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Supporting Information

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Axial Ligand Effects: Utilization of Chiral Sulfoxide Additives for the Induction of Asymmetry in (Salen)Ru(II) Olefin Cyclopropanation Catalysts

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General. GC analyses of cyclopropanation reactions were carried out on Hewlett Packard 5890A and 6890 gas chromatographs equipped with FID detectors. For the determination of the *trans:cis* ratio of the cyclopropanes, a 30-m HP-5 capillary column with 0.32-mm inner diameter and 0.25-mm film thickness was used. For GC determination of enantiomeric excess, Supelco β-DEX series (120 and 225) chiral columns were used and for HPLC determination of enantiomeric excess, a Pirkle Covalent (*S,S*) Whelk-O 1 purchased from Regis Technologies was used. The calibration curve for yield determination of the product styrene cyclopropanation, 2-phenyl cyclopropane carboxylic acid ethyl ester, was produced using an analytically pure sample.[1] ^{1}H NMR spectra were recorded on an Inova-500 FT-NMR spectrometer (499.733 MHz) and are reported as follows: chemical shift (multiplicity (b = broad, s = singlet, d = doublet, t = triplet, q = quartet, and m = multiplet), and integration). Chemical shifts for ^{1}H NMR spectra are reported in ppm downfield from tetramethylsilane (TMS, δ scale) using residual solvent signals in the deuterated solvents as references. ^{31}P NMR spectra were recorded on a Mercury-400 FT-NMR spectrometer (161.898 MHz) and chemical shifts are reported in ppm downfield of an external H_3PO_4 standard.

Catalysts **1**-**2** were synthesized and characterized by methods previously reported by our laboratory.[1] Diamino-*N,N'*-bis(3,5-di-*tert*-butylsalicylidene) salen ligands were prepared from the condensation of 3,5-di-*tert*-butyl salicyladehyde with the corresponding diamines. [$RuCl_2$(*p*-cymene)]$_2$[2] and sulfoxides **9**[3], **10**[3], and **11**[4] were all prepared according to literature procedures. Dichloromethane was distilled over calcium hydride; tetrahydrofuran (THF), toluene, and hexane were distilled over sodium/benzophenone. All solvents were distilled under nitrogen and saturated with nitrogen prior to use. All olefins were purchased from Aldrich Chemical Company, dried over calcium hydride, vacuum distilled, and stored at 0 ºC under nitrogen prior to use. Ethyl diazoacetate (EDA, 91% in CH_2Cl_2) was purchased from Aldrich and degassed via three freeze-pump-thaw cycles before used. Deuterated solvents were purchased from Cambridge Isotope Laboratories, distilled over calcium hydride, and vacuum transferred into an air-tight solvent bulb prior to transfer into the inert-atmosphere glovebox. All other reagents were purchased from Aldrich Chemical Company and used without further purification unless otherwise noted. All reactions were carried out either under a dry nitrogen atmosphere using standard Schlenk techniques or in an inert-atmosphere glovebox unless otherwise noted.

Synthesis of *Bis*(triphenylphosphine)-1,2-ethanediamino-*N,N'*-*bis*(3,5-di-*tert*-butylsalicylidene)ruthenium(II) (3). This compound was prepared by modifying a literature

method.[5] A THF (15 mL) solution of (Salen)H_2, (1.59g, 3.22 mmol) was treated with LDA (6.44 mmol from a 1.5 M solution of the monotetrahydrofuran complex in cyclohexane) at room temperature and stirred for 20 min. This mixture was then added to a THF (20 mL) solution of $[RuCl_2(p\text{-cymene})]_2$ (986 mg, 3.22 mmol) and PPh_3 (1.69 g, 6.44 mmol) at room temperature. The reaction was warmed to 60 °C and stirred for an additional 24 h, resulting in a dark red solution. This mixture was evaporated *in vacuo*, extracted into toluene, filtered via cannula, and concentrated to approximately 5 mL. Hexanes (30 mL) was added via cannula and the solution was cooled to – 10 °C which resulted in the slow precipitation of a dark red solid which was filtered via cannula to yield 2.91 g (81 %). ^{1}H NMR (C_6D_6): δ 1.34 (s, 18H, ^{t}Bu), 1.58 (s, 18H, ^{t}Bu) 2.69 (b, 4H, NCH_2CH_2N), 5.88 (b, 2H, aromatics), 6.9-7.0 (m, 20H, aromatics), 7.4-7.6 (m, 14H, aromatics). ^{31}P{^{1}H} NMR (C_6D_6): δ 28.0. Anal: Calcd. for $C_{68}H_{76}N_2O_2P_2Ru$: C, 73.16; H, 6.86; N, 2.51; Found: C, 73.41; H, 6.93; N, 2.48.

