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Development of chiral *C*₂-symmetric *N*-heterocyclic carbene Rh(I) catalysts through control of their steric properties.

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ABSTRACT: Chiral square-planar Rh(I) complexes based on new C_2 -symmetric NHC ligands have been synthesized selectively in a few steps as single diastereoisomers. These chiral pre-catalysts were applied to the asymmetric transfer hydrogenation of 1-phenylpropanone and to the 1,2-addition of arylboronic acids to aldehydes. We demonstrated a proper functionalization of the aromatic rings connected to the nitrogen atoms of the NHC ligand improved significantly the asymmetric induction of the chiral Rh(I) NHC catalysts. Bulky substituents allowed a better control of the steric features of the catalyst quadrants because they behaved as conformational and chirality relays of the NHC chiral backbone.

INTRODUCTION

N-heterocyclic carbenes (NHCs) have been used as ligands in transition metal complexes for several decades.¹ Numerous studies on synthesis, coordination and reactivity of NHC ligands resulted in significant applications in homogeneous catalysis for various chemical transformations in racemic and asymmetric series.² During the past two decades, chiral monodentate C_2 -symmetric *N*-heterocyclic carbene ligands were prepared according to three strategies: the use of chiral *N*-substituents (Figure 1, **A**), the synthesis of rigid tricyclic NHCs (Figure 1, **B**) and the use of chiral amine backbones (Figure 1, **C**).²



Figure 1. General structures of chiral monodentate *C*₂-symmetric *N*-heterocyclic carbene (NHC) ligands.

NHC ligands of type **C** draw a parallel with the stereochemical model of BINAP ligand. Because the point chirality is far from

the NHC coordination center, it does not have a significant influence on a chemical reaction. However, the conformation of the aromatic *N*-substituents can be controlled provided the rotation around the C–N-bond is restricted by ortho substituents on the aryls (Figure 2).³



Figure 2. Examples of catalysts based on monodentate C_2 -symmetric NHC ligands with chiral amine backbones.

Following the pioneering work of Grubbs et al. (Figure 2) for the first enantioselective ruthenium catalyzed olefin metathesis in the desymmetrization of achiral trienes,³ chiral NHC based catalysts have been developed for various organic reactions using well-defined organometallic species⁴ or one-pot procedures.⁵ In recent reports, steric fine tuning of such chiral NHC ligands has been investigated through a modular strategy and proved to be determining. Indeed, Dorta et al. have developed chiral NHC ligands substituted by naphthyl wingtips for effective Pd catalyzed cross-couplings and Ir catalyzed hydroamination reactions (Figure 2).^{4h-j,4m} At the meantime, Plenio et al. have reported chiral NHC ligands based on bulky triptycene are useful in the Cu catalyzed enantioselective borylation of α , β unsaturated esters (Figure 2).^{4k} Herein, we report on the design and development of new C_2 -symmetric NHC ligands based on a chiral diphenylethylene diamine backbone (Figure 2). The resulting pure diastereomeric Rh(I) complexes were applied to the asymmetric transfer hydrogenation of ketones and to the 1,2addition of arylboronic acids to aldehydes. Along our study, we demonstrated a proper functionalization of the aromatic rings connected to the nitrogen atoms improved the asymmetric induction of the enantiomerically pure NHC ligand. Because bulky substituents behaved as conformational and chirality relays of the NHC chiral backbone, the use of sterically demanding groups allowed a better control of the steric features of the catalyst quadrants.6

RESULTS AND DISCUSSIONS

The NHC ligand synthesis started by a double Buchwald-Hartwig amination reaction⁷ using (S,S)-diphenylethvlenediamine (DPEN) and one of the substituted 1-bromo-2methoxy-benzene **1a-e** previously prepared⁸ (Schemes 1, S1). The resulting secondary diamines 2a-e were isolated in good to high yields (e.g. 66-98%) after purification by flash chromatography. The molecular structures of 2a-e were consistent with their elemental analyses, mass and NMR spectra. The corresponding dihydroimidazolium salts **3a-e** were prepared as pure diastereoisomers in 69% to quantitative yields by reacting amines 2a-e with excess of triethylorthoformate and tetrafluoroborate ammonium (Scheme 1). Salts 3a-e were characterized by their elemental analyses, mass and NMR spectra. The identifications of the CH units between the N atoms are of particular significance in the cations **3a-e** as their ¹H and ¹³C signals are observed respectively around $\delta 8.9$ ppm and 158 ppm which is typical of such dihydroimidazolium salts. Afterwards, Rh(I) complexes 4a-e were prepared in two steps. At first, pure diastereomeric salts **3a-e** were allowed to react with Ag(I) oxide in acetonitrile at 60 °C for 24 hours (Scheme 1). Second, the resulting Ag(I) complexes reacted subsequently with $[Rh(COD)Cl]_2$ (COD = 1,5-cyclooctadiene) without any purification, through transmetallation in dichloromethane for 64 hours (Scheme 1). The resulting Rh(I) complexes 4a-e were isolated as pure diastereoisomers in average to high yields (56-90%) after purification by flash chromatography and recrystallization. They were characterized by their elemental analyses, mass and NMR spectra. The ¹³C NMR resonances of the carbene carbon nuclei were observed at δ 212-213 ppm with coupling constants J(Rh,C) of 46-47 Hz and confirmed the formation of the carbene complexes. Because the rotation around the Rh-C axis was restricted by the steric hindrance, ¹³C and ¹H NMR spectra indicated all the atoms were inequivalent. Single crystals of Rh(I) complex 4d were obtained by slow evaporation of a chloroform/n-hexane mixture. According to an X-ray

diffraction analysis, complex **4d** crystallized in an orthorhombic crystal system with a $P2_12_12_1$ space group and a Flack parameter of -0.045(12). The ORTEP of **4d** comprised two independent Rh complexes and one molecule of n-pentane (Figure 3, Figure S1, Table S1). Each central Rh atom adopted a square planar coordination geometry, being coordinated to the chloride, the 1,5-cyclooctadiene and the carbene ligand without any crystallographic mirror plane bisecting the molecule in the Cl-Rh-C(NHC) plane (Figure 3). The measured distances of 1.991(6) Å (Figure 3) and 2.007(6) Å (Figure S1) between the Rh and carbon of the carbene proved to be similar to the 2.02-2.07 Å usually measured for unsaturated¹⁰ and saturated¹¹ carbene ligands.



