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Chiral Bis(oxazoline) Ligands as C_2-Symmetric Chiral Auxiliaries for the Synthesis of Enantiomerically Pure Bis-Cyclometalated Rhodium(III) Complexes

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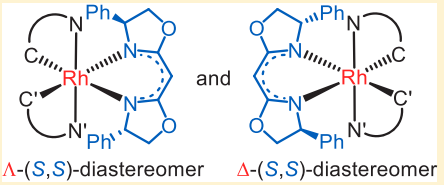
Supporting Information

ABSTRACT: The synthesis of enantiomerically pure bis-cyclometalated rhodium(III) complexes using chiral bis(oxazoline) ligands as C_2-symmetric chiral auxiliaries is described. Bis(oxazolines) are versatile chiral ligands for asymmetric catalysis but have not been applied to the resolution of racemic mixtures of transition-metal complexes. Due to their C_2 symmetry, chiral bis(oxazolines) are particularly useful for the synthesis of nonracemic transition-metal complexes with lower symmetry, and this is demonstrated with the synthesis of an enantiomerically pure rhodium(III) complex containing two different cyclometalated ligands.



INTRODUCTION

Nonracemic transition-metal complexes play an important role as chiral catalysts for the asymmetric synthesis of chiral compounds used in academia and industry.[1] They typically contain chiral ligands to control the overall chirality of the metal complexes. Following a different strategy, we and others have recently demonstrated that chiral transition-metal complexes composed from entirely achiral ligands can be exquisite transition-metal catalysts for a large variety of asymmetric conversions, including asymmetric photocatalysis.[2,3] Such chiral-at-metal complexes feature a configurationally stable stereogenic metal center for generating metal-centered chirality which at the same time must be a reactive metal center for performing the asymmetric catalysis.

Controlling the metal-centered configuration with tailored chiral ligands is well established.[4] However, chiral-at-metal complexes consist of entirely achiral ligands so that modified or different synthetic strategies need to be employed. Chiral-auxiliary-mediated methods for the synthesis of enantiomerically pure metal complexes have been reported, including using chiral counterions, cleavable chiral linkers, and temporary chiral ligands in which the coordinative strength can be varied.[4,5] Our group[6,7] and others[8] have had great success with the development and application of such temporarily coordinating chiral bidentate ligands as chiral auxiliaries for the synthesis of enantiomerically pure octahedral transition-metal complexes. Upon binding of the bidentate auxiliary ligand to the central metal, it either implements the metal-centered configuration or leads to a mixture of two diastereomers which can be resolved. Finally, the auxiliary is removed in a traceless fashion, typically upon labilization with a Brønsted acid, to provide the nonracemic metal complexes (Figure 1).

A fluorinated salicyloxazoline, first reported by Monari, Bandini, and Ceroni,[8b] has been our auxiliary of choice for the synthesis of enantiomerically pure bis-cyclometalated rhodium(III) complexes.[9,10] Recently, we realized a limitation of its practicability when we introduced a synthetic method for the preparation of bis-cyclometalated rhodium(III) catalysts with two different cyclometalating ligands.[11] Due to its lower symmetry and the non-C_2 symmetry of the chiral salicyloxazoline, four diastereomers were obtained upon coordination of the chiral salicyloxazoline auxiliary to the bis-cyclometalated rhodium complex, two featuring metal-centered Λ configuration and two Δ configuration. This posed an additional challenge for the separation of the Λ- and Δ-configured stereoisomers. A C_2-symmetric chiral auxiliary bidentate ligand would solve this problem.

Here, we report the use of chiral bis(oxazoline) (BOX) ligands as C_2-symmetric chiral auxiliaries for the synthesis of bis-cyclometalated rhodium(III) complexes. C_2-symmetric chiral bis(oxazolines) belong to one of the most popular classes of chiral ligands for the synthesis of chiral transition-metal complexes used in asymmetric catalysis due to their C_2 symmetry, which reduces the number of competing transition states, and due to their easy and flexible synthesis.[12,13] However, to the best of our knowledge, the use of BOX ligands as chiral auxiliaries for the synthesis of nonracemic metal complexes has not been reported before.

RESULTS AND DISCUSSION

We first explored the use of simple C_2-symmetric BOX ligands as chiral auxiliaries for the synthesis of our standard bis-cyclometalated rhodium(III) catalyst Λ- and **Δ-RhS**,[9,14] in which rhodium is cyclometalated by two 5-*tert*-butyl-2-phenylbenzothiazoles and the octahedral coordination sphere is supplemented by two acetonitriles. The monocationic complexes are typically synthesized as their hexafluorophos-

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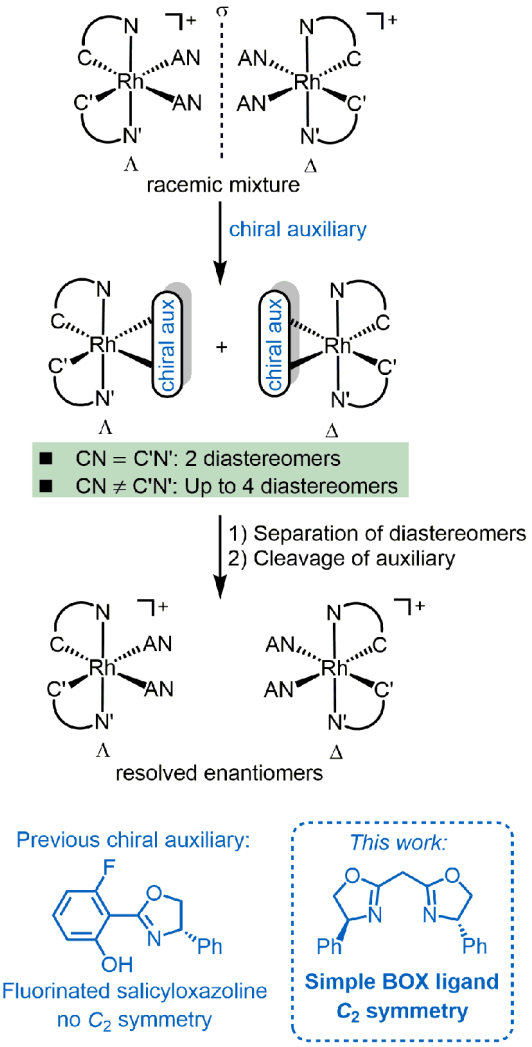
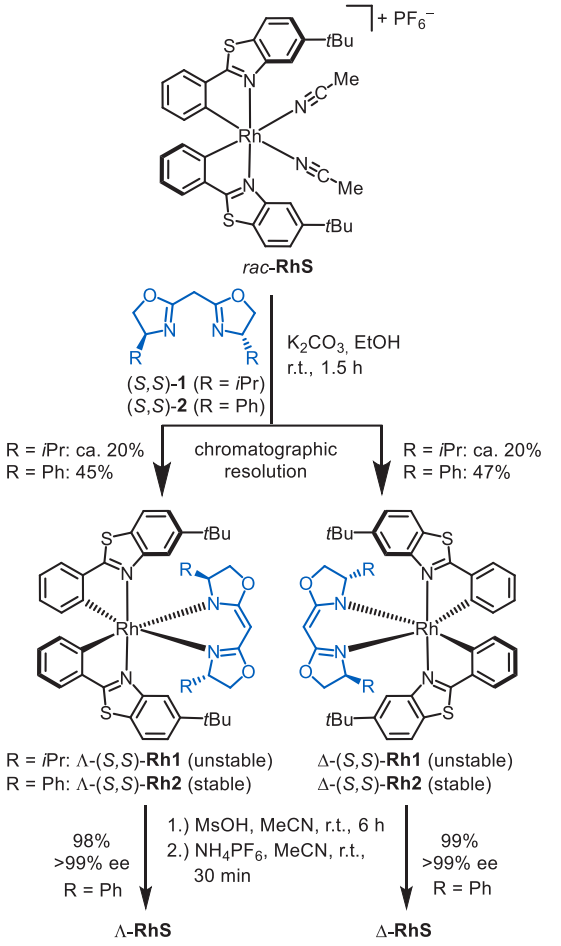


Figure 1. Chiral auxiliaries for the resolution of stereoisomers of bis-cyclometalated rhodium(III) complexes used as chiral catalysts. AN = acetonitrile, CN and C′N′ = cyclometalated ligands.

