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Chiral Diphosphane- and NHC-Containing Ruthenium Catalysts for the Catalytic Asymmetric Arylation of Aldimines with Organoboron Reagents

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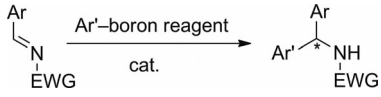
Keywords: Chirality / Amines / Ruthenium / Asymmetric catalysis / Arylboronic acids / N,P ligands

For the first time, we report the application of $[RuCl_2(\eta^6\text{-}p\text{-cymene})]_2$ in the arylation of *N*-activated aldimines with boronic acids and its derivatives to afford chiral amines, which are important intermediates in the syntheses of key bioactive compounds. The behavior of the chiral ligands, the imine substrates, and the organoboron reagents were studied. Very good enantioselectivities were obtained.

Introduction

Many important drugs[1] used in the treatment of several chronic illnesses, like Parkinson's and Alzheimer's disease, have a chiral amine moiety. For this reason, it is important to develop new and more efficient methods for the creation of chiral amine units. The asymmetric addition of an aryl group to the C=N unit of an imine is one example. The arylation reaction of electron-withdrawing-group *N*-substituted arylimines with organoboron reagents is a suitable method for this (Scheme 1).



Scheme 1. Asymmetric synthesis of chiral amines. Addition of organoboron reagents to activated imines containing electron-withdrawing groups (EWGs).

In 2004, Tomioka[2] and co-workers used hemilabile chiral P,O-ligands and rhodium precatalysts along with arylboronic acids and arylboroxine compounds as the aryl transfer reagents to obtain enantioenriched arylamines in excellent yields. Hayashi[3] reported excellent results (98% yield and 99% *ee*) using chiral diene ligands coordinated to a rhodium center in the catalytic asymmetric arylation of *N*-tosylarylimines with arylboroxine reagents in aqueous media.

Employing analogous methods, Ellman's group[4–6] used chiral phosphane ligands with rhodium precatalysts, diphenylphosphinoylimine substrates, and arylboronic acids to give the corresponding chiral amines with excellent yields and enantioselectivities. Chiral palladium-containing catalysts have also been used. Ma's group[7] has reported the successful application of chiral Pd–NHC (N-heterocyclic carbene) catalysts, and Lu's group[8] has employed chiral palladium pyridine–oxazoline catalysts.

Not long ago, we employed chiral palladium catalysts in the arylation reaction of substituted *N*-tosylarylimines.[9] This reaction was reviewed in a very recent paper.[10] However, we were also interested in investigating new ruthenium catalysts for this reaction. This decision was made as a result of ruthenium being cheaper than rhodium and palladium and having an impressive application profile in organometallic chemistry.[11–15]

Results and Discussion

(i) Diphosphane–Ruthenium Complexes

Preliminary tests were conducted by using commercial $[RuCl_2(\eta^6\text{-}p\text{-cymene})]_2$ as a precatalyst and several commercial chiral phosphanes (Figure 1), which were already successfully used in the catalytic reaction with Rh and Pd.[9] By starting with the DioxPhos ligand (**3**, an analogue of the DIOP ligand, see Figure 1), *o*-chloro-*N*-tosylbenzaldimine as the substrate, and phenylboronic acid as the aryl source, the desired amine product was obtained in 63% yield and 57% *ee* (Table 1, Entry 1).

Motivated by this result, we applied this procedure to several imine substrates, which were synthesized according to literature procedures.[16] To compare the contribution of the electron-withdrawing and electron-donating effects on the outcome of the reaction, both electron-rich and electron-deficient imine substrates and arylboronic acid reagents were screened. Generally, the best yields were obtained when electron-poor imines were used (Table 1, Entries 1, 2, 11, and 15), as expected from the literature pre-

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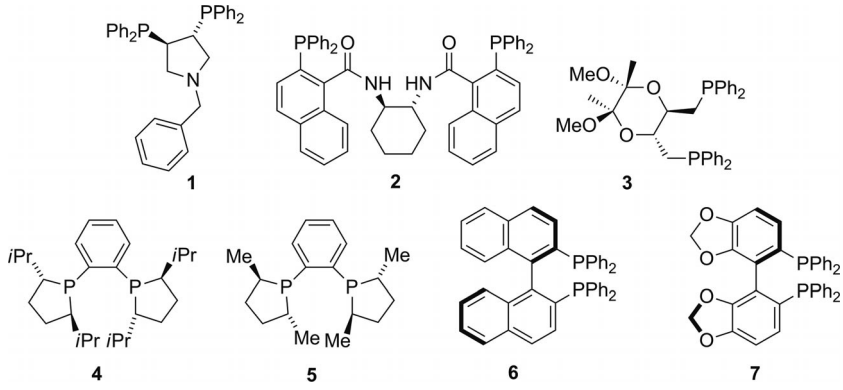
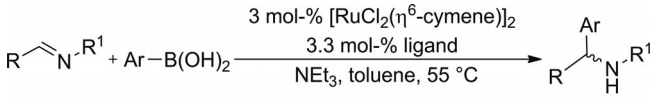


Figure 1. Library of chiral diphosphane ligands used in this work.

Table 1. Catalytic enantioselective arylation of *N*-protected aldimines with arylboronic acids.



R^1 = Ts, except for Entry 8 (Ms)

Entry[a]	R	L	Ar	*T* [h]	Yield [%][b]	*ee* [%][c]
1	*o*-ClC_6H_4	3	Ph	72	63	57 (*R*)
2	*p*-ClC_6H_4	3	Ph	48	14	90 (*R*)
3	2-naphthyl	3	Ph	48	12	44 (*R*)
4	*o*-$CH_3C_6H_5$	3	Ph	48	<10	14 (*S*)
5	cyclohexyl	3	Ph	48	17	17 (*S*)
6	*p*-BrC_6H_4	3	Ph	48	12	69 (*S*)
7	*p*-$NO_2C_6H_4$	3	Ph	48	<10	5 (*R*)
8	*p*-ClC_6H_4	3	Ph	48	10	75[d]
9	$CH_3CH_2CH_2$	3	Ph	48	13	8 (*R*)
10	*o*-ClC_6H_4	3	*p*-ClC_6H_4	48	12	88 (*S*)
11	*o*-ClC_6H_4	2	Ph	72	39	90 (*R*)
12	*o*-ClC_6H_4	6	Ph	72	<10	98 (*R*)
13	*o*-ClC_6H_4	1	Ph	72	16	16 (*R*)
14	*o*-ClC_6H_4	4	Ph	72	27	91 (*R*)
15	*o*-ClC_6H_4	5	Ph	72	38	94 (*R*)
16	*o*-ClC_6H_4	7	Ph	72	<10	12 (*S*)

[a] Reagents and conditions: imine (0.2 mmol), $ArB(OH)_2$ (2 equiv.), toluene (2 mL), NEt_3 (2 equiv.). [b] Isolated yields after chromatography. [c] Determined by chiral stationary-phase HPLC. [d] Preferred configuration not determined.

cedent.[17] A significant decrease in the yield was observed when electron-rich imine substrates were used (Table 1, Entry 4).

