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Substituted salen–Ru(II) complexes as catalysts in the asymmetric cyclopropanation of styrene by ethyl diazoacetate: the influence of substituents and achiral additives on activity and enantioselectivity

Xiaoquan Yao, Min Qiu, Weiran Lü, Huilin Chen and Zhuo Zheng*

Dalian Institute of Chemical Physics, Chinese Academy of Sciences, Dalian 116023, PR China

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Abstract—A series of alkyl-, halogen- and nitro-substituted salen ligands, **1**, have been employed in the asymmetric cyclopropanation of styrene with ethyl diazoacetate by its ruthenium(II) complex with $[RuCl_2(p\text{-cymene})]_2$ or $RuCl_2(PPh_3)_3$ as precursors. The introduction of appropriate electron withdrawing groups in the salen ligands benefited the enantioselectivity of the reaction. Some additives, including *O*-donor, *N*-donor and *P*-donor ligands, were added to the reaction to improve the enantioselectivity and activity, and e.e.s of up to 80% were achieved. In the salen/$[RuCl_2(p\text{-cymene})]_2$ system, the (1*R*,2*S*)-isomer was obtained in 80.2% e.e. by using the salen ligand **1f** derived from 3,5-dibrominated salicylaldehyde with Et_3N as additive. E.e.s of up to 81.3% for (1*S*,2*R*)-isomers were achieved by using the complex **2** synthesized from the nitro-substituted ligand **1m** and $RuCl_2(PPh_3)_3$. A possible mechanism was also discussed.

1. Introduction

Catalytic asymmetric cyclopropanation of olefins with diazoacetate esters has been one of the most important methodologies for the formation of chiral cyclopropane compounds.[1] Catalysts containing various metals and optically active ligands, such as Cu–Schiff bases,[2] Co–dioximate,[3] and complexes with C_2 symmetry including Cu–semicorrin,[4] Cu–bisoxazoline,[5] Cu–bipyridine,[6] Rh_2(5*S*-MEPY),[7] etc., have been employed successfully. Although copper–Schiff base complexes have a long history of use in the reaction, the optically active salen ligands derived from (*R*,*R*)-*trans*-1,2-diaminocyclohexane and salicylaldehydes were exceptional in several asymmetric processes including epoxidation,[8] epoxide opening,[9] kinetic resolution,[10] Diels–Alder cycloaddition[11] and the trimethylsilylcyanation of aldehydes,[12] and proved to be uniformly ineffective for asymmetric alkene aziridination and cyclopropanation when using their copper(II) complexes.[13] Recently, however, the salen–Co(III) complexes, using 1,2-diphenylethylenediamine as the chiral source, were reported by Fukuda and Katsuki, and a salen-like Co(II) complex, MPAC, by Yamada et al., to be efficient catalysts in the asymmetric cyclopropanation of styrene by *tert*-butyl diazoacetate.[14,15]

Among all the catalysts reported, the Ru(II) complexes have attracted more and more attention in recent years. Ru–Pybox[16] and Ru–porphyrin[17] have been successfully employed in the asymmetric cyclopropanation of styrene and diazoacetate. Very recently, Katsuki et al. also reported a chiral (NO)–salen–Ru complex derived from (*R*,*R*)-1,2-diaminocyclohexane and (α*R*)-3-formyl-2-hydroxy-2′-phenyl-1,1′-binaphthyl, which effectively catalyzed the asymmetric cyclopropanation of styrene by *tert*-butyl diazoacetate with high *cis*- and enantioselectivity.[18] It is also noteworthy that solubility dependent enantiofacial selection was observed by using THF and hexane as solvents, respectively.[18b] The same ligands have also been employed in the Co(II)-catalyzed asymmetric cyclopropanation.[18d]

In our previous studies, some modified Aratani's catalysts derived from halogen- or nitro-substituted salicylaldehydes were reported.[19] The introduction of electron-withdrawing groups to the ligands clearly improved the enantioselectivity for the asymmetric cyclopropanation of styrene with ethyl diazoacetate. Herein, we report a series of alkyl-, halogen- and nitro-substituted salen ligands **1**, derived from the corresponding substituted salicylaldehydes and (*R*,*R*)-1,2-

* Corresponding author. Tel.: +86+411-4671991-712; fax: +86+411-4684746; e-mail: zhengz@ms.dicp.ac.cn

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diaminocyclohexane, and their utility in the asymmetric cyclopropanation of styrene with ethyl diazoacetate by their ruthenium(II) complexes formed in situ (Scheme 1). Two ruthenium(II) precursors, $[RuCl_2(p\text{-cymene})]_2$ and $RuCl_2(PPh_3)_3$, were used. At present with some of the additives, e.e.s of around 80% were achieved.