Scheme 1. Chiral Bis(oxazoline) Mediated Synthesis of Λ- and Δ-RhS



phate salts. Despite all ligands being achiral, octahedral metal-centered chirality leads to Λ (left-handed helical twist) and Δ enantiomers (right-handed helical twist). Chiral bis(oxazoline) ligands were easily prepared via a single-step procedure starting from readily available *β*-amino alcohols and symmetrically disubstituted diethyl malonimidate dihydrochloride. We started our investigations with the isopropyl-substituted BOX ligand (*S*,*S*)-**1** (Scheme 1). Gratifyingly, the addition of 1.10 equiv of this ligand to a suspension of *rac*-**RhS** in ethanol in the presence of 3 equiv of K_2CO_3 led to the formation of the corresponding Λ- and Δ-configured auxiliary complexes after only 1 h at room temperature. Analysis of the ^{1}H NMR of the crude material confirmed the conversion to a 1:1 mixture of diastereomeric complexes by showing a combination of two different sets of signals as well as the full consumption of the racemic starting material (see the Supporting Information for more details). However, when we attempted to separate the two diastereomers via column chromatography on deactivated silica gel (1% of Et_3N), we found that they largely decomposed during purification, resulting in only low yields of about 20% for each diastereomer Λ- and Δ-(*S*,*S*)-**Rh1** after chromatographic resolution. Therefore, we envisioned the phenyl-substituted BOX ligand (*S*,*S*)-**2** as a promising next alternative, expecting stabilizing *π*−*π*-stacking interactions of the phenyl moieties with the cyclometalated ligands of the rhodium complex. Following the above conditions, we obtained Λ- and Δ-(*S*,*S*)-**Rh2** by reaction of *rac*-**RhS** with the ligand (*S*,*S*)-**2**, with conversion being complete after only 1.5 h. Indeed, the diastereomeric mixture of Λ- and Δ-(*S*,*S*)-**Rh2** could be chromatographed on deactivated silica gel without showing any traces of degradation of the complexes, providing the single diastereomers Λ- and Δ-(*S*,*S*)-**Rh2** in high yields of 45% and 47%, respectively. Absolute configurations were assigned on the basis of the crystal structure of Λ-(*S*,*S*)-**Rh2** (Figure 2). The BOX ligand coordinates as a six-membered chelate in its monodeprotonated form to generate a neutral rhodium complex.[15] The structure also reveals the anticipated *π*−*π*-stacking interactions between the two phenyl moieties of the BOX ligand (*S*,*S*)-**2** and the benzothiazole moieties of the rhodium complex.

With the individual diastereomers in hand, we next engaged in the synthesis of single enantiomers using an acid-induced replacement of the coordinated BOX ligand by two acetonitrile ligands, followed by counterion exchange with NH_4PF_6. Accordingly, the addition of 10.0 equiv of trifluoroacetic acid (TFA) to a suspension of either Λ- or Δ-(*S*,*S*)-**Rh2** in acetonitrile was first executed at room temperature (Table 1, entry 1). Although TLC indicated completion of the reaction after 1 h, ^{1}H NMR of the isolated compound after performance

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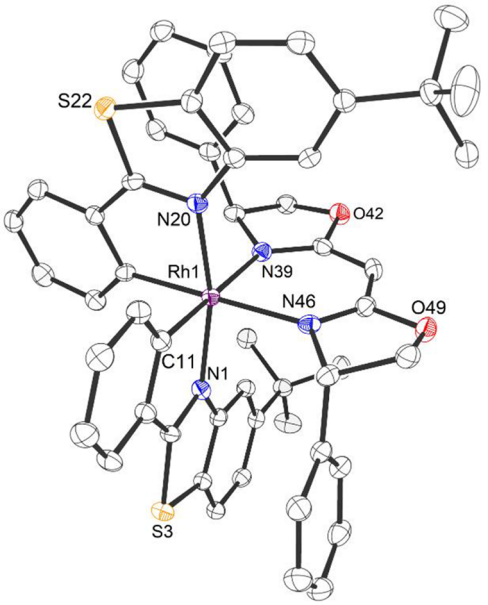


Figure 2. Crystal structure of the auxiliary complex Λ-(*S*,*S*)-**Rh2** as an ORTEP drawing with 50% probability thermal ellipsoids. Solvent molecules are omitted for clarity.

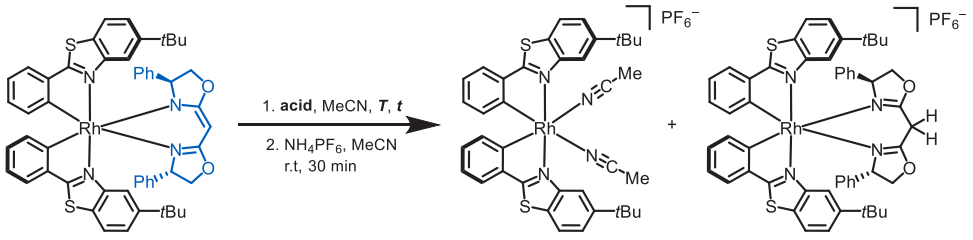
of the subsequent anion exchange and purification of the crude material by regular silica gel chromatography showed that correspondingly Λ- or Δ-(*S*,*S*)-**Rh2**-H was obtained as the major product, while the desired complex Λ- or Δ-**RhS** was only formed in traces (see the Supporting Information for more details). Since both monocationic complexes had the same R_f value, they were isolated as a mixture. The relative amount of **RhS** in comparison to (*S*,*S*)-**Rh2**-H was determined by ^{1}H NMR and revealed that the initial conditions led to the formation of **RhS** in a ratio of only 1:5.5 (Table 1, entry 1). Thus, different reaction conditions were next attempted in order to improve the reaction outcome with regard to the target complex. Table 1 shows a number of different conditions.

Notably, increasing the amount of TFA to 20.0 equiv in addition to prolonging the reaction time and executing the reaction at elevated temperature could significantly enhance the obtained ratio in favor of the desired complex, with **RhS** now being formed as the major species (Table 1, entry 2). Conducting the reaction at 50 °C for 22 h finally resulted in complete dissociation of the BOX ligand from the metal center, providing **RhS** as the sole product of the reaction in 81% yield (entry 3). Alternatively, the application of 5.00 equiv of methanesulfonic acid (MsOH) instead of TFA already allowed the transformation to proceed at room temperature in a significantly reduced reaction time and with reasonable product to side product ratios (entries 4 and 5). Readjustment to 10.0 equiv of MsOH afforded the single enantiomers Λ-**RhS** (entry 6) and Δ-**RhS** after 6 h with retention of the absolute configuration in excellent yields of 98% and 99%, respectively. HPLC performed on a chiral stationary phase exhibited the high enantiomeric purity (>99% ee) of the individual enantiomers (Figure 3).

Having established the conditions for the chiral bis(oxazoline)-mediated synthesis of nonracemic rhodium(III) catalysts on the basis of the bis-cyclometalated complex **RhS**, we then sought out to transfer the strategy to the synthesis of an enantiomerically pure rhodium complex with two different cyclometalating ligands. To this end, *rac*-**RhNS** was prepared according to our previously reported procedure[11] and reacted with BOX ligand (*S*,*S*)-**2** (Scheme 2).

As expected, this resulted in the formation of only two diastereomers due to the C_2-symmetric nature of the chiral auxiliary. Λ-(*S*,*S*)-**Rh3** (44%) and Δ-(*S*,*S*)-**Rh3** (45%) could be obtained conveniently after separation of the diastereomeric complexes by silica gel chromatography. Configurations were assigned with reference to the obtained crystal structure of Λ-(*S*,*S*)-**Rh3** shown in Figure 4. The subsequent stereospecific

Table 1. Optimization of the Acid-Induced Cleavage of the Auxiliary Ligand[a]



		conditions (1st step)		
entry	acid (equiv)	*T* (°C)	*t* (h)	**RhS**:(*S*,*S*)-**Rh2**-H[b]
1[c]	TFA (10)	room temp	1	1:5.5
2	TFA (20)	40	15	1.5:1
3	TFA (20)	50	22	>20:1 (81%)[d]
4	MsOH (5)	0 to room temp	5	5.2:1
5[e]	MsOH (5)	room temp	6	14:1
6[e]	MsOH (10)	room temp	6	>20:1 (98%)[d]

[a]Reaction conditions first step unless specified otherwise: Λ- or Δ-(*S*,*S*)-**Rh2** was dissolved in MeCN (0.04 M), the indicated acid was added in one portion, and the resulting solution was stirred at the indicated temperature for the indicated time under an atmosphere of nitrogen. [b]Ratios were determined by ^{1}H NMR after column chromatographic purification of the second step. Isolated yields are only provided, if conversion to Λ-/Δ-**RhS** was complete. [c]Λ-(*S*,*S*)-**Rh3** was employed. [d]Isolated yields of **RhS** are provided in parentheses. [e]MsOH was added at 0 °C, and the resulting solution was stirred for a further 15 min at 0 °C before the ice bath was removed.