The best yields (38–63%) were obtained with *o*-chloro-*N*-tosylbenzaldimine, phenylboronic acid, and ligands **3**, **2**, and **5** (Table 1, Entries 1, 11, and 15). The best enantioselectivities were obtained with ligands **2**–**6** (88–98%*ee*). This was generally achieved with the *o*-chlorophenyl-substituted imine substrate, but in certain cases, the *p*-chlorophenyl-substituted substrates (Table 1, Entry 2) or the *p*-chlorophenyl-substituted arylboronic acid (Table 1, Entry 10) gave high enantioselectivities. The presence of an electron-donating group in either the substrate or the arylboronic acid reagent was of no advantage. In all of the reactions involving the *o*-chlorophenyl-substituted imine substrate and phenylboronic acid, the product configuration was (*R*), except when (*R*)-SegPhos (**7**) was used as ligand (Table 1, Entry 16). The change in the enantiofacial selectivity might be attributed to a subtle difference in the reaction mechanism. In addition, the imine activating group was investigated, and the mesyl (Ms) group was considered for this activation. Considering that the yield remained the same, the enantioselectivity dropped dramatically from 90%*ee* (with Ts, Table 1, Entry 2) to 75%*ee* (with Ms, Table 1, Entry 8), therefore, no improvements were gained. The lower enantioselectivity might be attributed to the reduced steric hindrance during the aryl addition step.[18] It was also possible to conduct the reaction with alkylimine substrates (see Table 1, Entries 5 and 9). However, this resulted in moderate enantioselectivities.

Secondary diaryl alcohols – the products of aldehyde arylation[19] – have been detected in this reaction, which was previously reported with chiral Ru catalysts.[20] The secondary alcohol product was always obtained in almost racemic form for all of the reactions using *o*-chloro-*N*-tosylbenzaldimine (<5%*ee*). The enantiopurities of all of the other secondary alcohol products were not determined.

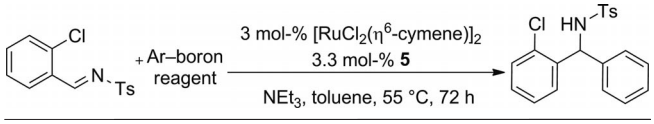
These imine substrates are very susceptible to hydrolysis, and under the reaction conditions (with arylboronic acids), there is sufficient water present to promote a ruthenium-catalyzed imine hydrolysis. This was confirmed by conducting an experiment with only the imine and the catalyst. Although we did not quantify the amount of the secondary alcohol produced in the reactions, as this came to our attention after the reactions were performed and analyzed, the analyses of the HPLC chromatograms showed that there were more than vestigial quantities present. In fact, an additional experiment was performed by using the conditions shown in Table 1, Entry 1, for a shorter time, which yielded the product amine (isolated yield of 8%, 57%*ee*) along with the corresponding secondary alcohol (35% yield) in racemic form. It seems that, at the outset, the formation of the alcohol might be more rapid than that of the amine, but the alcohol formation reaches a threshold, and then arylation of the imine proceeds.

To avoid this unwanted side reaction, we decided to implement some new countermeasures. One such measure was to add the *o*-chloro-*N*-tosylbenzaldimine substrate slowly to the reaction mixture containing phenylboronic acid and

(*R*)-Me-DuPhos (**5**). The addition was carried out over a 7 h period, and then the reaction was left for 2 d. The isolated yield was less than 10% with an enantioselectivity of 78%*ee*, in favor of the (*R*) enantiomer. Analysis of the crude product by HPLC showed that there was a vestigial quantity of the alcohol (racemic) present and small quantities of both the imine substrate and its aldehyde precursor. This strategy failed to improve the reaction yield. The lower observed enantioselectivity (78%*ee*), compared to that obtained in the original reaction (Table 1, Entry 15), might be an indication of subtle ligand dynamics forming hemilabile catalysts, perhaps during the course of the reaction.

Another approach to resolve this problem was to use more anhydrous arylboron reagents, like sodium tetraphenylborate (Ph_4BNa), potassium trifluoro(phenyl)borate ($PhBF_3K$), 1,3-propanediol boronic ester ($C_9H_{11}BO_2$), Ph_3B,[21] and phenylboroxine [$(PhBO)_3$]. This strategy worked to some extent, as the quantity of alcohol was reduced, but the isolated yield of the amine product did not improve. All of the results (except for those from using Ph_3B, which showed no improvements) are shown in Table 2. What was very surprising was the change in the configuration of the product from (*R*) to (*S*), even when phenylboronic acid was used (Table 2, Entry 6) in the presence of activated molecular sieves (MS). When the amount of water is reduced, there may be an alternative reaction mechanism taking place (see below for further discussion). The best aryl transfer reagents were phenylboroxine and 1,3-propanediol boronic ester (Table 2, Entries 1 and 4). It should be noted that this is the first report on the use of a boronic ester in this reaction. The only boron reagent that could compete successfully with phenylboronic acid in terms of enantioselectivity was Ph_4BNa, which gave an enantioselectivity of 93%*ee*.

Table 2. Catalytic enantioselective arylation of *o*-chloro-*N*-tosylbenzaldimine with several organoboron reagents.

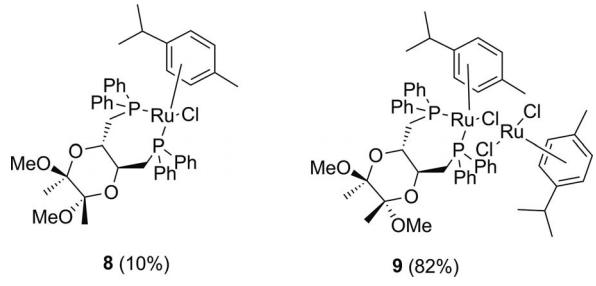


Entry[a]	Ar–boron reagent	Yield [%][b]	*ee* [%][c]
1	$(PhBO)_3$	31	74 (*S*)
2	Ph_4BNa	<10	93 (*S*)
3	$PhBF_3K$	<10	68 (*S*)
4	$C_9H_{11}BO_2$	26	56 (*S*)
5[d]	$(PhBO)_3$	<10	78 (*S*)
6[d]	$PhB(OH)_2$	11	68 (*S*)

[a] Reagents and conditions: imine (0.2 mmol), Ar–boron reagent (2 equiv.), toluene (2 mL), NEt_3 (2 equiv.). [b] Isolated yields after chromatography. [c] Determined by chiral stationary-phase HPLC. [d] MS (3 Å; 200 mg) were added to the reaction vessel.