2. Results and discussion

Initially, the classic salen ligand **1a** was tested. The salen–Ru(II) complexes were prepared by mixing $[RuCl_2(p\text{-cymene})]_2$ with a small excess of ligand and 2 equivalents of Et_3N in *iso*-propanol. Poor yields and enantioselectivities were observed (entry 1 in Table 1). Other less hindered alkyl-substituted ligands, **1b**–**1d**, were subsequently tested. Some asymmetric induction was observed (entries 2–4 in Table 1). In contrast to the asymmetric epoxidation of simple olefins, in which the bulky alkyl substituents at C(3) and C(3′) have a positive effect on the enantiocontrol of the reaction,[20] these results suggested that bulky alkyl substituents at C(3) and C(3′) were detrimental to the enantioselectivity and yield of the reaction.

In our previous studies,[19] the introduction of electron withdrawing groups to the modified Aratani's catalysts improved the enantioselectivity of the asymmetric cyclopropanation. In the Ru(II)–Pybox-catalyzed system, the electron withdrawing groups also proved to enhance catalytic activity and enantioselectivity.[21] The series of halo- and nitro-substituted salen ligands **1e**–**1m** were evaluated in the reaction.

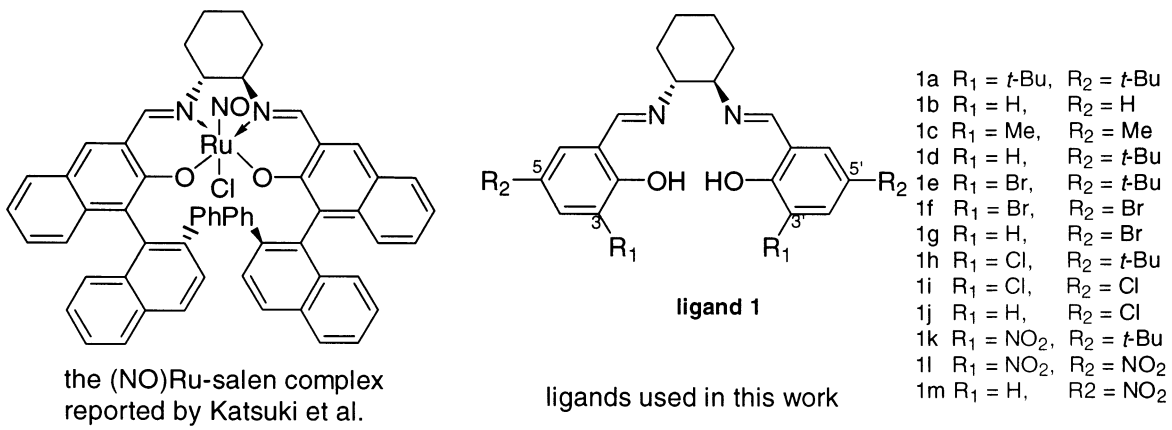
As can be seen from the data in Table 1, the introduction of halogen atoms at C(3) and C(3′) benefited the enantioselectivity and catalytic activity. The ligand **1e**, bearing a bromine atom at C(3) and C(3′) and *tert*-butyl at C(5) and C(5′), was employed at room temperature, and increased enantioselectivity from an e.e. of 33.3 to 74.2% for the *trans* isomers compared with the ligand **1d** (entry 5 versus entry 4). Correspondingly, the chloro-substituted ligand **1h** gave an e.e. of 61.4%. When the bulky alkyl substituents at C(5) and C(5′) in ligand **1e** or **1h** were substituted by a halogen atom, the catalytic activity improved, but lower enantioselectivity was observed (entries 6 and 9).

Considering the octahedral coordination structure of the saturated Ru(II)–salen complexes, we suspected that there might be two *iso*-propanol molecules in the catalyst prepared in situ from **1** and $[RuCl_2(p\text{-cymene})]_2$ in *iso*-propanol. In fact, a similar example has been reported for the salen–Co(III) complex catalyst system by Katsuki, in which the authors noted that the presence of methanol improved the observed enantioselectivity.[14a] Therefore, other alcohols and some non-protic solvents were tried by using the ligand **1e** as a prototype. The results of these reactions are summarized in Table 2.

It can be seen from Table 2 that both enantioselectivity and catalytic activity were markedly influenced by the addition of alcohols (entry 1 versus entries 3–5 in Table 2). The bulky alkyl alcohols were beneficial to the enantioselectivity, but yields decreased slightly (entries 3–5). When L-menthol was used as an additive, moderate e.e.s and yield were obtained. It is also noteworthy that the configuration of the *cis* isomers and the ratio of *cis*/*trans* became inverted when THF was used as the solvent.

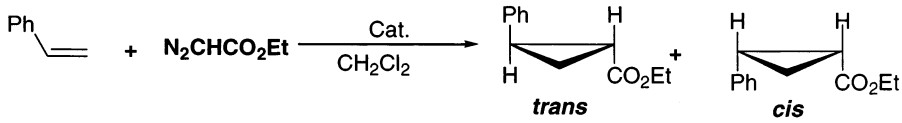
It is well known that some *N*-donor additives can improve the enantioselectivity in the asymmetric cyclopropanation catalyzed by the salen (or salen-like) metal complexes.[15,18] Herein, we also tried to introduce some *N*-donor additives into the reaction as axial ligands by using excess base in the catalyst preparation; Et_3N was used initially, as shown in Table 3.