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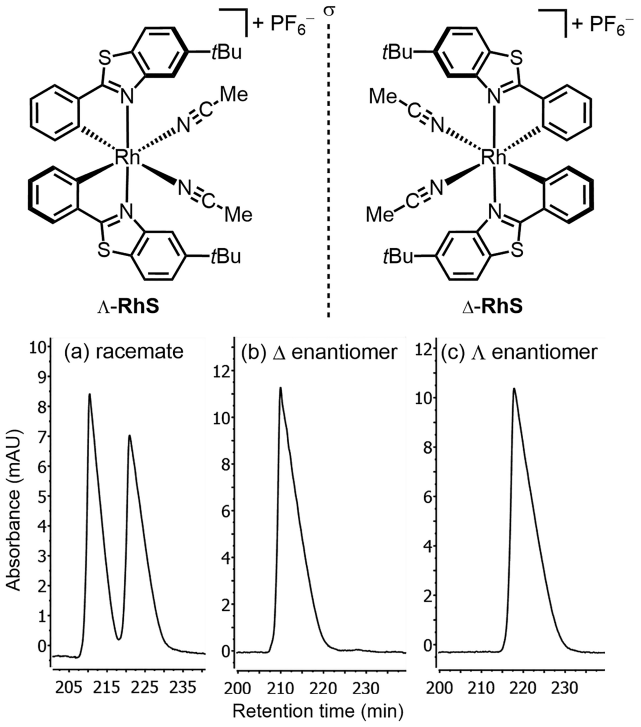


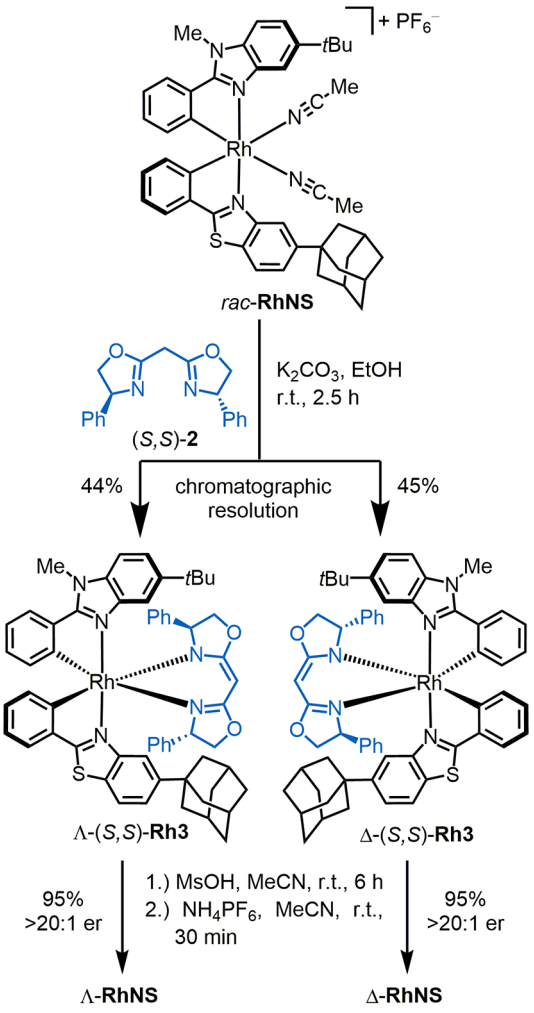
Figure 3. HPLC traces on a chiral stationary phase: (a) racemic complex **RhS** as a reference; (b) Δ enantiomer of **RhS** synthesized with (*S*,*S*)-**2** as the chiral auxiliary; (c) Λ enantiomer of **RhS** synthesized with (*S*,*S*)-**2** as the chiral auxiliary. Conditions: Daicel Chiralpak IB-N5 column (250 × 4.6 mm), column temperature 25 °C, λ_{abs} = 254 nm, flow rate 0.6 mL/min, solvent A: 0.1% aqueous TFA, solvent B: MeCN, gradient 40−50% B in 180 min, 50% B maintained for a further 60 min.

substitution of the coordinated auxiliary ligand gave the enantiopure complexes Λ-**RhNS** and Δ-**RhNS** (95% yield each) with retention of configuration by following the above optimized conditions. CD spectra confirmed their mirror-image structures (see the Supporting Information). Since a satisfactory separation of the two enantiomers Λ- and Δ-**RhNS** could not be achieved by chiral HPLC, the single enantiomers were reconverted into Λ- and Δ-(*S*,*S*)-**Rh3**, respectively, in order to validate the enantiopurity via determination of the diastereomeric ratio from the ^{1}H NMR of the crude materials. Hereby, Λ- as well as Δ-(*S*,*S*)-**Rh3** were obtained with a dr value of more than 20:1 (see the Supporting Information for more details).

CONCLUSIONS

In conclusion, we developed the first auxiliary-mediated strategy for the synthesis of nonracemic bis-cyclometalated rhodium(III) catalysts using a simple chiral bis(oxazoline) ligand as the chiral auxiliary and demonstrated the feasibility of the approach with the preparation of the established benzothiazole complex Λ- and Δ-**RhS**. In the first step, a pair of two chromatographically stable diastereomers was obtained by reaction of a racemic mixture of the complex with a phenyl-substituted BOX ligand. The crucial acid-induced dissociation of the coordinated BOX ligand in the subsequent second step was accomplished despite the ability of the ligand to coordinate in its neutral form, providing the final catalyst conveniently with excellent enantiomeric purities (>99% ee for

Scheme 2. Chiral Bis(oxazoline) Mediated Synthesis of Λ- and Δ-RhNS



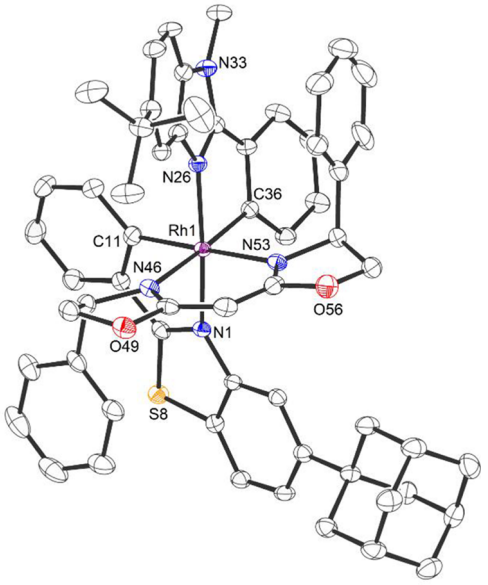


Figure 4. Crystal structure of auxiliary complex Λ-(*S*,*S*)-**Rh3** as an ORTEP drawing with 50% probability thermal ellipsoids. Solvent molecules are omitted for clarity.

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each enantiomer) and in high yields. Additionally, we complemented our studies with the synthesis of the bis-cyclometalated complex Λ- and Δ-**RhNS**, which has a lower symmetry due to two different cyclometalating ligands, thereby disclosing the particular benefit of the C_2-symmetric auxiliary. This process reduces the amount of possible stereoisomers to two, which represents a significant enhancement of our previously reported synthetic protocol since it greatly facilitates the separation of the diastereomers and renders the preparation of this class of catalysts less time consuming. Thus, chiral BOX ligands are an economical tool for the synthesis of nonracemic bis-cyclometalated rhodium complexes, which have been used extensively over the past few years as chiral transition-metal catalysts.[7,14,16,17] Further investigations addressing the generality of the introduced auxiliary-mediated approach for the asymmetric synthesis of chiral transition-metal catalysts different from rhodium are currently being pursued.