Figure 3. ORTEP of compound $(S_{av}S_{av}R,R)$ -**4d**·(**0.5 n-pentane**): at the 50% probability level. One complex, one pentane molecule and hydrogen atoms are omitted for clarity. Selected bond lengths (Å) and angles (°): Rh1-Cl1 = 2.3767(15), Rh1-Cl = 1.991(6), Rh1-C7 = 2.226(7), Rh1-C8 = 2.205(7), Rh1-C4 = 2.091(6), Rh1-C11 = 2.3767(15), N1-C1 = 1.344(7), N2-C1 = 1.354(8), C7-C8 = 1.354(10), C4-C11 = 1.384(9), N1-C1-N2 = 106.4(5), N1-C1-Rh1 = 124.0(5), N2-C1-Rh1 = 129.6(4), C1-Rh1-Cl1 = 90.1(16). CCDC 1848614.⁹

The isolated NHC Rh(I) complexes 4a-e were then applied as pre-catalysts in two asymmetric organic reactions. At first, we studied the asymmetric transfer hydrogenation of propiophenone to 1-phenylpropanol 5 as such a reaction was often studied applying chiral NHC Rh(I) complexes as catalysts (Table 1).^{10,12} While using 5 mol% of KOtBu as a base in *i*PrOH at 80 °C, the pre-catalysts **4a-b** substituted respectively by H and Me at the meta position of each 2-MeO-aromatic unit led to average to good yields of secondary alcohol 5 along with low enantiomeric excess (Ee) (entries 1,2). If complex 4c bearing cyclohexyl substituents led to poor results (entry 4), the use of complex 4d holding bulky tBu groups afforded product 5 in a high yield with a 49% Ee (entry 5). Complex 4e bearing adamantyl substituents allowed a further increase of the steric hindrance and led to secondary alcohol 5 in high yield with an improved 60% Ee (entry 7). Hence, the results demonstrated the use of sterically demanding substituents allowed a better control of the Rh catalyst quadrants as they acted as conformational and chirality relays of the chiral DPEN backbone. Finally, a slight increase of Ee was observed through the use of 10 mol% of tBuOK. Indeed, it is well established the transfer hydrogenation of ketones depends on the nature and amount of the base cocatalyst (entries 8-10).^{10c} In order to check if catalysts were decomposing along the reactions, Hg(0) trapping experiments were performed (entries 3, 6). While decreases of yield and Ee were observed for catalyst 4b, the reaction was almost quenched using catalyst 4d.

Scheme 1. Synthesis of the dihydroimidazolium salts 3a-e and the Rh(I) complexes 4a-e.



Table 1. Rh(I) catalyzed transfer hydrogenation of propiophenone to 1-phenylpropanol 5.

	O Rh(I) cat. (1 mol%) OH base (5 mol%)				
Ph' Ph' Ph' <i>i</i> PrOH 0.2 mmol 80 °C, 5 h (<i>R</i>)-5					
Entry	Pre-catalyst	Base	Yield (%) ^a	Ee (%) ^b	
1	(R_a,R_a,S,S) -4a	tBuOK (5)	47	8	
2	(R_a, R_a, S, S) -4b	<i>t</i> BuOK (5)	80	13	
3°	(R_a, R_a, S, S) -4b	tBuOK (5)	65	3	
4	(R_a, R_a, S, S) -4c	tBuOK (5)	6	-	
5	(R_a, R_a, S, S) -4d	tBuOK (5)	99	49	
6 ^c	(R_a, R_a, S, S) -4d	tBuOK (5)	7	-	
7	(R_a, R_a, S, S) -4e	tBuOK (5)	95	60	
8	(R_a, R_a, S, S) -4d	tBuOK (10)	99	53	
9	(R_a, R_a, S, S) -4d	tBuONa (10)	8	-	
10	(R_a, R_a, S, S) -4d	KOH (10)	85	21	

[[]a] Typical experiments are provided. Yields measured by GC.[b] Ee values measured by HPLC.[c] in presence of one Hg(0) drop.

Table 2. Rh(I) catalyzed 1,2-addition of phenylboronic acid to1-naphtaldehyde.

H	0		Н	0 、 Ph
	+ PhB(OH) ₂	cat. (3 mol% base (6 eq.)		
		tBuOH/MeO	- 🔍	
1 eq 0.15 mr	. 2 eq. nol	(5:1) 80 °C, 4 h		(S)-6
Entry	Pre-catalyst	Base (eq.)	Yield (%) ^a	Ee (%) ^b
1	(R_a, R_a, S, S) -4a	KF (6)	54	17
2^d	(R_a, R_a, S, S) -4b	KF (6)	89	2
3	(R_a, R_a, S, S) -4c	KF (6)	77	21
4 ^c	(R_a, R_a, S, S) -4d	KF (6)	82	71
5	(R_a, R_a, S, S) -4e	KF (6)	56	59
6	(R_a, R_a, S, S) -4d	tBuOK (2)	12	-
7	(R_a, R_a, S, S) -4d	AgF (2)	0	-
8	(R_a, R_a, S, S) -4d	KF (2)	84	45

[a] Typical experiments are provided. Isolated yields. [b] Ee values measured by HPLC. [c] 71% yield and 71% ee in presence of one Hg(0) drop.



At the end of the reactions, e.g. 5 hours, analyses of the catalytic reaction mixtures by dynamic light scattering (DLS) revealed the presence of particles in the 641 nm range with Hg(0) addition and around 769 nm without (Figure S2). Though all these results must be interpreted with caution,¹³ they tend to suggest the molecular catalyst may gradually decompose throughout this catalyzed transfer hydrogenation to lead to inactive particles which apparently aggregate during the reaction to give larger particles (Figure S2).

Afterwards, chiral Rh(I) complexes 4a-e were applied as precatalysts in another reference reaction, the asymmetric 1,2-addition of phenylboronic acid to 1-naphtaldehyde (Table 2). Indeed, the enantioselective addition of aryl nucleophiles to aromatic aldehydes is a well-established route to synthesize chiral diarylmethanols which are essential building blocks for the synthesis of various biologically active and pharmacy relevant compounds.¹⁴ Many antihistamines, antiarrhythmic and therapeutic agents feature chiral diarylmethanol and diaryl carbinol derivatives as fundamental structural units. By comparison to the several chiral phosphine based Rh(I) complexes which were successfully applied to catalyze this reaction,¹⁵ only few Rh species based on \hat{C}_2 symmetric NHC have been used.¹⁶ Indeed, the selected reaction was reported to be catalyzed by NHC Rh(I) complex bearing substituents with planar^{16a-b} or central chirality^{16c-d} on the NHC nitrogen atoms with modest to average Ee values. Therefore, after a brief optimization of the experimental conditions, our study was started at 80 °C using tBuOH/MeOH (5:1) solvent mixture and KF as a base (Scheme S2, Table 2). Rh(I) complexes 4a-c bearing respectively H, Me and cyclohexyl substituents led to secondary alcohol 6 in average to good

yields but low enantioselectivities (<21%) (entries 1-3). However, the use of Rh(I) complex 4d carrying bulky tBu groups afforded 6 in a high yield (82%) with a 71% Ee (entry 4). An increase of the steric hindrance through the use of complex 4e bearing adamantyl substituents was here less effective as alcohol 6 was retrieved in lower yield (56%) and Ee (59%) (entry 5). The use of a reduced amount of KF or even of other bases led to significant decreases of reactivity and selectivity (entries 6-8). At that stage, the positive role of a large excess of KF¹⁶ remains unclear as it might act concomitantly as a base and as a ligand through coordination of the fluoride anion to the Rh(I) complex. In order to check if any decomposition was occurring along the catalyzed 1,2-addition of phenylboronic acid to 1naphtaldehyde, Hg(0) trapping experiment was performed using catalyst 4d (Entry 4). The reaction yield was reduced by 10% but no change was noticed for the Ee. At the end of the reactions, analyses of the unfiltered catalytic reaction mixtures by dynamic light scattering (DLS) revealed the presence of particles in the 454 nm range with Hg(0) addition and in the 568 nm range without (Figure S3). Because the catalytic reaction was still running in the presence of Hg(0), the observed particles were, apparently, not related to any active Rh species and the molecular catalyst was rather stable throughout this catalytic process.13

