\(^13\text{C NMR (75 MHz, CDCl}_3\) δ 173.2, 144.9, 136.0, 129.4, 128.2, 56.3, 30.5, 26.6, 21.6, 21.4.
The lactam 3c was prepared following the representative procedure (Table 2, conditions A) using 3.9 mg of CuCl and 55.9 mg of alkene 1c. DABCO (8.5 mg) was added after ca. 16 hours and the reaction was stopped after subsequent 3 hours. The lactam 3c (32.7 mg) was obtained in 59% yield as a colorless oil. The NMR data are consistent with literature values reported for R-enantiomer of 3c.\textsuperscript{31} 
\[ 1^1H \text{NMR (400 MHz, CDCl}_3) \delta 7.94 (d, J = 8.4 \text{ Hz}, 2H), 7.32 (d, J = 8.2 \text{ Hz}, 2H), 5.91-5.66 (m, 1H), 5.09-4.98 (m, 2H), 4.41 (tt, J = 8.1, 1.4 Hz, 1H), 2.52 (ddd, J = 17.6, 11.2, 9.2 Hz, 1H), 2.43 (s, 3H), 2.34 (ddd, J = 17.7, 9.5, 2.4 Hz, 1H), 2.24-2.04 (m, 4H), 1.87 (ddt, J = 13.1, 9.1, 2.1 Hz, 1H), 1.80-1.70 (m, 1H). \]
\[ 1^3C \text{NMR (75 MHz, CDCl}_3) \delta 173.4, 144.9, 136.8, 136.0, 129.4, 128.3, 115.5, 59.8, 33.5, 30.6, 29.3, 23.4, 21.6. \]
IR: 2924, 1731, 1354, 1165, 1088, 953, 667 cm\textsuperscript{-1}. HRMS (ESI\textsuperscript{+}): exact mass calcld for C\textsubscript{15}H\textsubscript{20}NO\textsubscript{3}S [M + H]\textsuperscript{+}: 294.1158, found: 294.1169.

The lactam 3d was prepared following the representative procedure (Table 2, conditions A) using 3.9 mg of CuCl and 60.1 mg of alkene 1d. DABCO (8.5 mg) was added after 5 hours and the reaction was stopped after subsequent 10 hours. The lactam 3d (37.7 mg) was obtained in 63% yield as a white solid. The NMR data are consistent with literature values.\textsuperscript{30} 
\[ 1^1H \text{NMR (300 MHz, CDCl}_3) \delta 7.57 (d, J = 8.4 \text{ Hz}, 2H), 7.35-7.22 (m, 3H), 7.22-7.02 (m, 4H), 5.45 (dd, J = 8.4, 2.2 Hz, 1H), 2.82-2.43 (m, 3H), 2.39 (s, 3H), 2.08-1.89 (m, 1H). \]
\[ 1^3C \text{NMR (75 MHz, CDCl}_3) \delta 173.5, 144.8, 140.6, 135.4, 129.1, 128.7, 128.5, 128.0, 126.0, 63.0, 30.6, 28.3, 21.6. \]
4-Allyl-1-tosylpyrrolidin-2-one (3e)

The lactam 3e was prepared following the representative procedure (Table 2, conditions A) using 3.8 mg of CuCl and 53.2 mg of alkene 1e. DABCO (8.5 mg) was added after 5 hours and the reaction was stopped after subsequent 10 hours. The lactam 3e (31.6 mg) was obtained in 59% yield as a white solid.

mp 64.5-66 °C.

$^{1}$H NMR (CDCl$_3$, 400 MHz) $\delta$ 7.92 (d, $J$ = 8.6, 2H), 7.34 (d, $J$ = 8.6, 2H), 5.72-5.62 (m, 1H), 5.08-5.03 (m, 2H), 4.00 (dd, $J$ = 10.2, 7.4, 1H), 3.52 (dd, $J$ = 10.0, 6.4, 1H), 2.56 (dd, $J$ = 17.2, 8.4, 1H) 2.50-2.38 (m+s, 4 H), 2.20-2.10 (m, 3H).

$^{13}$C NMR (CDCl$_3$, 75 MHz) $\delta$ 172.5, 145.1, 135.1, 134.0, 129.6, 128.0, 118.0, 51.8, 38.1, 37.7; 31.0; 21.6.

IR: 2917, 1730, 1355, 1164, 1120, 1088, 956, 927, 659, 558, 546 cm$^{-1}$.

HRMS (+ESI): exact mass calcd for C$_{14}$H$_{18}$NO$_3$S [M + H]$^+$: 280.1002, found: 280.1012.

4-(4-Chlorophenyl)-1-tosylpyrrolidin-2-one (3f)

The lactam 3f was prepared following the representative procedure (Table 2, conditions A) using 3.9 mg of CuCl and 66.5 mg of alkene 1f. DABCO (8.7 mg) was added after ca. 13 hours and the reaction was stopped after subsequent 3 hours. The lactam 3f (37.6 mg) was obtained in 63% yield as an off-white solid.

The NMR data are consistent with reported literature values.$^{14}$

$^{1}$H NMR (400 MHz, CDCl$_3$) $\delta$ 7.92 (d, $J$ = 8.4 Hz, 2H), 7.35 (d, $J$ = 8.0 Hz, 2H), 7.28 (d, $J$ = 8.5 Hz, 2H), 7.06 (d, $J$ = 8.5 Hz, 2H), 4.31 (dd, $J$ = 10.0, 7.8 Hz, 1H), 3.75 (dd, $J$ = 10.0, 7.5 Hz, 1H), 3.57 (p, $J$ = 8.2 Hz, 1H), 2.84 (dd, $J$ = 17.3, 8.4 Hz, 1H), 2.56 (dd, $J$ = 17.3, 8.9 Hz, 1H), 2.46 (s, 3H).

$^{13}$C NMR (75 MHz, CDCl$_3$) $\delta$ 171.7, 145.4, 138.4, 134.9, 133.5, 129.7, 129.2, 128.1, 127.9, 53.5, 39.4, 36.6, 21.7.
4,4-Dimethyl-1-tosylpyrrolidin-2-one (3a)

Table 2, conditions B:
Copper(I) chloride (2.8 mg, 0.028 mmol, 15 mol%) was placed in a dry 100 mL round bottom flask and dried under vacuum while gently heated with a heat gun. Next, trifluorotoluene (1.9 mL) and bis(oxazoline) ligand L (5.9 mg, 0.032 mmol, 17 mol%) were added under argon and the mixture was stirred under argon flow at 60 °C for 2 hours. After that time alkene 1a (50.8 mg, 0.19 mmol) and flame dried 4 Å molecular sieves (ca. 35 mg) were added. The argon atmosphere was replaced with oxygen. Next, the balloon with oxygen was attached to the flask through an inlet hose adapter and the mixture was stirred under oxygen (1 atm) at 120 °C (oil bath temperature). The progress of the reaction was monitored by TLC (eluent: ethyl acetate/hexanes 1:4 v/v) and after 5 hours no more starting material was observed. Next, DABCO (8.5 mg, 0.075 mmol, 40 mol%) was added and the stirring under oxygen at 120 °C was continued until the intermediate aldehyde disappeared based on TLC (after about 3 hours). After that time the mixture was filtered through a pad of Celite and the Celite was washed with dichloromethane and ethyl acetate. The crude product was purified by flash chromatography on silica gel (elution: ethyl acetate/hexanes 0%–20%) to afford 3a (33.4 mg) in 66% yield as a white solid.

The compound was previously reported; however there is no NMR and MS analysis provided in the literature.

$^1$H NMR (CDCl$_3$, 300 MHz) $\delta$ 7.91 (d, J = 8.4 Hz, 2H), 7.33 (d, J = 8.4 Hz, 2H), 3.59 (s, 2H), 2.43 (s, 3H), 2.24 (s, 2H), 1.10 (s, 6 H).

$^{13}$C NMR (CDCl$_3$, 75 MHz) $\delta$ 172.7, 145.1, 135.2, 129.6, 127.9, 59.5, 46.9, 33.2, 26.6, 21.6.

IR: 2961, 2925, 1735, 1359, 1290, 1215, 1166, 1129, 1090, 961, 745, 664, 623 cm$^{-1}$.


4,4-Dimethyl-1-(4-nitrophenyl)pyrrolidin-2-one (3g)

Table 2, conditions C:
Copper(I) cyanide (3.6 mg, 0.040 mmol, 20 mol%) was placed in the dry 100 mL round bottom flask and dried under vacuum while gently heated with a heat gun. Next, toluene (1.9 mL) and bis(oxazoline) ligand L (8.2 mg, 0.045 mmol, 23 mol%) were added under argon and the mixture was stirred under argon flow at 60 °C for about 2 hours. After that
time the alkene 1g (56.6 mg, 0.19 mmol) and flame dried 4 Å molecular sieves (ca. 35 mg) were added and the argon atmosphere was replaced with oxygen. Next, the balloon with oxygen was attached to the flask through an inlet hose adapter and the mixture was stirred under oxygen (1 atm) at 120 °C (oil bath temperature) for 41 hours. After that time the mixture was filtered through a pad of Celite and the Celite was washed with dichloromethane and ethyl acetate. The crude product was purified by flash chromatography on silica gel (elution: ethyl acetate/hexanes 0%–20%) to afford 1g (26.9 mg) in 48% yield as a yellow solid.

mp 145-147 °C.

\[^1\]H NMR (CDCl\(_3\), 300 MHz) \(\delta\) 8.38 (d, \(J = 9.2\) Hz, 2H), 8.23 (d, \(J = 9.2\) Hz, 2H), 3.63 (s, 2H), 2.28 (s, 2H), 1.13 (s, 6 H).

\[^{13}\]C NMR (CDCl\(_3\), 75 MHz) \(\delta\) 172.8, 150.8, 143.4, 129.4, 124.2, 59.6, 46.7, 33.5, 26.6.