EXPERIMENTAL SECTION

General Methods and Materials. See the Supporting Information for experimental details on the synthesis of cyclometalating ligands and the racemic rhodium(III) complexes. All reactions were carried out under a nitrogen atmosphere in oven-dried glassware unless noted otherwise. Solvents were distilled under nitrogen from calcium hydride (MeCN, CH_2Cl_2), sodium/benzophenone (THF), or sodium (toluene) prior to use. Reagents that were purchased from commercial suppliers were used without further purification. Flash column chromatography was performed with silica gel 60 M from Macherey-Nagel (irregularly shaped, 230−400 mesh, pH 6.8, pore volume 0.81 mL g^{-1}, mean pore size 66 Å, specific surface 492 m^2 g^{-1}, particle size distribution 0.5% < 25 μm and 1.7% > 71 μm, water content 1.6%). ^{1}H NMR and $^{13}C\{^1H\}$ NMR spectra were recorded on a Bruker AV II 300 MHz, AV III HD 250 MHz, AV III 500 MHz, AV III HD 500 MHz, or AV II 600 MHz spectrometer at ambient temperature. Chemical shift values δ are reported in ppm with the solvent resonance as internal standard. All ^{13}C NMR signals are singlets unless noted otherwise. Samples for NMR measurements were about 15−30 mg of the substance dissolved in 0.60 mL of deuterated solvent. 1D-^{1}H spectra were aquired with 65536 data points, 16 transients, a sweep width of 11−20 ppm, and a relaxation delay of 6−7 s. 1D-^{13}C spectra were aquired with 65536 data points, 2000−8000 transients, a sweep width of 262 ppm, and a relaxation delay of 2−3 s. IR spectra were recorded on a Bruker Alpha FT-IR spectrometer. CD spectra were acquired with a JASCO J-810 CD spectropolarimeter (600−200 nm, data pitch 0.5 nm, bandwidth 1 nm, response 1 s, sensitivity standard, scanning speed 50 nm/min, accumulation of three scans). High-resolution mass spectrometry was performed on a Finnigan LTQ-FT Ultra mass spectrometer (Thermo Fischer Scientific) using ESI or APCI as the ionization source. EI mass spectra were recorded on an AccuTOF GCv instrument (JEOL). Melting points were determined on a Mettler Toledo MP70 apparatus using capillary tubes closed on one end. Chiral HPLC was performed on an Agilent 1260 instrument.

General Procedure I: Synthesis of Chiral Bis(oxazoline) Ligands. According to a slightly modified procedure,[18] to a solution of the β-amino alcohol (2.00 equiv) in CH_2Cl_2 (0.10 M) was added diethyl malonimidate dihydrochloride (1.00 equiv). The resulting cloudy solution was stirred at room temperature until TLC confirmed full consumption of the starting materials. The reaction mixture was diluted with H_2O and extracted three times with CH_2Cl_2. The combined organic layers were washed once with brine and dried over Na_2SO_4, and the solvent was removed under reduced pressure. Purification of the obtained oily residue by bulb-to-bulb distillation (Kugelrohr distillation, 150 °C at 0.2 mbar) afforded the respective bis(oxazoline).

*Synthesis of (S,S)-**1**.* Following general procedure I, to a solution of L-valinol (893 mg, 8.65 mmol, 2.00 equiv) in CH_2Cl_2 (43.3 mL) was added diethyl malonimidate dihydrochloride (1.00 g, 4.33 mmol, 1.00 equiv) and the resulting solution was stirred for 45 h at room temperature. Bulb-to-bulb distillation gave bis((*S*)-4-isopropyl-4,5-dihydrooxazol-2-yl)methane ((*S,S*)-**1**) (797 mg, 3.34 mmol, 77%) as a white waxy solid. Analytical data were in agreement with the literature.[19] ^{1}H NMR (300 MHz, $CDCl_3$): δ 4.25 (dd, *J* = 8.9, 7.6 Hz, 2H), 4.01−3.88 (m, 4H), 3.33 (s, 2H), 1.80−1.69 (m, 2H), 0.94 (d, *J* = 6.8 Hz, 6H), 0.86 (d, *J* = 6.8 Hz, 6H) ppm.

*Synthesis of (S,S)-**2**.* Following general procedure I, to a solution of (*S*)-2-phenylglycinol (1.19 g, 8.65 mmol, 2.00 equiv) in CH_2Cl_2 (43.3 mL) was added diethyl malonimidate dihydrochloride (1.00 g, 4.33 mmol, 1.00 equiv) and the resulting solution was stirred for 68 h at room temperature. Purification by bulb-to-bulb distillation yielded bis((*S*)-4-phenyl-4,5-dihydrooxazol-2-yl)methane ((*S,S*)-**2**) (1.01 g, 3.30 mmol, 76%) as a yellow oil. Analytical data were in agreement with the literature.[20] ^{1}H NMR (300 MHz, CD_2Cl_2): δ 7.37−7.25 (m, 10H), 5.26−5.20 (m, 2H), 4.68 (dd, *J* = 10.2, 8.4 Hz, 2H), 4.14 (t, *J* = 8.2 Hz, 2H), 3.53 (s, 2H) ppm.

General Procedure II: Synthesis of Chiral Bis(oxazolinato) Rhodium(III) Complexes. The racemic rhodium complex (1.00 equiv), K_2CO_3 (3.00 equiv), and BOX ligand (*S,S*)-**2** (1.10 equiv) were suspended in EtOH (25 mM, absolute) and stirred at room temperature until TLC indicated completion of the reaction. The reaction mixture was diluted with EtOAc and filtered over a short plug of Celite. After removal of the solvent under reduced pressure, the resulting mixture of two diastereomers was transferred to a silica gel column with EtOAc and a few drops of CH_2Cl_2 (HPLC grade) for dissolution and purified by column chromatography (*n*-pentane/EtOAc with a gradient, plus 1% Et_3N). The silica gel employed was deactivated prior to use by stirring in the initial solvent mixture together with 1% of Et_3N for about 10 min.

Synthesis of Λ- *and* Δ-*(S,S)-**Rh2**.* Following general procedure II, *rac*-**RhS** (80.0 mg, 92.7 μmol, 1.00 equiv), K_2CO_3 (38.4 mg, 0.28 mmol, 3.00 equiv), and BOX ligand (*S,S*)-**2** (31.2 mg, 0.10 mmol, 1.10 equiv) were suspended in EtOH (3.78 mL, absolute) and stirred for 1.5 h at room temperature. Purification by column chromatography (*n*-pentane/EtOAc, gradient 100/1 → 80/1 → 60/1, plus 1% Et_3N) afforded Λ-(*S,S*)-**Rh2** (39.4 mg, 41.9 μmol, 45%) and Δ-(*S,S*)-**Rh2** (40.9 mg, 43.5 μmol, 47%) as yellow solids.

Λ-*(S,S)-**Rh2***. TLC (*n*-pentane/EtOAc 30/1 + 1% Et_3N): R_f = 0.30. ^{1}H NMR (300 MHz, CD_2Cl_2): δ 8.44 (d, *J* = 1.2 Hz, 2H), 7.76 (d, *J* = 8.5 Hz, 2H), 7.59 (dd, *J* = 8.5, 1.8 Hz, 2H), 6.90−6.87 (m, 2H), 6.77−6.68 (m, 6H), 6.36 (br s, 3H), 6.18−6.15 (m, 3H), 5.95 (br s, 4H), 4.59 (dd, *J* = 8.6, 2.9 Hz, 2H), 4.50 (t, *J* = 8.3 Hz, 2H), 4.40 (s, 1H), 3.69 (dd, *J* = 7.9, 3.0 Hz, 2H), 1.55 (s, 18H) ppm. ^{13}C NMR (126 MHz, CD_2Cl_2): δ 176.9 (d, $J_{C,Rh}$ = 2.9 Hz, 2C), 172.9 (d, $J_{C,Rh}$ = 29.2 Hz, 2C), 169.9 (2C), 151.9 (2C), 151.6 (2C), 145.3 (2C), 142.3 (2C), 133.0 (2C), 129.7 (4C), 127.3 (4C), 126.4 (2C), 125.7 (2C), 125.5 (2C), 123.3 (2C), 121.9 (2C), 121.7 (2C), 118.9 (2C), 74.9 (2C), 70.1 (2C), 53.7, 35.6 (2C), 32.0 (6C) ppm. IR (neat): $\tilde{\nu}$ 3043 (w), 2958 (w), 2924 (w), 2855 (w), 1737 (w), 1607 (w), 1578 (w), 1529 (m), 1471 (w), 1439 (w), 1412 (w), 1360 (w), 1344 (w), 1319 (w), 1286 (w), 1261 (w), 1239 (w), 1201 (w), 1146 (w), 1100 (w), 1063 (w), 1032 (w), 990 (w), 959 (w), 931 (w), 892 (w), 875 (w), 846 (w), 813 (w), 755 (w), 723 (m), 697 (w), 669 (w), 647 (w), 581 (w), 543 (w), 462 (w) cm^{-1}. HRMS (APCI): *m/z* calcd for $C_{53}H_{50}N_4O_2RhS_2$ $[M + H]^+$ 941.2425, found 941.2416. Mp: 273 °C dec (EtOAc). CD (CH_2Cl_2): γ, nm (Δε, M^{-1} cm^{-1}) 411 (−48), 369 (+110), 352 (+91), 339 (+54), 329 (+87), 304 (−41), 268 (+73), 250 (+110), 220 (−131), 207 (−24).

