Title
Dirhodium(II) Tetrakis[N-benzene-fused Phthaloyl-(S)-piperidinonate] as a Chiral Lewis Acid: Catalytic Enantioselective Aldol Reactions of Acetate-derived Silylketene Acetals and Aldehydes

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DIRHODIUM(II) TETRAKIS[N-BENZENE-FUSED PHTHALOYL-(S)-PIPERIDINONATE] AS A CHIRAL LEWIS ACID: CATALYTIC ENANTIOSELECTIVE ALDOL REACTIONS OF ACETATE-DERIVED SILYLKETENE ACETALS AND ALDEHYDES†

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Abstract – A first example of chiral dirhodium(II) complex-catalyzed enantioselective Mukaiyama aldol reactions is described. The aldol addition reaction of methyl acetate-derived trimethylsilylketene acetal with specific aldehydes such as benzyloxyacetaldehyde and electron-poor aromatic aldehydes is effectively catalyzed by dirhodium(II) tetrakis[N-benzene-fused phthaloyl-(S)-piperidinonate] (1a), providing silylated aldol adducts in up to 94% ee.

The Lewis acid-catalyzed addition of silyl enol ethers and silyketene acetalts to carbonyl compounds, popularly known as the Mukaiyama aldol reaction, is one of the most powerful methods available for achieving carbon-carbon bond formation.1 Over the past fifteen years, remarkable progress has been achieved in the development of enantioselective variants through catalysis by chiral Lewis acid complexes derived from Sn(II), Ti(IV), B, Al, Cu(II), Ag(I), and Zr(IV) with excellent levels of enantioselection.2–10 Aside from their effectiveness in diazo decomposition,11 dirhodium(II) complexes are now becoming recognized as a new class of chiral Lewis acid catalysts. Doyle and co-workers demonstrated that chiral dirhodium(II) carboxamidates function as effective catalysts for enantioselective hetero-Diels–Alder (HDA) reactions and [2+2] cycloaddition reactions of trimethylsilylketene with ethyl glyoxylate.12,13 We also have disclosed that Rh$_2$(S-BPTPI)$_4$ (1a), a dirhodium(II) carboxamidate complex

† Dedicated to the memory of the late Dr. Kenji Koga, Professor Emeritus of the University of Tokyo.
that incorporates (S)-3-benzene-fused phthalimido-2-piperidinonate as chiral bridging ligands, is a highly efficient Lewis acid catalyst for endo- and enantioselective HDA reactions of a diverse range of aldehydes with Danishefsky-type dienes as well as with monooxygenated dienes, in which up to 99% ee and turnover numbers as high as 48,000 are achieved [eqn. (1)].

In an effort to extend the applicability of Rh$_2$(S-BPTPI)$_4$ in Lewis acid catalyzed reactions, we investigated the enantioselective Mukaiyama aldol reaction of acetate-derived silylketene acetics and aldehydes.

At the outset, we explored the aldol reaction of benzyloxyacetaldehyde (3a) and O-methyl O-trimethylsilylketene acetal (6a) derived from methyl acetate in the presence of 5 mol % of Rh$_2$(S-BPTPI)$_4$ and pulverized 4Å molecular sieves (MS) at 0 °C. After focusing mostly on solvent effects, toluene was found to be the optimal solvent for use in this reaction, giving silylated aldol adduct (7a) in 75% yield with 79% ee (Table 1, Entry 1). The enantioselectivity of this reaction was determined by HPLC analysis of the free aldol adduct (8a) derived from 7a (1N hydrochloric acid in THF). The preferred absolute stereochemistry of 8a was established as S by its conversion to the known 3-hydroxy-γ-butyrolactone (9) [[α]$_D$ $^{26}$ $-$64.2° (c 1.11, EtOH), lit., $^{18}$ [α]$_D$ $^9$ $-$85.9° (c 2.2, EtOH) for the (S)-enantiomer]. The use of ether and ethyl acetate resulted in essentially the same rate and yield as those found for toluene (6 h, 77%), but caused a marked decrease in enantioselectivity (68% ee and 52% ee, Entries 2 and 3). Somewhat surprisingly, the reaction in dichloromethane proceeded reluctantly to give (S)-7a in only modest yield and enantioselectivity (45% yield, 59% ee, Entry 4). Using toluene as the solvent, we next evaluated the abilities of other chiral dirhodium(II) complexes, Rh$_2$(S-PTPI)$_4$ (1b) $^{14,19}$
Table 1. The Enantioselective Mukaiyama Aldol Reaction of Benzyloxyacetaldehyde (3a) and Silyketene Acetals (6a-d) Catalyzed by Chiral Dirhodium(II) Complexes<sup>a)</sup>