In the salen/$[RuCl_2(p\text{-cymene})]_2$/$Et_3N$ system, the bulky alkyl group at C(3) and C(3′) proved to be unfavorable to enantioselectivity and activity, and only a substituent with the appropriate size and electron withdrawing effect at C(3) and C(3′) favored the enantiocontrol of the cyclopropanation. In contrast to the trend observed in Table 1, the best result, with respect to both e.e. and yield, was achieved when ligand **1f**, derived from 3,5-



Scheme 1.

Table 1. The asymmetric cyclopropanation of styrene with ethyl diazoacetate using $[RuCl_2(p\text{-cymene})]_2$ as catalyst precursor[a]



Entry	Ligand	Yield (%)[b]	*cis*/*trans*[c]	% e.e. (*cis*)[c,d]	% e.e. (*trans*)[c,e]
1	**1a**	15	34:66	0	12.9
2	**1b**	51	32:68	54.5	38.2
3	**1c**	43	24:76	52.3	44.0
4	**1d**	41	34:66	49.0	33.3
5	**1e**	58	14:86	60.6	74.2
6	**1f**	78	24:76	36.2	35.6
7	**1g**	57	26:74	58.5	57.8
8	**1h**	57	22:78	45.8	61.4
9	**1i**	74	24:76	40.9	41.9
10	**1j**	55	34:66	58.4	45.0
11	**1k**	40	20:80	19.2	38.8
12	**1l**	82	26:74	43.6	42.8
13	**1m**	52	29:71	24.5	30.3

[a] Reaction conditions: 1 mmol of ethyl diazoacetate, 10 mmol of styrene, 2% catalyst prepared in situ (based on the diazoacetate), 3.0 mL of CH_2Cl_2, room temperature.
[b] Determined by GC with diethyl adipate as internal standard.
[c] The e.e.s for the cyclopropanation product and the ratio of *trans* and *cis* isomers were determined by capillary GC using a chiral column (cyclodex-β, 2,3,6-methylated, 30 m×0.25 mm i.d.), and the configuration of the four isomers was determined by comparing the GC elution order with an authentic sample prepared according to the literature.[2]
[d] (1*R*,2*S*) as the major enantiomer.
[e] (1*R*,2*R*) as the major enantiomer.

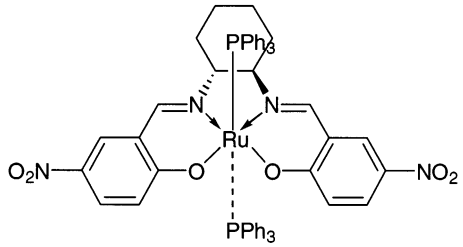
Table 2. The influence of the additives on the asymmetric cyclopropanation of styrene with ethyl diazoacetate using ligand **1e**[a]

Entry	Solvent or additive[b]	Yield (%)[c]	*cis*/*trans*[d]	% e.e. (*cis*)[e,f]	% e.e. (*trans*)
1[g]	CH_2Cl_2/styrene	58	21:79	33.8	53.2
2[h]	THF	68	62:38	−26.9	2.8
3	EtOH	77	20:80	33.0	22.5
4	*i*-PrOH	58	14:86	60.6	74.2
5	*tert*-BuOH	58	26:74	67.7	49.7
6[i]	L-Menthol	72	18:72	46.8	68.8

[a] Reaction conditions: 1 mmol of ethyl diazoacetate, 10 mmol of styrene, 2% catalyst prepared in situ (based on the diazoacetate), 3.0 mL of CH_2Cl_2, room temperature.
[b] The alcohols were added in the process of the preparation of the catalysts as solvents except entry 5.
[c] Determined by GC with diethyl adipate as internal standard.
[d] The e.e.s for the cyclopropanation product and the ratio of *trans* and *cis* isomers were determined by capillary GC using a chiral column (cyclodex-β, 2,3,6-methylated, 30 m×0.25 mm i.d.), and the configuration of the four isomers was determined by comparing the GC elution order with an authentic sample prepared according to the literature.[12]
[e] (1*R*,2*S*) as the major enantiomer, except (1*S*,2*R*) was the major enantiomer in entry 2.
[f] (1*R*,2*R*) as the major enantiomer.
[g] The catalyst was prepared in situ in 5 mL of CH_2Cl_2/styrene (1:1), 2 equiv. Et_3N were added as base, and the solution was stirred at room temperature for 4 hours.
[h] The catalyst was prepared in situ in 3 mL THF, 2 equiv. Et_3N were added as base, and the solution was stirred at room temperature for 4 hours.
[i] The catalyst was prepared in situ in 3 mL of CH_2Cl_2, 6 equiv. of L-menthol and 2 equiv. of Et_3N were added, and the solution was stirred at room temperature for 4 hours. 12 equiv. of L-menthol was also tried, but there was no obvious difference observed.

dibrominated salicylaldehyde, was used. This gave e.e. of only 35% without excess Et_3N present. E.e.s of around 70% and a 98% yield were obtained at room temperature with Et_3N present (entry 7 in Table 3 versus entry 6 in Table 1). When the reaction was carried out at 0°C, better enantioselectivity was observed with a slightly decreased yield. E.e.s of up to 80.2% were achieved by reducing the reaction temperature further to −15°C but the yield of the reaction lowered to 68% (entries 8, 9 in Table 3).