To better understand this phenomenon, we decided to carry out two key experiments using $(PhBO)_3$ and $PhB(OH)_2$ in the presence of activated molecular sieves (3 Å). Both the yields and the enantioselectivities dropped significantly (compare Table 1, Entry 15 with Table 2, Entry 6 and compare Table 2, Entry 1 with Entry 5). Water may play an important role as a coligand on the active catalyst.

We also tried to get a handle on the type of active catalyst involved in this reaction. For this purpose, the enantiopode (*S*)-**3** [as we had no (*R*)-**3** available] was stirred with $[RuCl_2(\eta^6\text{-}p\text{-cymene})]_2$ (0.5 equiv.) in dry CH_2Cl_2 at room temperature overnight. After purification by silica gel column chromatography, two principle fractions were obtained, which yielded orange solids. These compounds were identified by mass spectrometry to be the monomer **8** (10% yield, Figure 2) with observed molecular peaks at *m*/*z* = 843 [M(^{35}Cl)] and 845 [M(^{37}Cl)] and the dimer **9** (82% yield, Figure 2) with observed molecular peaks at *m*/*z* = 1149 [M(^{35}Cl × 3)] and 1151 [M(^{35}Cl × 2 + ^{37}Cl)]. These isolated complexes were then screened in the appropriate arylation reaction of *o*-chloro-*N*-tosylbenzaldimine with phenylboronic acid by using the conditions shown in Table 1. It was found that each complex was capable of arylating this substrate. In the case of **8** (at a loading of 5 mol-%), the product was obtained with a yield of 41% and an enantioselectivity of 34%*ee* in favor of the (*R*) enantiomer. In the case of complex **9** (at 20 mol-% loading), the product was obtained with a yield of 27% and an enantioselectivity of 54% in favor again of the (*R*) enantiomer. Vestigial quantities of both the alcohol (racemic) and the aldehyde were observed. The fact that the major amine product had the (*R*) configuration came as a surprise, as the (*S*) enantiomer was expected. This result mirrors those seen earlier when water was kept at a minimum in the reaction with (*R*)-Me-DuPhos (**5**, see discussion above and Table 2), and together they seem to imply that water may form an alternative competing active catalyst to those putative catalysts shown in Figure 2, perhaps with water substituting for the chloride ions.



8 (10%) **9** (82%)

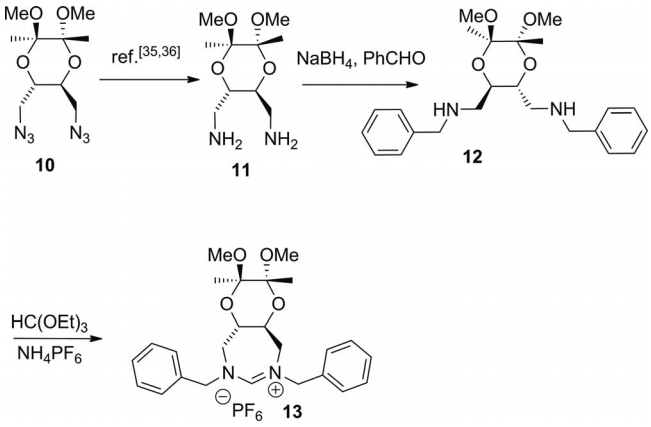
Figure 2. The monomeric (**8**) and dimeric (**9**) ruthenium complexes exhibiting catalytic activity.

(ii) NHC–Ruthenium Complexes – New Catalysts

Although the preliminary results with these chiral diphosphane ligands were very encouraging, we were also interested in investigating other ligand types, notably, N-heterocyclic carbenes (NHCs), which show strong σ-electron-donating properties[22–24] and strong NHC–metal bonding.[25] The possibility of tuning the electronic and stereochemical characteristics of NHC ligands, almost at will, represents another strong advantage of this class of li-

gands.[26] Making structural changes to the catalyst can lead to better results.[27]

Previous work in our laboratory[28–31] and from other groups[32–38] has shown the applicability of the conformationally locked cyclic diacetal backbone in asymmetric synthesis and particularly in asymmetric catalysis. Chiral diamine **11**[35,36] (Scheme 2) was obtained from the commercially available diazide **10** through a simple metal-catalyzed hydrogenation.[35] Diamine **11** underwent a reductive amination to give the dibenzylated amine **12** (which had previously been obtained by an alternative route[36]), which was then converted by standard methods to the dihydroimidazolinium salt **13** in 57% yield.

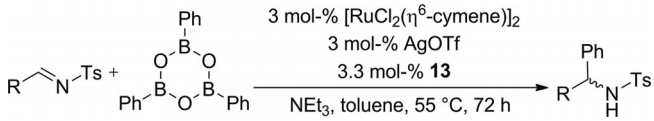


Scheme 2. Synthetic pathway to the mono(dihydroimidazolinium) salt **13**.

To use this dihydroimidazolinium salt **13** (Scheme 2) as a chiral NHC ligand, deprotonation of the imidazolium halide was required. Silver salts are often employed for the in situ generation of cationic transition-metal catalysts.[39–41] They behave as halide scavenger agents, forming a weak Ag–NHC bond, and easily undergo a transmetalation step with the required metal atom.[42–44] We decided to carry out a screening study with some ruthenium precatalysts, the NHC ligand precursor **13** (Scheme 2), and silver salts to form the active carbene species. In the first reaction, silver triflate (AgOTf) was added to **13**, followed by the addition of $[RuCl_2(\eta^6\text{-}p\text{-cymene})]_2$ (in situ) with *N*-tosylnaphthaldimine as the substrate and $PhB(OH)_2$ as the phenyl transfer agent. The desired amine product was obtained in 15% yield and 89%*ee* [the major enantiomer had the (*S*) configuration]. The low yield was probably due to the hydrolysis of the imine substrate, as 2-naphthaldehyde was detected in the HPLC chromatogram. Consequently, we decided to use $(PhBO)_3$ as the phenyl transfer reagent,[43] with $[RuCl_2(\eta^6\text{-}p\text{-cymene})]_2$, AgOTf, and the NHC precursor **13**. The results obtained are shown in Table 3.