<table>
<thead>
<tr>
<th>Entry</th>
<th>Rh(II) catalyst</th>
<th>Silyketene acetal</th>
<th>Aldol adduct</th>
<th>β-Hydroxy Ester</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>R&lt;sup&gt;1&lt;/sup&gt;</td>
<td>R&lt;sup&gt;2&lt;/sup&gt;</td>
<td>Solvent</td>
<td>Temp. (°C)</td>
</tr>
<tr>
<td>1</td>
<td>Rh&lt;sub&gt;2&lt;/sub&gt;(S-BPTP)&lt;sub&gt;1&lt;/sub&gt; (1a)</td>
<td>6a Me Me</td>
<td>toluene</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>Rh&lt;sub&gt;2&lt;/sub&gt;(S-BPTP)&lt;sub&gt;1&lt;/sub&gt; (1a)</td>
<td>6a Me Me</td>
<td>Et&lt;sub&gt;2&lt;/sub&gt;O</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>Rh&lt;sub&gt;2&lt;/sub&gt;(S-BPTP)&lt;sub&gt;1&lt;/sub&gt; (1a)</td>
<td>6a Me Me</td>
<td>EtOAc</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>Rh&lt;sub&gt;2&lt;/sub&gt;(S-BPTP)&lt;sub&gt;1&lt;/sub&gt; (1a)</td>
<td>6a Me Me</td>
<td>CH&lt;sub&gt;2&lt;/sub&gt;Cl&lt;sub&gt;2&lt;/sub&gt;</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>Rh&lt;sub&gt;2&lt;/sub&gt;(S-BPTP)&lt;sub&gt;1&lt;/sub&gt; (1b)</td>
<td>6a Me Me</td>
<td>toluene</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>Rh&lt;sub&gt;2&lt;/sub&gt;(S-BPTP)&lt;sub&gt;1&lt;/sub&gt; (1c)</td>
<td>6a Me Me</td>
<td>toluene</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>Rh&lt;sub&gt;2&lt;/sub&gt;(S-BPTP)&lt;sub&gt;1&lt;/sub&gt; (1a)</td>
<td>6a Me Me</td>
<td>toluene</td>
<td>–23</td>
</tr>
<tr>
<td>8</td>
<td>Rh&lt;sub&gt;2&lt;/sub&gt;(S-BPTP)&lt;sub&gt;1&lt;/sub&gt; (1a)</td>
<td>6b Et Me</td>
<td>toluene</td>
<td>–23</td>
</tr>
<tr>
<td>9</td>
<td>Rh&lt;sub&gt;2&lt;/sub&gt;(S-BPTP)&lt;sub&gt;1&lt;/sub&gt; (1a)</td>
<td>6c Me Et</td>
<td>toluene</td>
<td>–23</td>
</tr>
<tr>
<td>10</td>
<td>Rh&lt;sub&gt;2&lt;/sub&gt;(S-BPTP)&lt;sub&gt;1&lt;/sub&gt; (1a)</td>
<td>6d Me Pr</td>
<td>toluene</td>
<td>–23</td>
</tr>
</tbody>
</table>

<sup>a)</sup> All reactions were performed on a 0.3 mmol scale (0.2 M) using 3 equiv. of silyketene acetal. <sup>b)</sup> Isolated yield.
<sup>c)</sup> Determined by HPLC (Daicel Chiralpak IA column followed by Daicel Chiralpak AS-H column) unless otherwise stated. <sup>d)</sup> See text.
<sup>e)</sup> Determined by HPLC (Daicel Chiralpak AD-H column).

and Rh<sub>2</sub>(S-PTTL)<sub>4</sub> (1c), derived from N-phthaloyl-(S)-piperidinone and N-phthaloyl-(S)-tert-leucine, respectively. Catalysis by Rh<sub>2</sub>(S-PTTL)<sub>4</sub> gave (S)-7a in 71% ee (Entry 5), whereas Rh<sub>2</sub>(S-PTTL)<sub>4</sub> brought about a reversal of enantioselection, giving (R)-7a in 18% ee (Entry 6). Thus we were gratified to find that the enantioselectivity was further enhanced up to 86% ee using toluene and Rh<sub>2</sub>(S-BPTP)<sub>1</sub> and a lower temperature (–23 °C) without compromising the product yield (Entry 7). We also examined the steric effect of acetate-derived silyketene acetal on enantioselectivity. The use of triethylsilyl ketene acetal (6b) resulted in a lower enantioselectivity (68% ee, Entry 8). Varying the alkoxy substituent was also detrimental in this reaction as trimethylsilyl ketene acetas (6c,d) derived from ethyl and isopropyl acetates diminished the enantioselectivity (66% ee and 35% ee, Entries 9 and 10). These results clearly indicate that the use of the less sterically demanding silyketene acetal (6a) is crucial for a high level of enantioselectivity in this reaction.

With optimized conditions in hand, we then turned our attention to applying the present protocol to aldehydes other than 3a. Some representative results are presented in Table 2. The use of electron-poor aromatic aldehydes including 4-nitrobenzaldehyde (3b), 2,4-dinitrobenzaldehyde (3c), and pentafluorobenzaldehyde (3d) afforded the corresponding aldol adducts (8d-f) in higher yields and enantioselectivities than those found with benzyloxyacetaldehyde (3a), although these reactions required much longer reaction times to reach completion (Entries 1 vs. 2-4). The highest enantioselectivity (94% ee) was achieved in the case of 4-nitrobenzaldehyde (3b) (Entry 2). The sense of asymmetric induction
Table 2. The Enantioselective Mukaiyama Aldol Reaction of Aldehydes (3a-d) and 6a Catalyzed by Rh₂(S-BPTPI)₄.