IR: 3102, 2960, 2923, 1736, 1526, 1370, 1350, 1175, 1155, 1128, 1108, 1087, 759, 609, 558, 460 cm\(^{-1}\).

HRMS (+ESI): exact mass calcd for \(\text{C}_{12}\text{H}_{14}\text{N}_{2}\text{NaO}_{5}\text{S} \ [\text{M} + \text{Na}]^+\): 321.0516, found: 321.0521.

\[\begin{array}{c}
\text{O} \\
\text{NMs}
\end{array}\]

**4,4-Dimethyl-1-(methylsulfonyl)pyrrolidin-2-one (3h)**

Table 2, conditions **C**: Copper(I) cyanide (3.4 mg, 0.038 mmol, 20 mol%) was placed in the dry 100 mL round bottom flask and dried under vacuum while gently heated with a heat gun. Next, toluene (1.9 mL) and bis(oxazoline) ligand L (7.7 mg, 0.042 mmol, 22 mol%) were added under argon and the mixture was stirred under argon flow at 60 °C for about 2 hours. After that time the alkene 1h (36.7 mg, 0.19 mmol) and flame dried 4 Å molecular sieves (ca. 35 mg) were added and the argon atmosphere was replaced with oxygen. Next, the balloon with oxygen was attached to the flask through an inlet hose adapter and the mixture was stirred under oxygen (1 atm) at 120 °C (oil bath temperature) for 41 hours. After that time the mixture was filtered through a pad of Celite and the Celite washed with dichloromethane and ethyl acetate. The crude product was purified by flash chromatography on silica gel (elution: ethyl acetate/hexanes 0%–20%) to afford 3h (18.9 mg) in 52% yield as a colorless oil. Additionally, 5.1 mg (14%) of unreacted starting material was recovered.

\[^1\]H NMR (CDCl\(_3\), 300 MHz) \(\delta\) 3.57 (s, 2H), 3.25 (s, 3H), 2.38 (s, 2H), 1.20 (s, 6H).

\[^{13}\]C NMR (CDCl\(_3\), 75 MHz) \(\delta\) 173.9, 58.7, 47.0, 40.4, 33.3, 26.7.

IR: 2961, 2919, 2850, 1731, 1344, 1158, 1135, 1114, 977, 783, 532, 511 cm\(^{-1}\).

HRMS (+ESI): exact mass calcd for \(\text{C}_{7}\text{H}_{13}\text{NO}_{3}\text{S} \ [\text{M} + \text{H}]^+\): 191.0611, found: 191.0608.
Table 2, conditions D:
Copper(I) chloride (3.9 mg, 0.038 mmol, 20 mol%) was placed in a dry 100 mL round bottom flask and dried under vacuum while gently heated with a heat gun. Next, trifluorotoluene (1.9 mL) and bis(oxazoline) ligand L (7.9 mg, 0.043 mmol, 23 mol%) were added under argon and the mixture was stirred under argon flow at 60 °C for 2 hours. After that time alkene 1i (50.8 mg, 0.19 mmol) and flame dried 4 Å molecular sieves (ca. 35 mg) were added. The argon atmosphere was replaced with oxygen. Next, the balloon with oxygen was attached to the flask through an inlet hose adapter and the mixture was stirred under oxygen (1 atm) at 105 °C (oil bath temperature). The progress of the reaction was monitored by TLC (eluent: ethyl acetate/hexanes 1:4 v/v) and after 17 hours no more starting material was observed. Next, DABCO (7.2 mg, 0.064 mmol, 34 mol%) was added and the stirring under oxygen at 105 °C was continued until the intermediate aldehyde disappeared based on TLC (after 3 hours). After that time the mixture was filtered through a pad of Celite and the Celite was washed with dichloromethane and ethyl acetate. The crude product was purified by flash chromatography on silica gel (elution: ethyl acetate/hexanes 0%–12%) to afford 3i (40.1 mg) in 54% yield as a white solid.

mp 127-129 °C.

1H NMR (300 MHz, CDCl3) δ 7.90 (s, 2H), 3.72 (s, 2H), 3.60 (s, 2H), 2.26 (s, 2H), 1.44 (s, 18H), 1.10 (s, 6H).

13C NMR (75 MHz, CDCl3) δ 172.5, 164.4, 145.2, 132.0, 126.6, 64.6, 59.6, 47.0, 36.2, 33.3, 31.7, 26.6.

IR: 2965, 1732, 1406, 1393, 1356, 1288, 1169, 1115, 1004, 968, 884, 728, 633, 603, 589 cm⁻¹.


3-Benzyl-1-tosylpyrrolidin-2-one (3j)
The lactam 3j was prepared following the representative procedure (Table 2, conditions A) using 3.8 mg of CuCl and 62.6 mg of alkene 1j. DABCO (8.6 mg) was added after ca.
14 hours and the reaction was stopped after subsequent 3 hours. The lactam 3j (37.7 mg) was obtained in 46% yield (based on 80% purity according to NMR) as a colorless oil. The compound was previously reported; however there is no spectral analysis provided in the literature.

$^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 7.92 (d, $J = 8.4$ Hz, 2H), 7.34 (d, $J = 8.0$ Hz, 2H), 7.25-7.15 (m, 3H), 7.09-7.02 (m, 2H), 3.77 (ddd, $J = 9.9, 8.5, 3.1$ Hz, 1H), 3.63 (ddd, $J = 9.9, 8.8, 7.1$ Hz, 1H), 3.10 (dd, $J = 13.6, 4.0$ Hz, 1H), 2.79-2.67 (m, 1H), 2.63 (dd, $J = 13.5, 9.1$ Hz, 1H), 2.46 (s, 3H), 2.12-2.00 (m, 1H), 1.85-1.70 (m, 1H).

$^{13}$C NMR (75 MHz, CDCl$_3$) $\delta$ 174.4, 145.1, 138.0, 135.1, 129.6, 128.8, 128.6, 128.1, 126.6, 45.3, 44.9, 35.9, 24.3, 21.7.

IR: 2924, 1731, 1357, 1228, 1165, 1121, 1089, 701, 584, 548 cm$^{-1}$.


### Synthesis of 2-Dihydrofuranones (Table 3)

![Synthesis of 2-Dihydrofuranones](image)

Conditions **A**: CuCN (20 mol%), L (22 mol%), PhCH$_3$, 120 °C, 4 Å MS.

Conditions **B**: CuCl (15 mol%), L (17 mol%), PhCF$_3$, 120 °C, 4 Å MS.

![Representative Procedure](image)

Representative Procedure (Table 3, Conditions B): 4-phenyldihydrofuran-2(3H)-one (5c)

Copper(I) chloride (2.8 mg, 0.028 mmol, 15 mol%) was placed in a dry 100 mL round bottom flask and dried under vacuum while gently heated with a heat gun. Next, trifluorotoluene (1 mL) and bis(oxazoline) ligand L (5.9 mg, 0.032 mmol, 17 mol%) were added under argon and the mixture was stirred under argon flow at 60 °C for about 2 hours. After that time flame dried 4 Å molecular sieves (ca. 35 mg) and solution of alkene 4c (31.1 mg, 0.19 mmol) in trifluorotoluene (1 mL) were added. The argon atmosphere was replaced with oxygen. Next, the balloon with oxygen was attached to the flask through an inlet hose adapter and the mixture was stirred under oxygen (1 atm) at 120 °C (oil bath temperature) for about 26 hours. After that time the mixture was filtered through a pad of Celite and the Celite was washed with dichloromethane and ethyl acetate. The filtrate was concentrated, dried, and purified by flash chromatography on silica gel (elu-
tion: ethyl acetate/hexanes 0%–10%–20%) to afford 5c (13.5 mg) in 43% yield as a white solid.

The NMR data are consistent with reported literature values.\textsuperscript{33}
\textsuperscript{1}H NMR (400 MHz, CDCl\textsubscript{3}) \(\delta\) 7.41-7.34 (m, 2H), 7.34-7.27 (m, 1H), 7.27-7.20 (m, 2H), 4.67 (t, \(J = 8.5\) Hz, 1H), 4.27 (t, \(J = 8.5\) Hz, 1H), 3.79 (p, \(J = 8.4\) Hz, 1H), 2.93 (dd, \(J = 17.5, 8.7\) Hz, 1H), 2.68 (dd, \(J = 17.5, 9.1\) Hz, 1H).

\textsuperscript{13}C NMR (75 MHz, CDCl\textsubscript{3}) \(\delta\) 176.3, 139.4, 129.1, 127.7, 126.7, 74.0, 41.1, 35.7.