To investigate the reaction scope with $(PhBO)_3$ as the phenyl transfer reagent, a number of reactions were performed. In some cases, small quantities of molecular sieves (3 Å; 200 mg)[6–8] were added to determine the influence of water on the reaction yield and enantioselectivity (Table 3, Entries 5–7). In the case of *N*-tosyl-2-naphthaldimine (Table 3, Entry 7), the yield increased significantly.

Table 3. Catalytic enantioselective arylation of *N*-tosylarylaldimines with $(PhBO)_3$ and NHC precursor **13**.



Entry[a]	R	Yield [%][b]	*ee* [%][c]
1	*o*-ClC_6H_4	29	20 (*S*)
2	*p*-ClC_6H_4	32	31 (*R*)
3	2-naphthyl	22	72 (*R*)
4	*p*-$CH_3OC_6H_4$	53	80 (*S*)
5[d]	*o*-ClC_6H_4	27	*rac*
6[d]	*p*-ClC_6H_4	19	23 (*S*)
7[d]	2-naphthyl	77	<10 (*S*)

[a] Reagents and conditions: imine (0.2 mmol), $(PhBO)_3$ (2 equiv.), toluene (2 mL), NEt_3 (2 equiv.). [b] Isolated yields after chromatography. [c] Determined by chiral stationary-phase HPLC. [d] MS (3 Å; 200 mg) were added to the reaction vessel. *rac* = racemic product.

When molecular sieves were used, the enantioselectivities dropped significantly (Table 3, compare Entries 1 and 5, and compare Entries 3 and 7). This result seems to support the postulate that water coordinates with the metal atom, making the catalyst more bulky and leading to greater enantiofacial discrimination at the imine reaction site. High enantioselectivities (72 and 80%*ee*) were obtained when electron-rich substrates were used (Table 3, Entries 3 and 4, respectively). Vestigial quantities of the corresponding secondary alcohols were observed by HPLC analysis.

It is known from the literature that NHC–Ag^I complexes can be used in catalysis.[45,46] To determine if the silver complex was, in fact, catalyzing the reaction, an experiment was performed by using the same protocol, but in the absence of $[RuCl_2(\eta^6\text{-}p\text{-cymene})]_2$. Only the substrate and the organoboron reagent were recovered, showing that the silver–NHC complex derived from **13** (Scheme 2) was not the active catalyst in this particular transformation.

Conclusions

We report the first application of ruthenium catalysts in the arylation of both electron-rich and electron-deficient *N*-protected aldimine substrates, using boronic acids and its derivatives as the aryl transfer reagents. Commercial chiral diphosphane ligands and a new NHC-type chiral ligand were used for the first time in this catalytic transformation. Some very good enantioselectivities were obtained. We are currently conducting thorough mechanistic and structural studies to understand the nature of the active catalysts involved in this reaction.

Experimental Section

General Remarks: All of the reagents were obtained from Aldrich, Fluka, and Acros. The commercial phosphane ligands were obtained either from Strem Chemicals or from Aldrich, with the ex-

ception of ligand **1**, (*R*)- and (*S*)-DioxPhos ligand **3** and diazide **10**, which were obtained from ChiraTecnics, Lda (Portugal). Toluene as well as NEt_3[47] were distilled from CaH_2 under an inert gas. Phenylboronic acid and derivatives were used as received. Phenylboroxine and the *N*-protected imine substrates were synthesized according to literature procedures.[16,41] Column chromatography was carried out on silica gel (sds, 70–200 μm). Thin layer chromatography (TLC) was carried out on aluminium-backed Kieselgel 60 F254 plates (Merck). The plates were visualized either by UV light or with phosphomolybdic acid in ethanol. NMR spectroscopic data were recorded with a Bruker Avance instrument (400 MHz) by using $CDCl_3$ as the solvent and by using the signal from the residual $CHCl_3$ as an internal standard. High performance liquid chromatographic (HPLC) analyses were performed with an Agilent 1100 series instrument. The conditions used were p_{max} = 50 bar, $flux_{max}$ = 1 mL/min, detector = wavelength light (λ = 230 nm), eluent = hexane/2-propanol, column = Chiralcel OD-H (0.46 cm × 25 cm) and AD-H (0.46 cm × 25 cm), both fitted with a guard column composed of the same stationary phase. Mass spectra were recorded either with a Waters-Micromass MaldiTOF or with a MicroTOF Focus (Bruker Daltonics) by using the TOF (time-of-flight) technique.

General Procedure for the Synthesis of the Imine Substrates:[16] By using a Dean–Stark apparatus to facilitate water removal, $BF_3{\cdot}Et_2O$ (0.6 mmol) was added (through a syringe) to a refluxing solution of the aldehyde (0.036 mol) and the amine with an EWG group (0.036 mol) in benzene (135 mL). The mixture was heated at reflux until the theoretical amount of water (0.036 mol) was collected. The solution was then cooled and washed with NaOH (2 M solution) and water. The organic phase was separated and dried with $MgSO_4$, and the solvent was evaporated under vacuum to yield a solid, which was crystallized from dichloromethane/petroleum ether (b.p. 60–80 °C) to give the desired product.

***N*-(2-Chlorobenzylidene)-4-methylbenzenesulfonamide:**[7,17,48] White solid (35% yield). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 2.45 (s, 3 H, CH_3), 7.32–7.38 (m, 2 H, Ar), 7.45–7.56 (m, 2 H, Ar), 7.89–7.92 (d, J = 8.4 Hz, 2 H, Ar), 8.14–8.17 (dd, J = 1.5, 7.8 Hz, 2 H, Ar), 9.5 (s, 1 H, HC=N) ppm. HPLC [Chiralcel AD-H column, hexane/2-propanol (90:10), flow rate = 0.7 mL/min, wavelength detector at 230 nm]: t_R = 26.1 min.

***N*-(4-Chlorobenzylidene)-4-methylbenzenesulfonamide:**[7,17,48] White solid (40% yield). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 2.44 (s, 3 H, CH_3), 7.35 (d, J = 8.1 Hz, 2 H, Ar), 7.45–7.48 (m, 4 H, Ar), 7.85–7.90 (m, 2 H, Ar), 8.99 (s, 1 H, HC=N) ppm. HPLC [Chiralcel OD-H column, hexane/2-propanol (93:7), flow rate = 1.0 mL/min, wavelength detector at 230 nm]: t_R = 7.4 min.