<table>
<thead>
<tr>
<th>Entry</th>
<th>R</th>
<th>Aldol reaction</th>
<th>Yield (%)</th>
<th>Ee (%)</th>
<th>Config</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>3a</td>
<td>12</td>
<td>8a</td>
<td>79</td>
<td>S</td>
</tr>
<tr>
<td>2</td>
<td>3b</td>
<td>36</td>
<td>8d</td>
<td>91</td>
<td>S</td>
</tr>
<tr>
<td>3</td>
<td>3c</td>
<td>24</td>
<td>8e</td>
<td>87</td>
<td>S</td>
</tr>
<tr>
<td>4</td>
<td>3d</td>
<td>48</td>
<td>8f</td>
<td>90</td>
<td>S</td>
</tr>
</tbody>
</table>

a) All reactions were performed on a 0.3 mmol scale (0.2 M) using 3 equiv. of silylketene acetal. b) Isolated yield. c) Determined by HPLC (Daicel Chiralpak IA column followed by Daicel Chiralpak AS-H column). d) Determined by HPLC (Daicel Chiralpak AS column). e) Determined by its conversion to the known (S)-3-hydroxy-3-(4-nitrophenyl)propanoic acid. See ref 22. f) Determined by HPLC (Daicel Chiralpak AD-H column). g) Assigned by analogy. h) Determined by HPLC (Daicel Chiralcel OD-H column).

(nucleophilic attack from the aldehyde si enantioface) is consistent with the proposed model for the Rh₂(S-BPTPI)₄-catalyzed enantioselective HDA reaction, which contains a hydrogen bond between the formyl hydrogen atom and the carboxamidate oxygen atom in rhodium catalyst-aldehyde complexes (Figure 1). However, the present method was found to be highly sensitive to the nature of the aldehyde component, and the use of most aldehydes such as benzaldehyde, 4-methoxybenzaldehyde, cinnamaldehyde and hydrocinnamaldehyde resulted in the production of racemic aldol adducts. Thus the scope of the present Rh₂(S-BPTPI)₄ catalytic process is limited to benzyloxyacetalddehyde and aromatic aldehydes bearing strong electron-withdrawing groups.

In summary, we document the first example of enantioselective Mukaiyama aldol reactions catalyzed by a chiral dirhodium(II) complex. High levels of enantioselectivity up to 94% ee have been achieved, when Rh₂(S-BPTPI)₄ is used as a chiral Lewis acid catalyst, albeit with a limited range of silylketene acetics and aldehydes. Further studies are currently in progress to extend the utility of dirhodium(II) carboxamidate complexes as chiral catalysts for a range of Lewis acid catalyzed reactions.

Figure 1. Plausible Stereochemical Pathway
EXPERIMENTAL

General. Melting points were determined on a Büchi 535 digital melting point apparatus and are uncorrected. IR spectra were recorded on a JASCO FT/IR-5300 spectrometer and absorbance bands are reported in wavenumber (cm\(^{-1}\)). \(^1\)H NMR spectra were recorded on JEOL JNM-EX 270 (270 MHz) spectrometer. Chemical shifts are reported relative to internal standard (tetramethylsilane; \(\delta_H 0.00, \text{CDCl}_3; \delta_H 7.26 \text{ or } \text{CD}_3\text{OD}; \delta_H 3.30\)). Data are presented as follows: chemical shift (\(\delta\), ppm), multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, sep = septet, m = multiplet, br = broad), coupling constant and integration. \(^{13}\)C NMR spectra were recorded on JEOL JNM-AL 400 (100 MHz) spectrometer. The following internal references were used: CDCl\(_3\) (\(\delta 77.0\)). Optical rotations were measured on a JASCO P-1030 digital polarimeter at the sodium D line (589 nm). EIMS spectra were obtained on a JEOL JMS-FABmate spectrometer, operating with ionization energy of 70 eV. FAB-MS spectra were obtained on a JEOL JMS-HX 110 spectrometer. Column chromatography was carried out on Merck Kieselgel 60 (70–230 mesh) or Kanto silica gel 60 N (63–210 mesh). Analytical thin layer chromatography (TLC) was carried out on Merck Kieselgel 60 F\(_{254}\) plates with visualization by ultraviolet, anisaldehyde stain solution or phosphomolybdic acid stain solution. Analytical high performance liquid chromatography (HPLC) was performed on a JASCO PU-1580 intelligent HPLC pump with JASCO UV-1575 intelligent UV/VIS detector. Detection was performed at 254 nm. Chiralcel OD-H, Chiralpak IA, AS, AS-H and AD-H columns (0.46 cm \(\times\) 25 cm) from Daicel were used. Retention times (\(t_R\)) and peak ratios were determined with Shimadzu C-R8A chromatopac integrator.