\textbf{5,5-Diphenyldihydrofuran-2(3H)-one (5a)}

Table 3, conditions A:
Copper(I) cyanide (3.5 mg, 0.038 mmol, 20 mol%) was placed in the dry 100 mL round bottom flask and dried under vacuum while gently heated with a heat gun. Next, toluene (1.4 mL) and bis(oxazoline) ligand L (8.2 mg, 0.042 mmol, 22 mol%) were added under argon and the mixture was stirred under argon flow at 60 °C for about 2 hours. After that time solution of alkene 4a (45.3 mg, 0.19 mmol) in toluene (0.5 mL) and flame dried 4 Å molecular sieves (ca. 35 mg) were added. The argon atmosphere was replaced with oxygen. Next, the balloon with oxygen was attached to the flask through an inlet hose adapter and the mixture was stirred under oxygen (1 atm) at 120 °C (oil bath temperature) for about 40 hours. After that time the mixture was filtered through a pad of Celite and washed with dichloromethane and ethyl acetate. The filtrate was concentrated, dried, and purified by chromatography on silica gel (elution: ethyl acetate/hexanes 0%–20%) to afford 5a (23.3 mg) in 51% yield as a white solid.

The NMR data are consistent with reported literature values.\textsuperscript{34}
\textsuperscript{1}H NMR (400 MHz, CDCl\textsubscript{3}) \(\delta\) 7.46-7.39 (m, 4H), 7.35 (t, \(J = 7.6\) Hz, 4H), 7.31-7.24 (m, 2H), 2.91 (t, \(J = 7.8\) Hz, 2H), 2.58 (t, \(J = 7.8\) Hz, 2H).

\textsuperscript{13}C NMR (75 MHz, CDCl\textsubscript{3}) \(\delta\) 176.0, 143.0, 128.6, 127.8, 125.3, 89.7, 35.6, 29.0.

\textbf{3,3-Dimethylisobenzofuran-1(3H)-one (5b)}

A) from 2-(2-vinylphenyl)propan-2-ol (4b):

\[\text{O} \quad \text{O} \]

\[\text{Ph} \quad \text{Ph} \]

\[\text{O} \quad \text{O} \]

\[\text{Ph} \quad \text{Ph} \]
The lactone 5b was prepared following the representative procedure (Table 3, conditions B) using 2.8 mg of CuCl, 5.8 mg of ligand, and 31.0 mg of 4b. The reaction was completed overnight. The lactone 5b (21.6 mg) was obtained in 70% yield as white solid.

B) from 2-(2-allylphenyl)propan-2-ol (4b'):
The lactone 5b was prepared following the representative procedure procedure (Table 3, conditions B) using 2.8 mg of CuCl, 5.7 mg of ligand, and 33.6 mg of 4b'. The reaction was completed after 29 hours. The lactone 5b (13.8 mg) was obtained in 45% yield as white solid.

The NMR data are consistent with reported literature values.\textsuperscript{35} 1H NMR (400 MHz, CDCl\textsubscript{3}) \(\delta\) 7.86 (dt, \(J = 7.7, 1.0\) Hz, 1H), 7.66 (td, \(J = 7.5, 1.2\) Hz, 1H), 7.50 (td, \(J = 7.5, 0.9\) Hz, 1H), 7.40 (dt, \(J = 7.7, 0.9\) Hz, 1H), 1.66 (s, 6H)
13C NMR (75 MHz, CDCl\textsubscript{3}) \(\delta\) 169.8, 155.0, 134.1, 128.9, 125.7, 125.3, 120.6, 85.4, 27.3.

Synthesis of 2-Formylpyrrolidines and 2-Ketopyrrolidine (Table 4)

\[
\begin{align*}
\text{R} & \quad \text{O}_2 \\
\text{NHR'} & \quad \text{(1 atm)} \\
\text{[Cu]} & \quad \text{(conditions A, B, or C)} \\
\text{[R]} & \quad \text{4-24 h} \\
\text{R''} & \\
\text{R''} & \\
\text{R} & \\
\end{align*}
\]

Conditions A: CuCl (20 mol%), PhCH\textsubscript{3}, 105 °C, 4 Å MS.
Conditions B: CuCl (20 mol%), PhCH\textsubscript{3}, 120 °C, 4 Å MS.
Conditions C: CuCl (15 mol%), L (17 mol%), PhCF\textsubscript{3}, 120 °C, 4 Å MS.

Representative Procedure (Table 4, Conditions A): (2S,5S)-5-Methyl-1-tosylpyrrolidine-2-carbaldehyde (2b).

Copper(I) chloride (3.9 mg, 0.039 mmol, 20 mol%) was placed in a dry 100 mL round bottom flask and dried under vacuum while gently heated with a heat gun. Next, the flask was back-filled with argon and toluene (1.9 mL), flame dried 4 Å molecular sieves (ca. 35 mg) and (S)-N-(hex-5-en-2-yl)-4-methylbenzenesulfonamide (48.2 mg, 0.19 mmol) were added. The argon atmosphere was replaced with oxygen. Next, the balloon with oxygen was attached to the flask through an inlet hose adapter and the mixture was stirred under oxygen (1 atm) at 105 °C (oil bath temperature). The progress of the reaction was monitored by TLC (eluent: ethyl acetate/hexanes 1:4 v/v) and the reaction was completed in 6 hours. After that time the mixture was filtered through a pad of Celite and the Celite was washed with dichloromethane and ethyl acetate. The filtrate was concentrated, dried,
and the crude product was purified by flash chromatography on silica gel (elution: ethyl acetate/hexanes 0%–12%–20%) to afford 2b (34.8 mg) in 68% yield as a waxy solid. The crude NMR indicated the presence of single diastereomer (dr > 20:1). Its stereoechemistry has been assigned as the 2,5-cis-pyrrolidine via nOe analysis (enhancement of H_b signal was observed when H_a was irradiated).

\[ \text{nOe} \]

\[ \begin{array}{c}
  \text{H}_a \\
  \text{H}_b \\
  \text{N} \\
  \text{Ts} \\
 \end{array} \]

mp 64–66 °C.
\[ [\alpha]_{D}^{25} = -95.9 \ (c\ 1.06, \text{CHCl}_3). \]

\(^1H\ NMR\ (300\ MHz, \text{CDCl}_3) \delta 9.63 \ (d, J = 2.4\ Hz, 1H), 7.71 \ (d, J = 8.4\ Hz, 2H), 7.33 \ (d, J = 8.7\ Hz, 2H), 3.84 \ (td, J = 7.4, 2.4\ Hz, 1H), 3.80-3.70 \ (m, 1H), 2.43 \ (s, 3H), 2.08-1.93 \ (m, 1H), 1.78-1.58 \ (m, 2H), 1.54-1.41 \ (m, 1H), 1.36 \ (d, J = 6.6\ Hz, 3H).

\(^{13}C\ NMR\ (75\ MHz, \text{CDCl}_3) \delta 200.2, 144.0, 134.0, 129.9, 127.6, 68.0, 57.5, 32.5, 25.5, 22.7, 21.5.

IR: 2972, 2926, 1733, 1340, 1305, 1157, 1089, 1040, 815, 662, 594, 550 cm\(^{-1}\).

HRMS (+ESI): exact mass calcd for C\(_{13}\)H\(_{18}\)NO\(_3\)S [M + H]\(^+\): 268.1002, found: 268.0995.

---

4,4-Dimethyl-1-tosylpyrrolidine-2-carbaldehyde (2a)

The aldehyde 2a was prepared following the representative procedure at 120 °C (Table 4, conditions B) using 3.9 mg of CuCl and 50.9 mg of alkene 1a. The reaction was completed after 5 hours. The aldehyde 2a (33.0 mg) was obtained in 62% yield as a colorless oil. The NMR data are consistent with reported literature values.

\(^1H\ NMR\ (400\ MHz, \text{CDCl}_3) \delta 9.72 \ (d, J = 2.9\ Hz, 1H), 7.72 \ (d, J = 8.3\ Hz, 2H), 7.35 \ (d, J = 7.9\ Hz, 2H), 3.83 \ (ddd, J = 8.5, 7.4, 2.9\ Hz, 1H), 3.30 \ (d, J = 9.8\ Hz, 1H), 2.96 \ (d, J = 9.8\ Hz, 1H), 2.44 \ (s, 3H), 1.81 \ (dd, J = 12.8, 7.5\ Hz, 1H), 1.70 \ (dd, J = 12.8, 8.6\ Hz, 1H), 1.05 \ (s, 3H), 0.66 \ (s, 3H).

\(^{13}C\ NMR\ (75\ MHz, \text{CD}_2\text{Cl}_2) \delta 200.9, 145.2, 134.1, 130.7, 128.4, 67.3, 61.9, 42.2, 39.2, 26.7, 25.9, 22.1.
Supporting Information

(±)-cis-5-(But-3-en-1-yl)-1-tosylpyrrolidine-2-carbaldehyde (2c)

The aldehyde 2c was prepared following the representative procedure (Table 4, conditions A) using 3.9 mg of CuCl and 55.9 mg of alkene 1c. The reaction was completed after ca. 6 hours. The aldehyde 2c (39.4 mg) was obtained in 67% yield as an oil. The crude NMR indicated the presence of one diastereomer (dr > 20:1). The cis configuration of 2c was assigned by analogy to 2b, 2d, 2k, and 2l. The NMR data are consistent with literature values reported for (2S,5S)-enantiomer of 2c.37

\[ ^1\text{H NMR (400 MHz, CDCl}_3\text{)} \delta 9.63 (d, J = 2.2 Hz, 1H), 7.71 (d, J = 8.3 Hz, 2H), 7.33 (d, J = 8.1 Hz, 2H), 5.82 (ddt, J = 16.9, 10.2, 6.4 Hz, 1H), 5.10-4.96 (m, 2H), 3.86 (td, J = 7.6, 2.3 Hz, 1H), 3.68 (ddt, J = 9.2, 6.7, 4.8 Hz, 1H), 2.44 (s, 3H), 2.17-1.93 (m, 4H), 1.76-1.67 (m, 1H), 1.62-1.50 (m, 3H). \]

\[ ^{13}\text{C NMR (75 MHz, CDCl}_3\text{)} \delta 200.1, 144.1, 137.5, 129.9, 127.6, 115.2, 67.8, 61.3, 35.2, 30.2, 29.8, 25.5, 21.5. \]

IR: 2922, 1734, 1345, 1158, 1090, 1040, 816, 664, 594, 551 cm\(^{-1}\).