4-Methyl-*N*-(naphthalen-2-ylmethylene)benzenesulfonamide:[7,17,48] Pale yellow solid (64% yield). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 2.44 (s, 3 H, CH_3), 7.35–7.38 (m, 2 H, Ar), 7.78–7.65 (m, 2 H, Ar), 7.87–7.97 (m, 5 H, Ar), 8.02–8.05 (m, 1 H, Ar), 8.33 (s, 1 H, Ar), 9.18 (s, 1 H, HC=N) ppm. HPLC [Chiralcel OD-H column, hexane/2-propanol (80:20), flow rate = 0.5 mL/min, wavelength detector at 230 nm]: t_R = 12.4 min.

***N*-(4-Chlorobenzylidene)methanesulfonamide:** White solid (33% yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 3.14 (s, 3 H, CH_3), 7.50–7.52 (d, 2 H, Ar), 7.89–7.91 (d, 2 H, Ar), 8.99 (s, 1 H, HC=N) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 40.39 (CH_3), 129.85, 130.62, 132.50, 141.85, 170.41 (HC=N) ppm. MS: m/z = 218.01 [M + 1]$^+$. HPLC [Chiralcel OD-H column, hexane/2-propanol (80:20), flow rate = 0.5 mL/min, wavelength detector at 230 nm]: t_R = 10.5 min.

***N*-Butylidene-4-methylbenzenesulfonamide:**[7,17,48] Colorless oil (10% yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.95 (m, 3 H, CH_3), 1.51 (m, 2 H, CH_2), 2.33 (m, 2 H, CH_2), 2.42 (s, 3 H, CH_3), 7.31 (d, 2 H, Ar), 7.81 (d, 2 H, Ar), 8.45 (s, 1 H, HC=N) ppm. HPLC [Chiralcel OD-H column, hexane/2-propanol (80:20), flow rate = 0.3 mL/min, wavelength detector at 230 nm]: t_R = 18.8 min.

4-Methyl-*N*-(2-methylbenzylidene)benzenesulfonamide:[7,17,48] Yellow solid (73% yield). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 2.44 (s, 3 H, CH_3), 2.61 (s, 3 H, CH_3), 7.25–7.36 (m, 4 H, Ar), 7.45–7.50 (t, J = 7.5 Hz, 1 H, Ar), 7.88–7.91 (d, J = 8.1 Hz, 2 H, Ar), 7.99–8.02 (d, J = 7.8 Hz, 1 H, Ar), 9.35 (s, 1 H, HN=C) ppm. HPLC [Chiralcel OD-H column, hexane/2-propanol (80:20), flow rate = 0.5 mL/min, wavelength detector at 230 nm]: t_R = 14 min.

***N*-(4-Bromobenzylidene)-4-methylbenzenesulfonamide:**[7,17,48] White solid (30% yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 2.44 (s, 3 H, CH_3), 7.34–7.36 (m, 1 H, Ar), 7.62–7.65 (d, 1 H, Ar), 7.77–7.79 (d, 1 H, Ar), 7.87–7.89 (d, 1 H, Ar), 8.98 (s, 1 H, HN=C) ppm. HPLC [Chiralcel OD-H column, hexane/2-propanol (80:20), flow rate = 0.7 mL/min, wavelength detector at 230 nm]: t_R = 10.7 min.

***N*-(Cyclohexylmethylene)-4-methylbenzenesulfonamide:**[7,17,48] White solid (15% yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.15–1.29 (m, 6 H, CH_2), 1.76–1.81 (m, 5 H, CH_2), 2.32 (s, 3 H, CH_3), 7.19–7.21 (d, 2 H, Ar), 7.69–7.73 (d, 2 H, Ar), 8.37 (s, 1 H, HN=C) ppm. HPLC [Chiralcel OD-H column, hexane/2-propanol (80:20), flow rate = 0.5 mL/min, wavelength detector at 230 nm]: t_R = 11 min.

4-Methyl-*N*-(4-nitrobenzylidene)benzenesulfonamide:[7,17,48] Pale yellow solid (22% yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 2.46 (s, 3 H, CH_3), 7.38 (d, 2 H, Ar), 7.91 (d, 2 H, Ar), 8.11 (d, 2 H, Ar), 8.33 (d, 2 H, Ar), 9.10 (s, 1 H, HN=C) ppm. HPLC [Chiralcel AD-H column, hexane/2-propanol (90:10), flow rate = 0.7 mL/min, wavelength detector at 230 nm]: t_R = 26.4 min.

Preparation of Phenylboroxine:[41] A solution of phenylboronic acid (1.7 g, 14 mmol) in benzene (80 mL) was heated at reflux for 2 h, during which H_2O (0.7 mL, 42 mmol) was removed azeotropically (with a Dean–Stark apparatus). The mixture was concentrated under reduced pressure to ca. 10 mL, and then it was cooled to room temperature. The precipitate was collected by filtration, washed with hexane (5×) to give the boroxine (1 g, 23% yield) as white crystals. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.50–7.54 (m, 6 H, Ar), 7.59–7.63 (m, 3 H, Ar), 8.25–8.27 (m, 6 H, Ar) ppm.

General Procedure for the Catalytic Asymmetric Arylation of *N*-Protected Aldimines with Organoboron Reagents: Toluene (2 mL) was added to a round-bottomed flask containing $[RuCl_2(\eta^6\text{-}p\text{-cymene})]_2$ (3 mol-%), the chiral ligand (3.3 mol-%) and AgOTf (3 mol-%, in the case of NHC precursor **13**), and the organoboron reagent (0.4 mmol) under nitrogen. The mixture was stirred at 55 °C for 30 min to form the active catalytic species. The *N*-protected aldimine substrate (0.2 mmol) and NEt_3 (0.4 mmol) were added to the flask, and the mixture was stirred at 55 °C for 2–3 d. HCl (0.2 M solution, 5 mL) was added to quench the reaction. AcOEt (3 × 10 mL) was used to extract the product from the aqueous phase. The combined organic phases were washed with NaCl (aqueous, saturated), dried with anhydrous $MgSO_4$, filtered, and concentrated under vacuum. Purification by column chromatography (SiO_2 gel, hexane/AcOEt, 5:1) provided the final chiral diarylamine product. Note: Racemic products for chiral HPLC analysis were prepared by using the appropriate *N*-protected aldimines (0.5 mmol) with phenylboronic acid (1.0 mmol) in the presence of $Pd(OAc)_2$ (5 mol-%) and 2,2′-bypiridyl (10 mol-%) in dioxane (1.5 mL) at 100 °C for 48–72 h.