All non-aqueous reactions were carried out in flame-dried glassware under argon atmosphere unless otherwise noted. Reagents and solvents were purified by standard means. O-Methyl-O-trimethylsilylketene acetal (5a) was prepared from methyl acetate according to the procedure of Shibasaki.\(^{15}\) 4Å MS was used after pulverized and dried (150 °C, 1 mmHg, 12 h).

Typical procedure for the Mukaiyama aldol reaction (Table 1, Entry 7): Methyl (S)-4-benzyloxy-3-trimethylsilyloxybutyrate (7a). To an oven-dried flask equipped with a rubber septum and a Teflon-coated magnetic stirring bar were added pulverized 4Å MS (50 mg), 1a (22 mg, 0.015 mmol, 5 mol %), 3a (45 mg, 0.30 mmol) and toluene (1.2 mL). The resulting suspension was cooled to −23 °C under an argon atmosphere. After stirring for 10 min, a solution of 6a (132 mg, 0.90 mmol) in toluene (0.3 mL) was added to the mixture at −23 °C, and the septum was replaced by a greased glass stopper. After 12 h of stirring at this temperature in a closed system, the reaction mixture was then filtered through a plug of Celite with EtOAc (10 mL). Filtration and concentration \textit{in vacuo} followed by column chromatography (silica gel, 19:1 hexane/EtOAc) provided 7a (72.0 mg, 81%) as a colorless oil; \(R_f = 0.35\) (9:1 hexane/EtOAc); [\(\alpha\)]\(D\)\(^{24}\) −19.6° (c 1.01, CHCl\(_3\)) for 86% ee; IR (neat) \(\nu\): 1738 cm\(^{-1}\); \(^1\)H NMR
(270 MHz, CDCl$_3$) $\delta$ 0.10 (s, 9H, Si(CH$_3$)$_3$), 2.47 (dd, $J$ = 7.9, 15.2 Hz, 1H, C2-H), 2.60 (dd, $J$ = 4.6, 15.2 Hz, 1H, C2-H), 3.38 (dd, $J$ = 5.9, 9.2 Hz, 1H, C4-H), 3.44 (dd, $J$ = 5.3, 9.2 Hz, 1H, C4-H), 3.66 (s, 3H, CO$_2$CH$_3$), 4.31 (m, 1H, C3-H), 4.53 (s, 2H, PhCH$_2$O), 7.27–7.37 (m, 5H, ArH). $^{13}$C NMR (100 MHz, CDCl$_3$) $\delta$ 0.1 (CH$_3$), 40.1 (CH$_2$), 51.4 (CH$_3$), 68.4 (CH), 73.2 (CH$_3$), 73.9 (CH$_2$), 127.4 (CH), 128.2 (CH), 138.0 (C), 171.7 (C=O); HRMS (FAB) calcd for C$_{15}$H$_2_5$O$_4$Si (M+H)$^+$ 297.1522, found 297.1516; Anal. Calcd for C$_{15}$H$_2_2$O$_4$Si: C, 60.78; H, 8.16. Found: C, 60.63; H, 8.02.

**Methyl (S)-4-benzyloxy-3-hydroxybutyrate (8a).** A solution of 7a (72 mg, 0.24 mmol) in THF (2 mL) was added in one portion to 1N hydrochloric acid (0.2 mL) at 23 °C. After 0.5 h of stirring at this temperature, the reaction was quenched with saturated NaHCO$_3$ solution (2 mL), and the whole was extracted with EtOAc (3 × 5 mL). The combined organic layers were washed with water (3 mL), and brine (2 × 3 mL), and dried over anhydrous Na$_2$SO$_4$. Filtration and evaporation in vacuo followed by column chromatography (silica gel, 3:1 hexane/EtOAc) provided 8a (53.4 mg, 98%) as a colorless oil; $R_f$ = 0.39 (1:1 hexane/EtOAc); $[\alpha]_D^{25}$ = −9.49° (c 1.00, CHCl$_3$) for 86% ee; $^1$H NMR (270 MHz, CDCl$_3$) $\delta$ 2.56 (d, $J$ = 6.6 Hz, 2H, C2-H), 2.92 (d, $J$ = 4.6 Hz, 1H, OH), 3.48 (dd, $J$ = 5.9, 9.9 Hz, 1H, C4-H), 3.52 (dd, $J$ = 4.6, 9.9 Hz, 1H, C4-H), 3.70 (s, 3H, CO$_2$CH$_3$), 4.25 (m, 1H, C3-H), 4.56 (s, 2H, PhCH$_2$O), 7.29–7.39 (m, 5H, ArH). The enantiomeric excess of 8a was determined to be 86% by HPLC with a Chiralpak IA followed by AS-H column (9:1 hexane/i-PrOH, 1.0 mL/min): $t_R$ (major) = 22.8 min for (S)-enantiomer; $t_R$ (minor) = 25.1 min for (R)-enantiomer. The absolute configuration of 8a was determined to be S by chemical correlation (vide infra).