HRMS (+ESI): exact mass calcd for C\(_{16}\)H\(_{22}\)NO\(_3\)S [M + H]\(^+\): 308.1315, found: 308.1327.

(±)-cis-5-Phenyl-1-tosylpyrrolidine-2-carbaldehyde (2d)

The aldehyde 2d was prepared following the representative procedure (Table 4, conditions A) using 3.9 mg of CuCl and 59.9 mg of alkene 1d. The reaction was completed after 5 hours. The aldehyde 2d (51.2 mg) was obtained in 82% yield as an oil. The crude NMR indicated the presence of one diastereomer (dr > 20:1). Its stereochemistry has been assigned as the 2,5-cis-pyrrolidine via nOe analysis (enhancement of H\(_b\) signal was observed when H\(_a\) was irradiated).

Compound 2d was previously reported as a part of the mixture of diastereomers.9
Supporting Information

$^1$H NMR (400 MHz, CDCl$_3$) δ 9.86 (d, J = 2.0 Hz, 1H), 7.68 (d, J = 8.3 Hz, 2H), 7.40-7.23 (m, 7H), 4.78 (dd, J = 7.3, 4.7 Hz, 1H), 4.21-4.13 (m, 1H), 2.44 (s, 3H), 2.10-1.92 (m, 2H), 1.91-1.81 (m, 2H).

$^{13}$C NMR (75 MHz, CDCl$_3$) δ 199.6, 144.2, 141.2, 134.1, 129.8, 128.5, 127.8, 127.5, 126.2, 68.2, 64.6, 35.0, 25.7, 21.5.

IR: 2923, 1733, 1347, 1158, 1091, 1041, 700, 668, 586, 545 cm$^{-1}$.


4-allyl-1-tosylpyrrolidine-2-carbaldehyde (2e)

The aldehyde 2e was prepared following the representative procedure (Table 4, conditions A) using 3.9 mg of CuCl and 53.3 mg of alkene 1e. The reaction was completed after 4 hours. The aldehyde 2e (29.8 mg) was obtained in 53% yield as a colorless oil. The crude NMR indicated the presence of mixture of diastereomers (dr = 1.5:1).

$^1$H NMR (300 MHz, CDCl$_3$) δ 9.70 (d, J = 2.0 Hz, 1H, minor diastereomer), 9.65 (d, J = 3.1 Hz, 1H, major diastereomer), 7.77-7.65 (m, 2H, both diastereomers), 7.40-7.30 (m, 2H, both diastereomers), 5.73-5.47 (m, 1H, both diastereomers), 5.12-4.77 (m, 2H, both diastereomers), 3.93-3.85 (m, 1H, minor diastereomer), 3.77 (tt, J = 8.1, 2.9 Hz, 1H, major diastereomer), 3.66 (dd, J = 9.4, 6.4 Hz, 1H, minor diastereomer), 3.39 (dd, J = 10.6, 7.4 Hz, 1H, major diastereomer), 3.18 (dd, J = 10.6, 7.6 Hz, 1H, major diastereomer), 2.76 (dd, J = 9.5, 7.7 Hz, 1H, minor diastereomer), 2.45 (s, 3H, minor diastereomer), 2.44 (s, 3H, major diastereomer), 2.30-1.40 (m, 5H, both diastereomers).

$^{13}$C NMR (75 MHz, CDCl$_3$) δ 200.3, 199.7, 144.2, 144.2, 135.0, 134.9, 133.4, 129.9, 129.7, 127.7, 117.2, 117.0, 66.7, 66.0, 53.8, 53.7, 37.7, 37.5, 36.8, 36.5, 33.2, 33.0, 21.5.

IR: 2922, 1732, 1597, 1344, 1158, 1090, 918, 816, 664, 595, 549 cm$^{-1}$.

HRMS (+ESI): exact mass calcd for C$_{15}$H$_{20}$NO$_3$S [M + H]$^+$: 294.1158, found: 294.1166.

4-(4-Chlorophenyl)-1-tosylpyrrolidine-2-carbaldehyde (2f)

The aldehyde 2f was prepared following the representative procedure (Table 4, conditions A) using 3.9 mg of CuCl and 66.6 mg of alkene 1f. The reaction was completed after ca. 9 hours. The aldehyde 2f was obtained in 62% yield (based on 80% purity according to NMR) as a colorless oil. The crude NMR indicated the presence of mixture of diastereomers (dr = 1.9:1).
\[ ^1H \text{ NMR (500 MHz, CDCl}_3 \delta 9.82 (d, J = 1.5 \text{ Hz, 1H, minor diastereomer}), 9.67 (d, J = 2.9 \text{ Hz, 1H, major diastereomer}), 7.76 (d, J = 8.3 \text{ Hz, 2H, major diastereomer}), 7.73 (d, J = 8.1 \text{ Hz, 2H, minor diastereomer}), 7.38 (d, J = 8.0 \text{ Hz, 2H, major diastereomer}), 7.35 (d, J = 7.9 \text{ Hz, 2H, minor diastereomer}), 7.27 (d, J = 7.1 \text{ Hz, 2H, major diastereomer}), 7.20 (d, J = 8.4 \text{ Hz, 2H, minor diastereomer}), 7.08 (d, J = 8.5 \text{ Hz, 2H, major diastereomer}), 6.91 (d, J = 8.5 \text{ Hz, 2H, minor diastereomer}), 4.10 (dd, J = 10.0, 1.7 \text{ Hz, 1H, minor diastereomer}), 3.99 - 3.90 (m, 1H, both diastereomers), 3.72 (dd, J = 11.0, 7.8 \text{ Hz, 1H, major diastereomer}), 3.52 (dd, J = 11.0, 9.0 \text{ Hz, 1H, major diastereomer}), 3.32 (tt, J = 10.4, 7.0 \text{ Hz, 1H, minor diastereomer}), 3.06 (t, J = 9.5 \text{ Hz, 1H, minor diastereomer}), 2.96 (p, J = 8.3 \text{ Hz, 1H, major diastereomer}), 2.54-2.48 (m, 1H, minor diastereomer), 2.47 (s, 3H, both diastereomers), 2.40-2.31 (m, 1H, major diastereomer), 2.07 (ddd, J = 12.7, 10.2, 8.9 \text{ Hz, 1H, major diastereomer}), 1.85 (ddd, J = 13.0, 10.9, 9.3 \text{ Hz, 1H, minor diastereomer}). \]

\[ ^13C \text{ NMR (75 MHz, CDCl}_3 \delta 200.1, 199.0, 144.5, 144.4, 137.3, 137.3, 133.5, 133.3, 133.2, 133.1, 130.1, 130.0, 129.0, 128.8, 128.2, 128.1, 127.7, 66.7, 66.0, 54.8, 54.6, 42.5, 42.0, 35.2, 33.9, 21.6. \]

IR: 2924, 1732, 1494, 1343, 1157, 1090, 1013, 815, 663, 547 cm\(^{-1}\).

HRMS (+ESI): exact mass calcd for C\(_{13}\)H\(_{17}\)N\(_2\)O\(_5\)S [M + H\(^+\)]: 364.0769, found: 364.0785.

\[ \bigg[ \begin{array}{c}
\text{O} \\
\text{NNs}
\end{array} \bigg] \]

4,4-Dimethyl-1-((4-nitrophenyl)sulfonyl)pyrroloidine-2-carbaldehyde (2g)

The aldehyde 2g was prepared following the representative procedure at 120 °C (Table 4, conditions B) using 3.9 mg of CuCl and 56.7 mg of alkene 1g. The reaction was completed after 24 hours. The aldehyde 2g (24.8 mg) was obtained in 42% yield as a yellow solid.

mp 120-122 °C.

\[ ^1H \text{ NMR (400 MHz, CDCl}_3 \delta 9.69 (d, J = 2.7 \text{ Hz, 1H}), 8.41 (d, J = 8.9 \text{ Hz, 2H}), 8.04 (d, J = 8.8 \text{ Hz, 2H}), 3.96 (ddd, J = 8.5, 7.6, 2.7 \text{ Hz, 1H}), 3.33 (d, J = 9.8 \text{ Hz, 1H}), 3.03 (d, J = 9.8 \text{ Hz, 1H}), 1.90-1.77 (m, 2H), 1.08 (s, 3H), 0.73 (s, 3H). \]

\[ ^13C \text{ NMR (75 MHz, CDCl}_3 \delta 198.9, 150.4, 142.6, 128.8, 124.5, 66.6, 61.2, 41.5, 38.7, 25.9, 25.4. \]

IR: 3110, 2964, 1731, 1527, 1348, 1309, 1164, 1095, 1072, 735 cm\(^{-1}\).

HRMS (+ESI): exact mass calcd for C\(_{13}\)H\(_{17}\)N\(_2\)O\(_5\)S [M + H\(^+\)]: 313.0853, found: 313.0863.
1-((3,5-Di-tert-butyl-4-methoxyphenyl)sulfonyl)-4,4-dimethylpyrrolidine-2-carbaldehyde (2i)

The aldehyde 2i was prepared following the representative procedure at 120 °C (Table 4, conditions B) using 3.9 mg of CuCl and 75.2 mg of alkene 1i. The reaction was completed after 12 hours. The aldehyde 2i (41.7 mg) was obtained in 54% yield as an oil.