Δ-*(S,S)-**Rh2***. TLC (*n*-pentane/EtOAc 30/1 + 1% Et_3N): R_f = 0.23. ^{1}H NMR (500 MHz, CD_2Cl_2): δ 9.00 (d, *J* = 1.7 Hz, 2H), 7.91 (d, *J* = 8.6 Hz, 2H), 7.64 (dd, *J* = 8.6, 1.8 Hz, 2H), 7.27 (dd, *J* = 7.1, 0.4 Hz, 2H), 6.77 (m, 6H), 6.61 (m, 4H), 6.45 (m, 2H), 5.90 (dd, *J* = 7.5, 0.8 Hz, 2H), 5.47 (d, *J* = 7.8 Hz, 2H), 4.39 (s, 1H), 4.11−4.07 (m, 2H), 3.72 (dd, *J* = 10.7, 9.1 Hz, 2H), 3.52 (dd, *J* = 10.9, 8.3 Hz, 2H), 1.54 (s, 18 H) ppm. ^{13}C NMR (126 MHz, CD_2Cl_2): δ 176.8 (d, $J_{C,Rh}$ = 3.2 Hz, 2C), 173.5 (d, $J_{C,Rh}$ = 30.2 Hz, 2C), 171.6 (2C), 151.6 (2C), 151.1 (2C), 143.9 (2C), 139.5 (2C), 134.3 (2C), 128.9 (2C), 127.7 (4C), 127.2 (4C), 126.0 (2C), 124.6 (2C), 124.1 (2C), 121.9 (2C),

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121.5 (2C), 120.0 (2C), 74.7 (2C), 70.1 (2C), 57.3, 35.8 (2C), 31.7 (6C) ppm. IR (neat): $\tilde{\nu}$ 3055 (w), 2959 (w), 2885 (w), 1730 (w), 1602 (w), 1580 (w), 1538 (m), 1461 (w), 1438 (w), 1413 (w), 1356 (w), 1312 (w), 1291 (w), 1279 (w), 1252 (w), 1233 (w), 1203 (w), 1154 (w), 1123 (w), 1102 (w), 1059 (w), 1039 (m), 989 (w), 959 (w), 932 (w), 888 (w), 845 (w), 809 (w), 778 (w), 750 (w), 721 (w), 695 (w), 670 (w), 647 (w), 607 (w), 585 (w), 536 (w), 459 (w) cm^{-1}. HRMS (APCI): *m*/*z* calcd for $C_{53}H_{50}N_4O_2RhS_2$ $[M + H]^+$ 941.2425, found 941.2439. Mp: 167 °C (EtOAc). CD (CH_2Cl_2): γ, nm ($\Delta\varepsilon$, M^{-1} cm^{-1}) 417 (+43), 377 (−47), 361 (−46), 332 (+80), 312 (−99), 283 (+21), 270 (+33), 248 (−33), 228 (+27), 221 (−9), 217 (+115), 207 (+30).

Synthesis of Λ- *and* Δ-*(S,S)-**Rh3***. Following general procedure II, *rac*-**RhNS** (36.9 mg, 39.3 μmol, 1.00 equiv), K_2CO_3 (16.3 mg, 0.12 mmol, 3.00 equiv), and BOX ligand (*S*,*S*)-**2** (13.3 mg, 0.04 mmol, 1.10 equiv) were suspended in EtOH (1.60 mL, absolute) and stirred for 2.5 h at room temperature. Purification by column chromatography (*n*-pentane/EtOAc, gradient 20/1 → 15/1 → 10/1 → 7/1, plus 1% Et_3N) afforded Λ-(*S*,*S*)-**Rh3** (17.7 mg, 17.4 μmol, 44%) and Δ-(*S*,*S*)-**Rh3** (18.0 mg, 17.7 μmol, 45%) as yellow solids.

Λ-*(S,S)-**Rh3***. TLC (*n*-pentane/EtOAc 5/1 + 1% Et_3N): R_f = 0.40. ^1H NMR (500 MHz, CD_2Cl_2): δ 8.46 (d, *J* = 1.6 Hz, 1H), 7.97 (d, *J* = 1.6 Hz, 1H), 7.76 (d, *J* = 8.6 Hz, 1H), 7.54 (dd, *J* = 8.5, 1.8 Hz, 1H), 7.51 (dd, *J* = 8.7, 1.8 Hz, 1H), 7.23 (d, *J* = 8.7 Hz, 1H), 6.97 (dd, *J* = 7.1, 0.6 Hz, 1H), 6.93 (dd, *J* = 7.4, 1.3 Hz, 1H), 6.80−6.77 (m, 1H), 6.74−6.67 (m, 6H), 6.33 (br s, 2H), 6.26 (d, *J* = 7.4 Hz, 1H), 6.16 (d, *J* = 7.5 Hz, 1H), 5.96 (br s, 4H), 5.75 (br s, 1H), 4.63 (dd, *J* = 8.7, 3.2 Hz, 1H), 4.55−4.48 (m, 3H), 4.33 (s, 1H), 3.70 (dd, *J* = 8.1, 3.2 Hz, 1H), 3.63 (s, 3H), 3.61 (dd, *J* = 7.4, 2.3 Hz, 1H), 2.19−2.13 (m, 9H), 1.90−1.84 (m, 6H), 1.52 (s, 9H) ppm. ^{13}C NMR (126 MHz, CD_2Cl_2): δ 176.3 (d, $J_{C,Rh}$ = 3.5 Hz, 1C), 174.3 (d, $J_{C,Rh}$ = 30 Hz, 1C), 173.8 (d, $J_{C,Rh}$ = 29 Hz, 1C), 170.0, 169.8, 158.9 (d, $J_{C,Rh}$ = 3.1 Hz, 1C), 152.3, 151.7, 147.3, 146.2, 145.4, 142.3, 141.0, 136.6, 134.2, 133.6, 133.1, 129.9, 129.4, 128.5, 127.2 (2C), 126.8 (2C), 126.5 (2C), 126.1, 125.6 (2C), 125.3, 125.1, 123.9, 122.5, 121.6, 121.5, 121.3, 120.9, 118.8, 114.4, 108.7, 74.8, 74.7, 70.2, 70.1, 53.0, 43.8 (3C), 37.1 (3C), 37.1, 35.4, 32.2 (3C), 31.9, 29.6 (3C) ppm. IR (neat): $\tilde{\nu}$ 2900 (m), 2848 (w), 1612 (w), 1580 (w), 1531 (w), 1476 (w), 1451 (w), 1414 (w), 1347 (w), 1322 (w), 1288 (w), 1260 (w), 1207 (w), 1111 (w), 1064 (w), 1034 (w), 992 (w), 962 (w), 933 (w), 867 (w), 797 (w), 758 (w), 724 (w), 696 (w), 668 (w), 637 (w), 615 (w), 542 (w), 460 (w) cm^{-1}. HRMS (APCI): *m*/*z* calcd for $C_{60}H_{59}N_5O_2RhS$ $[M + H]^+$ 1016.3439, found 1016.3464. Mp: 141 °C dec (EtOAc). CD (CH_3OH): γ, nm ($\Delta\varepsilon$, M^{-1} cm^{-1}) 388 (−13), 353 (+60), 299 (−42), 269 (+29), 260 (+25), 245 (+57), 216 (−69), 202 (−18).