**Determination of absolute configuration of 8a: (S)-3-Hydroxy-$\gamma$-butyrolactone (9).** A solution of (S)-8a (50 mg, 0.22 mmol, 79% ee) in MeOH (5 mL) was stirred with 10% Pd/C (10 mg) under 1 atm of H$_2$ at rt for 2 h. The catalyst was removed by filtration, and the filtrate was concentrated in vacuo. The residue was purified by column chromatography (silica gel, EtOAc) to afford (S)-9 (22.2 mg, 99%) as a colorless oil; $R_f$ = 0.32 (EtOAc); $[\alpha]_D^{26}$ = −64.2° (c 1.11, EtOH) [lit., $^{18}$ $[\alpha]_D^{9}$ = −85.9° (c 2.2, EtOH) for (S)-enantiomer]; $^1$H NMR (270 MHz, CDCl$_3$) $\delta$ 2.54 (dd, $J$ = 2.0, 17.8 Hz, 1H, C2-H), 2.76 (dd, $J$ = 5.9, 17.8 Hz, 1H, C2-H), 2.83 (br, 1H, OH), 4.31 (dd, $J$ = 1.3, 8.5 Hz, 1H, C4-H), 4.42 (dd, $J$ = 4.6, 8.5 Hz, 1H, C4-H), 4.69 (m, 1H, C3-H).

**Methyl (S)-4-benzyloxy-3-triethylsilyloxybutyrate (7b).** The product was prepared following the procedure for the preparation of 7a, using 3a (45 mg, 0.30 mmol), silylketene acetal (6b) (170 mg, 0.90 mmol) and 4Å MS (50 mg). The crude product was purified by column chromatography (silica gel, 19:1 hexane/EtOAc) to provide 7b (80.2 mg, 79%) as a colorless oil; $R_f$ = 0.37 (9:1 hexane/EtOAc); $[\alpha]_D^{24}$
-16.7° (c 1.01, CHCl₃) for 68% ee; IR (neat) ν: 1742 cm⁻¹; ¹H NMR (270 MHz, CDCl₃) δ 0.59 (q, J = 7.9 Hz, 6H, Si(CH₃)₂), 0.93 (t, J = 7.9 Hz, 9H, Si(CH₂CH₃)₃), 2.48 (dd, J = 7.9, 15.2 Hz, 1H, C2-H), 2.62 (dd, J = 4.6, 15.2 Hz, 1H, C2-H), 3.38 (dd, J = 5.9, 9.2 Hz, 1H, C4-H), 3.47 (dd, J = 4.6, 9.2 Hz, 1H, C4-H), 3.65 (s, 3H, CO₂CH₃), 4.31 (m, 1H, C3-H), 4.53 (s, 2H, PhCH₂O), 7.27–7.37 (m, 5H, ArH). ¹³C NMR (100 MHz, CDCl₃) δ 4.8 (CH₃), 6.8 (CH₃), 40.3 (CH₂), 51.5 (CH₃), 68.4 (CH), 73.3 (CH₃), 74.0 (CH₂), 127.5 (CH), 128.2 (CH), 136.0 (C), 171.9 (C=O); HRMS (FAB) calcd for C₁₅H₃₂O₄Si (M+H)⁺ 339.1992, found 339.1994.

**Ethyl (S)-4-benzyloxy-3-trimethylsilyloxybutyrate (7c).** The product was prepared following the procedure for the preparation of 7a, using 3a (45 mg, 0.30 mmol), silylketene acetal (6c) (144 mg, 0.90 mmol) and 4Å MS (50 mg). The crude product was purified by column chromatography (silica gel, 19:1 hexane/EtOAc) to provide 7c (76.4 mg, 82%) as a colorless oil; Rᵥ = 0.37 (9:1 hexane/EtOAc); [α]D²⁴ –12.4° (c 1.00, CHCl₃) for 66% ee; IR (neat) ν: 1738 cm⁻¹; ¹H NMR (270 MHz, CDCl₃) δ 0.11 (s, 9H, Si(CH₃)₃), 1.25 (t, J = 7.2 Hz, 3H, CO₂CH₂CH₃), 2.44 (dd, J = 8.5, 15.2 Hz, 1H, C2-H), 2.59 (dd, J = 4.6, 15.2 Hz, 1H, C2-H), 3.38 (dd, J = 5.9, 9.9 Hz, 1H, C4-H), 3.45 (dd, J = 5.2, 9.9 Hz, 1H, C4-H), 4.12 (m, 2H, CO₂CH₂CH₃), 4.31 (m, 1H, C3-H), 4.53 (s, 2H, PhCH₂O), 7.27–7.37 (m, 5H, ArH). ¹³C NMR (100 MHz, CDCl₃) δ 0.2 (CH₃), 14.3 (CH₃), 40.3 (CH₂), 60.3 (CH₂), 68.5 (CH), 73.2 (CH₃), 73.9 (CH₃), 127.5 (CH), 128.2 (CH), 138.0 (C), 171.3 (C=O); HRMS (FAB) calcd for C₁₅H₃₂O₄Si (M+H)⁺ 311.1679, found 311.1675; Anal. Calcd for C₁₅H₃₂O₄Si: C, 61.90; H, 8.44. Found: C, 61.82; H, 8.32.