The reaction scope of the enantioselective 1,2-addition of aryl nucleophiles to aldehydes was then investigated (Scheme 2). Similar to 1-naphtaldehyde, the reaction of heterocyclic aldehydes with phenylboronic acid led to secondary alcohols **7-9** in low to good yields, Ee values being average to good. Though the cyclohexanecarboxaldehyde reacted in a similar way to offer alcohol **10**, the reaction of linear 3-phenylpropanal afforded **11** in lower yield and Ee. A similar trend was observed for the reaction of alkyl- or halide substituted benzaldehydes with phenylboronic acid as alcohols **12-15** were obtained in good yields but much lower enantioselectivities. Finally, the reaction of 1-naphtaldehyde with fluoro- or methoxysubstituted phenylboronic acid resulted in alcohols **16-17** with fair yields but low Ee values. On the whole, hindered substrates seemed to allow better asymmetric induction, probably due to more efficient ligand-substrate interactions. Hence, the enantioselectivity of such Rh(I) catalyzed 1,2-addition of aryl nucleophiles to aldehydes proved to be highly dependent of the reagent molecular structures.

CONCLUSIONS

Herein, we have reported the straightforward synthesis of enantiomerically pure Rh(I) complexes based on new C₂-symmetric NHC ligands bearing a chiral diphenylethylene diamine backbone. Applications to the asymmetric transfer hydrogenation of ketones and the 1,2-addition of arylboronic acids to aldehydes were subsequently investigated. Though the enantioselectivity of the developed Rh(I) NHC catalysts proved to depend on the substrate structure, we demonstrated a proper functionalization of the aromatic rings connected to the carbene nitrogen atoms improved drastically the asymmetric induction of the implied Rh(I) NHC catalysts. Indeed, the presence of sterically demanding substituents allowed a better control of the steric features of the catalyst quadrants because these bulky groups behaved as conformational and chirality relays of the NHC chiral backbone. Further applications of this concept will be reported in due course.

EXPERIMENTAL SECTION

General Methods and Instrumentation. All solvents were dried using standard methods and stored over molecular sieves (4 Å). All sensitive salts were weighted in a glovebox. All reactions were carried out under a dry nitrogen atmosphere using standard Schlenk techniques and were repeated two to four times. Analytical thin layer chromatography (TLC) was performed on Merck pre-coated 0.20 mm silica gel Alugram Sil 60 G/UV254 plates. Flash chromatography was carried out with Macherey silica gel (Kielselgel 60). ¹H (300 MHz), ¹³C{¹H} (75 MHz) NMR spectra were acquired on Bruker Avance spectrometers. Chemical shifts (δ) are reported downfield of Me₄Si in ppm and coupling constants are expressed in Hz. Chloroform-d was purchased from Eurisotop and freshly filtered through basic alumina prior to use. 1,3,5-trimethoxybenzene and 1,2,4,5-tetrachlorobenzene were used as internal standards when needed. ¹H NMR shifts are given relative to the residual solvent resonance of CDCl₃ (at 7.26 ppm), and ${}^{13}C{}^{1}H$ NMR shifts are given relative to the residual solvent peak of CDCl3 (at 77.16 ppm). HPLC analyses were performed on a Hitachi LaChromElite equipment with a Peltier oven and a DAD detector. Optical rotations were measured on a Perkin-Elmer 343 using a 10 cm cell. Gas chromatography analyses were done on GC Shimadzu 2010+with FID detectors using Supelco SPB-5 column (30 m, 0.25 mm, 0.25 µm) and with nitrogen as gas carrier. GC-MS analyses were performed on a Shimadzu QP2010+ (EI mode) using Supelco column SLBTM-5ms (30m, 0.25mm, 0.25µm). HRMS-ESI analyses were performed at CUMA-Pharm. Dept.-University Lille Nord de-France. Elemental analyses were performed on an Elementar Vario Micro Cube apparatus at UCCS, University Lille Nord de France. X-ray diffraction analyses were performed at UCCS, University Lille Nord de France, on a Bruker APEX DUO. DLS measurements were performed on a Malvern Zetasizer Nano Series at 25 °C after decantation of the crude reaction solutions (20 minutes) and without any filtration. Aldehyde substrates

were used as received. Purchased boronic acids were purified by flash chromatography on silica gel prior to use.

- General procedure for the synthesis of diamine precursors.

Rac-BINAP (10 mol%) was introduced in a large Schlenk tube along with a magnetic stirring bar. In a glovebox, Pd2(dba)3 (5 mol%) and NaOtBu (2.8 equivalents) were subsequently added. Under a nitrogen flow, toluene (4 mL) was transferred to the Schlenk and the resulting mixture was stirred at room temperature for 30 minutes. In a separate Schlenk flask, (S,S)-DPEN (x mmol from glovebox) was dissolved in 4 mL toluene and transferred to the reaction mixture via cannula. The temperature was set at 30 °C and the reaction was stirred for further 60 minutes. Afterwards, the substituted 2-bromoanisole (2*x mmol) was dissolved in 4 mL toluene in a third Schlenk tube and the resulting solution was transferred to the reaction medium via cannula. The reaction was then stirred for 24 hours at 115 °C under a nitrogen flow. At the end, the resulting mixture was cooled and the remaining solvents were evaporated under vacuum. The residue was then dissolved in ethyl acetate and filtered over Celite. Purification was performed by flash chromatography on silica gel with a solid deposit and using petroleum ether and ethyl acetate solvent mixtures with a 5% elution gradient.

- General procedure for the synthesis of imidazolium salts.

The diamine precursor (1 equivalent) and NH₄BF₄ (2 equivalents) were introduced in a Schlenk tube containing a magnetic stirring bar. After a drying under vacuum of 30 minutes, $CH(OEt)_3$ (3 mL) was transferred to the Schlenk under a nitrogen flow and the remaining mixture was stirred overnight at 120 °C. After 12 hours, the reaction was stopped and the remaining solvent evaporated under vacuum. Purification of the product was carried out through flash chromatography on silica gel with a solid deposit and using petroleum ether and acetone solvent mixtures with a 20% elution gradient. Due to the hygroscopic nature of the resulting imidazolium salt, the latter was repeatedly dissolved in dry toluene and then evaporated under vacuum. Such an azeotrope treatment needed to be repeated 3 times in order to obtain a dry product which required to be stored under nitrogen.

- General procedure for the synthesis of Rh(I) complexes.

Ag₂O (2 equivalents) was introduced to a Schlenk tube containing the dry imidazolium compound and a magnetic stirring bar. After a drying under vacuum of 30 minutes, CH₃CN (7 mL, degassed using the freeze-pump-thaw method) was transferred to the Schlenk under a nitrogen flow and the resulting mixture was stirred at 60 °C for 24 hours in the darkness. Afterwards, [Rh(COD)Cl]2 (0.5 equivalents) was dissolved in CH₂Cl₂ (3 mL, degassed using the freeze-pump-thaw method) in a second Schlenk tube and transferred to the reaction mixture previously cooled at room temperature. The reaction was then pursued in the darkness under stirring and a nitrogen flow for 64 hours. At the end, the reaction mixture was filtered over Celite with an ethyl acetate wash. The resulting yellow solution was concentrated under vacuum and purified by flash chromatography on neutral alumina with a liquid deposit and using petroleum ether and acetone solvent mixtures with a 15% elution gradient. After the corresponding fractions were gathered and evaporated under vacuum, the resulting yellow solid was recrystallized twice from dichloromethane and pentane.