Examining the results shown in Table 3, the addition of Et_3N resulted in a marked decrease in the catalytic activity, except for the dihalo-substituted ligands **1f** and **1i**. Higher reaction temperature was tried for the low activity catalysts using the ligand **1e** as a prototype; this



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Scheme 2.

resulted in improved catalytic activity, but regio- and enantioselectivity were changed unfavorably (entry 2 in Table 3).

Other bases, including *n*-Bu_3N, pyridine, 2,6-lutidine and DMAP, were also employed for ligand **1e**. Et_3N gave the best result in enantioselectivity, while 2,6-lutidine gave a far higher activity than the others, but with poor e.e.s (Table 4).

As a new attempt, the *P*-donor axial ligand was also employed by using $RuCl_2(PPh_3)_3$ as a precursor. The free triphenylphosphine ligand released during the coordination of **1** with Ru(II) precursor must be removed before introducing the styrene and dichloromethane.[22] The structure of the catalysts formed in situ was confirmed by the isolated complex **2**, which was prepared from $RuCl_2(PPh_3)_3$ and ligand **1m**, and easily isolated from the *iso*-propanol solution as a stable crystal in air (Scheme 2). It was characterized by NMR and ESI MS, and should have the structure described in Scheme 2, in which there are two PPh_3 molecules occupying the axial position. The results of **1e**–**1m** are listed in Table 5.

By using $RuCl_2(PPh_3)_3$ as a precursor, similar results were observed for the halogen-substituted ligands **1e**–**1j** to those obtained in salen/$[Ru(p\text{-cymene})Cl_2]_2$ systems. However, it was surprising that e.e.s of up to 81.3% for (1*S*)-isomers and a yield of greater than 90% was achieved by using the nitro-substituted ligand **1m**, while only poor e.e.s were observed for the opposite (1*R*)-isomers when $[Ru(p\text{-cymene})Cl_2]_2$ was used as the precursor (entry 9 in Table 5 versus entry 13 in Table 1 and entry 16 in Table 3). Correspondingly, the other two nitro-substituted ligands **1k** and **1l** also give better enantioselectivities for (1*S*)-isomers in this system.

The abnormal enantioselectivity caused by the introduction of PPh_3 as an axial ligand led us to investigate the effect of variation of reaction temperature on the behavior of ligand **1m**, and it was found that a higher yield was obtained from reaction at 0°C compared to 35°C (entries 10, 11). We also attempted to add 1 equiv. of PPh_3 into the catalyst prepared in situ from **1m** and $[RuCl_2(p\text{-cymene})]_2$ in CH_2Cl_2/styrene but far lower catalytic activity and e.e.s for (1*S*)-isomers were obtained (entry 12). The preliminary in situ temperature variation ^{31}P NMR study showed that there was no free PPh_3 observed in the system from –40 to 25°C. We suspect that the coordinatively unsaturated species in the reaction catalyzed by complex **2** might not be formed by the isolation of PPh_3 in the axial position, but by the breakage of an N–Ru bond, which might result in a chiral environment favoring (1*S*)-isomers.

3. Conclusion

In summary, for the salen–Ru(II)-catalyzed asymmetric cyclopropanation system, the substituents on the salicyl-

Table 3. The influence of Et_3N on the asymmetric cyclopropanation of styrene with ethyl diazoacetate using the substituted salen ligands **1a**–**1k**[a]

Entry	Ligand	Additive[b]	Temp. (°C)	Yield (%)	*cis*:*trans*	% e.e. (*cis*)[c]	% e.e. (*trans*)[d]
1	**1a**	Et_3N	Rt	23	35:65	–	–
2	**1b**	Et_3N	Rt	24	31:69	33.7	23.7
3	**1c**	Et_3N	Rt	28	24:76	37.6	31.0
4	**1d**	Et_3N	Rt	24	28:72	29.0	13.6
5	**1e**	Et_3N	Rt	35	29:71	42.9	55.0
6	**1e**	Et_3N	35	60	68:32	42.9	47.2
7	**1f**	Et_3N	Rt	98	25:75	68.2	60.0
8	**1f**	Et_3N	0	91	23:77	78.4	69.1
9	**1f**	Et_3N	−15	68	22:78	80.2	65.4
10	**1g**	Et_3N	Rt	36	29:71	33.4	31.4
11	**1h**	Et_3N	Rt	37	27:73	11.0	36.5
12	**1i**	Et_3N	Rt	61	24:76	51.5	44.8
13	**1j**	Et_3N	Rt	41	32:68	49.6	32.6
14	**1k**	Et_3N	Rt	35	19:81	32.9	48.1
15	**1l**	Et_3N	Rt	79	27:73	21.9	24.2
16	**1m**	Et_3N	Rt	29	31:69	16.0	17.6

[a] Reaction conditions: 1 mmol of ethyl diazoacetate, 10 mmol of styrene, 2% catalyst prepared in situ (based on the diazoacetate), 3.0 mL of CH_2Cl_2, at the selected temperature.