$^1$H NMR (300 MHz, CDCl$_3$) $\delta$ 9.68 (d, $J = 3.0$ Hz, 1H), 7.69 (s, 2H), 3.78 (td, $J = 8.2$, 3.0 Hz, 1H), 3.69 (s, 3H), 3.30 (d, $J = 10.1$ Hz, 1H), 2.99 (d, $J = 10.0$ Hz, 1H), 1.80 (dd, $J = 12.7$, 8.3 Hz, 1H), 1.71 (dd, $J = 12.7$, 8.5 Hz, 1H), 1.44 (s, 18H), 1.05 (s, 3H), 0.57 (s, 3H).

$^{13}$C NMR (75 MHz, CDCl$_3$) $\delta$ 200.2, 163.8, 145.5, 130.1, 126.1, 66.5, 64.7, 61.1, 41.5, 38.5, 36.1, 31.8, 26.1, 25.2.

IR: 2961, 1735, 1394, 1346, 1253, 1226, 1163, 1124, 1066, 1033, 1003, 637, 591, 537 cm$^{-1}$.

HRMS (+ESI): exact mass calcd for C$_{22}$H$_{36}$NO$_4$S [M + H]$^+$: 410.2360, found: 410.2379.

$\text{(±)-trans-3-Benzyl-1-tosylpyrrolidine-2-carbaldehyde (2j)}$

The aldehyde 2j was prepared following the representative procedure (Table 4, conditions A) using 3.9 mg of CuCl and 62.7 mg of alkene 1j. The reaction was completed after 18 hours. The aldehyde 2j (39.9 mg) was obtained in 61% yield as a colorless oil.

The crude NMR indicated the presence of mixture of diastereomers (dr = 4.8:1). The mixture was further purified via preparative HPLC to obtain NMR spectra of the major isomer. The trans configuration of 2j was assigned by analogy to 2t.

$^1$H NMR (500 MHz, CDCl$_3$) $\delta$ 9.65 (d, $J = 2.6$ Hz, 1H), 7.70 (d, $J = 8.0$ Hz, 2H), 7.34 (d, $J = 8.0$ Hz, 2H), 7.25 - 7.15 (m, 3H), 6.96 (d, $J = 7.0$ Hz, 2H), 3.57-3.45 (m, 2H), 3.37 (ddd, $J = 10.4$, 7.8, 5.7 Hz, 1H), 2.65-2.54 (m, 2H), 2.46 (s, 3H), 2.32-2.23 (m, 1H), 1.90-1.79 (m, 1H), 1.42-1.31 (m, 1H).

$^{13}$C NMR (75 MHz, CDCl$_3$) $\delta$ 199.7, 144.1, 138.0, 129.9, 128.9, 128.5, 127.6, 126.6, 47.9, 42.3, 37.3, 29.9, 21.6.

IR: 2923, 1731, 1344, 1159, 1094, 665, 549 cm$^{-1}$.
HRMS (ESI\(^+\)): exact mass calcd for \(\text{C}_{19}\text{H}_{22}\text{NO}_3\text{S} \ [\text{M} + \text{H}]^+\): 344.1315, found: 344.1330.

\[
\begin{array}{c}
\text{NTs} \\
\text{O} \\
\text{O} \\
\end{array}
\]

**(2S,5R)-5-Isopropyl-1-tosylpyrrolidine-2-carbaldehyde (2k)**

The aldehyde 2k was prepared following the representative procedure (Table 4, conditions A) using 3.8 mg of CuCl and 53.6 mg of alkene 1k. The aldehyde 2k (39.5 mg) was obtained in 70% yield as a waxy white solid.

The crude NMR indicated the presence of single diastereomer (dr > 20:1). Its stereochemistry has been assigned as the 2,5-*cis*-pyrrolidine via nOe analysis (enhancement of \(H_b\) signal was observed when \(H_a\) was irradiated and vice versa).

mp 102-105 °C.

\([\alpha]_{D}^{28} \text{ – 55.3} \ (c \ 1.21, \ \text{CH}_2\text{Cl}_2).\]

\(^1\text{H} \text{NMR} (400 \text{ MHz, CDCl}_3) \delta 9.67 \ (d, J = 2.0 \text{ Hz, 1H}), 7.71 \ (d, J = 8.3 \text{ Hz, 2H}), 7.34 \ (d, J = 7.6 \text{ Hz, 2H}), 3.88 \ (\text{ddd, } J = 8.0, 6.7, 2.0 \text{ Hz, 1H}), 3.50 \ (\text{ddd, } J = 8.0, 6.0, 4.1 \text{ Hz, 1H}), 2.43 \ (s, 3H), 2.17-2.05 \ (m, 1H), 2.00-1.89 \ (m, 1H), 1.69-1.58 \ (m, 2H), 1.43-1.32 \ (m, 1H), 0.96 \ (d, J = 6.9 \text{ Hz, 3H}), 0.90 \ (d, J = 6.8 \text{ Hz, 3H}).\]

\(^{13}\text{C} \text{NMR} (75 \text{ MHz, CDCl}_3) \delta 200.3, 144.1, 133.8, 129.9, 127.7, 68.0, 67.2, 31.5, 25.7, 25.6, 21.5, 20.1, 16.8.\]

IR: 2961, 2925, 2872, 1739, 1342, 1158, 1090, 1024, 1003, 674, 659, 603, 551 cm\(^{-1}\).

HRMS (+ESI): exact mass calcd for \(\text{C}_{15}\text{H}_{22}\text{NO}_3\text{S} \ [\text{M} + \text{H}]^+\): 296.1315, found: 296.1310.
(2S,5R)-5-(tert-Butyl)-1-tosylpyrrolidine-2-carbaldehyde (2l)

The aldehyde 2l was prepared following the representative procedure (Table 4, conditions A) using 3.8 mg of CuCl and 56.0 mg of alkene 1l. The reaction was completed after 24 hours. The aldehyde 2l (34.2 mg) was obtained in 59% yield as a colorless oil. The crude NMR indicated the presence of single diastereomer (dr > 20:1). Its stereochemistry has been assigned as the 2,5-cis-pyrrolidine via nOe analysis (enhancement of Hb signal was observed when Ha was irradiated and vice versa).

\[
\begin{align*}
\text{[a]}^{27}_D & = -46.9 \text{ (c 0.46, CH}_2\text{Cl}_2) \\
^{1}H \text{ NMR (400 MHz, CDCl}_3 & \text{) } \delta 9.80 \text{ (d, } J = 1.2 \text{ Hz, 1H), 7.73} \text{ (d, } J = 8.3 \text{ Hz, 2H), 7.34} \text{ (d, } J = 7.8 \text{ Hz, 2H), 4.00-3.91} \text{ (m, 1H), 3.70} \text{ (dd, } J = 9.0, 1.9 \text{ Hz, 1H), 2.44} \text{ (s, 3H), 2.06-1.90} \text{ (m, 1H), 1.82-1.70} \text{ (m, 2H), 1.32-1.21} \text{ (m, 1H), 0.95 (s, 9H).} \\
^{13}C \text{ NMR (75 MHz, CDCl}_3 & \text{) } \delta 201.6, 144.2, 134.1, 129.9, 128.0, 70.8, 68.7, 35.4, 27.8, 26.8, 26.3, 21.6. \\
\text{IR: 2961, 1733, 1474, 1347, 1160, 1091, 993, 816, 666, 593, 551 cm}^{-1}. \\
\text{HRMS (+ESI): exact mass calcd for C}_{16}\text{H}_{23}\text{NNaO}_3\text{S [M} + \text{Na}]^+ & \text{: 332.1291, found: 332.1306.}
\end{align*}
\]

(2S,5R)-5-Benzyl-1-tosylpyrrolidine-2-carbaldehyde (2m)

The aldehyde 2m was prepared following the representative procedure (Table 4, conditions A) using 3.9 mg of CuCl and 62.7 mg of alkene 1m. The reaction was completed overnight. The aldehyde 2m (38.7 mg) was obtained in 60% yield as a colorless oil. The crude NMR indicated the presence of single diastereomer (dr > 20:1). The cis configuration of 2m was assigned by analogy to 2b, 2d, 2k, and 2l.
$[\alpha]_D^{26} + 2.1$ (c 0.65, CH$_2$Cl$_2$).

$^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 9.50 (d, $J = 2.6$ Hz, 1H), 7.75 (d, $J = 8.3$ Hz, 2H), 7.38–7.21 (m, 7H), 3.88 (ddt, $J = 9.0, 7.1, 3.4$ Hz, 1H), 3.78 (td, $J = 7.5, 2.7$ Hz, 1H), 3.24 (dd, $J = 13.4, 3.5$ Hz, 1H), 2.87 (dd, $J = 13.4, 9.1$ Hz, 1H), 2.44 (s, 3H), 1.79–1.57 (m, 3H), 1.52–1.40 (m, 1H).

$^{13}$C NMR (75 MHz, CDCl$_3$) $\delta$ 199.9, 144.2, 137.4, 133.7, 130.0, 129.8, 128.5, 127.7, 126.8, 68.1, 62.7, 42.3, 29.2, 25.5, 21.6.

IR: 2923, 1733, 1454, 1345, 1158, 1091, 815, 735, 702, 665, 590, 551 cm$^{-1}$.