- General procedure for the $\bar{R}h(I)$ catalyzed transfer hydrogenation of ketones.

Prior to the reaction, dry isopropanol was degassed under a nitrogen flow for 2 hours. Catalyst (1 mol%) and potassium tert-butoxide (10 mol%) were introduced in a Schlenk tube containing a magnetic stirring bar and dried under vacuum for 10 minutes. Under nitrogen, distilled propiophenone (0.2 mmol, 0.030 mL) and dry isopropanol (2 mL) were transferred to the Schlenk tube via syringe. The reaction mixture was then heated to 80° C under stirring for 5 hours. After this time, a 0.1 mL aliquot of the reaction mixture was taken for GC analysis to ensure the reaction had gone to completion. At the end, the isopropanol was evaporated under vacuum and the product was purified by flash chromatography on silica gel with a (9:1) petroleum ether and ethyl acetate solvent mixture. Typical experiments are provided in Table 1.

- General procedure for the $Rh(\mathbf{I})$ catalyzed additions of boronic acids to aldehydes.

Catalyst **7d** (3 mol%), purified boronic acid (2 equivalents, 0.3 mmol) and potassium fluoride (6 equivalents, 0.9 mmol, 0.052 g) were introduced in a Schlenk tube containing a magnetic stirring bar and

dried under vacuum for 10 minutes. Under nitrogen, distilled t-butanol (2.5 mL) and methanol (0.5 mL), as well as the aldehyde (0.15 mmol) were transferred to the Schlenk tube via syringe. The reaction mixture was then left under stirring at 80° C for 4 hours. At the end, the reaction was cooled and subsequently quenched with brine. The aqueous solution was extracted thrice with ethyl acetate (3 x 10 mL) and the organic phases were dried over anhydrous magnesium sulfate and concentrated under vacuum. Purification of the product was performed via preparative thin layer chromatography on glass silica plates. Typical experiments are provided in Scheme 2.

$(1S,2S)\text{-}N^{1},N^{2}\text{-bis}(5\text{-}(tert\text{-butyl})\text{-}2\text{-methoxyphenyl})\text{-}1,2\text{-}diphenylethane-1,2\text{-}diamine}$ (2d)

To synthesize compound 2d, reagents were used as follows:

(S,S)-DPEN (0.376 g, 1.8 mmol), (+/-)BINAP (0.110 g, 10 mol%), Pd₂(dba)₃ (0.081 g, 5 mol%), NaOtBu (0.476 g, 5.0 mmol) and 4-tBu-2-bromoanisole (**1d**) (0.862 g, 3.6 mmol). The product was obtained as a white solid (0.714 g, 75% yield), Rf = 0.6, petroleum ether and ethyl acetate solvent mixture (95:5).

¹H NMR (300 MHz, CDCl₃): δ 0.98 (s, 18 H, *t*Bu), 3.74 (s, 6 H, OMe), 4.51 (s, 2 H, CH), 5.22 (bs, 2 H, NH), 6.30 (s, 2 H_{Ar}) 6.51 (dd, *J* = 8.3, *J* = 2.2, 2 H_{Ar}), 6.59 (d, *J* = 8.3, 2 H_{Ar}), 7.04 (m, 10 H_{Ar}). ¹³C{¹H} NMR (75 MHz, CDCl₃): δ 31.5 (3 CH₃, Me), 34.2 (C), 55.7 (CH₃, OMe), 64.6 (CH), 109.1 (CH), 110.1 (CH), 113.3 (CH), 127.3 (CH), 127.8 (2 CH), 128.2 (2 CH), 136.7 (C), 140.9 (C), 143.9 (C), 145.4 (C). HRMS (ESI+): m/z calcd for C₃₆H₄₅N₂O₂ [MH⁺] 537.34756, found 537.34604. Elemental analysis: calcd (%) for (C₃₆H₄₄N₂O₂): C, 80.56; H, 8.26; N, 5.22; found C, 80.77; H, 8.32; N, 5.08. [α]^D₂ = -103 (*CH*₂*Cl*₂ 9 *mM*).

$(R_a,R_a,4S,5S)-1,3-bis(5-(tert-butyl)-2-methoxyphenyl)-4,5-diphenyl-4,5-dihydro-1H-imidazol-3-ium tetrafluoroborate (3d)$

To synthesize compound **3d**, diamine **2d** (0.714 g, 1.3 mmol) was combined with NH₄BF₄ (0.279 g, 2.7 mmol) in 3 mL CH(OEt)₃. The product was obtained as a beige solid (0.738 g, 87% yield). $R_f = 0.6$, petroleum ether and acetone solvent mixture (2:8).

¹H NMR (300 MHz, CDCl₃): δ 1.14 (s, 18 H, *t*Bu), 3.96 (s, 6 H, OMe), 5.76 (s, 2 H, CH), 6.87 (m, 2 H_{Ar}), 7.24 (m, 2 H_{Ar}), 7.27 (m, 2 H_{Ar}), 7.40 (m, 10 H_{Ar}), 8.93 (s, 1 H, imid). ¹³C{¹H} NMR (75 MHz, CDCl₃): δ 31.1 (3 CH₃, Me), 34.2 (C), 56.4 (CH₃, OMe), 75.5 (CH), 111.8 (CH), 122.4 (C), 124.0 (CH), 127.3 (CH), 128.0 (2 CH), 129.6 (2 CH), 130.1 (CH), 135.2 (C), 144.7 (C), 151.0 (C), 158.0 (CH, imid). HRMS (ESI+): m/z calcd for C₃₇H₄₃N₂O₂ [M⁺] 547.33191, found 547.32965. Elemental analysis: calcd (%) for (C₃₇H₄₃BF₄N₂O₂ + 1 H₂O) C, 68.10; H, 6.95; N, 4.29; found C, 67.84; H, 7.02; N, 4.09. [*α*]_D²⁰ = -304 (*CH₂Cl₂, 1 mM*)

$(R_a,R_a)\mbox{-chloro-(1,5)-cyclooctadiene-((4S,5S)-1,3-bis(5-tertiobutyl-2-methoxy-phenyl)-4-5-diphenylimidazolidin-2-ylidene)} rhodium (4d)$

To synthesize complex **4d**, Ag₂O (0.269 g, 1.2 mmol) and [Rh(COD)Cl]₂ (0.143 g, 0.3 mmol) reacted with imidazolium salt **3d** (0.369 g, 0.6 mmol). The complex was obtained as a yellow solid (0.329 g, 72% yield). R_f = 0.7, petroleum ether and acetone solvent mixture (85:15). Recrystallisation by using CH₂Cl₂ and n-hexane followed by drying under vacuum (0.329 g, 72% yield).