[b] 6 equiv. of base (based on the ruthenium(II) precursor) were added as additive in the procedure of the preparation of the catalyst in situ.

[c] (1*R*,2*S*) as the major enantiomer.

[d] (1*R*,2*R*) as the major enantiomer.

Table 4. The influence of the additives on the asymmetric cyclopropanation of styrene with ethyl diazoacetate using ligand **1e**[a]

Entry	Additive[b]	Temp. (°C)	Yield (%)	*cis*:*trans*	% e.e. (*cis*)[c]	% e.e. (*trans*)[d]
1	Et_3N	35	60	68:32	42.9	47.2
2	n-Bu_3N	35	34	40:60	3.6	33.5
3	Pyridine	35	39	43:57	17.0	5.0
4	2,6-Lutidine	35	82	22:78	22.0	11.2
5	DMAP	35	Trace	–	–	–

[a] Reaction conditions: 1 mmol of ethyl diazoacetate, 10 mmol of styrene, 2% catalyst prepared in situ (based on the diazoacetate), 3.0 mL of CH_2Cl_2.
[b] 6 equiv. of the bases (based on the ruthenium(II) precursor) were added in the preparation of the catalyst in situ, except entry 2, where 4 equivalents of DMAP were added.
[c] (1*R*,2*S*) as the major enantiomer.
[d] (1*R*,2*R*) as the major enantiomer.

Table 5. Asymmetric cyclopropanation of styrene with ethyl diazoacetate using $RuCl_2(PPh_3)_3$ as precursor[a]

Entry	Ligand	Temp. (°C)	Yield (%)	*cis*:*trans*	% e.e. (*cis*)[b]	% e.e. (*trans*)[c]
1	**1e**	Rt	57	24:76	59.0	51.8
2	**1f**	Rt	56	25:75	29.6	28.4
3	**1g**	Rt	44	36:64	13.5	13.7
4	**1h**	Rt	58	25:75	49.0	37.2
5	**1i**	Rt	54	28:72	41.6	38.1
6	**1j**	Rt	54	35:65	28.8	22.3
7	**1k**	Rt	66	24:76	−7.9	−5.5
8	**1l**	Rt	87	21:79	−15.3	−18.4
9	**1m**	Rt	92	43:57	−79.7	−81.3
10	**1m**	0	87	44:56	−73.2	−54.7
11	**1m**	35	77	42:58	−53.1	−60.2
12[d]	**1m**	Rt	24	39:61	−10.4	−18.8

[a] Reaction conditions: 1 mmol of ethyl diazoacetate, 10 mmol of styrene, 2% catalyst prepared in situ (based on the diazoacetate), 3.0 mL of CH_2Cl_2, room temperature.
[b] (1*R*,2*S*) as the major enantiomer except (1*S*,2*R*) as the major enantiomer in entry 7.
[c] (1*R*,2*R*) as the major enantiomer except (1*S*,2*S*) as the major enantiomer in entry 7.
[d] The catalyst was prepared in situ in 5 mL of CH_2Cl_2/styrene (1:1); 2 equiv. Et_3N were added as base. The mixture was stirred at room temperature for 4 hours, and then 1 equiv. of PPh_3 was added and the mixture stirred for another 4 hours.

aldehyde are of great importance to the enantioselectivity observed. Bulky alkyl substituents at C(3) and C(3′) disfavored the enantioselectivity in the asymmetric cyclopropanation. With the introduction of electron withdrawing groups, enantioselectivity improved. The enantioselectivity and activity were also affected dramatically by the presence of additives. E.e.s of up to 80.2% for the (1*R*,2*S*)-isomer were achieved by using ligand **1f** derived from 3,5-dibromosalicylaldehyde in the salen/$[Ru(p\text{-cymene})Cl_2]_2$ system with Et_3N as an additive. By using $RuCl_2(PPh_3)_3$ as a precursor, the ligand **1m** gave e.e.s of around 80% for (1*S*)-isomers of ethyl 2-phenylcyclopropanecarboxylate.

4. Experimental

All reactions were carried out under an inert argon atmosphere. *Iso*-propanol was refluxed with sodium and distilled under argon atmosphere. Dichloromethane was distilled from CaH_2. Styrene was freshly distilled and degassed with argon. Melting points were taken using a Yazawz BY-1 and are uncorrected. Nuclear magnetic resonance spectra were recorded with a Bruker DRX-400 (400 MHz). Optical rotations were measured on a JASCO-1020. GC analysis was performed using an HP-4890D. ESI MS spectra were recorded with an HP1100 LC/MSD. The ligand **1m** and complex **2** were the original compounds and ligands **1a**–**1l** have been previously reported.