HRMS (+ESI): exact mass calcd for C$_{19}$H$_{22}$NO$_3$S $[M + H]^+$: 344.1315, found: 344.1319.

$^2$H NMR (400 MHz, CDCl$_3$) $\delta$ 9.63 (d, $J = 2.3$ Hz, 1H), 7.72 (d, $J = 8.3$ Hz, 2H), 7.34 (d, $J = 8.0$ Hz, 2H), 3.92–3.80 (m, 2H), 2.69–2.58 (m, 1H), 2.56–2.46 (m, 1H), 2.44 (s, 3H), 2.21–2.08 (s+m, 4H), 2.04–1.92 (m, 1H), 1.79-1.68 (m, 2H), 1.55 (dt, $J = 8.0, 6.1$ Hz, 2H).

$^{13}$C NMR (75 MHz, CDCl$_3$) $\delta$ 199.9, 144.2, 137.4, 133.7, 130.0, 127.7, 67.8, 60.5, 35.0, 30.5, 30.0, 25.5, 21.5, 15.3.

IR: 2919, 1733, 1597, 1448, 1344, 1158, 1090, 1040, 816, 665, 595, 553 cm$^{-1}$.

HRMS (+ESI): exact mass calcd for C$_{15}$H$_{22}$NO$_3$S$_2$ $[M + H]^+$: 328.1036, found: 328.1050.

$\left(2S,5R\right)$-5-$\left(\text{Methylthio}\right)$ethyl)-1-tosylpyrrolidine-2-carbaldehyde (2n)

The aldehyde 2n was prepared following the representative procedure (Table 4, conditions A) using 3.9 mg of CuCl and 59.8 mg of alkene 1n. The reaction was completed after 5 hours. The aldehyde 2n (24.9 mg) was obtained in 40% yield as a colorless oil. The crude NMR indicated the presence of single diastereomer (dr > 20:1). The cis configuration of 2n was assigned by analogy to 2b, 2d, 2k, and 2l.

$[\alpha]_D^{23} + 2.8$ (c 0.77, CHCl$_3$).

$^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 9.63 (d, $J = 2.3$ Hz, 1H), 7.72 (d, $J = 8.3$ Hz, 2H), 7.34 (d, $J = 8.0$ Hz, 2H), 3.92-3.80 (m, 2H), 2.69-2.58 (m, 1H), 2.56-2.46 (m, 1H), 2.44 (s, 3H), 2.21-2.08 (s+m, 4H), 2.04-1.92 (m, 1H), 1.79-1.68 (m, 2H), 1.55 (dt, $J = 8.0, 6.1$ Hz, 2H).

$^{13}$C NMR (75 MHz, CDCl$_3$) $\delta$ 199.9, 144.2, 137.4, 133.7, 130.0, 127.7, 67.8, 60.5, 35.0, 30.5, 30.0, 25.5, 21.5, 15.3.

IR: 2919, 1733, 1597, 1448, 1344, 1158, 1090, 1040, 816, 665, 595, 553 cm$^{-1}$.

HRMS (+ESI): exact mass calcd for C$_{19}$H$_{22}$NO$_3$S $[M + H]^+$: 344.1315, found: 344.1319.

$\left(2S,5R\right)$-5-((Benzyloxy)methyl)-1-tosylpyrrolidine-2-carbaldehyde (2o)

The aldehyde 2o was prepared following the representative procedure (Table 4, conditions A) using 3.9 mg of CuCl and 68.3 mg of alkene 1o. The reaction was completed after 6 hours. The aldehyde 2o (51.2 mg) was obtained in 72% yield as an oil. The crude NMR indicated the presence of single diastereomer (dr > 20:1). The cis con-
Figuration of 2o was assigned by analogy to 2b, 2d, 2k, and 2l. The NMR data are consistent with literature values reported for mixture of 2o and its enantiomer (racemic mixture). \(^9\)

\[ [\alpha]_D^{27} -17.3 \text{ (c 1.21, CH}_2\text{Cl}_2). \]

\(^1\)H NMR 300 MHz, CDCl\(_3\) \(\delta\) 9.58 (d, \(J = 2.7\) Hz, 1H), 7.70 (d, \(J = 8.3\) Hz, 2H), 7.41–7.26 (m, 7H), 4.55 (ABq, \(J = 11.7\) Hz, \(\Delta\nu = 6.7\) Hz, 2H), 3.92-3.66 (m, 3H), 3.60 (dd, \(J = 9.4, 6.9\) Hz, 1H), 2.43 (s, 3H), 2.12-1.96 (m, 1H), 1.90 (ddt, \(J = 13.4, 6.9, 3.3\) Hz, 1H), 1.75 (dtd, \(J = 12.3, 7.4, 3.6\) Hz, 1H), 1.65-1.45 (m, 1H).

\(^1\)H NMR 270 MHz, CDCl\(_3\) \(\delta\) 9.59 (d, \(J = 2.7\) Hz, 1H), 7.71 (d, \(J = 8.3\) Hz, 2H), 7.34 (d, \(J = 7.8\) Hz, 2H), 3.86-3.67 (m, 4H), 2.44 (s, 3H), 2.12-1.98 (m, 1H), 1.95-1.83 (m, 1H), 1.79-1.66 (m, 1H), 1.60-1.46 (m, 1H), 0.88 (s, 9H), 0.08 (s, 6H).

\(^1\)H NMR 270 MHz, CDCl\(_3\) \(\delta\) 200.1, 144.2, 137.8, 133.6, 129.9, 128.4, 127.7, 127.6, 127.6, 73.5, 72.9, 67.8, 60.6, 28.1, 26.1, 21.5.

\(^{13}\)C NMR (75 MHz, CDCl\(_3\) \(\delta\)) 200.3, 144.2, 137.8, 133.6, 129.9, 128.4, 127.7, 127.6, 68.0, 65.8, 62.3, 27.5, 26.1, 25.9, 21.5, 18.3, -5.4, -5.5.

IR: 2953, 2929, 2857, 1735, 1348, 1253, 1160, 1090, 1027, 835, 814, 777, 663, 595, 551 cm\(^{-1}\).

HRMS (+ESI): exact mass calcld for C\(_{19}\)H\(_{32}\)NO\(_4\)SSi [M + H]\(^+\): 398.1816, found: 398.1802.

\(2S,5R\)-5-(((tert-Butyldimethylsilyl)oxy)methyl)-1-tosylpyrrolidine-2-carbaldehyde (2p)

The aldehyde 2p was prepared following the representative procedure (Table 4, conditions A) using 3.8 mg of CuCl and 73.1 mg of alkene 1p. The reaction was completed after 12 hours. The aldehyde 2p (40.2 mg) was obtained in 53% yield as a colorless oil. The crude NMR indicated the presence of single diastereomer (dr > 20:1). The cis configuration of 2p was assigned by analogy to 2b, 2d, 2k, and 2l.

\[ [\alpha]_D^{28} -26.2 \text{ (c 1.09, CH}_2\text{Cl}_2). \]

\(^1\)H NMR (400 MHz, CDCl\(_3\) \(\delta\)) 9.59 (d, \(J = 2.7\) Hz, 1H), 7.71 (d, \(J = 8.3\) Hz, 2H), 7.34 (d, \(J = 7.8\) Hz, 2H), 3.86-3.67 (m, 4H), 2.44 (s, 3H), 2.12-1.98 (m, 1H), 1.95-1.83 (m, 1H), 1.79-1.66 (m, 1H), 1.60-1.46 (m, 1H), 0.88 (s, 9H), 0.08 (s, 6H).

IR: 2953, 2929, 2857, 1735, 1348, 1253, 1160, 1090, 1027, 835, 814, 777, 663, 595, 551 cm\(^{-1}\).

HRMS (+ESI): exact mass calcld for C\(_{19}\)H\(_{32}\)NO\(_4\)SSi [M + H]\(^+\): 398.1816, found: 398.1802.
The aldehyde 2q was prepared following the representative procedure (Table 4, conditions A) using 3.8 mg of CuCl and 56.1 mg of alkene 1q. The reaction was completed after 23 hours. The aldehyde 2q (30.2 mg) was obtained in 51% yield as a colorless oil. The crude NMR indicated the presence of single diastereomer (dr > 20:1). The cis configuration of 2q was assigned by analogy to 2b, 2d, 2k, and 2l. The NMR data are consistent with reported literature values.\[^8\] 
\[^{[\alpha]D}_{20}^{28} +28.8 \text{ (c 0.60, CHCl}_3\); lit.\[^8\]^{[\alpha]D}_{23}^{23} +17.2 \text{ (c 0.60, CHCl}_3}\). 

\[^1\text{H NMR (400 MHz, CDCl}_3\)} \delta 9.63 (d, \(J = 2.3 \) Hz, 1H), 7.72 (d, \(J = 8.3 \) Hz, 2H), 7.34 (d, \(J = 7.6 \) Hz, 2H), 3.86 (td, \(J = 7.6, 2.3 \) Hz, 1H), 3.66 (ddt, \(J = 9.0, 6.6, 4.6 \) Hz, 1H), 2.44 (s, 3H), 2.06-1.92 (m, 1H), 1.92-1.80 (m, 1H), 1.78-1.65 (m, 1H), 1.56-1.41 (m, 3H), 1.40-1.27 (m, 4H), 0.92 (t, \(J = 7.0 \) Hz, 3H).

\[^{13}\text{C NMR (75 MHz, CDCl}_3\)} \delta 200.3, 144.0, 134.1, 129.9, 127.6, 67.7, 62.0, 36.0, 29.9, 28.2, 25.5, 22.5, 21.5, 14.0.