***N*-[(4-Chlorophenyl)(phenyl)methyl]-4-methylbenzenesulfonamide:**[7,17,48] White solid (14% yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ = 2.17 (s,

3 H, CH_3), 5.04–5.05 (d, 1 H, CH), 5.52–5.54 (d, 1 H, NH), 7.03–7.07 (m, 4 H, Ar), 7.15–7.19 (m, 4 H, Ar), 7.21–7.23 (m, 3 H, Ar), 7.54–7.56 (d, 2 H, Ar) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 21.64 (CH_3), 60.83 (CH), 126.62, 127.34, 127.43, 127.89, 128.07, 128.30, 128.79, 128.90, 128.92, 129.59, 129.76, 130.01, 132.51, 133.64, 137.28, 139.07, 140.19, 143.63 ppm. MS (ESI-TOF): *m*/*z* = 394.07 $[M + 1]^+$. HPLC [Chiralcel OD-H column, hexane/2-propanol (93:7), flow rate = 1.0 mL/min, wavelength detector at 230 nm]: t_R = 18.0 (*S*), 24.0 (*R*) min.

***N*-[(2-Chlorophenyl)(phenyl)methyl]-4-methylbenzenesulfonamide:**[7,17,48] White solid (63% yield). ^1H NMR (400 MHz, $CDCl_3$): δ = 2.38 (s, 3 H, CH_3), 5.31–5.33 (d, 1 H, CH), 5.90–5.92 (d, 1 H, NH), 7.05–7.08 (m, 2 H, Ar), 7.14–7.16 (m, 4 H, Ar), 7.22–7.24 (m, 4 H, Ar), 7.33–7.35 (m, 1 H, Ar), 7.60–7.62 (d, 2 H, Ar) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 21.64 (CH_3), 58.77 (CH), 127.07, 127.35, 127.39, 127.98, 128.78, 128.79, 128.79, 128.97, 129.48, 129.55, 129.56, 129.57, 130.03, 132.93, 137.05, 137.61, 139.40, 143.52 ppm. MS (ESI-TOF): *m*/*z* = 394.07 $[M + 1]^+$. HPLC [Chiralcel AD-H column, hexane/2-propanol (90:10), flow rate = 0.7 mL/min, wavelength detector at 230 nm]: t_R = 27.9 (*S*), 31.8 (*R*) min.

4-Methyl-*N*-[naphthalen-2-yl(phenyl)methyl]benzenesulfonamide:[7,17,48] Yellow solid (12% yield). ^1H NMR (400 MHz, $CDCl_3$): δ = 2.42 (s, 3 H, CH_3), 5.41–5.43 (d, 1 H, CH), 5.72–5.74 (d, 1 H, NH), 7.02–7.04 (d, 1 H, Ar), 7.14–7.23 (m, 4 H, Ar), 7.28–7.30 (d, 2 H, Ar), 7.43–7.45 (m, 2 H, Ar), 7.50 (s, 1 H, Ar), 7.53–7.55 (d, 2 H, Ar), 7.63–7.68 (m, 2 H, Ar), 7.79–7.81 (d, 2 H, Ar) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 21.49 (CH_3), 61.59 (CH), 122.89, 125.28, 126.37, 126.50, 126.56, 127.31, 127.60, 127.65, 127.81, 128.09, 128.61, 128.73, 129.42, 129.84, 132.75, 133.11, 137.39, 137.63, 139.20, 140.52, 143.37, 143.71 ppm. MS (ESI-TOF): *m*/*z* = 410.12 $[M + 1]^+$. HPLC [Chiralcel OD-H column, hexane/2-propanol (80:20), flow rate = 0.5 mL/min, wavelength detector at 230 nm]: t_R = 20.2 (*R*), 22.1 (*S*) min.

***N*-[(4-Chlorophenyl)(phenyl)methyl]methanesulfonamide:** White solid (10% yield). ^1H NMR (400 MHz, $CDCl_3$): δ = 2.70 (s, 3 H, CH_3), 5.17–5.18 (m, 1 H, CH), 5.73–5.75 (m, 1 H, NH), 7.28–7.40 (m, 9 H, Ar) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 42.18 (CH_3), 60.79 (CH), 127.45, 127.48, 128.45, 128.93, 129.19, 129.24, 129.25, 129.91, 132.53, 134.06, 139.33, 140.29 ppm. MS (ESI-TOF): *m*/*z* = 318.04 $[M + 1]^+$. HPLC [Chiralcel OD-H column, hexane/2-propanol (80:20), flow rate = 0.5 mL/min, wavelength detector at 230 nm]: t_R = 15.2, 18.1 min.

4-Methyl-*N*-(1-phenylbutyl)benzenesulfonamide:[7,17,48] Colorless oil (13% yield). ^1H NMR (400 MHz, $CDCl_3$): δ = 0.84–0.98 (m, 3 H, CH_3), 1.60–1.67 (m, 2 H, CH_2), 2.28–2.32 (m, 2 H, CH_2), 2.24 (s, 3 H, CH_3), 4.07–4.11 (d, 1 H, CH), 4.21–4.25 (d, 1 H, NH), 7.31–7.83 (m, 9 H, Ar) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 18.61 (CH_3), 19.89 (CH_2), 29.75 (CH_3), 44.89 (CH_2), 64.63 (CH), 126.15, 126.64, 127.20, 127.45, 127.49, 127.90, 128.34, 128.56, 129.01, 129.80, 129.85, 130.13 ppm. MS (ESI-TOF): *m*/*z* = 302.13 $[M]^+$. HPLC [Chiralcel OD-H column, hexane/2-propanol (80:20), flow rate = 0.5 mL/min, wavelength detector at 230 nm]: t_R = 15.0 (*S*), 16.3 (*R*) min.

4-Methyl-*N*-[phenyl(*o*-tolyl)methyl]benzenesulfonamide:[7,17,48] Yellow solid (<10% yield). ^1H NMR (400 MHz, $CDCl_3$): δ = 2.17 (s, 3 H, CH_3), 2.43 (s, 3 H, CH_3), 5.30 (s, 1 H, CH), 6.02 (s, 1 H, NH), 7.06–7.23 (m, 5 H, Ar), 7.28–7.38 (m, 4 H, Ar), 7.51–7.56 (m, 2 H, Ar), 7.80–7.82 (m, 2 H, Ar) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 21.62 (CH_3), 22.84 (CH_3), 58.41 (CH), 125.80, 126.28, 126.30, 126.39, 126.63, 127.20, 127.26, 127.69, 127.74, 127.77, 128.64, 128.70, 128.85, 129.47, 129.89, 130.70, 139.16, 143.81 ppm. MS (ESI-TOF): *m*/*z* = 374.13 $[M + 1]^+$. HPLC [Chiralcel OD-H column, hexane/2-propanol (80:20), flow rate = 0.5 mL/min, wavelength detector at 230 nm]: t_R = 12.3 (*R*), 15.3 (*S*) min.