**Ethyl (S)-4-benzyloxy-3-hydroxybutyrate (8b).** The product was prepared following the procedure for the preparation of 8a using 7c (76 mg, 0.24 mmol). The crude product was purified by column chromatography (silica gel, 3:1 hexane/EtOAc) to provide 8b (56.6 mg, 97%) as a colorless oil; Rᵥ = 0.32 (2:1 hexane/EtOAc); [α]D²⁴ +6.63° (c 1.01, CHCl₃) for 66% ee [lit.²⁴ [α]D +8.0° (c 1.5, CHCl₃) for 71% ee of (R)-enantiomer]; ¹H NMR (270 MHz, CDCl₃) δ 1.26 (t, J = 7.3 Hz, 3H, CO₂CH₂CH₃), 2.54 (d, J = 6.3 Hz, 2H, C2-H), 2.97 (d, J = 4.3 Hz, 1H, OH), 3.50 (dd, J = 5.9, 9.6 Hz, 1H, C4-H), 3.52 (dd, J = 4.3, 9.6 Hz, 1H, C4-H), 4.16 (q, J = 7.3 Hz, 2H, CO₂CH₂CH₃), 4.23 (m, 1H, C3-H), 4.56 (s, 2H, PhCH₂O), 7.29–7.36 (m, 5H, ArH). The enantiomeric excess of 8b was determined to be 66% by HPLC with a Chiralpak AD-H column (9:1 hexane/PrOH, 1.0 mL/min): tᵣ (major) = 9.1 min for (S)-enantiomer; tᵣ (minor) = 9.7 min for (R)-enantiomer.

**Isopropyl (S)-4-benzyloxy-3-trimethylsilyloxybutyrate (7d).** The product was prepared following the procedure for the preparation of 7a, using 3a (45 mg, 0.30 mmol), silylketene acetal (6d) (157 mg, 0.90 mmol) and 4Å MS (50 mg). The crude product was purified by column chromatography (silica gel, 19:1
hexane/EtOAc) to provide 7d (76.9 mg, 79%) as a colorless oil; $R_f = 0.38$ (9:1 hexane/EtOAc); $[\alpha]_D^{24} -4.39^\circ$ (c 1.03, CHCl$_3$) for 35% ee; IR (neat) v: 1732 cm$^{-1}$; $^1$H NMR (270 MHz, CDCl$_3$) $\delta$ 0.11 (s, 9H, Si(CH$_3$)$_3$), 1.22 (d, $J = 5.9$ Hz, 6H, CO$_2$CH(CH$_3$)$_2$), 2.42 (dd, $J = 7.9$, 15.2 Hz, 1H, C2-H), 2.54 (dd, $J = 4.6$, 15.2 Hz, 1H, C2-H), 3.38 (dd, $J = 5.9$, 9.8 Hz, 1H, C4-H), 3.44 (dd, $J = 5.2$, 9.8 Hz, 1H, C4-H), 4.31 (m, 1H, C3-H), 4.53 (s, 2H, PhCH$_2$O), 5.00 (sep, 1H, CO$_2$CH(CH$_3$)$_2$), 7.29–7.37 (m, 5H, ArH). $^{13}$C NMR (100 MHz, CDCl$_3$) $\delta$ 0.2 (CH$_3$), 21.9 (CH$_3$), 40.5 (CH$_2$), 67.6 (CH), 68.5 (CH), 73.2 (CH$_2$), 73.9 (CH$_2$), 127.5 (CH), 128.2 (CH), 138.0 (C), 170.9 (C=O); HRMS (FAB) calcd for C$_{17}$H$_{28}$O$_2$Si (M+H)$^+$ 325.1835, found 325.1837; Anal. Calcd for C$_{17}$H$_{28}$O$_2$Si: C, 62.92; H, 8.70. Found: C, 62.52; H, 8.55.

**Isopropyl (S)-4-benzyloxy-3-hydroxybutyrate (8c).**$^{25}$ The product was prepared following the procedure for the preparation of 8a using 7d (77 mg, 0.24 mmol). The crude product was purified by column chromatography (silica gel, 3:1 hexane/EtOAc) to provide 8c (58.7 mg, 98%) as a colorless oil; $R_f = 0.38$ (2:1 hexane/EtOAc); $[\alpha]_D^{25} -3.74^\circ$ (c 1.00, CHCl$_3$) for 35% ee [lit.$^{25}$ $[\alpha]_D^{22} +9.5^\circ$ (c 10, CHCl$_3$) for 95% ee of (R)-enantiomer]; $^1$H NMR (270 MHz, CDCl$_3$) $\delta$ 1.23 (d, $J = 6.3$ Hz, 6H, CO$_2$CH(CH$_3$)$_2$), 2.52 (d, $J = 6.3$ Hz, 2H, C2-H), 3.00 (d, $J = 4.3$ Hz, 1H, OH), 3.48 (dd, $J = 5.9$, 9.6 Hz, 1H, C4-H), 3.51 (dd, $J = 4.3$, 9.6 Hz, 1H, C4-H), 4.23 (m, 1H, C3-H), 4.56 (s, 2H, PhCH$_2$O), 5.04 (sep, $J = 6.3$ Hz, 1H, CO$_2$CH(CH$_3$)$_2$), 7.29–7.37 (m, 5H, ArH). The enantiomeric excess of 8c was determined to be 35% by HPLC with a Chiralpak AD-H column (9:1 hexane/i-PrOH, 1.0 mL/min): $t_R$ (major) = 7.9 min for (S)-enantiomer; $t_R$ (minor) = 8.5 min for (R)-enantiomer.