**Gram scale synthesis of (2R,5R)-5-butyl-1-tosylpyrrolidine-2-carbaldehyde (2q)**

Copper(I) chloride (69.5 mg, 0.68 mmol, 20 mol%) was placed in a dry 500 mL 3-neck round bottom flask and dried under vacuum while gently heated with a heat gun. Next, the flask was back-filled with argon and toluene (29 mL), flame dried 4 Å molecular sieves (ca. 625 mg), and a solution of (R)-4-methyl-N-(non-1-en-5-yl)benzenesulfonamide (1.0047 g, 3.4 mmol) in toluene (5 mL) were added. The argon atmosphere was replaced with oxygen. Next, one balloon with oxygen was attached to each neck of the flask through an inlet hose adapter and the mixture was stirred under oxygen (1 atm) at 105 °C (oil bath temperature). The progress of the reaction was monitored by TLC (eluent: ethyl acetate/hexanes 1:4 v/v) and the reaction was completed in 20 hours. After that time the mixture was filtered through a pad of Celite and the Celite was washed with dichloromethane and ethyl acetate. The filtrate was concentrated, dried, and the crude product was purified by flash chromatography on silica gel (elution: ethyl acetate/hexanes 0%–12%–20%) to afford 2q (0.6382 g) in 61% yield as a colorless oil.
(±)-cis-5-(Furan-3-yl)-1-tosylpyrrolidine-2-carbaldehyde (2r)

The aldehyde 2r was prepared following the representative procedure (Table 4, conditions A) using 3.9 mg of CuCl and 58.0 mg of alkene 1r. The reaction was completed after ca. 23 hours. The aldehyde 2r (23.7 mg) was obtained in 39% yield as an oil.

The crude NMR indicated the presence of one diastereomer (dr > 20:1). The cis configuration of 2r was assigned by analogy to 2b, 2d, 2k, and 2l.

\[ ^1H \text{NMR (400 MHz, CDCl}_3) \delta \text{9.66 (d, } J = 2.6 \text{ Hz, 1H), 7.70 (d, } J = 8.3 \text{ Hz, 2H), 7.37-7.28 (m, 3H), 6.40-6.21 (m, 2H), 4.90 (dd, } J = 7.9, 3.1 \text{ Hz, 1H), 4.02 (td, } J = 7.7, 2.6 \text{ Hz, 1H), 2.44 (s, 3H), 2.18-2.03 (m, 2H), 2.01-1.92 (m, 1H), 1.83-1.72 (m, 1H).} \]

\[ ^13C \text{NMR (75 MHz, CDCl}_3) \delta 199.9, 153.5, 144.2, 142.2, 134.4, 129.9, 127.6, 110.4, 107.6, 67.5, 58.3, 31.0, 26.4, 21.5. \]

IR: 2926, 1733, 1347, 1159, 1091, 665, 591 cm\(^{-1}\).

HRMS (+ESI): exact mass calcd for C\(_{16}\)H\(_{18}\)NO\(_4\)S [M + H]\(^+\): 320.0951, found: 320.0960.

4-Phenyl-1-tosylpyrrolidine-2-carbaldehyde (2s)

The aldehyde 2s was prepared following the representative procedure (Table 4, conditions A) using 3.9 mg of CuCl and 59.9 mg of alkene 1s. The reaction was completed after ca. 10 hours. The aldehyde 2s was obtained in 64% yield (based on 80% purity according to NMR) as a colorless oil.

The crude NMR indicated the presence of mixture of diastereomers (dr = 2.0:1). The NMR data are consistent with reported literature values.\(^9\)

\[ ^1H \text{NMR (300 MHz, CDCl}_3) \delta 9.84 (s, 1H, minor diastereomer), 9.68 (d, } J = 3.1 \text{ Hz, 1H, major diastereomer), 7.82-7.70 (m), 7.43-7.21 (m), 7.21-7.09 (m), 7.04-6.94 (m), 4.16-4.03 (m, 1H, minor diastereomer), 4.03-3.89 (m, 1H, both diastereomers), 3.76 (dd, } J = 11.0, 7.8 \text{ Hz, 1H, major diastereomer), 3.57 (dd, } J = 10.9, 9.3 \text{ Hz, 1H, major diastereomer), 3.43-3.27 (m, 1H, minor diastereomer), 3.08 (dd, } J = 10.2, 9.0 \text{ Hz, 1H, minor diastereomer), 3.04-2.87 (m, 1H, major diastereomer), 2.58-2.49 (m, 1H, minor diastereomer), 2.47 (s, 3H, major diastereomer), 2.46 (s, 3H, minor diastereomer), 2.43-2.31 (m, 1H, major diastereomer), 2.19-2.02 (m, 1H, major diastereomer), 1.95-1.81 (m, 1H, minor diastereomer). \]
$^1$H NMR (400 MHz, CDCl$_3$) δ 9.71 (d, $J = 2.8$ Hz, 1H), 7.75 (d, $J = 8.4$ Hz, 2H), 7.36 (d, $J = 8.2$ Hz, 2H), 7.23-7.13 (m, 3H), 6.92-6.82 (m, 2H), 3.90 (dd, $J = 7.2$, 2.7 Hz, 1H), 3.64 (ddd, $J = 10.0$, 7.7, 6.6 Hz, 1H), 3.59-3.47 (m, 2H), 2.48 (s, 3H), 2.29-2.16 (m, 1H), 1.85-1.72 (m, 1H).

$^{13}$C NMR (75 MHz, CDCl$_3$) δ 198.5, 144.3, 138.7, 133.8, 130.0, 128.8, 127.7, 127.4, 127.0, 72.5, 48.5, 46.1, 32.9, 21.6.

IR: 2925, 1733, 1346, 1159, 1092, 663, 591 cm$^{-1}$.


1-Tosylindoline-2-carbaldehyde (2u)

The aldehyde 2u was prepared following the representative procedure (Table 4, conditions A) using 3.8 mg of CuCl and 59.9 mg of alkene 1u. The reaction was completed after 21 hours. The aldehyde 2u (20.0 mg) was obtained in 35% yield as a yellow oil.
Supporting Information

$^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 9.85 (d, $J = 1.4$ Hz, 1H), 7.71 (d, $J = 8.1$ Hz, 1H), 7.61 (d, $J = 8.3$ Hz, 2H), 7.25-7.19 (m, 3H), 7.12-7.09 (m, 2H), 4.50 (ddd, $J = 10.7$, 4.9, 1.4 Hz, 1H), 3.17 (dd, $J = 16.4$, 4.8 Hz, 1H), 2.90 (dd, $J = 16.4$, 10.7 Hz, 1H), 2.37 (s, 3H).

$^{13}$C NMR (75 MHz, CDCl$_3$) $\delta$ 199.3, 144.7, 141.0, 133.7, 130.2, 129.8, 128.2, 127.3, 125.2, 125.0, 116.3, 68.0, 29.3, 21.6.

IR: 2923, 1736, 1479, 1352, 1164, 1055, 664, 577 cm$^{-1}$.

HRMS (ESI$^+$): exact mass calcd for C$_{16}$H$_{13}$NNaO$_3$S [M + Na$^+$]: 324.0665, found: 324.0677.

$^{(4,4}$-Dimethyl-1-tosylpyrrolidin-2-yl)(phenyl)methanone (2v)

Table 4, conditions C:
Copper(I) chloride (3.0 mg, 0.030 mmol, 16 mol%) was placed in a dry 100 mL round bottom flask and dried under vacuum while gently heated with a heat gun. Next, toluene (1.9 mL) and bis(oxazoline) ligand L (5.8 mg, 0.032 mmol, 17 mol%) were added under argon and the mixture was stirred under argon flow at 60 °C for 2 hours. After that time alkene 1v (65.3 mg, 0.19 mmol) and flame dried 4 Å molecular sieves (ca. 35 mg) were added. The argon atmosphere was replaced with oxygen. Next, the balloon with oxygen was attached to the flask through an inlet hose adapter and the mixture was stirred under oxygen (1 atm) at 120 °C (oil bath temperature) for about 15 hours. After that time the mixture was filtered through a pad of Celite and the Celite was washed with dichloromethane and ethyl acetate. The filtrate was concentrated, dried, and purified by flash chromatography on silica gel (elution: ethyl acetate/hexanes 0%–20%) to afford 2v as 3:1 mixture (based on NMR) with 1v (calculated yield: 49%). The mixture was further purified via preparative HPLC to obtain the product 2v as a white solid.

The NMR data are consistent with reported literature values.$^{38}$

$^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 8.01-7.93 (m, 2H), 7.80 (d, $J = 8.3$ Hz, 2H), 7.63-7.53 (m, 1H), 7.52-7.43 (m, 2H), 7.30 (d, $J = 7.9$ Hz, 2H), 5.38 (t, $J = 8.5$ Hz, 1H), 3.17 (d, $J = 9.8$ Hz, 1H), 2.42 (s, 3H), 2.10 (dd, $J = 8.3$, 1.3 Hz, 1H), 1.75 (dd, $J = 12.6$, 8.8 Hz, 1H), 1.06 (s, 3H), 0.96 (s, 3H).

$^{13}$C NMR (75 MHz, CDCl$_3$) $\delta$ 197.8, 143.3, 136.2, 135.2, 133.4, 129.4, 128.7, 128.5, 127.6, 63.4, 60.3, 45.2, 39.5, 26.0, 25.7, 21.5.