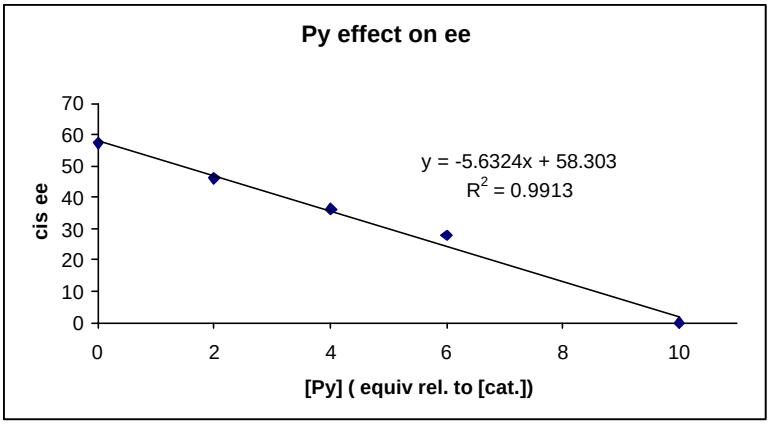
Synthesis of *Bis*(triphenylphosphine)-1,3-propylenediamino-*N,N'*-*bis*(3,5-di-*tert*-butylsalicylidene)ruthenium(II) (4). A THF (15 mL) solution of (Salen)H_2, (509 mg, 1.0 mmol) was treated with LDA (1.5 M solution of the monotetrahydrofuran complex in cyclohexane, 2.0 mmol) at room temperature and stirred for 20 min. This mixture was then added to a THF (20 mL) solution of $[RuCl_2(p\text{-cymene})]_2$ (305 mg, 0.5 mmol) and PPh_3 (528 mg, 2.0 mmol) at room temperature. The reaction was warmed to 40 °C and stirred for an additional 24 h, resulting in a dark red solution. This mixture was evaporated *in vacuo*, extracted into toluene, filtered via cannula, and concentrated to approximately 5 mL. Hexanes (30 mL) was added via cannula and the solution was cooled to – 10 °C which resulted in the slow precipitation of a dark red solid which was filtered via cannula to yield 340 mg (30 %, unoptimized). ^{1}H NMR (C_6D_6): δ 0.90 (m, 2H, NCH$_2$CH_2CH$_2$N), 1.41 (s, 18H, ^{t}Bu), 1.93 (s, 18H, ^{t}Bu) 2.88 (b, 4H, NCH_2CH$_2$CH_2N), 6.69 (b, 2H, aromatics), 6.9-7.0 (m, 18H, aromatics), 7.4-7.6 (m, 14H, aromatics), 7.67 (b, 2H, aromatics). ^{31}P{^{1}H} NMR (C_6D_6): δ 28.5. EIMS: m/z 868.0 [(M^+-PPh_3), Calcd. 868.1], 606.0 [(M^+-2PPh_3), Calcd. 605.8].

Synthesis of *Bis*(triphenylphosphine)-1,2-phenylenediamino-*N,N'*-*bis*(3,5-di-*tert*-butylsalicylidene)ruthenium(II) (5). This compound was prepared as above. Attempts to purify compound **5** by recrystallization from toluene-hexane at – 10 ºC were not successful. Instead, it was purified by washing with MeOH (20 mL) and hexanes (20 mL), respectively. Yield = 200 mg (29 %). ^{1}H NMR (C_6D_6): δ 1.31 (s, 18H, ^{t}Bu), 1.71 (s, 18H, ^{t}Bu), 6.11 (d, 2H, aromatics, J = 2.5 Hz), 6.78 (m, 22H, aromatics), 7.39-7.47 (m, 16H, aromatics). ^{31}P{^{1}H} NMR (C_6D_6): δ 30.2. Anal: Calcd. for $C_{72}H_{76}N_2O_2P_2Ru$: C, 74.27; H, 6.58; N, 2.41; Found: C, 73.62; H, 6.94; N, 2.38.