Δ-*(S,S)-**Rh3***. TLC (*n*-pentane/EtOAc 5/1 + 1% Et_3N): R_f = 0.27. ^1H NMR (500 MHz, CD_2Cl_2): δ 9.05 (d, *J* = 1.5 Hz, 1H), 8.54 (d, *J* = 1.4 Hz, 1H), 7.92 (d, *J* = 8.6 Hz, 1H), 7.59 (dd, *J* = 8.6, 1.7 Hz, 1H), 7.56 (dd, *J* = 8.7, 1.7 Hz, 1H), 7.47 (d, *J* = 8.7 Hz, 1H), 7.42 (d, *J* = 7.7 Hz, 1H), 7.31 (d, *J* = 7.6 Hz, 1H), 6.76−6.72 (m, 4H), 6.69 (d, *J* = 7.3 Hz, 2H), 6.62−6.57 (m, 4H), 6.47−6.42 (m, 2H), 5.90−5.83 (m, 2H), 5.57 (d, *J* = 7.8 Hz, 1H), 5.41 (d, *J* = 7.8 Hz, 1H), 4.37 (s, 1H), 4.17 (s, 3H), 4.07−4.03 (m, 2H), 3.71 (m, 2H), 3.57 (dd, *J* = 9.9, 8.3 Hz, 1H), 3.43 (dd, *J* = 11.3, 8.3 Hz, 1H), 2.22−2.16 (m, 6H), 2.12 (m, 3H), 1.82 (m, 6H), 1.53 (s, 9H) ppm. ^{13}C NMR (126 MHz, CD_2Cl_2): δ 176.2 (d, $J_{C,Rh}$ = 3.1 Hz, 1C), 175.1 (d, $J_{C,Rh}$ = 31.0 Hz, 1C), 173.8 (d, $J_{C,Rh}$ = 30.3 Hz, 1C), 171.7, 171.2, 160.0 (d, $J_{C,Rh}$ = 3.7 Hz, 1C), 152.0, 151.1, 146.6, 144.4, 143.8, 140.9, 139.8, 135.2, 134.3, 134.1, 133.8, 129.1, 128.5, 127.6 (4C), 127.5, 127.3 (2C), 127.3 (2C), 125.9, 125.8, 124.6, 123.1, 122.9, 121.8, 121.3, 121.0, 120.8, 120.4, 116.1, 108.9, 74.9, 74.5, 70.1, 69.9, 56.5, 43.6 (3C), 37.4, 37.2 (3C), 35.5, 32.4, 32.0 (3C), 29.6 (3C) ppm. IR (neat): $\tilde{\nu}$ 2899 (m), 2847 (w), 1603 (w), 1581 (w), 1534 (w), 1504 (w), 1475 (w), 1458 (w), 1437 (w), 1415 (w), 1353 (w), 1310 (w), 1289 (w), 1256 (w), 1232 (w), 1209 (w), 1149 (w), 1103 (w), 1062 (w), 1034 (w), 989 (w), 960 (w), 865 (w), 799 (w), 751 (w), 723 (w), 695 (w), 668 (w), 650 (w), 609 (w), 536 (w), 459 (w) cm^{-1}. HRMS (APCI): *m*/*z* calcd for $C_{60}H_{59}N_5O_2RhS$ $[M + H]^+$ 1016.3439, found 1016.3468. Mp: 181 °C dec (EtOAc). CD (CH_3OH): γ, nm ($\Delta\varepsilon$, M^{-1} cm^{-1}) 393 (+19), 357 (−54), 323 (+20), 310 (+5), 295 (+27), 245 (−46), 215 (+35), 207 (−6), 203 (+7).

General Procedure III: Acid-Induced Removal of Coordinated Auxiliary Ligand. To a solution of Λ- or Δ-(*S*,*S*)-**2**/**3** (1.00 equiv) in MeCN (0.04 M) was added methanesulfonic acid (10.0 equiv) in one portion at 0 °C. After 15 min, the ice bath was removed and the solution was stirred for a further 6 h at room temperature. Alternatively, the reaction mixture may be stirred for 16 h without affecting the ee value of the final catalyst. The solvent was removed under reduced pressure (250−50 mbar for a maximum of 10 min), NH_4PF_6 (15.0 equiv) was added to the residual yellow oil, and MeCN (0.02 M) was added. The resulting suspension was stirred for 30 min at room temperature before the solvent was removed under reduced pressure. Purification by column chromatography (CH_2Cl_2/MeCN 20/1) provided the enantiomerically pure rhodium(III) complexes.

Synthesis of Λ-***RhS***. Following general procedure III with Λ-(*S*,*S*)-**Rh2** (20.0 mg, 21.3 μmol, 1.00 equiv), Λ-**RhS** (18.0 mg, 20.9 μmol, 98%) was obtained as a pale yellow solid after column chromatographic purification. The enantiomeric excess was established by HPLC analysis using a Daicel Chiralpak IB-N5 column, ee >99.9% (HPLC: 254 nm, H_2O + 0.1% TFA/MeCN 40−50% MeCN in 180 min, 50% MeCN maintained for a further 60 min, flow rate 0.6 mL/min, 25 °C, t_R(Δ-**RhS**) = 210.0 min, t_R(Λ-**RhS**) = 217.8 min). Analytical data were in agreement with the literature.[9] ^1H NMR (300 MHz, CD_2Cl_2): δ 8.50 (br s, 2H), 8.02 (d, *J* = 8.6 Hz, 2H), 7.72 (dd, *J* = 8.6, 1.7 Hz, 2H), 7.67 (dd, *J* = 7.6, 1.2 Hz, 2H), 7.03 (dt, *J* = 7.5, 0.8 Hz, 2H), 6.83 (dt, *J* = 7.6, 1.4 Hz, 2H), 6.21 (d, *J* = 7.8 Hz, 2H), 2.18 (br s, 6H), 1.46 (s, 18H) ppm.

Synthesis of Δ-***RhS***. Following general procedure III with Δ-(*S*,*S*)-**Rh2** (22.0 mg, 23.4 μmol, 1.00 equiv), Δ-**RhS** (19.9 mg, 23.1 μmol, 99%) was obtained as a pale yellow solid after purification by column chromatography. The enantiomeric excess was established by HPLC analysis using a Daicel Chiralpak IB-N5 column, ee >99% (HPLC: 254 nm, H_2O + 0.1% TFA/MeCN 40−50% MeCN in 180 min, 50% MeCN maintained for a further 60 min, flow rate 0.6 mL/min, 25 °C, t_R(Δ-**RhS**) = 210.0 min, t_R(Λ-**RhS**) = 217.8 min). Analytical data were in agreement with the literature.[9] ^1H NMR (300 MHz, CD_2Cl_2): δ 8.48 (d, *J* = 1.5 Hz, 2H), 8.03 (d, *J* = 8.6 Hz, 2H), 7.72 (dd, *J* = 8.6, 1.8 Hz, 2H), 7.67 (dd, *J* = 7.6, 1.2 Hz, 2H), 7.03 (dt, *J* = 7.5, 0.9 Hz, 2H), 6.83 (dt, *J* = 7.6, 1.3 Hz, 2H), 6.20 (d, *J* = 7.8 Hz, 2H), 2.17 (br s, 6H), 1.46 (s, 18H) ppm.

Synthesis of Λ-***RhNS***. Following general procedure III with Λ-(*S*,*S*)-**Rh3** (20.0 mg, 19.7 μmol, 1.00 equiv), Λ-**RhNS** (17.5 mg, 18.7 μmol, 95%) was obtained as a pale yellow solid after column chromatographic purification. Since the enantiomeric excess could not be established by chiral HPLC, Λ-**RhNS** was reconverted into Λ-(*S*,*S*)-**Rh3** and a dr value of >20:1 was determined by ^1H NMR of the crude material (see the Supporting Information for details). CD (CH_3OH): λ, nm ($\Delta\varepsilon$, M^{-1} cm^{-1}) 389 (−29), 355 (+88), 298 (−95), 244 (+65), 228 (+14), 220 (+26), 214 (−17), 206 (+66). All other analytical data were in agreement with *rac*-**RhNS** (see the Supporting Information).

