Kinetic Resolution of Planar-Chiral Ferrocenes by Molybdenum-Catalyzed Enantioselective Metathesis

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Supporting Information

Experimental Section.

General. All anaerobic and/or moisture sensitive manipulations were carried out with standard Schlenk techniques under predried nitrogen or with glovebox techniques under prepurified argon.

\[ 1^H \text{NMR (at 400 MHz)} \text{ and } ^{13}C \text{NMR (at 100 MHz)} \text{ chemical shifts are reported in ppm downfield of internal tetramethylsilane.} \]

Tetrahydrofuran and benzene were distilled from benzophenone ketyl under nitrogen prior to use. Dichloromethane was distilled from CaH\(_2\) under nitrogen prior to use. Cp-Na\(_1\), Cp\(_2\)H\(_5\)Bu\(_3\), Cp\(_2\)H\(_5\)Cy\(_3\), Cp\(_2\)H\(_5\)(SiMe\(_3\))\(_2\), Fe(acac)\(_3\), Mo=NC\(_5\)H\(_5\)2,6-Pr\(_2\)=(CHMe\(_2\)Ph)(OTf)\(_2\)(dme), 3,3′-Bu\(_2\)-H\(_6\)-binaphthol K\(_2\) salt, and (H\(_3\)IMes)(PCy\(_2\))\(_2\)Ru=CHPh (the 2nd-generation Grubbs’ catalyst) were prepared according to the reported methods. All the other chemicals were obtained from commercial sources.

Allylcyclopentadienes. Monosubstituted allylic cyclopentadienes (C\(_5\)H\(_5\)-allyl, C\(_5\)H\(_5\)-crotol, C\(_5\)H\(_5\)-cinnamyl, C\(_5\)H\(_5\)-CH\(_2\)CH=CMMe\(_2\), C\(_5\)H\(_5\)-methallyl) were prepared from Cp-Na and the corresponding allylic chlorides or bromides in THF and purified by vacuum distillation prior to use.

Trisubstituted allylcyclopentadienes (C\(_5\)H\(_5\)(allyl)Bu\(_2\), C\(_5\)H\(_5\)(allyl)Cy\(_2\), C\(_5\)H\(_5\)(allyl)(SiMe\(_3\))\(_2\)) were prepared from (C\(_5\)H\(_5\)-1,3-R\(_2\))Li (R = ‘Bu, Cy, or SiMe\(_3\)), which were generated from the corresponding C\(_5\)H\(_5\)R\(_2\) and ‘BuLi in THF, and allyl bromide and purified by vacuum distillation prior to use. All these cyclopentadiene derivatives were obtained as mixtures of double-bond regioisomers, and thus characterized by GC analyses only.

Racemic Diallylferrocene Substrates (1). A typical procedure is given for the synthesis of 1a. To a THF (8 mL) solution of Fe(acac)\(_2\) (2.54 g, 10.0 mmol) was added a solution of (C\(_5\)H\(_5\)-1-allyl-2,4-’Bu\(_2\))Li, which was prepared from C\(_5\)H\(_5\)(allyl)Bu\(_2\) (2.18 g, 10.0 mmol) and ‘BuLi (1.60 M hexane solution, 6.3 mL, 10.1 mmol) in THF (25 mL), at –78 °C and the mixture was stirred at 0 °C for 1 h. After cooling the mixture to –78 °C, to this was added a solution of (C\(_5\)H\(_5\)-allyl)-Na, which was prepared from C\(_5\)H\(_5\)-allyl (1.06 g, 10.0 mmol) and NaH (240 mg, 10.0 mmol) in THF (10 mL). The resulting mixture was stirred at room temperature for 3 h. The mixture was diluted with hexane and filtered through a pad of Celite. After removal of the solvent, the remaining dark-red oil was purified by column chromatography on alumina using hexane as an eluent and following vacuum-transferred gave 1a as dark-red oil. The reaction conditions were not optimized. The characterization data of the diallylferrocene substrates are given below.

rac-1,1′-Diallyl-2,4-ditert-butylferrocene (1a). Yield: 42%. \[ 1^H \text{NMR (CDCl}_3\): } \delta \ 1.19 (s, 9H), 1.28 (s, 9H), 3.09 (d, J = 6.6 Hz, 2H), 3.14 (dd, J = 16.0 and 5.7 Hz, 1H), 3.25 (dd, J = 16.0 and 6.8 Hz, 1H), 3.72 (s, 1H), 3.74 (s, 1H), 3.89 (s, 1H), 4.06 (s, 1H), 4.13 (s, 1H), 4.92-5.02 (m, 4H), 5.86-5.96 (m, 2H). \[ ^{13}C(\text{H}) \text{NMR (CDCl}_3\): } \delta \ 30.5, 31.5, 31.90, 31.92, 33.8, 34.3, 64.1, 67.7, 68.2, 68.7, 69.4, 70.5, 81.8, 86.6, 96.8, 98.8, 114.6, 115.0, 138.3, 138.4. \]