¹H NMR (300 MHz, CDCl₃): δ 1.15 (s, 9 H, *t*Bu), 1.28 (s, 9 H, *t*Bu), 1.35 (m, 3 H, CH₂, COD), 1.58 (m, 3 H, CH₂, COD), 1.91 (m, 2 H, CH₂, COD), 3.13 (m, 1 H, CH, COD), 3.49 (m, 1 H, CH, COD), 3.80 (s, 3 H, OMe), 3.90 (s, 3 H, OMe), 4.52 (m, 1 H, CH, COD), 4.64 (m, 1 H, CH, COD), 4.92 (d, *J* = 6.0, 1 H, CH), 5.50 (d, *J* = 6.0, 1 H, CH), 6.82 (dd, *J* = 9.0, 4 H_{Ar}), 7.00 (d, *J* = 3.0, 2 H_{Ar}), 7.30 (m, 9 H_{Ar}), 7.57 (d, *J* = 8.5, 2 H_{Ar}), 8.51 (d, *J* = 1.3, 1 H_{Ar}).

¹³C{¹H} NMR (75 MHz, CDCl₃): δ 27.3 (CH₂), 29.6 (CH₂), 31.2 (CH₂), 31.4 (3 CH₃, CMe), 31.6 (3 CH₃, CMe), 33.3 (CH₂), 33.9 (C), 34.6 (C), 55.5 (CH₃, OMe), 55.6 (CH₃, OMe), 66.7 (d, *J*_{CH-Rh} = 14.8, CH), 69.2 (d, *J*_{CH-Rh} = 14.6, CH), 74.2 (CH), 76.5 (CH), 97.4 (d, *J*_{CH-Rh} = 7.0, CH), 98.0 (d, *J*_{CH-Rh} = 6.4, CH), 109.7 (CH), 111.5 (CH), 124.4 (CH), 126.1 (CH), 127.6 (C), 127.8 (2 CH), 127.9 (2 CH), 128.2 (CH), 128.3 (CH), 128.5 (C), 128.6 (4 CH), 128.8 (CH), 132.4 (CH), 140.2 (C), 141.2 (C), 142.2 (C) 143.8 (C), 152.3 (C), 154.3 (C), 212.6 (d, *J*_{C-Rh} = 46.4, C). HRMS (ESI+): m/z calcd for $C_{45}H_{54}N_2O_2Rh$ [M-Cl] 757.32348, found 757.32159.

Elemental analysis: calcd (%) for (C₄₅H₅₄N₂O₂Rh + 1 H₂O) C, 66.62; H, 6.96; N, 3.45; found C, 66.75; H, 7.13; N, 3.06. $[\alpha]_D^{20} = -108 (CH_2Cl_2, 4 \text{ mM}).$

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the web.

Additional data, experimental procedures and characterizations for other compounds, copies of ¹H and ¹³C NMR spectra of all final products (new or reported), copies of HRMS spectra of new compounds, copies of HPLC analyses. (PDF) Cif file of compound **4d**. (CIF)

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The authors declare no competing financial interest.

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REFERENCES

(1) (a) Díez-González, S.; Marion, N.; Nolan, S. P. N-Heterocyclic Carbenes in Late Transition Metal Catalysis Chem. Rev. 2009, 109, 3612-3676. (b) Lin, J. C. Y.; Huang, R. T. W.; Lee, C. S.; Bhattacharyya, A.; Hwang, W. S.; Lin, I. J. B. Coinage Metal-N-Heterocyclic Carbene Complexes Chem. Rev. 2009, 109, 3561-3598. (c) Clavier, H.; Nolan, S. P. Percent Buried Volume for Phosphine and N-Heterocyclic Carbene Ligands: Steric Properties in Organometallic Chemistry Chem. Commun. 2010, 46, 841-861. (d) Nolan, S. P. The Development and Catalytic Uses of N-Heterocyclic Carbene Gold Complexes Acc. Chem. Res. 2011, 44, 91-100. (e) Hopkinson, M. N.; Richter, C.; Schedler, M.; Glorius, F. An Overview of N-Heterocyclic Carbenes Nature 2014, 510, 485-496. (f) Izquierdo, F.; Manzini, S.; Nolan, S. P. The Use of the Sterically Demanding IPr* and Related Ligands in Catalysis Chem. Commun. 2014, 50, 14926-14937. (g) Charra, V.; de Frémont, P.; Braunstein, P. Multidentate N-heterocyclic Carbene Complexes of the 3d Metals: Synthesis, Structure, Reactivity and Catalysis Coord. Chem. Rev. 2017, 341, 153-176. (h) Hameury, S.; de Frémont, P.; Braunstein, P. Metal Complexes with Oxygen-Functionalized NHC Ligands: Synthesis and Applications Chem. Soc. Rev. 2017, 46, 632-733. (i) Gómez-Suárez, A.; Nelson, D. J.; Nolan, S. P. Quantifying and Understanding the Steric Properties of N-Heterocyclic Carbenes Chem. Commun. 2017, 53, 2650-2660. (j) Zhong, R.; Lindhorst, A. C.; Groche, F. J.; Kühn, F. E. Immobilization of N-Heterocyclic Carbene Compounds: A Synthetic Perspective Chem. Rev. 2017, 117, 1970–2058.

(2) (a) Perry, M. C.; Burgess, K. Chiral N-Heterocyclic Carbene-Transition Metal Complexes in Asymmetric Catalysis Tetrahedron Asym. 2003, 14, 951-961. (b) César, V.; Bellemin-Laponnaz, S.; Gade, L. H. Chiral N-Heterocyclic Carbenes as Stereodirecting Ligands in Asymmetric Catalysis Chem. Soc. Rev. 2004, 33, 619-636. (c) Michon, C.; Angelici, R. J. Novel Chiral Functionalized N-Heterocyclic Carbenes and their Rhodium(I) complexes: Applications in Asymmetric Catalysis ChemTracts 2004, 17, 534-541. (d) M. Mauduit and H. Clavier, N-Heterocyclic Carbenes in Synthesis, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, Germany, 2006, pp. 183-222. (e) Wang, F.; Jun Liu, J.; Wang, W.; Li, S.; Shi, M. Chiral NHC-Metal-Based Asymmetric Catalysis Coord. Chem. Rev. 2012, 256, 804-853. (f) L. Wu, A. Salvador and R. Dorta, N-Heterocyclic Carbenes, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, Germany, 2014, pp. 39-84. (g) Zhao, D.; Candish, L.; Paul, D.; Glorius, F. N-Heterocyclic Carbenes in Asymmetric Hydrogenation ACS Catal. 2016, 6, 5978-5988. (h) Janssen-Müller, D.; Schlepphorst, C.; Glorius. F. Privileged Chiral N-Heterocyclic Carbene Ligands for Asymmetric Transition-Metal Catalysis Chem. Soc. Rev. 2017, 46, 4845-4854.

(3) (a) Seiders, T. J.; Ward, D. W.; Grubbs, R. H. Enantioselective Ruthenium-Catalyzed Ring-Closing Metathesis *Org. Lett.* **2001**, *3*, 3225-3228. (b) Fujimura, O.; Grubbs, R. H. Asymmetric Ring-Closing Metathesis: Kinetic Resolution Catalyzed by a Chiral Molybdenum Alkylidene Complex *J. Am. Chem. Soc.* **1996**, *118*, 2499-2500. (c) Costabile, C.; Cavallo, L. Origin of Enantioselectivity in the Asymmetric Ru-Catalyzed Metathesis of Olefins *J. Am. Chem. Soc.* **2004**, *126*, 9592– 9600.