4.1. Ligand preparation: general procedure for the synthesis of ligands 1a–1k and 1m

In a 50 mL Schlenk flask, (*R*,*R*)-1,2-diammoniumcyclohexane mono-(+)-tartrate salt (1 mmol), K_2CO_3 (2 mmol) and distilled water (5 mL) were added. The mixture was stirred until dissolution, and then 20 mL ethanol was added. The resulting mixture was heated to reflux, and a solution of substituted salicylaldehyde (2 mmol) in ethanol (10 mL) was added over a period of 30 minutes, and then stirred under reflux for 2 hours. After the resulting mixture was cooled to 0°C, water (10 mL) was added slowly and the temperature was maintained below 5°C overnight. The product was collected by filtration and washed with ethanol (5 mL). The

crude solid was redissolved in 20 mL CH_2Cl_2, washed with water (2×10 mL) and brine (15 mL). After drying over Na_2SO_4, the solvent was removed under vacuum, and the product was isolated as a yellow powder.

4.1.1. (*R*,*R*)-*N*,*N*′-Bis(3,5-di-*tert*-butyl-salicylidene)-1,2-cyclohexanediamine 1a. Mp 202–203°C; $[\alpha]_D^{20}=-309$ (*c* 1, CH_2Cl_2); ^{1}H NMR ($DCCl_3$) δ 13.77 (s, 2H), 8.34 (s, 2H), 7.34 (d, $J=2.2$ Hz, 2H), 7.02 (d, $J=2.2$ Hz, 2H), 3.70–3.30 (m, 2H), 2.0–1.4 (m, 8H), 1.44 (s, 18H), 1.27 (s, 18H); ^{13}C NMR: 165.9, 158.1, 139.9, 136.4, 126.8, 117.9, 72.4, 35.0, 34.1, 33.3, 29.5, 24.4.

4.1.2. (*R*,*R*)-*N*,*N*′-Bis-salicylidene-1,2-cyclohexanediamine 1b. Mp 59–60°C; $[\alpha]_D^{20}=-394$ (*c* 1, CH_2Cl_2); ^{1}H NMR ($DCCl_3$) δ 13.02 (s, 2H), 8.24 (s, 2H), 7.24–7.20 (m, 2H), 7.13 (dd, $J=1.6$ Hz, 7.7 Hz, 2H), 6.88 (d, $J=8.2$ Hz, 2H), 6.89–6.76 (m, 2H), 3.30–3.28 (m, 2H), 1.9–1.4 (m, 8H); ^{13}C NMR: 164.6, 160.9, 132.1, 131.4, 118.5, 116.7, 72.5, 33.0, 24.1.

4.1.3. (*R*,*R*)-*N*,*N*′-Bis(3,5-di-methyl-salicylidene)-1,2-cyclohexanediamine 1c. Mp 105–107°C; $[\alpha]_D^{20}=-384$ (*c* 1, CH_2Cl_2); ^{1}H NMR ($DCCl_3$) δ 13.38 (s, 1H), 8.18 (s, 1H), 6.92 (s, 2H), 6.77 (s, 2H), 3.28–3.25 (m, 2H), 2.20 (s, 6H), 2.17 (s, 6H), 1.9–1.4 (m, 8H); ^{13}C NMR: 164.7, 156.9, 134.1, 129.1, 126.9, 125.2, 117.5, 72.6, 33.1, 24.1, 20.2, 15.3.

4.1.4. (*R*,*R*)-*N*,*N*′-Bis(5-*tert*-butyl-salicylidene)-1,2-cyclohexanediamine 1d. Mp 116–118°C; $[\alpha]_D^{20}=-179$ (*c* 1, CH_2Cl_2); ^{1}H NMR ($DCCl_3$) δ 13.14 (s, 2H), 8.26 (s, 2H), 7.27 (dd, $J=1.3$ Hz, 8.7 Hz, 2H), 7.12 (s, 2H), 6.82 (d, $J=8.7$ Hz, 2H), 3.30–3.28 (m, 2H), 1.9–1.4 (m, 8H), 1.23 (s, 18H); ^{13}C NMR: 164.9, 158.6, 141.1, 129.4, 127.9, 117.9, 116.2, 72.7, 33.8, 33.1, 31.3, 24.1.

4.1.5. (*R*,*R*)-*N*,*N*′-Bis(3-bromo-5-*tert*-butyl-salicylidene)-1,2-cyclohexanediamine 1e. Mp 197–200°C; $[\alpha]_D^{20}=-309$ (*c* 1, CH_2Cl_2); ^{1}H NMR ($DCCl_3$) δ 14.17 (s, 2H), 8.22 (s, 2H), 7.53 (s, 2H), 7.10 (d, $J=1.3$ Hz, 2H), 3.34–3.29 (m, 2H), 1.9–1.4 (m, 8H), 1.25 (s, 18H); ^{13}C NMR: 164.5, 155.8, 142.3, 132.9, 127.4, 118.3, 110.6, 72.2, 34.0, 32.9, 31.2, 24.0.