***N*-[(4-Bromophenyl)(phenyl)methyl]-4-methylbenzenesulfonamide:**[7,17,48] White solid (12% yield). ^1H NMR (400 MHz, $CDCl_3$): δ = 2.40 (s, 3 H, CH_3), 4.96–4.98 (d, 1 H, CH), 5.51–5.52 (d, 1 H, NH), 6.99–7.05 (m, 4 H, Ar), 7.15–7.17 (d, 2 H, Ar), 7.21–7.23 (m, 3 H, Ar), 7.31–7.35 (m, 2 H, Ar), 7.54–7.56 (m, 2 H, Ar) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 21.74 (CH_3), 60.99 (CH), 121.79, 126.64, 127.35, 127.43, 128.11, 128.92, 129.27, 129.60, 129.89, 131.74, 136.84, 137.09, 137.38, 138.24, 139.56, 140.10, 143.52, 143.86 ppm. MS (ESI-TOF): *m*/*z* = 440.02 $[M + 1]^+$. HPLC [Chiralcel OD-H column, hexane/2-propanol (80:20), flow rate = 0.7 mL/min, wavelength detector at 230 nm]: t_R = 11.6 (*S*), 14.2 (*R*) min.

***N*-[Cyclohexyl(phenyl)methyl]-4-methylbenzenesulfonamide:**[7,17,48] Light yellow oil (17% yield). ^1H NMR (400 MHz, $CDCl_3$): δ = 0.85–1.10 (m, 3 H, CH_2), 1.22–1.28 (m, 4 H, CH_2), 1.33–1.59 (m, 4 H, CH_2), 2.41 (s, 3 H, CH_3), 3.30–3.32 (d, 1 H, CH), 4.85–4.87 (d, 1 H, NH), 7.29–7.36 (m, 5 H, Ar), 7.67–7.69 (d, 2 H, Ar), 7.79–7.83 (d, 2 H, Ar) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 21.65 (CH_3), 22.37 (CH_2), 22.88 (CH_2), 25.81 (CH_2), 26.55 (CH_2), 28.89 (CH_2), 38.53 (CH), 66.33 (CH), 126.56, 126.63, 127.02, 127.13, 128.22, 129.57, 129.88, 130.06, 130.71, 139.05, 143.30, 145.13 ppm. MS (ESI-TOF): *m*/*z* = 266.13 [M + 1 – Ph]$^+$. HPLC [Chiralcel OD-H column, hexane/2-propanol (80:20), flow rate = 0.5 mL/min, wavelength detector at 230 nm]: t_R = 10.9 (*S*), 14.0 (*R*) min.

***N*-[(2-Chlorophenyl)(4-chlorophenyl)methyl]-4-methylbenzenesulfonamide:**[7,17,48] White solid (12% yield). ^1H NMR (400 MHz, $CDCl_3$): δ = 2.37 (s, 3 H, CH_3), 5.41–5.42 (d, 1 H, CH), 5.87–5.89 (d, 1 H, NH), 7.01–7.04 (d, 2 H, Ar), 7.14–7.25 (m, 8 H, Ar), 7.58–7.60 (d, 2 H, Ar) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 21.70 (CH_3), 58.23 (CH), 127.30, 128.78, 128.89, 129.24, 129.39, 129.59, 129.85, 130.02, 130.18, 130.34, 130.62, 132.86, 133.85, 135.77, 136.96, 137.16, 137.95, 143.65 ppm. MS (ESI-TOF): *m*/*z* = 428.03 $[M + 1]^+$. HPLC [Chiralcel OD-H column, hexane/2-propanol (70:30), flow rate = 0.7 mL/min, wavelength detector at 230 nm]: t_R = 8.2 (*S*), 11.7 (*R*) min.

4-Methyl-*N*-[(4-nitrophenyl)(phenyl)methyl]benzenesulfonamide:[7,17,48] Light orange solid (<10% yield). ^1H NMR (400 MHz, $CDCl_3$): δ = 2.40 (s, 3 H, CH_3), 5.25–5.27 (d, 1 H, CH), 5.61–5.62 (d, 1 H, NH), 6.98–7.00 (d, 2 H, Ar), 7.17–7.19 (d, 2 H, Ar), 7.35–7.39 (m, 4 H, Ar), 7.57–7.59 (m, 3 H, Ar), 8.07–8.09 (d, 2 H, Ar) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 21.70 (CH_3), 61.07 (CH), 123.80, 124.45, 126.85, 127.20, 127.34, 127.44, 128.38, 128.56, 128.60, 129.26, 129.74, 130.64, 136.96, 139.40, 142.85, 144.04, 147.35, 147.80 ppm. MS (ESI-TOF): *m*/*z* = 405.09 $[M + 1]^+$. HPLC [Chiralcel AD-H column, hexane/2-propanol (90:10), flow rate = 0.7 mL/min, wavelength detector at 230 nm]: t_R = 19.9 (*S*), 25.5 (*R*) min.

Synthesis of the Chiral NHC Precursor 13

[(2*S*,3*S*,5*S*,6*S*)-5,6-Dimethoxy-5,6-dimethyl-1,4-dioxane-2,3-diyl]dimethanamine (11):[35,36] To a round-bottomed flask containing diazide **10** (5 mmol), dry EtOH (50 mL), and Pd/C (10 mol-%) was attached a rubber balloon filled with H_2, and the mixture was stirred 24 h. The mixture was then filtered through a sintered glass filter, and the filtrate was concentrated under vacuum. The diamine product (81% yield) was obtained as a colorless oil. ^1H NMR (400 MHz, $CDCl_3$): δ = 1.32 (s, 6 H, CH_3), 1.83 (br. s, 4 H, NH_2), 2.76 (d, 4 H, CH_2), 3.28 (s, 3 H, OCH_3), 3.59 (m, 2 H, CHO) ppm.