(4) Applications of isolated C2 symmetric chiral NHC complexes in homogeneous catalysis: (a) Herrmann, W. A.; Goossen, L. J.; Köcher, C.; Artus, G. R. J. Chiral Heterocylic Carbenes in Asymmetric Homogeneous Catalysis Angew. Chem. Int. Ed. 1996, 35, 2805-2807. (b) Glorius, F.; Altenhoff, G.; Goddard, R.; Lehmann, C. Oxazolines as Chiral Building Blocks for Imidazolium Salts and N-Heterocyclic Carbene Ligands Chem. Commun. 2002, 2704-2705. (c) Winn, C. L.; Guillen, F.; Pytkowicz, J.; Roland, S.; Mangeney, P.; Alexakis A. Enantioselective Copper Catalysed 1,4-Conjugate Addition Reactions using Chiral N-Heterocyclic Carbenes J. Organomet. Chem. 2005, 690, 5672-5692. (d) Funk, T. W.; Berlin, J. M.; Grubbs, R. H. Highly Active Chiral Ruthenium Catalysts for Asymmetric Ring-Closing Olefin Metathesis J. Am. Chem. Soc. 2006, 128, 1840-1846. (e) Michon, C.; Ellern, A.; Angelici, R. J. Chiral Tetradentate Amine and Aminocarbene Ligands: Synthesis, Reactivity and X-ray Structural Characterizations Inorg. Chimica Acta 2006, 359, 4549-4556. (f) Shu, L.; Shi, Y. Chiral N-Heterocyclic Carbene-Pd(0)-Catalyzed Asymmetric Diamination of Conjugated Dienes and Triene J. Org. Chem. 2008, 73, 749-751. (g) Lillo, V.; Prieto, A.; Bonet, A.; Mar Díaz-Requejo, M.; Ramírez, J.; Pérez, P. J.; Fernández, E. Asymmetric α-Boration of α,β-Unsaturated Esters with Chiral (NHC)Cu Catalysts Organometallics 2009, 28, 659-662. (h) Wu, L.; Falivene, L.; Drinkel, E.; Grant, S.; Linden, A.; Cavallo, L.; Dorta, R. Synthesis of 3-Fluoro-3-aryl Oxindoles: Direct Enantioselective a Arylation of Amides Angew. Chem. Int. Ed. 2012, 51, 2870-2873. (i) Wu, L.; Salvador, A.; Ou, A.; Shi, M. W.; Skelton, B. W.; Dorta, R. Monodentate Chiral N-Heterocyclic Carbene-Palladium-Catalyzed Asymmetric Suzuki-Miyaura and Kumada Coupling Synlett 2013, 24, 1215-1220. (j) Sipos, G.; Ou, A.; Skelton, B. W.; Falivene, L.; Cavallo, L.; Dorta, R. Unusual NHC-Iridium(I) Complexes and Their Use in the Intramolecular Hydroamination of Unactivated Aminoalkenes Chem. Eur. J. 2016, 22, 6939-6946. (k) Savka, R.; Bergmann, M.; Kanai, Y.; Foro, S.; Plenio, H. Triptycene-Based Chiral and meso-N-Heterocyclic Carbene Ligands and Metal Complexes Chem. Eur. J. 2016, 22, 9667-9675. (1) Paul, D.; Beiring, B.; Plois, M.; Ortega, N.; Kock, S.; Schlüns, D.; Neugebauer, J.; Wolf, R.; Glorius, F. A Cyclometalated Ruthenium-NHC Precatalyst for the Asymmetric Hydrogenation of (Hetero)arenes and Its Activation Pathway Organometallics 2016, 35, 3641-3646. (m) Gao, P.; Sipos, G.; Foster, D.; Dorta, R. Developing NHC-Iridium Catalysts for the Highly Efficient Enantioselective Intramolecular Hydroamination Reaction ACS Catal. 2017, 7, 6060-6064.

(5) Applications of C₂ symmetric chiral NHC ligands in homogeneous catalysis using a one-pot procedure: (a) Tominaga, S.; Oi, Y.; Kato, T.; An, D. K.; Okamoto, S. y-Selective Allylic Substitution Reaction with Grignard Reagents Catalyzed by Copper N-Heterocyclic Carbene Complexes and its Application to Enantioselective Synthesis Tetrahedron Lett. 2004, 45, 5585-5588. (b) Arao, T.; Kondo, K.; Aoyama, T. Development of an N-Heterocyclic Carbene Ligand Based on Concept of Chiral Mimetic Tetrahedron Lett. 2006, 47, 1417-1420. (c) Martin, D.; Kehrli, S.; d'Augustin, M.; Clavier, H.; Mauduit, M.; Alexakis, A. Copper-Catalyzed Asymmetric Conjugate Addition of Grignard Reagents to Trisubstituted Enones. Construction of All-Carbon Quaternary Chiral Centers J. Am. Chem. Soc. 2006, 128, 8416-8417. (d) Matsumoto, Y.; Yamada, K.; Tomioka, K. C2 Symmetric Chiral NHC Ligand for Asymmetric Quaternary Carbon Constructing Copper-Catalyzed Conjugate Addition of Grignard Reagents to 3-Substituted Cyclohexenones J. Org. Chem. 2008, 73, 4578-4581. (e) Chaulagain, M. R.; Sormunen, G. J.; Montgomery, J. New N-Heterocyclic Carbene Ligand and Its Application in Asymmetric Nickel-Catalyzed Aldehyde/Alkyne Reductive Couplings J. Am. Chem. Soc. 2007, 129, 9568-9569. (f) Kehrli, S.; Martin, D.; Rix, D.; Mauduit, M.; Alexakis, A. Formation of Quaternary Chiral Centers by N-Heterocyclic Carbene-Cu-Catalyzed Asymmetric Conjugate Addition Reactions with Grignard Reagents on Trisubstituted Cyclic Enones Chem. Eur. J. 2010, 16, 9890-9904. (g) Urban, S.; Ortega, N.; Glorius, F. Ligand-Controlled Highly Regioselective and Asymmetric Hydrogenation of Quinoxalines Catalyzed by Ruthenium N-Heterocyclic Carbene Complexes Angew. Chem. Int. Ed. 2011, 50, 3803-3806. (h) Ortega, N.; Urban, S.; Beiring, B.; Glorius, F. Ruthenium NHC Catalyzed Highly Asymmetric Hydrogenation of Benzofurans Angew. Chem. Int. Ed. 2012, 51, 1710-1713. (i) Ortega, N.; Beiring, B.; Urban, S.; Glorius, F. Highly Asymmetric Synthesis of (+)-Corsifuran A. Elucidation of the Electronic Requirements in the Ruthenium-NHC Catalyzed Hydrogenation of Benzofurans Tetrahedron 2012, 68, 5185-5192. (j) Urban, S.; Beiring, B.; Ortega, N.; Paul, D.; Glorius, F. Asymmetric Hydrogenation of Thiophenes and Benzothiophenes J. Am. Chem. Soc. 2012, 134, 15241-15244. (k) Ortega, N.; Tang, D.-T. D.; Urban, S.; Zhao, D.; Glorius, F. Ruthenium-NHC-Catalyzed Asymmetric Hydrogenation of Indolizines: Access to Indolizidine Alkaloids Angew. Chem. Int. Ed. 2013, 52, 9500-9503. (1) Wysocki, J.; Ortega, N.; Glorius, F. Asymmetric Hydrogenation of Disubstituted Furans Angew. Chem. Int. Ed. 2014, 53, 8751-8755. (m) Schlepphorst, C.; Wiesenfeldt, M. P.; Glorius, F. Enantioselective Hydrogenation of Imidazo[1,2-a]pyridines Chem. Eur. J. 2018, 24, 356-359. (n) Pace, V.; Rae, J. P.; Procter, D. J. Cu(I)-NHC Catalyzed Asymmetric Silyl Transfer to Unsaturated Lactams and Amides Org. Lett. 2014, 16, 476-479. (o) Kumar, R.; Hoshimoto, Y.; Yabuki, H.; Ohashi, M.; Ogoshi, S. Nickel(0)-Catalyzed Enantio- and Diastereoselective Synthesis of Benzoxasiloles: Ligand-Controlled Switching from Inter- to Intramolecular Aryl-Transfer Process J. Am. Chem. Soc. 2015, 137, 11838-11845. (p) Ahlin, J. S. E.; Cramer, N. Chiral N-Heterocyclic Carbene Ligand Enabled Nickel(0)-Catalyzed Enantioselective Three-Component Couplings as Direct Access to Silylated Indanols Org. Lett. 2016, 18, 3242-3245. (q) Kumar, R.; Tamai, E.; Ohnishi, A.; Nishimura, A.; Hoshimoto, Y.; Ohashi, M.; Ogoshi, S. Nickel-Catalyzed Enantioselective Synthesis of Cyclobutenes via [2+2] Cycloaddition of $\alpha,\beta\text{-Unsaturated Carbonyls with}$ 1,3-Enynes Synthesis 2016, 48, 2789-2794. (r) Loup, J.; Zell, D.; Oliveira, J. C. A.; Keil, H.; Stalke, D.; Ackermann, L. Asymmetric Iron-Catalyzed C-H Alkylation Enabled by Remote Ligand meta-Substitution Angew. Chem. Int. Ed. 2017, 56, 14197-14201. (6) (a) Knowles, W. S. Asymmetric Hydrogenation Acc. Chem. Res.