4.1.6. (*R*,*R*)-*N*,*N*′-Bis(3,5-di-bromo-salicylidene)-1,2-cyclohexanediamine 1f. Mp 140–142°C; $[\alpha]_D^{20}=-267$ (*c* 1, CH_2Cl_2); ^{1}H NMR ($DCCl_3$) δ 14.32 (s, 2H), 8.14 (s, 2H), 7.64 (s, 2H), 7.24 (s, 2H), 3.37–3.35 (m, 2H), 2.0–1.4 (m, 8H); ^{13}C NMR: 163.2, 157.8, 137.7, 132.9, 119.6, 112.1, 109.7, 71.9, 32.8, 23.8, 18.4.

4.1.7. (*R*,*R*)-*N*,*N*′-Bis(5-bromo-salicylidene)-1,2-cyclohexanediamine 1g. Mp 189–190°C; $[\alpha]_D^{20}=-99$ (*c* 1, CH_2Cl_2); ^{1}H NMR ($DCCl_3$) δ 13.24 (s, 2H), 8.15 (s, 2H), 7.31 (dd, $J=2.2$ Hz, 8.8 Hz, 2H), 7.25 (d, $J=8.8$ Hz, 2H), 6.79 (d, 2H), 3.30–3.28 (m, 2H), 1.9–1.4 (m, 8H); ^{13}C NMR: 163.4, 159.9, 134.9, 133.4, 119.8, 118.8, 110.0, 72.5, 32.8, 24.0.

4.1.8. (*R*,*R*)-*N*,*N*′-Bis(3-chloro-5-*tert*-butyl-salicylidene)-1,2-cyclohexanediamine 1h. Mp 209–212°C; $[\alpha]_D^{20}=-266$ (*c* 1, CH_2Cl_2); ^{1}H NMR ($DCCl_3$) δ 14.14 (s, 2H), 8.25 (s, 2H), 7.37 (d, $J=2.0$ Hz, 2H), 7.06 (d, $J=2.0$ Hz, 2H), 3.34–3.32 (m, 2H), 2.0–1.4 (m, 8H), 1.23 (s, 18H); ^{13}C NMR: 164.6, 154.9, 141.8, 130.0, 126.6, 120.8, 118.5, 72.4, 34.0, 33.0, 31.2, 24.0.

4.1.9. (*R*,*R*)-*N*,*N*′-Bis(3,5-di-chloro-salicylidene)-1,2-cyclohexanediamine 1i. Mp 139–141°C; $[\alpha]_D^{20}=-371$ (*c* 1, CH_2Cl_2); ^{1}H NMR ($DCCl_3$) δ 14.20 (s, 2H), 8.18 (s, 2H), 7.34 (s, 2H), 7.07 (s, 2H), 3.37–3.33 (m, 2H), 2.0–1.4 (m, 8H); ^{13}C NMR: 163.3, 156.2, 132.2, 129.1, 122.8, 122.5, 119.1, 72.1, 32.8, 23.8.

4.1.10. (*R*,*R*)-*N*,*N*′-Bis(5-chloro-salicylidene)-1,2-cyclohexanediamine 1j. Mp 191°C; $[\alpha]_D^{20}=-199$ (*c* 1, CH_2Cl_2); ^{1}H NMR ($DCCl_3$) δ 13.22 (s, 2H), 8.14 (s, 2H), 7.17 (dd, $J=2.3$ Hz, 8.8 Hz, 2H), 7.09 (d, $J=1.4$ Hz, 2H), 6.83 (d, $J=8.8$ Hz, 2H), 3.30–3.24 (m, 2H), 1.9–1.4 (m, 8H); ^{13}C NMR: 163.5, 159.4, 132.0, 130.4, 123.1, 119.2, 118.3, 72.5, 32.8, 23.9.

4.1.11. (*R*,*R*)-*N*,*N*′-Bis(3-nitro-5-*tert*-butyl-salicylidene)-1,2-cyclohexanediamine 1k. Mp 105–106°C; $[\alpha]_D^{20}=-566$ (*c* 1, CH_2Cl_2); ^{1}H NMR ($DCCl_3$) δ 15.10 (s, 2H), 8.38 (s, 2H), 8.05 (d, $J=2.4$ Hz, 2H), 7.46 (d, $J=2.4$ Hz, 2H), 3.48–3.41 (m, 2H), 2.0–1.4 (m, 8H) 1.27 (s, 18H); ^{13}C NMR: 164.9, 155.8, 140.3, 137.4, 134.4, 126.6, 119.8, 71.5, 34.1, 32.8, 30.9, 23.9.