Anal. Calcd for C\(_{24}\)H\(_{34}\)Fe: C, 76.18; H, 9.06. Found: C, 76.06; H, 8.93. HRMS Calcd for C\(_{24}\)H\(_{34}\)Fe: 378.02. Found: 378.20.005.
rac-1- Allyl-1’-((E)-2-butenyl)-2,4-di(tert-butyl)ferrocene (1b).  Yield: 36%.  

rac-1- Allyl-1’-((E)-3-phenylallyl)-2,4-di(tert-butyl)ferrocene (1c).  Yield: 42%.  

rac-1- Allyl-1’-((3-methyl-2-butenyl)-2,4-di(tert-butyl)ferrocene (1d).  Yield: 33%.  

rac-1- Allyl-1’-((2-methylallyl)-2,4-di(tert-butyl)ferrocene (1e).  Yield: 36%.  

rac-1- Allyl-1’-((2-methylallyl)-2,4-dicyclohexylferrocene (1f).  Yield: 30%.  

rac-1- Allyl-1’-((2-methylallyl)-2,4-bis(trimethylsilyl)ferrocene (1g).  Yield: 14%.  

Kinetic Resolution of Racemic 1 by Molybdenum-Catalyzed Asymmetric Ring-Closing Metathesis Reaction.  The reaction conditions and the results are summarized in Table 1 of the main text.  A typical procedure is given for the reaction of entry 6: a THF solution of Mo=NC6H4=CH2,2,6-Pr3- (=CH2)(CHPh)(OTf)2 (dme) (0.1 M, 100 µL, 10 µmol) and a THF solution of 3,3’-Bu2-H2-binaphthol K2 salt (0.1 M, 100 µL, 10 µmol) was mixed at −30 °C, and then the mixture was stirred at room temperature for 1 h. To this was added 1e (39.3 mg, 100 µmol) and benzene (20 mL) and the solution was stirred at 50 °C for 24 h. After quenching by addition of acetone (ca. 100 µL), the reaction mixture was passed through a pad of silica gel using hexane/Et2O (9/1) as an eluent. The solvent was removed under reduced pressure and the residue was
purified by preparative HPLC (LC-908 recycle HPLC system (Japan Analytical Industry Co. Ltd.) with a GPC column (JAIGEL-H, chloroform, 3.5 mL/min)) to give the RCM product 2e (16.8 mg, 46%) and the recovered 1e (18.5 mg, 47%). The recovered 1e was quantitatively converted to 2e by a treatment with the 2nd-generation Grubbs' catalyst (2 mol %) in refluxing CH₂Cl₂ for a chiral HPLC analysis. The characterization data of the RCM products and the conditions for chiral HPLC analysis are described below.

1.1'-{(2-Buten-1,4-diyI)-2,4-di(tert-butyI)ferrocene (2a). ⁱH NMR (CDCl₃): δ 1.15 (s, 9H), 1.31 (s, 9H), 2.74 (dd, J = 7.3 and 14.6 Hz, 1H), 2.88 (dd, J = 7.3 and 14.6 Hz, 1H), 3.02 (dd, J = 6.0 and 15.1 Hz, 1H), 3.48 (dd, J = 6.0 and 15.1 Hz, 1H), 3.79 (s, 1H), 3.80 (s, 1H), 3.93 (s, 1H), 3.98-3.99 (m, 2H), 4.13 (s, 1H), 5.93-6.02 (m, 1H). ¹³C(¹H) NMR (CDCl₃): δ 24.1, 24.3, 30.4, 31.4, 32.0, 32.6, 63.3, 65.7, 66.3, 66.9, 70.1, 70.6, 82.0, 86.2, 97.6, 99.6, 130.2, 131.6. Anal. Calcld for C₃₂H₄₀Fe: C, 75.43; H, 8.63. Found: C, 75.29; H, 8.77. HRMS Calcd for C₃₂H₄₀Fe: 350.1695. Found: 350.1697. [α]D³⁰ = -9.2 (c 0.56, CHCl₃ for the sample of (R)-66% ee). Chiral HPLC Analysis Conditions: Chiralcel OD-H × 2; eluent: hexane/PrOH = 1000/1; flow rate: 0.5 mL/min; t₁ = 32.1 min (R-isomer), t₂ = 34.8 min (S-isomer).