(6) (a) Knowles, W. S. Asymmetric Hydrogenation Acc. Chem. Res.
1983, 16, 106-112. (b) Brown, J. M., in: Jacobsen, E. N.; Pfaltz, A.;
Yamamoto, H. (Eds.), Comprehensive Asymmetric Catalysis, Springer-Verlag, Berlin, Germany, 1999, vol 1-3, pp. 122–181. (c) Walsh, P. J.,
in: Walsh, P. J.; Kozlowski, M. C. (Eds.) Fundamentals of Asymmetric Catalysis, University Science Book, Casebound, 2009, Chap. 4, pp. 114-164. (d) Gridnev, I. D.; Imamoto, T. Mechanism of Enantioselection in Rh-Catalyzed Asymmetric Hydrogenation. The Origin of Utmost Catalytic Performance Chem. Commun. 2009, 48, 7447-7464. (7) (a) Wolfe, J. P.; Wagaw, S.; Marcoux, J.-F.; Buchwald, S. L. Rational Development of Practical Catalysts for Aromatic Carbon–Nitrogen Bond Formation *Acc. Chem. Res.* **1998**, *31*, 805. (b) Hartwig, F. F. Carbon–Heteroatom Bond-Forming Reductive Eliminations of Amines, Ethers, and Sulfides *Acc. Chem. Res.* **1998**, *31*, 852. (c) Yang, B. H.; Buchwald, S. L. Palladium-Catalyzed Amination of Aryl Halides and Sulfonates *J. Organomet. Chem.* **1999**, *576*, 125–146. (d) Surry, D. S.; Buchwald, S. L. Dialkylbiaryl Phosphines in Pd-Catalyzed Amination: a User's guide *Chem. Sci.* **2011**, *2*, 27–50. (e) Maiti, D.; Fors, B. P.; Henderson, J. L.; Nakamura, Y.; Buchwald, S. L. Palladium-Catalyzed Coupling of Functionalized Primary and Secondary Amines with Aryl and Heteroaryl Halides: Two Ligands Suffice in Most Cases *Chem. Sci.* **2011**, *2*, 57–68.

(8) (a) Burtner, R. R.; Brown, J. M. Synthetic Choleretics. II. Phenol Derivatives J. Am. Chem. Soc. 1953, 75, 2334-2340.

(b) Del Rosso, P. G.; Almassio, M. F.; Palomar, G. R.; Garay, R. O. Nitroaromatic Compounds Sensing. Synthesis, Photophysical Characterization and Fluorescence Quenching of a New Amorphous Segmented Conjugated Polymer with Diphenylfluorene Chromophores *Sensors and Actuators, B: Chemical* **2011**, *160*, 524-532.

(c) Li, K.; Guan, X.; Ma, C.-W.; Lu, W.; Chen, Y.; Che, C.–M. Blue Electrophosphorescent Organoplatinum(II) Complexes with Dianionic Tetradentate Bis(carbene) Ligands *Chem. Commun.* **2011**, *47*, 9075-9077.

(9) All data can be obtained free of charge from The Cambridge Crystallographic Data Centre: www.ccdc.cam.ac.uk/data request/cif.

(10) (a) Herrmann, W. A.; Köcher, C.; Gooßen, L. J.; Artus, G. R. J. Heterocyclic Carbenes: A High-Yielding Synthesis of Novel, Functionalized N-Heterocyclic Carbenes in Liquid Ammonia Chem. Eur. J. 1996, 2, 1627-1636. (b) Enders, D.; Gielen, H.; Runsink, J.; Breuer, K.; Brode, S.; Boehn, K. Diastereoselective Synthesis of Chiral (Triazolinylidene)rhodium Complexes Containing an Axis of Chirality Eur. J. Inorg. Chem. 1998, 913-919. (c) Ahmed, M.; Buch, C.; Routaboul, L.; Jackstell, R.; Klein, H.; Spannenberg, A.; Beller, M. Hydroaminomethylation with Novel Rhodium-Carbene complexes: An Efficient Catalytic Approach to Pharmaceuticals Chem. Eur. J. 2007, 13, 1594-1601. (d) Jokić, N. B.; Zhang-Presse, M.; Goh, S. L. M.; Straubinger, C. S.; Bechlars, B.; Herrmann, W; A.; Kühn, F. E. Symmetrically Bridged Bis-N-Heterocyclic Carbene Rhodium (I) Complexes and Their Catalytic Application for Transfer Hydrogenation Reaction J. Organomet. Chem. 2011, 696, 3900-3905. (e) Truscott, B. J.; Nahra, F.; Slawin, A. M. Z.; Cordes, D. B.; Nolan, S. P. Fluoride, Bifluoride and Trifluoromethyl Complexes of Iridium(I) and Rhodium(I) Chem. Commun. 2015, 51, 62-65. (f) Gil, W.; Trzeciak, A. M. N-Heterocyclic Carbene-Rhodium Complexes as Catalysts for Hydroformylation and Related Reactions Coord. Chem. Rev. 2011, 255, 473-483.