4.1.12. Preparation of (*R*,*R*)-*N*,*N*′-bis(3,5-di-nitro-salicylidene)-1,2-cyclohexanediamine 1l. In a 50 mL Schlenk flask, (*R*,*R*)-1,2-diammoniumcyclohexane (1 mmol) was dissolved in ethanol (10 mL). The solution was heated under reflux, and a solution of 3,5-dinitrosalicylaldehyde (2 mmol) in ethanol (10 mL) was added over a period of 30 minutes; the reaction mixture was then stirred under reflux for 2 hours. The mixture was cooled to room temperature. The crystalline product was collected and washed with ethanol (5 mL) and diethyl ether (5 mL), affording product **1l** as orange crystalline powder (85% yield). Mp 248–249°C; $[\alpha]_D^{20}=-148$ (*c* 1, DMSO); ^{1}H NMR (DMSO-d_6) δ 13.56 (s, 2H), 8.92 (s, 2H), 8.76 (d, $J=3.42$ Hz, 2H), 8.66 (d, $J=3.42$ Hz, 2H), 4.26–4.24 (m, 2H), 2.1–1.0 (m, 8H); ^{13}C NMR: 169.7, 167.7, 140.7, 137.6, 129.9, 127.5, 117.2, 63.3, 30.7, 23.4.

4.1.13. (*R*,*R*)-*N*,*N*′-Bis(5-nitro-salicylidene)-1,2-cyclohexanediamine 1m. Mp 219–221°C; $[\alpha]_D^{20}=-20.9$ (*c* 1, CH_2Cl_2); ^{1}H NMR ($DCCl_3$) δ 14.32 (s, 2H), 8.36 (s, 2H), 8.15–8.12 (m, 4H), 6.93 (d, $J=8.9$ Hz, 2H), 3.52–3.45 (m, 2H), 2.05–1.50 (m, 8H); ^{13}C NMR: 167.5, 163.7, 139.3, 128.0, 127.9, 118.3, 117.0, 71.7, 32.6, 23.8. Anal. calcd for $C_{20}H_{20}N_4O_6$: C, 58.25; H, 4.89; N, 13.59; O, 23.58. Found: C, 58.53; H, 4.96; N, 13.77%.

4.2. Preparation of catalyst 2

In a 50 mL Schlenk flask, $Ru(PPh_3)Cl_2$ (0.2206 g, 0.230 mmol) was mixed with the ligand **1m** (0.1000 g, 0.242 mmol) in *iso*-propanol (15 mL); Et_3N (0.192 mL, 6 equiv.) was then added. The solution was stirred under reflux for two hours, then cooled to room temperature. The crystalline product was collected and recrystallized

from CH_2Cl_2 and hexane (1:6), affording 0.1935 g of product **2** as a red–brown crystal (81% yield). Mp >300°C; ^{31}P NMR δ 31.50; ^1H NMR (acetone-d_6) δ 8.22 (s, 2H), 7.53 (dd, $J=2.8$ Hz, 9.4 Hz, 2H), 7.33–7.11 (m, 32H), 6.22 (d, $J=9.4$ Hz, 2H), 2.59–2.57 (m, 2H), 1.8–1.0 (m, 8H); ^{13}C NMR: 173.1, 156.5, 134.6–122.5 (m, C-Ph), 73.2, 28.6, 24.6. Anal. calcd for $C_{56}H_{48}N_4O_6P_2Ru$: C, 64.92; H, 4.67; N, 5.41; O, 9.27; P, 5.98; Ru, 9.76. Found: C, 64.52; H, 5.02; N, 4.85%. ESI MS: m/z 1037 $[M+H]^+$.

4.3. General experimental using $[Ru(p\text{-cymene})Cl_2]_2$ as precursor

In a 25 mL Schlenk tube, $[Ru(p\text{-cymene})Cl_2]_2$ (0.0061 g, 0.01 mmol) was mixed with the ligand **1** (0.021 mmol) in *iso*-propanol (3 mL), then Et_3N (0.0167 mL, 6 equiv.; or 0.0053 mL, 2 equiv.) was added. The solution was refluxed for two hours, then concentrated in vacuo. The residue was vacuum dried at 90°C for 30 min and cooled to room temperature. The solid was dissolved in CH_2Cl_2 (5 mL), and styrene (10 mmol) was added to the solution. Ethyl diazoacetate (0.114 g, 1 mmol) in CH_2Cl_2 (5 mL) was added through a syringe pump over a period of six hours. The resulting mixture was stirred for another eight hours. The catalyst-free sample was analyzed as described in the footnote to Table 1.

4.4. General experimental using $Ru(PPh_3)Cl_2$ as precursor

In a 25 mL Schlenk tube, $Ru(PPh_3)Cl_2$ (0.0191 g, 0.02 mmol) was mixed with the ligand **1** (0.021 mmol) in *iso*-propanol, and then Et_3N (0.0167 mL, 6 equiv.) was added. The solution was refluxed for two hours, then concentrated in vacuo. The residue was washed with Et_2O (3×1 mL) and vacuum dried at 90°C for 30 min and cooled to room temperature. The solid was dissolved in CH_2Cl_2 (5 mL), and styrene (10 mmol) was added to the solution. A solution of ethyl diazoacetate (0.114 g, 1 mmol) in CH_2Cl_2 (5 mL) was added through a syringe pump over a period of six hours. The resulting mixture was stirred for another eight hours. The catalyst-free sample was analyzed as described in the footnote to Table 1.

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