Synthesis of Δ-***RhNS***. Following general procedure III with Δ-(*S*,*S*)-**Rh3** (30.0 mg, 29.5 μmol, 1.00 equiv), Δ-**RhNS** (26.2 mg, 27.9 mmol, 95%) was obtained as a pale yellow solid after purification by column chromatography. Since the enantiomeric excess could not be established by chiral HPLC, Δ-**RhNS** was reconverted into Δ-(*S*,*S*)-**Rh3** and a dr value of >20:1 was determined by ^1H NMR of the crude material (see the Supporting Information). CD (CH_3OH): λ, nm ($\Delta\varepsilon$, M^{-1} cm^{-1}) 389 (+30), 355 (−91), 298 (+101), 244 (−65), 228 (−18), 220 (−29), 214 (+10), 206 (−67). All other analytical data were in agreement with *rac*-**RhNS** (see the Supporting Information).

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.organomet.9b00533.

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Organometallics XXXX, XXX, XXX−XXX

Synthesis of ligands and metal complexes, experimental details, CD spectra, NMR spectra, HPLC traces, and crystallographic data (PDF)

Accession Codes

CCDC 1939489−1939490 contain the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/data_request/cif, or by emailing data_request@ccdc.cam.ac.uk, or by contacting The Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; fax: +44 1223 336033.

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Notes

The authors declare no competing financial interest.

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REFERENCES

(1) Walsh, P. J.; Kozlowski, M. C. *Fundamentals of Asymmetric Catalysis*; University Science Books: Sausalito, CA, 2009.

(2) (a) Cao, Z.-Y.; Brittain, W. D. G.; Fossey, J. S.; Zhou, F. Recent advances in the use of chiral metal complexes with achiral ligands for application in asymmetric catalysis. *Catal. Sci. Technol.* **2015**, *5*, 3441−3451. (b) Zhang, L.; Meggers, E. Stereogenic-only-at-metal asymmetric catalysts. *Chem. - Asian J.* **2017**, *12*, 2335−2342.

(3) For recent elegant examples of using reactive chiral-at-metal complexes as chiral auxiliaries, see: (a) Li, Z.-Z.; Yao, S.-Y.; Wu, J.-J.; Ye, B.-H. *In situ* generation of sulfoxides with predetermined chirality via a structural template with a chiral-at-metal ruthenium complex. *Chem. Commun.* **2014**, *50*, 5644−5647. (b) Li, Z.-Z.; Wen, A.-H.; Yao, S.-Y.; Ye, B.-H. Enantioselective Syntheses of Sulfoxides in Octahedral Ruthenium(II) Complexes via a Chiral-at-Metal Strategy. *Inorg. Chem.* **2015**, *54*, 2726−2733. (c) Yao, S.-Y.; Chen, X.-Y.; Ou, Y.-L.; Ye, B.-H. Chiral Recognition and Dynamic Thermodynamic Resolution of Sulfoxides by Chiral Iridium(III) Complexes. *Inorg. Chem.* **2017**, *56*, 878−885. (d) Li, L.-P.; Peng, H.-L.; Wei, L.-Q.; Ye, B.-H. Diastereoselective Photooxidation and Reduction of Chiral Iridium(III) Complexes. *Inorg. Chem.* **2019**, *58*, 785−793. (e) Li, L.-P.; Ye, B.-H. Efficient Generation of Singlet Oxygen and Photooxidation of Sulfide into Sulfoxide via Tuning the Ancillary of Bicyclometalated Iridium(III) Complexes. *Inorg. Chem.* **2019**, *58*, 7775−7784.

(4) (a) Brunner, H. Optically active organometallic compounds of transition elements with chiral metal atoms. *Angew. Chem., Int. Ed.* **1999**, *38*, 1194−1208. (b) Knof, U.; von Zelewsky, A. Predetermined chirality at metal centers. *Angew. Chem., Int. Ed.* **1999**, *38*, 302−322. (c) Amouri, H.; Gruselle, M. *Chirality in Transition Metal Chemistry*; Wiley: Chichester, U.K., 2008. (d) Meggers, E. Asymmetric synthesis of octahedral coordination complexes. *Eur. J. Inorg. Chem.* **2011**, *2011*, 2911−2926. (e) Constable, E. C. Stereogenic metal centres − from Werner to supramolecular chemistry. *Chem. Soc. Rev.* **2013**, *42*, 1637−1651. (f) Chen, L.-J.; Yang, H.-B.; Shionoya, M. Chiral metallosupramolecular architectures. *Chem. Soc. Rev.* **2017**, *46*, 2555−2576.

(5) Meggers, E. Chiral Auxiliaries as Emerging Tools for the Asymmetric Synthesis of Octahedral Metal Complexes. *Chem. - Eur. J.* **2010**, *16*, 752−758.

(6) Gong, L.; Wenzel, M.; Meggers, E. Chiral-auxiliary-mediated asymmetric synthesis of ruthenium polypyridyl complexes. *Acc. Chem. Res.* **2013**, *46*, 2635−2644.

(7) Zhang, L.; Meggers, E. Steering asymmetric Lewis acid catalysis exclusively with octahedral metal-centered chirality. *Acc. Chem. Res.* **2017**, *50*, 320−330.

(8) (a) Chepelin, O.; Ujma, J.; Wu, X.; Slawin, A. M. Z.; Pitak, M. B.; Coles, S. J.; Michel, J.; Jones, A. C.; Barran, P. E.; Lusby, P. J. Luminescent, enantiopure, phenylatopyridine iridium-based coordination capsules. *J. Am. Chem. Soc.* **2012**, *134*, 19334−19337. (b) Marchi, E.; Sinisi, R.; Bergamini, G.; Tragni, M.; Monari, M.; Bandini, M.; Ceroni, P. Easy separation of Δ and Λ isomers of highly luminescent [Ir^{III}]-cyclometalated complexes based on chiral phenol-oxazoline ancillary ligands. *Chem. - Eur. J.* **2012**, *18*, 8765−8773. (c) Davies, D. L.; Singh, K.; Singh, S.; Villa-Marcos, B. Preparation of single enantiomers of chiral at metal bis-cyclometallated iridium complexes. *Chem. Commun.* **2013**, *49*, 6546−6548. (d) Yao, S.-Y.; Ou, Y.-L.; Ye, B.-H. Asymmetric Synthesis of Enantiomerically Pure Mono- and Binuclear Bis(cyclometalated) Iridium(III) Complexes. *Inorg. Chem.* **2016**, *55*, 6018−6026. (e) Li, L.-P.; Yao, S.-Y.; Ou, Y.-L.; Wei, L.-Q.; Ye, B.-H. Diastereoselective Synthesis and Photophysical Properties of Bis-Cyclometalated Ir(III) Stereoisomers with Dual Stereocenters. *Organometallics* **2017**, *36*, 3257−3265.

(9) Ma, J.; Shen, X.; Harms, K.; Meggers, E. Expanding the family of bis-cyclometalated chiral-at-metal rhodium(III) catalysts with a benzothiazole derivative. *Dalton Trans* **2016**, *45*, 8320−8323.

(10) Ma, J.; Zhang, X.; Huang, X.; Luo, S.; Meggers, E. Preparation of chiral-at-metal catalysts and their use in asymmetric photoredox chemistry. *Nat. Protoc.* **2018**, *13*, 605−632.

(11) Grell, Y.; Hong, Y.; Huang, X.; Mochizuki, T.; Xie, X.; Harms, K.; Meggers, E. Chiral-at-Rhodium Catalyst Containing Two Different Cyclometalating Ligands. *Organometallics* **2019**, DOI: 10.1021/acs.organomet.9b00105.

(12) Yoon, T. P.; Jacobsen, E. N. Privileged chiral catalysts. *Science* **2003**, *299*, 1691−1693.