(11) (a) Coleman, A. W.; Hitchcock, P. B.; Lappert, M. F; Maskell, R. K.; Müller, J. H. Carbene complexes XIX. Optically active electronrich olefin-derived carbene-transition-metal complexes. Crystal structures of $[RhCl(COD)(C_7H_{12}N_2)],$ $[RhCl(COD)(C_9H_{16}N_2)].$ [RhCl(PPh₃)₂(C₉H₁₈N₂)] and [Co(CO)(NO)(PPh₃)(C₆H₁₂N₂)] J. Organomet. Chem. 1985, 296, 173-196. (b) Faller, J. W.; Fontaine, P. P. Stereodynamics and Asymmetric Hydrosilylation with Chiral Rhodium Complexes Containing a Monodentate N-Heterocyclic Carbene Organometallics 2006, 25, 5887-5893. (c) Türkmen, H.; Şahin, O.; Büyükgüngör, O.; Çetinkaya, B. Silver, Palladium and Rhodium Complexes of Acenaphthylene-Anullated N-Heterocyclic Carbene Ligands: A Comparative Study Eur. J. Inorg. Chem. 2006, 4915-4921. (d) Bon, R. S.; de Kanter, F. J. J.; Lutz, M.; Spek, A. L.; Jahnke, M. C.; Hahn, F. E.; Groen, M. B.; Orru, R. V. A. Multicomponent Synthesis of N-Heterocyclic Carbene Complexes Organometallics 2007, 26, 3639-3650. (e) Laï, R.; Daran, J. -C.; Heumann, A.; Zaragori-Benedetti, A.; Rafii, E. The synthesis and X-ray structure of a chiral rhodium-NHC complex: Implications for the use of NHCs in asymmetric hydroformylation catalysis Inorganica Chim. Acta 2009, 362, 4849-4852. (f)

Schwartsburd, L.; Mahon, M. F. Poulten, R. C.; Warren, M. R.; Whittlesey, M. K. Mechanistic Studies of the Rhodium NHC Catalyzed Hydrodefluorination of Polyfluorotoluenes *Organometallics* **2014**, *33*, 6165–6170.

(12) Gladiali, S.; Alberico, E. Asymmetric Transfer Hydrogenation: Chiral Ligands and Applications *Chem. Soc. Rev.* **2006**, *35*, 226-236.

(13) Crabtree, R. H. Resolving Heterogeneity Problems and Impurity Artifacts in Operationally Homogeneous Transition Metal Catalysts *Chem. Rev.* **2012**, *112*, 1536–1554.

(14) (a) Li, K.; Hu, N.; Luo, R.; Yuan, W.; Tang, W. A Chiral Ruthenium-Monophosphine Catalyst for Asymmetric Addition of Arylboronic Acids to Aryl Aldehydes J. Org. Chem. **2013**, 78, 6350-6355. (b) Lee, J.; Oh, Y.; Choi, Y. K.; Choi, E.; Kim, K.; Park, J.; Kim, M. J. Dynamic Kinetic Resolution of Diarylmethanols with an Activated Lipoprotein Lipase ACS Catal. **2015**, 5, 683-689. (c) Salvi, L.; Kim, J. G.; Walsh, P. J. Practical Catalytic Asymmetric Synthesis of Diaryl-, Aryl Heteroaryl-, and Diheteroarylmethanols J. Am. Chem. Soc. **2009**, 131, 12483-12493. (d) DeBerardinis, A. M.; Turlington, M.; Ko, J.; Sole, L.; Pu, L. Facile Synthesis of a Family of H₈BINOL-Amine Compounds and Catalytic Asymmetric Arylzinc Addition to Aldehydes J. Org. Chem. **2010**, 75, 2836-2850. (e) Jean, M.; Casanova, B.; Gnoatto, S.; van de Weghe, P. Strategy of Total Synthesis Based on the Use of Rh-Catalyzed Stereoselective 1,4-Addition Org. Biomol. Chem. **2015**, 13, 9168-9175.

(15) (a) Sakai, M.; Hayashi, H.; Miyaura, N. Rhodium-Catalyzed Conjugate Addition of Aryl- or 1-Alkenylboronic Acids to Enones Organometallics 1997, 16, 4229-4231. (b) Takaya, Y.; Ogasawara, M.; Hayashi, T.; Sakai, M.; Miyaura, N. Rhodium-Catalyzed Asymmetric 1,4-Addition of Aryl- and Alkenylboronic Acids to Enones J. Am. Chem. Soc. 1998, 120, 5579-5580. (c) Jagt, R. B. C.; Toullec, P. Y.; de Vries, J. G.; Feringa, B. L.; Minnaard, A. J. Rhodium/Phosphoramidite-Catalyzed Asymmetric Arylation of Aldehydes with Arylboronic Acids Org. Biomol. Chem. 2006, 4, 773-775. (d) Duan, H.-F.; Xie, J.-H.; Shi, W.-J.; Zhang, Q.; Zhou, Q.-L. Enantioselective Rhodium-Catalyzed Addition of Arylboronic Acids to Aldehydes Using Chiral SpiroMonophosphite Ligands Org. Lett. 2006, 8, 1479-1481. (e) Arao, T.; Suzuki, K.; Kondo, K.; Aoyama, T. Asymmetric Synthesis of Diarylmethanols: Development of a Hemilabile Phosphorus Ligand Based on the Concept of Conformational Control Synthesis 2006, 2006, 3809-3814. (f) Sieffert, N.; Boisson, J.; Py, S. Enantioselective Arylation of N-Tosylimines by Phenylboronic Acid Catalysed by a Rhodium/Diene Complex: Reaction Mechanism from Density Functional Theory Chem. Eur. J. 2015, 21, 9753-9768. (g) Kamikawa, K.; Tseng, Y.-Y.; Jian, J.-H.; Takahashi, T.; Ogasawara, M. Planar-Chiral Phosphine-Olefin Ligands Exploiting a (Cyclopentadienyl)manganese(I) Scaffold To Achieve High Robustness and High Enantioselectivity J. Am. Chem. Soc. 2017, 139, 1545-1553.

(16) (a) Duan, W.; Ma, Y.; He, F.; Zhao, L.; Chen, J.; Song, C. Synthesis of Novel Planar Chiral Ag and Rh N-Heterocyclic Carbene Complexes Derived from [2.2]Paracyclophane and Their Application in Ultrasound Assisted Asymmetric Addition Reactions of Organoboronic Acids to Aldehydes Tetrahedron Asym. 2013, 24, 241-248. (b) Chen, J.; Yang, S.; Chen, Z.; Song, C.; Ma, Y. Synthesis of Novel Macrocyclic Planar Chiral Carbene-Ag Complexes Derived From [2.2]Paracyclophane for Rh-Catalyzed Asymmetric 1,2-Additions of Arylboronic Acids to Aromatic Aldehydes Tetrahedron: Asym. 2015, 26, 288-295. (c) He, W.; Zhou, B.; Li, J.; Shi, J. Synthesis of New Chiral Benzimidazolylidene-Rh Complexes and Their Application in Asymmetric Addition Reactions of Organoboronic Acids to Aldehydes Catalysts 2016, 6, 132-140. (d) He, W.-P.; Zhou, B.-H.; Zhou, Y.-L.; Li, X.-R.; Fan, L.-M.; Shou, H.-W.; Li, J. Synthesis of New Benzimidazolium Salts and their Application in the Asymmetric Arylation of Aldehydes Tetrahedron Lett. 2016, 57, 3152-3155.