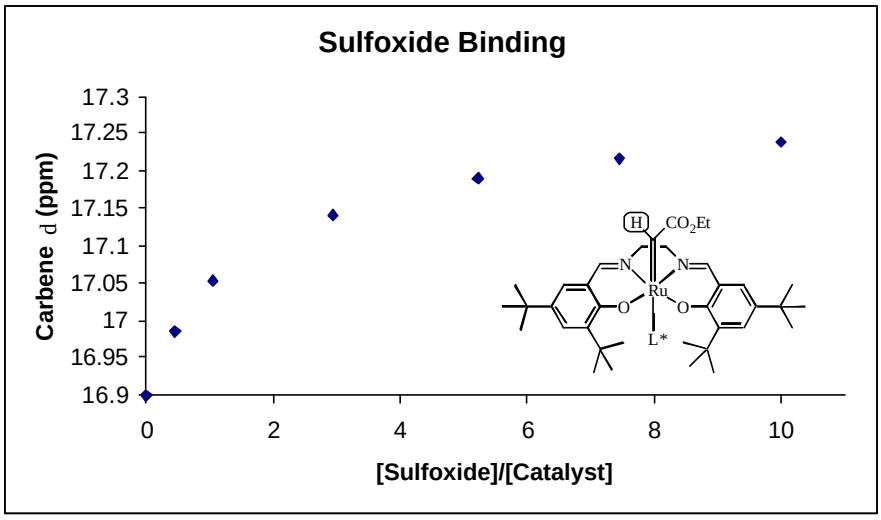
GC and HPLC Methods. For all cyclopropane diastereoselectivity determinations: 30-m HP-5 capillary GC column (initial temp = 50 °C, rate = 10 °C/min, final temp = 250 °C, final time = 10 min). For styrene, α-methyl styrene, and 4-fluoro styrene enantioselectivity: β-Dex 120 GC column (head pressure = 20 psi, temp program: initial temp = 100 °C, initial time = 0.0 min, rate = 0.5 °C/min, final temp = 140 °C, final time = 0.0 min.). For methyl methacrylate enantioselectivity: β-Dex 225 GC column (head pressure = 23 psi, temp program: initial temp = 70 °C isothermal for 100 min). For 4-methoxy styrene enantioselectivity: Pirkle Covalent (*S,S*) Whelk-O 1 HPLC column (hexanes/*iso*-propanol 97/3 at 0.6 mL/min). For 4-*tert* butyl styrene enantioselectivity: Pirkle Covalent (*S,S*) Whelk-O 1 HPLC column (hexanes/*iso*-propanol 98/2 at 0.4 mL/min).

Procedure for cyclopropane product isolation. For the volatile olefin substrates (styrene and methyl methacrylate) the isolation procedure reported previously by our laboratory[6] was utilized: the reaction mixture (including solvent, excess olefin, catalyst, sulfoxide, and cyclopropane product) was loaded on a silica gel column (2.0 cm x 10.0 cm) to remove catalyst and sulfoxide. The plug was washed with CH_2Cl_2 (150 mL) to elute product and excess olefin. The solvent and excess olefin were then easily removed via vacuum distillation to yield pure cyclopropane product. A slightly modified procedure was utilized for the less volatile substituted styrenes: the reaction mixture was loaded on a silica gel column as stated above, however, a mixture of hexanes and CH_2Cl_2 (4:1 respectively) was first used to elute excess olefin. After all the remaining olefin was removed from the column, it was flushed with CH_2Cl_2 to elute product, leaving catalyst and sulfoxide. Solvent was evaporated from the resulting solution to yield pure cyclopropane.