(13) (a) Ghosh, A. K.; Mathivanan, P.; Cappiello, J. C_2-Symmetric chiral bis(oxazoline)−metal complexes in catalytic asymmetric synthesis. *Tetrahedron: Asymmetry* **1998**, *9*, 1−45. (b) Johnson, J. S.; Evans, D. A. Chiral Bis(oxazoline) Copper(II) Complexes: Versatile Catalysts for Enantioselective Cycloaddition, Aldol, Michael, and Carbonyl Ene Reactions. *Acc. Chem. Res.* **2000**, *33*, 325−335. (c) Desimoni, G.; Faita, G.; Jørgensen, K. A. C_2-Symmetric Chiral Bis(Oxazoline) Ligands in Asymmetric Catalysis. *Chem. Rev.* **2006**, *106*, 3561−3651. (d) Dagorne, S.; Bellemin-Laponnaz, S.; Maisse-François, A. Metal Complexes Incorporating Monoanionic Bisoxazolinate Ligands: Synthesis, Structures, Reactivity and Applications in Asymmetric Catalysis. *Eur. J. Inorg. Chem.* **2007**, *2007*, 913−925. (e) Rasappan, R.; Laventine, D.; Reiser, O. Metal-bis(oxazoline) complexes: From coordination chemistry to asymmetric catalysis. *Coord. Chem. Rev.* **2008**, *252*, 702−714. (f) Hargaden, G. C.; Guiry, P. J. Recent Applications of Oxazoline-Containing Ligands in Asymmetric Catalysis. *Chem. Rev.* **2009**, *109*, 2505−2550. (g) Desimoni, G.; Faita, G.; Jørgensen, K. A. Update 1 of: C_2-Symmetric Chiral Bis(Oxazoline) Ligands in Asymmetric Catalysis. *Chem. Rev.* **2011**, *111*, PR284−PR437. (h) Wang, L.; Zhou, J.; Tang, Y. Sidearm Modified Bisoxazoline Ligands and Their Applications. *Chin. J. Chem.* **2018**, *36*, 1123−1129.

(14) Huang, X.; Meggers, E. Asymmetric Photocatalysis with Bis-cyclometalated Rhodium Complexes. *Acc. Chem. Res.* **2019**, *52*, 833−847.

(15) For the most relevant resonance structures of the monodeprotonated, Rh-coordinated BOX ligand, see (only the Λ isomer is shown):

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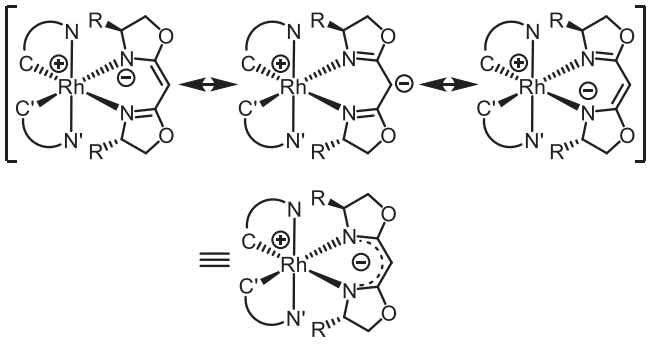

(16) (a) Deng, T.; Thota, G. K.; Li, Y.; Kang, Q. Enantioselective conjugate addition of hydroxylamines to α,β-unsaturated 2-acyl imidazoles catalyzed by a chiral-at-metal Rh(III) complex. *Org. Chem. Front.* **2017**, *4*, 573−577. (b) Li, K.; Wan, Q.; Kang, Q. Chiral-at-Metal Rh(III) Complex Catalyzed Asymmetric Conjugate Addition of Unactivated Alkenes with α,β-Unsaturated 2-Acyl Imidazoles. *Org. Lett.* **2017**, *19*, 3299−3302. (c) Li, S. W.; Gong, J.; Kang, Q. Chiral-at-Metal Rh(III) Complex-Catalyzed Decarboxylative Michael Addition of β-Keto Acids with α,β-Unsaturated 2-Acyl Imidazoles or Pyridine. *Org. Lett.* **2017**, *19*, 1350−1353. (d) Lin, S. X.; Sun, G. J.; Kang, Q. A visible-light-activated rhodium complex in enantioselective conjugate addition of α-amino radicals with Michael acceptors. *Chem. Commun.* **2017**, *53*, 7665−7668. (e) Sun, G.-J.; Gong, J.; Kang, Q. Chiral Rhodium(III) Complex-Catalyzed Cascade Michael-Alkylation Reactions: Enantioselective Synthesis of Cyclopropanes. *J. Org. Chem.* **2017**, *82*, 796−803. (f) Gong, J.; Wan, Q.; Kang, Q. Gold(I)/Chiral Rh(III) Lewis Acid Relay Catalysis Enables Asymmetric Synthesis of Spiroketals and Spiroaminals. *Adv. Synth. Catal.* **2018**, *360*, 4031−4036. (g) Li, S.-W.; Kang, Q. Catalytic asymmetric synthesis of diphenylbutazone analogues. *Chem. Commun.* **2018**, *54*, 10479−10482. (h) Li, S.-W.; Wan, Q.; Kang, Q. Chiral-at-Metal Rh(III) Complex-Catalyzed Michael Addition of Pyrazolones with α,β-Unsaturated 2-Acyl Imidazoles. *Org. Lett.* **2018**, *20*, 1312−1315. (i) Qurban, S.; Du, Y.; Gong, J.; Lin, S.-X.; Kang, Q. Enantioselective synthesis of tetrahydroisoquinoline derivatives *via* chiral-at-metal rhodium complex catalyzed [3 + 2] cycloaddition. *Chem. Commun.* **2019**, *55*, 249−252.

(17) (a) Wang, C.; Chen, L.-A.; Huo, H.; Shen, X.; Harms, K.; Gong, L.; Meggers, E. Asymmetric Lewis acid catalysis directed by octahedral rhodium centrochirality. *Chem. Sci.* **2015**, *6*, 1094−1100. (b) Huang, Y.; Song, L.; Gong, L.; Meggers, E. Asymmetric Synthesis of Hydrocarbazoles Catalyzed by an Octahedral Chiral-at-Rhodium Lewis Acid. *Chem. - Asian J.* **2015**, *10*, 2738−2743. (c) Tan, Y. Q.; Yuan, W.; Gong, L.; Meggers, E. Aerobic Asymmetric Dehydrogenative Cross-Coupling between Two C_{sp3}−H Groups Catalyzed by a Chiral-at-Metal Rhodium Complex. *Angew. Chem., Int. Ed.* **2015**, *54*, 13045−13048. (d) Song, L.; Gong, L.; Meggers, E. Asymmetric dual catalysis via fragmentation of a single rhodium precursor complex. *Chem. Commun.* **2016**, *52*, 7699−7702. (e) Lin, H.; Zhou, Z.; Cai, J.; Han, B.; Gong, L.; Meggers, E. Asymmetric Construction of 3,3-Disubstituted Oxindoles Bearing Vicinal Quaternary−Tertiary Carbon Stereocenters Catalyzed by a Chiral-at-Rhodium Complex. *J. Org. Chem.* **2017**, *82*, 6457−6467. (f) Luo, S.; Zhang, X.; Zheng, Y.; Harms, K.; Zhang, L.; Meggers, E. Enantioselective Alkynylation of Aromatic Aldehydes Catalyzed by a Sterically Highly Demanding Chiral-at-Rhodium Lewis Acid. *J. Org. Chem.* **2017**, *82*, 8995−9005. (g) Mietke, T.; Cruchter, T.; Larionov, V. A.; Faber, T.; Harms, K.; Meggers, E. Asymmetric Nazarov Cyclizations Catalyzed by Chiral-at-Metal Complexes. *Adv. Synth. Catal.* **2018**, *360*, 2093−2100. (h) Huang, X.; Zhang, Q.; Lin, J.; Harms, K.; Meggers, E. Electricity-driven asymmetric Lewis acid catalysis. *Nat. Catal.* **2019**, *2*, 34−40.

(18) Hari, D. P.; Waser, J. Enantioselective Copper-Catalyzed Oxy-Alkynylation of Diazo Compounds. *J. Am. Chem. Soc.* **2017**, *139*, 8420−8423.

(19) Marinova, M.; Torres-Werlé, M.; Taupier, G.; Maisse-François, A.; Achard, T.; Boeglin, A.; Honorat Dorkenoo, K. D.; Bellemin-Laponnaz, S. Chiral Self-Sorting Process with Ditopic Ligands: Alternate or Block Metallopolymer Assembly as a Function of the Metal Ion. *ACS Omega* **2019**, *4*, 2676−2683.

(20) Keeri, A. R.; Justyniak, I.; Jurczak, J.; Lewiński, J. Quest for Efficient Catalysts based on Zinc *tert*-Butyl Peroxides for Asymmetric Epoxidation of Enones: C_2- *vs* C_1-Symmetric Auxiliaries. *Adv. Synth. Catal.* **2016**, *358*, 864−868.

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