**Typical procedure for the Mukaiyama aldol reaction followed by desilylation (Table 2, Entry 2): Methyl (S)-3-hydroxy-3-(4-nitrophenyl)propionate (8d).**$^{26}$ To an oven-dried flask equipped with a rubber septum and a Teflon-coated magnetic stirring bar were added pulverized 4Å MS (50 mg), 1a (22 mg, 0.015 mmol, 5 mol %), 3b (45 mg, 0.30 mmol) and toluene (1.2 mL). The resulting suspension was cooled to $-23$ °C under an argon atmosphere. After stirring for 10 min, a solution of 6a (132 mg, 0.90 mmol) in toluene (0.3 mL) was added to the mixture at $-23$ °C, and the septum was replaced by a greased glass stopper. After 36 h of stirring at this temperature in a closed system, the reaction mixture was then filtered through a plug of Celite with EtOAc (10 mL). Concentration of the EtOAc solution gave the crude silylated aldol product, which was dissolved in THF (2 mL). This solution was added in one portion to 1N hydrochloric acid (0.2 mL) at 23 °C. After 0.5 h of stirring at this temperature, the reaction was quenched with saturated NaHCO$_3$ solution (2 mL), and the whole was extracted with EtOAc (3 x 5 mL). The combined organic layers were washed with water (3 mL), and brine (2 x 3 mL), and dried over anhydrous Na$_2$SO$_4$. Filtration and evaporation in vacuo followed by column chromatography (silica gel, 3:2 hexane/EtOAc) provided 8d (61.5 mg, 91%) as pale yellow solid; mp 50.0–52.0 °C; $R_f = 0.32$ (1:1...
hexane/EtOAc); \([\alpha]_D^{23}\) –37.1° (c 1.01, CHCl₃) for 94% ee; IR (KBr) ν: 3374, 1738, 1699, 1518, 1348 cm⁻¹; ¹H NMR (270 MHz, CDCl₃) δ 2.75 (d, J = 7.9 Hz, 1H, C2-H), 2.76 (d, J = 4.6 Hz, 1H, C2-H), 3.60 (d, J = 4.0 Hz, 1H, OH), 3.75 (s, 3H, CO₂CH₂), 5.24 (ddd, J = 4.0, 4.6, 7.9 Hz, 1H, C3-H), 7.57 (d, J = 8.6 Hz, 2H, ArH), 8.22 (d, J = 8.6 Hz, 2H, ArH); ¹³C NMR (100 MHz, CDCl₃) δ 42.7 (CH₃), 52.0 (CH), 69.2 (CH), 123.6 (CH), 126.3 (CH), 147.2 (C), 149.6 (C), 172.0 (C=O); HRMS (El) calcd for C₁₀H₁₁NO₅ (M⁺) 225.0637, found 225.0635. The enantiomeric excess of 8d was determined to be 94% by HPLC with a Chiralpak AS column (3:1 hexane/i-PrOH, 1.0 mL/min): tᵣ(minor) = 12.7 min for (R)-enantiomer; tᵣ(major) = 16.8 min for (S)-enantiomer. The absolute configuration of 8d was determined to be S by chemical correlation (vide infra).

Determination of absolute configuration of 8d: (S)-3-hydroxy-3-(4-nitrophenyl)propionic acid. A solution of (S)-8d (45.0 mg, 0.2 mmol, 94% ee) in MeOH (2 mL) was added in one portion to 1N KOH solution (0.2 mL) at 23 °C. After 0.5 h of stirred at this temperature, the reaction was quenched with 1N hydrochloric acid (1 mL), and the whole was extracted with EtOAc (3 × 5 mL). The combined organic layers were washed with water (3 mL), and brine (2 × 3 mL), and dried over anhydrous Na₂SO₄. Filtration and evaporation in vacuo followed by column chromatography (silica gel, EtOAc) provided (S)-3-hydroxy-3-(4-nitrophenyl)propionic acid (30.0 mg, 71%) as a white solid; mp 122–127 °C; Rᵣ = 0.39 (2:1 CHCl₃/MeOH); [α]₀°= 9.8° (c 0.5, MeOH) for (S)-enantiomer; ¹H NMR (270 MHz, CD₃OD) δ 2.69 (d, J = 6.6 Hz, 2H, C2-H), 5.20 (t, J = 6.6 Hz, 1H, C3-H), 7.64 (d, J = 8.6 Hz, 2H, ArH), 8.21 (d, J = 8.6 Hz, 2H, ArH).