$\text{Ph} \quad + \quad \text{O}_2$ (1 atm)

\[
\begin{array}{c}
\text{CuCl (16 mol%),} \\
\text{L (17 mol%)} \\
\text{PhCH}_3, 120 ^\circ\text{C} \\
4 \AA \text{ MS}
\end{array}
\]

\[
\begin{array}{c}
\text{Ph} \\
\text{NTs}
\end{array}
\]

(4,4-Dimethyl-1-tosylpyrrolidin-2-yl)(phenyl)methanone (2v)
Kinetics Studies (Figure 1).

Copper(I) chloride (3.8 mg, 0.038 mmol, 20 mol%) was placed in a dry 25 mL 2-neck round bottom flask and dried under vacuum while gently heated with a heat gun. Next, toluene (2 mL) and bis(oxazoline) ligand L (7.7 mg, 0.042 mmol, 22 mol%) were added under argon and the mixture was stirred under argon flow at 60 °C for 2 hours. After that time alkene 1a (51.0 mg, 0.19 mmol) and flame dried 4 Å molecular sieves (ca. 35 mg) were added at r.t. The argon atmosphere was replaced with oxygen. Next, the balloon with oxygen was attached to the flask through an inlet hose adapter and the mixture was stirred under oxygen (1 atm) at 105 °C (oil bath temperature). At time of 0.0, 0.3, 0.5, 1.0, 2.0, 4.0, 6.0, 8.0, 10.0, 19.0, and 24.0 h 10 µL aliquot of the reaction mixture per sample was collected through the septum in the side neck of the flask via 25 µL glass syringe and analyzed via reverse phase liquid chromatography tandem mass spectrometry (RPLC – MS/MS) run in positive ESI under multiple reaction monitoring (MRM) mode. Full scan mass spectrometry experiment for the final sample proved that presented six compounds are the only one that contain tosyl group, therefore for the purpose of presenting the data in graphical form it was assumed that the sum of concentrations of these six components equals 100% for every sample.

The graph below represents then the changes of relative concentration of analytes as a function of time. The size of data point markers were chosen arbitrary and do not intended to represent measured nor calculated error. The lines connecting the points are intended as visual aid and were obtained by fitting the data to mathematical functions not necessary directly related to the actual function describing the time/concentration relation.
Compounds S1, S2, and S3 were identified during the optimization process as byproducts of the reaction.

$^1$H NMR data for S1 are consistent with reported literature values.$^{39}$

$^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 7.74 (d, $J = 8.3$ Hz, 2H), 7.32 (d, $J = 7.9$ Hz, 2H), 4.04 (dd, $J = 10.6$, 3.1 Hz, 1H), 3.94-3.80 (m, 1H), 3.66 (dd, $J = 10.6$, 8.4 Hz, 1H), 3.20-3.08 (m, 2H), 2.43 (s, 3H), 1.83 (dd, $J = 12.9$, 7.4, 1.3 Hz, 1H), 1.74 (dd, $J = 12.9$, 8.2 Hz, 1H), 1.05 (s, 3H), 0.55 (s, 3H).

$^1$H NMR data for S2 are consistent with reported literature values.$^{40}$

$^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 7.74 (d, $J = 8.3$ Hz, 2H), 7.33 (d, $J = 7.7$ Hz, 2H), 3.79 (dd, $J = 11.9$, 2.8 Hz, 1H), 3.71 (dd, $J = 11.9$, 5.2 Hz, 1H), 3.66-3.57 (m, 1H), 3.22 (d, $J = 10.6$ Hz, 1H), 3.13 (dd, $J = 10.7$, 1.3 Hz, 1H), 2.44 (s, 3H), 1.70-1.54 (m, 3H), 1.02 (s, 3H), 0.44 (s, 3H).

$^1$H NMR data for S3 are consistent with reported literature values.$^{16}$

$^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 7.70 (d, $J = 7.8$ Hz, 1H), 7.19 (d, $J = 7.9$ Hz, 1H), 7.07 (s, 1H), 4.31 (dtt, $J = 10.6$, 6.7, 2.5 Hz, 1H), 3.46 (dd, $J = 15.2$, 7.0 Hz, 1H), 3.17 (dd, $J = 9.1$, 1.7 Hz, 1H), 2.67 (dd, $J = 15.2$, 2.6 Hz, 1H), 2.54 (d, $J = 9.1$ Hz, 1H), 2.40 (s, 3H), 1.80 (dd, $J = 12.4$, 6.5, 1.7 Hz, 1H), 1.28-1.22 (m, 1H), 1.15 (s, 3H), 0.95 (s, 3H).
Labeling Studies (Scheme 4).

Copper(I) chloride (3.8 mg, 0.038 mmol, 40 mol%) was placed in a dry 25 mL 2-neck round bottom flask and dried under vacuum while gently heated with a heat gun. Next, a solution of aldehyde 2a (26.9 mg, 0.096 mmol, obtained via a method described above) in toluene (2 mL), DABCO (8.5 mg, 0.075 mmol, 78 mol%) and flame dried 4 Å molecular sieves (ca. 35 mg) were added and the mixture was degassed using freeze-pump-thaw technique (3x). To the flask at negative pressure a balloon with oxygen-18 was attached through an inlet hose adapter. The mixture was stirred under oxygen-18 (1 atm) at 120 °C (oil bath temperature) for about 3 hours. After that time the gas phase analysis was performed using EI-MS and presence of C\(^{18}\)O (m/z = 30.0027) was confirmed. Control experiment with oxygen-16 indicated the presence of C\(^{16}\)O (m/z = 28.0404).

Next, the mixture was filtered through a pad of Celite and the Celite was washed with dichloromethane and ethyl acetate. The filtrate was concentrated, dried, and purified by chromatography on silica gel (elution: ethyl acetate/hexanes 0%–20%) to afford 3a’ (16.3 mg) in 63% yield as a white solid.

4,4-Dimethyl-1-tosylpyrrolidin-2-[\(^{18}\)O]one (3a’)
mp 133-135 °C.

\(^1\)H NMR (400 MHz, CDCl\(_3\)) \(\delta\) 7.91 (d, \(J = 8.3\) Hz, 2H), 7.33 (d, \(J = 8.3\) Hz, 2H), 3.59 (s, 2H), 2.43 (s, 3H), 2.23 (s, 2H), 1.10 (s, 6H).

\(^{13}\)C NMR (75 MHz, CDCl\(_3\)) \(\delta\) 172.6, 145.1, 135.2, 129.6, 127.9, 59.5, 47.0, 33.2, 26.6, 21.7.

IR: 2961, 2923, 1697, 1357, 1288, 1160, 1117, 1087, 660 cm\(^{-1}\).

HRMS (+ESI): exact mass calc'd for C\(_{13}\)H\(_{18}\)NO\(_2\)\(^{18}\)OS [M + H]\(^+\): 270.1044, found: 270.1051.
Control experiment with $^{16}$O$_2$:

Electron ionization mass spectrum showing the [M]$^+$ of C$^{16}$O ($m/z = 28.0404$) and nitrogen ($m/z = 28.0513$).

Extracted ion chromatogram for the the [M]$^+$ of C$^{16}$O. Sample was introduced after $t = 3$ min. Air (as a reference) was introduced before.
Extracted ion chromatogram for the the [M]$^{+}$ of nitrogen. Sample was introduced after t = 3 min. Air (as a reference) was introduced before.

Experiment with $^{18}$O$_2$:

Electron ionization mass spectrum showing the [M]$^{+}$ of C$^{18}$O (m/z = 30.0027) and nitrogen (m/z = 28.0073 and m/z = 29.0060).
Extracted ion chromatogram for the the [M]$^+$ of C$^{18}$O. Sample was introduced after $t = 1.2$ min.

Enantioselective Synthesis of 2-Formylpyrrolidine

Copper(I) chloride (3.8 mg, 0.038 mmol, 20 mol%) was placed in a dry 100 mL round bottom flask and dried under vacuum while gently heated with a heat gun. Next, toluene (1.9 mL) and bis(oxazoline) ligand L2 (14.2 mg, 0.042 mmol, 22 mol%) were added under argon and the mixture was stirred under argon flow at 60 °C for 2 hours. After that time alkene 1a (50.8 mg, 0.19 mmol) and flame dried 4 Å molecular sieves (ca. 35 mg) were added. The argon atmosphere was replaced with oxygen. Next, the balloon with oxygen was attached to the flask through an inlet hose adapter and the mixture was stirred under oxygen (1 atm) at 120 °C (oil bath temperature) for 24 h. After that time the mixture was filtered through a pad of Celite and the Celite was washed with dichloromethane and ethyl acetate. The crude product was next reduced with sodium borohydride accord-
Alcohol S2 (13.2 mg) was obtained in 25% yield as a colorless oil.

\(^1\)H NMR data for S2 are consistent with reported literature values.\(^{40}\)

e.e. = 44%, determined by HPLC analysis of the alcohol S2 [Regis (S,S)-Whelk chiral analytical column, 15% IPA/hexane, 1.2 mL/min, \(\lambda = 254\) nm, t(minor) = 11.26 min, t(major) = 11.97 min].

Stereochemistry of the product was assigned by comparison of literature and measured values of optical rotation:

\([\alpha]_{D}^{24} = -7.8. (c 0.51, CHCl_3); \text{lit.} [\alpha]_{D}^{24} = -26 (c 0.70, CHCl_3).\)
References.