1.1'-{(3-Methyl-2-buten-1,4-diyI)-2,4-di(tert-butyI)ferrocene (2e). ¹H NMR (CDCl₃): δ 1.14 (s, 9H), 1.28 (s, 9H), 1.93 (s, 3H), 2.59-2.67 (m, 2H), 3.12 (d, J = 14.7 Hz, 1H), 3.28 (dd, J = 7.4 and 14.7 Hz, 1H), 3.73 (s, 1H), 3.82 (s, 1H), 3.89 (s, 1H), 3.99 (s, 1H), 4.02 (s, 1H), 4.14 (s, 1H), 5.67 (t, J = 7.4 Hz, 1H). ¹³C(¹H) NMR (CDCl₃): δ 24.8, 26.7, 29.4, 30.4, 31.4, 32.1, 32.6, 63.6, 66.0, 66.1, 66.8, 70.3, 70.6, 83.1, 85.3, 98.3, 99.9, 124.1, 138.1. Anal. Calcld for C₂₀H₂₂Fe: C, 75.82; H, 8.85. Found: C, 76.08; H, 8.91. HRMS Calcd for C₂₀H₂₂Fe: 364.1852. Found: 364.1856. [α]D³⁰ = -22 (c 0.50, CHCl₃ for the sample of (R)-99.5% ee). Chiral HPLC Analysis Conditions: Chiralcel OD-H; eluent: hexane/PrOH = 1000/1; flow rate: 0.2 mL/min; t₁ = 18.4 min (R-isomer), t₂ = 20.3 min (S-isomer).

1.1'-{(3-Methyl-2-buten-1,4-diyI)-2,4-dicyclohexylferrocene (2f). ¹H NMR (CDCl₃): δ 0.87-0.97 (m, 1H), 1.08-1.40 (m, 9H), 1.66-1.75 (m, 6H), 1.83-1.89 (m, 3H), 1.93 (s, 3H), 1.97-2.10 (m, 2H), 2.33-2.39 (m, 1H), 2.67 (dd, J = 7.8 and 14.6 Hz, 1H), 2.78 (d, J = 14.4 Hz, 1H), 2.91 (dd, J = 7.8 and 14.6 Hz, 1H), 3.28 (dd, J = 14.4 Hz, 1H), 3.53 (br, 1H), 3.79 (br, 1H), 3.85 (br, 1H), 3.87 (br, 1H), 3.94 (br, 1H), 4.09 (br, 1H), 5.72 (t, J = 7.8 Hz, 1H). ¹³C(¹H) NMR (CDCl₃): δ 14.3, 22.8, 23.6, 26.65, 26.74, 26.8, 27.1, 29.6, 31.5, 31.7, 34.4, 34.5, 36.3, 37.25, 37.33, 63.2, 66.5, 66.6, 67.6, 70.3, 71.9, 84.9, 86.3, 93.0, 93.8, 123.6, 138.1. Anal. Calcld for C₂₀H₃₀Fe: C, 77.88; H, 8.71. Found: C, 77.70; H, 8.92. HRMS Calcd for C₂₀H₃₀Fe: 416.2165. Found: 416.2166. [α]D³⁰ = -23 (c 1.3, CHCl₃ for the sample of (R)-82% ee). Chiral HPLC Analysis Conditions: Chiralcel OD-H × 2; eluent: hexane/PrOH = 1000/1; flow rate: 0.4 mL/min; t₁ = 21.4 min (S-isomer), t₂ = 27.6 min (R-isomer).

1.1'-{(3-Methyl-2-buten-1,4-diyI)-2,4-bis(trimethylsilyI)ferrocene (2g). ¹H NMR (CDCl₃): δ 0.17 (s, 9H), 0.27 (s, 9H), 1.94 (s, 3H), 2.69 (d, J = 14.4 Hz, 1H), 2.75 (dd, J = 8.2 and 14.8 Hz, 1H), 3.02 (dd, J = 7.3 and 14.8 Hz, 1H), 3.10 (d, J = 14.4 Hz, 1H), 3.84 (s, 1H), 3.87 (s, 1H), 3.92 (s, 1H), 3.97 (s, 1H), 4.02 (s, 1H), 4.10 (s, 1H), 5.76 (t, J = 7.8 Hz, 1H). ¹³C(¹H) NMR (CDCl₃): δ -0.05, 0.9, 25.0, 26.7, 29.4, 66.4, 66.5, 69.7, 70.1, 74.7, 74.8, 76.2, 78.5, 86.1, 96.3, 124.1, 138.1. Anal. Calcld for C₂₁H₃₂FeSi₂: C, 63.61; H, 8.13. Found: C, 63.46; H, 8.04. HRMS Calcd for C₂₁H₃₂FeSi₂: 396.1390. Found: 396.1395. [α]D³⁰ = +50 (c 2.0, CHCl₃ for the sample of (R)-97% ee). Chiral HPLC Analysis Conditions: Chiralcel OD-H × 2; eluent: hexane/PrOH = 2000/1; flow rate: 0.5 mL/min; t₁ = 39.8 min (R-isomer), t₂ = 42.5 min (S-isomer).

References.


H-NMR at 400 MHz

1C-NMR at 101 MHz

X: parts per Million