Methyl 3-(2,4-dinitrophenyl)-3-hydroxypropionate (8e). The product was prepared following the procedure for the preparation of 8d, using 3c (59 mg, 0.30 mmol), silyketene acetal (6a) (132 mg, 0.90 mmol) and 4Å MS (25 mg). The crude product was purified by column chromatography (silica gel, 3:2 hexane/EtOAc) to provide 8e (70.5 mg, 87%) as a yellow solid; mp 91.5–93.0 °C; Rᵣ = 0.34 (1:1 hexane/EtOAc); [α]₀°= 80.6° (c 0.89, CHCl₃) for 92% ee; IR (KBr) ν: 3428, 1736, 1714, 1528, 1348 cm⁻¹; ¹H NMR (270 MHz, CDCl₃) δ 2.67 (d, J = 9.9, 16.5 Hz, 1H, C2-H), 3.00 (dd, J = 2.6, 16.5 Hz, 1H, C2-H), 3.78 (s, 3H, CO₂CH₃), 3.91 (d, J = 3.3 Hz, 1H, OH), 5.78 (ddd, J = 2.6, 3.3, 9.9 Hz, 1H, C3-H), 8.20 (d, J = 8.6 Hz, 1H, C6'-H), 8.51 (dd, J = 2.6, 8.6 Hz, 1H, C5'-H), 8.85 (d, J = 2.6 Hz, 1H, C3'-H); ¹³C NMR (100 MHz, CDCl₃) δ 41.9 (CH₂), 52.3 (CH₂), 65.8 (CH), 120.0 (CH), 127.6 (CH), 130.1 (CH), 144.6 (C), 146.9 (C), 147.0 (C), 172.0 (C=O); HRMS (FAB) calcd for C₁₀H₁₁N₂O₇ (M+H)+ 271.0566, found 271.0565. The enantiomeric excess of 8e was determined to be 92% by HPLC with a Chiralpak AD-H column (3:1 hexane/i-PrOH, 1.0 mL/min): tᵣ(minor) = 9.5 min for major enantiomer; tᵣ(minor) = 11.2 min for minor enantiomer. A sample for combustion analysis was obtained by recrystallizations from 10% EtOAc.
in hexane as yellow needles (>99% ee); mp 98.5–99.0 °C; Anal. Calcd for C_{10}H_{10}N_{2}O_{7}: C, 44.45; H, 3.73; N, 10.37. Found: C, 44.40; H, 3.75; N, 10.32. The absolute stereochemistry of 8e was not determined.

**Methyl 3-hydroxy-3-pentafluorophenylpropionate (8f).** The product was prepared following the procedure for the preparation of 8d, using 3d (59 mg, 0.30 mmol), silylketene acetal (6a) (132 mg, 0.90 mmol) and 4Å MS (50 mg). The crude product was purified by column chromatography (silica gel, 6:1 hexane/EtOAc) to provide 8f (72.9 mg, 90%) as a white solid; mp 80.0–81.0 °C; R_f = 0.26 (4:1 hexane/EtOAc); [α]_D^{23} = –4.07° (c 0.95, CHCl_3) for 88% ee; IR (KBr) ν: 3455, 1738, 1524, 1505 cm⁻¹; ^1H NMR (270 MHz, CDCl_3) δ 2.77 (dd, J = 4.0, 17.2 Hz, 1H, C2-H), 3.15 (dd, J = 9.2, 17.2 Hz, 1H, C2-H), 3.21 (d, J = 5.3 Hz, 1H, O-H), 3.75 (s, 3H, CO_2CH_3), 5.53 (dd, J = 4.0, 5.3, 9.2 Hz, 1H, C3-H); ^13C NMR (100 MHz, CDCl_3) δ 40.1 (CH_2), 52.2 (CH_2), 62.0 (CH), 115.0 (m, C), 137.5 (dm, J = 253 Hz, CF), 140.8 (dm, J = 255 Hz, CF), 144.9 (dm, J = 250 Hz, CF), 171.5 (C=O); HRMS (EI) calcd for C_{10}H_{7}O_{3}F_{5} (M⁺) 270.0315, found 270.0321. The enantiomeric excess of 8f was determined to be 88% by HPLC with a Chiralcel OD-H column (9:1 hexane/i-PrOH, 1.0 mL/min): t_R = 6.0 min for major enantiomer; t_R = 7.7 min for minor enantiomer. A sample for combustion analysis was obtained by recrystallizations from hexane as colorless fine needles (>99% ee); mp 84.0–84.5 °C; Anal. Calcd for C_{10}H_{7}O_{3}F_{5}: C, 44.46; H, 2.61; F, 35.16. Found: C, 44.23; H, 2.69; F, 35.04. The absolute stereochemistry of 8f was not determined.

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**REFERENCES AND NOTES**


11. For recent book and review, see: (a) M. P. Doyle, M. A. McKeve, and T. Ye, 'Modern Catalytic Methods for Organic Synthesis with Diazo Compounds,' Wiley-Interscience, New York, 1998; (b)


16. In the absence of 4Å MS, the aldol reaction proceeded to completion in 6 h, giving a mixture of 7a and 8a in 45% yield/77% ee and 32% yield/76% ee, respectively.


21. Although the use of 1.5 equiv of 6a under otherwise identical conditions afforded silylated aldol adduct 7a in 78% yield with 86% ee, the reaction required 24 h to reach completion.