Procedure for pyridine addition experiments. Variable amounts of pyridine (0, 2, 4, 6, 10 equiv relative to catalyst) were added to a solution containing catalyst **3**, styrene, and sulfoxide **7***R*, prepared as described in the above procedure. EDA preparation/addition as well as the reaction work-up was also done according to the aforementioned general cyclopropanation procedure.



Procedure for NMR monitoring of carbene-sulfoxide intermediate. Under N_2 in a glovc box and to seven 20-mL vials was added catalyst **3** (0.014 mmol) and C_6D_6 (2.5 mL). EDA (0.042 mmol, 3 equiv) was then added dropwise to each of the vials. The reactions were allowed to stir for 5 min or until N_2 evolution stopped. To each of the deep red solution was added variable amount of sulfoxide **7***R* (0, 0.5, 1, 3, 5, 7, and 10 equiv relative to catalyst). These solutions were then diluted to 5 mL with C_6D_6 and portions were transferred to either J-Young or Teflon-lined screw-cap NMR tubes and sealed tightly before taken out of the dry box. ^{1}H NMR spectra were then taken and the chemical shift of the carbene proton was noted. All experiments were repeated at least twice for statistical accuracy. The equilibrium constant was then determined using the program WinEQNMR.[7]

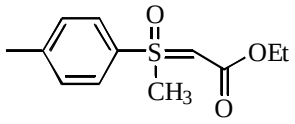


FORTRAN input parameters for WinEQNMR calculation

4,9,3,3,-1,199,1
0.01 0.0001
Sulfoxide Ru-Carbene pH
IDEAL DATA FOR 1:1 COMPLEX USING CHEMICAL SHIFT (TEST11.FIT)
Reaction: M + L = ML
FILE: jamdata.FIT
File prepared by Jason A. Miller, August 19, 2003
0.001625 0.003475 0.0 16.985 1.0
0.003580 0.003580 0.0 17.059 1.0
0.003875 0.003475 0.0 17.047 1.0
0.010375 0.003525 0.0 17.137 1.0
0.010525 0.003550 0.0 17.147 1.0
0.018975 0.003475 0.0 17.201 1.0
0.017825 0.003550 0.0 17.178 1.0
0.025925 0.003475 0.0 17.216 1.0
0.035580 0.003580 0.0 17.240 1.0
Keq
100 0.001
SHIFT M
16.9 0.001
SHIFT ML
17.3 0.001
1
2,1
Lig
M
1
1 1 0 0
1
1.0 2 2
1

1.0 1 3
1.0 2
1 2

Procedures for control experiments. A series of reactions was carried out to insure that the (salen)Ru(II) complex was necessary for the cyclopropane to be formed selectively and also to eliminate the possibility that the reaction was occurring through a sulfoxide-EDA ylide, **A**.



A

First, the general cyclopropanation procedure was followed in the absence of a (salen)Ru(II) complex using only (*R*)-methyl-*p*-tolyl sulfoxide, **7***R*, (0.25 mmol), styrene (2.5 mmol) and EDA (0.50 mmol) to yield no reaction.

To ascertain if the formation of sulfoxide-EDA ylide **A** is favored under our conditions: **7***R* (0.05 mmol) and EDA (0.50 mmol) were mixed in the presence of the catalyst, with and without styrene. Both reactions yielded no ylide product after 12 h.

Our (salen)Ru(II) system was then tested to see if it catalyzes the formation of **A**. Complex **3** (0.005 mmol) was reacted with sulfoxide **7***R* (0.05 mmol) and EDA (0.50 mmol) under standard cyclopropanation conditions and showed no evidence of the ylide intermediate.

Finally, we prepared and isolated **A** through the CuCN-catalyzed addition of EDA (0.34 mmol) to sulfoxide **7***R* as described by Dost and Gossleck.[8] The isolated ylide (0.12 mmol) was then subjected to catalyst **3** (0.001 mmol) in the presence of styrene (0.59 mmol). This reaction yielded no cyclopropane, thus proving that our catalyst is indeed directly responsible for the cyclopropanation and that the reaction does not occur through a sulfoxide-EDA ylide pathway.

References

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