***N*,*N*′-[(2*R*,3*R*,5*S*,6*S*)-5,6-Dimethoxy-5,6-dimethyl-1,4-dioxane-2,3-diyl]bis(methylene)bis(1-phenylmethanamine) (12):**[36] Diamine **11** (0.4 mmol) was added to a round-bottomed flask containing dry

MeOH (35 mL) and benzaldehyde (10 mmol). The mixture was heated at reflux and stirred under nitrogen overnight. After cooling the reaction mixture to room temperature, dry toluene (50 mL) and $NaBH_4$ (21 mmol, added in small portions over a 20 min period) were added. The mixture was stirred for 2 h, and then the solvents were removed under vacuum. H_2O (50 mL) and AcOEt (50 mL) were added to the crude mixture to extract the product, and the layers were separated. The organic layer was washed with brine, dried with anhydrous $MgSO_4$, and filtered. The solvent was evaporated under vacuum. The crude product was purified by column chromatography (SiO_2 gel, hexane/AcOEt, 1:1) to give the desired diamine product **12** (35% yield) as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.25 (s, 6 H, CH_3), 2.46 (s, 2 H, CH_2NH), 2.63 (s, 2 H, CH_2NH), 3.22 (s, 3 H, OCH_3), 3.68–3.81 (m, 6 H, CHO and CH_2Ar), 5.25 (s, 2 H, NH), 7.22 (m, 10 H, Ar) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 17.30 (CH_3), 47.81 (CH_2N), 49.30 (OCH_3), 53.54 (CH_2Ar), 68.93 (CHO), 98.17 (CO), 126.66 (Ar), 127.87 (Ar), 139.49 (Ar) ppm. MS (ESI-TOF): *m*/*z* = 415.27 [M + 1]$^+$.

(2*S*,3*S*,4a*R*,9a*R*)-6,8-Dibenzyl-2,3-dimethoxy-2,3-dimethyl-3,4a,5,8,9,9a-hexahydro-2*H*-[1,4]dioxino[2,3-*e*][1,3]diazepin-6-ium Hexafluorophosphate (13): Secondary diamine **12** (0.26 mmol), NH_4PF_6 (0.26 mmol), and triethyl orthoformate (0.26 mmol) were added to a round-bottomed flask under an inert gas. The reaction mixture was stirred at 120 °C for 3 h. The EtOH byproduct was evaporated under vacuum, and the crude product was recrystallized from EtOH to give the desired NHC precursor **13** (57% yield) as white crystals. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.14 (s, 6 H, CH_3), 3.02 (s, 6 H, OCH_3), 3.20–3.28 (m, 2 H, CH_2N), 3.37–3.42 (m, 2 H, CH_2N), 3.55–3.56 (m, 2 H, CHO), 4.67–4.79 (q, *J* = 12 Hz, 4 H, CH_2Ar), 7.33–7.38 (m, 10 H, Ar), 8.37 (s, 1 H, NH=N) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 17.10 (CH_3), 48.04 (OMe), 51.21 (CH_2Ar), 63.12 (NCH_2C), 67.20 (CHO), 99.08 (C–C), 128.78 (Ar), 129.18 (Ar), 129.28 (Ar), 132.63 (Ar–C), 159.06 (C=N) ppm. MS (MicroTOF): *m*/*z* = 425.25 [M]$^+$, 426.26 [M + 1]$^+$, 427.26 [M + 2]$^+$.

Preparation of a Ruthenium–Phosphane Complex: Into a round-bottomed flask under an inert gas were added $[RuCl_2(\eta^6\text{-}p\text{-cymene})]_2$ (21.4 mg, 0.5 equiv.), (*S*)-DioxPhos ligand (**3**, 20 mg), and dry CH_2Cl_2 (2 mL). The mixture was stirred at room temperature overnight. The crude product was purified by silica gel liquid chromatography (hexane/AcOEt, 1:1). Two fractions were obtained, and the solvents were evaporated to dryness. Data for fraction 1: Dimer complex **9** (82% yield) was obtained as an orange solid. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.62 (s, 3 H, CH_3), 0.77–0.78 (d, 3 H, CH_3), 1.02–1.04 (d, 3 H, CH_3), 1.24–1.27 (m, 3 H, CH_3), 1.58 (s, 3 H, CH_3), 1.78 (s, 3 H, OCH_3), 2.38 (s, 3 H, OCH_3), 2.48–2.58 (m, 4 H, CH_2P), 2.72–2.74 (m, 2 H, CH), 3.54–3.58 (m, 2 H, CHO), 4.83–4.85 (d, 2 H, cymene), 5.21–5.23 (d, 2 H, cymene), 5.25–5.27 (d, 2 H, cymene), 5.36–5.37 (d, 2 H, cymene), 7.34 (m, Ar), 7.46–7.53 (m, Ar), 7.89–7.93 (m, Ar), 7.99–8.03 (m, Ar) ppm. ^{31}P NMR (400 MHz, $CDCl_3$): δ = 19.67 ppm. MS (ESI): *m*/*z* = 1149 [M(^{35}Cl × 3)], 1151 [M(^{35}Cl × 2 + ^{37}Cl)]. Data for fraction 2: Monomer complex **8** (10% yield) was obtained as an orange solid. MS (ESI): *m*/*z* = 843 [M(^{35}Cl)], 845 [M(^{37}Cl)].

Supporting Information (see footnote on the first page of this article): ^{1}H and ^{13}C NMR spectra and mass spectra.

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[1] E. L. Gall, C. Haurena, S. Sengmany, T. Martens, M. Troupel, *J. Org. Chem.* **2009**, *74*, 7970–7973.
[2] M. Kuriyama, T. Soeta, X. Hao, Q. Chen, K. Tomioka, *J. Am. Chem. Soc.* **2004**, *126*, 8128–8129.
[3] N. Tokunaga, Y. Otomaru, K. Okamoto, K. Ueyama, R. Shintani, T. Hayashi, *J. Am. Chem. Soc.* **2004**, *126*, 13584–13585.
[4] D. J. Weix, Y. Shi, J. A. Ellman, *J. Am. Chem. Soc.* **2005**, *127*, 1092–1093.
[5] H. Nakagawa, J. C. Rech, R. W. Sindelar, J. A. Ellman, *Org. Lett.* **2007**, *9*, 5155–5157.
[6] M. Trincado, J. A. Ellman, *Angew. Chem.* **2008**, *120*, 5705; *Angew. Chem. Int. Ed.* **2008**, *47*, 5623–5626.
[7] G.-N. Ma, T. Zhang, M. Shi, *Org. Lett.* **2009**, *11*, 875–878.
[8] H. Dai, X. Lu, *Org. Lett.* **2007**, *9*, 3077–3080.
[9] C. S. Marques, A. J. Burke, *Eur. J. Org. Chem.* **2010**, 1639–1643.
[10] C. S. Marques, A. J. Burke, *ChemCatChem* **2011**, *3*, 635–645.
[11] V. Dragutan, I. Dragutan, L. Delaude, A. Demonceau, *Coord. Chem. Rev.* **2007**, *251*, 765–794.
[12] T. Naota, H. Takaya, S.-I. Murahashi, *Chem. Rev.* **1998**, *98*, 2599–2660.
[13] B. M. Trost, M. U. Frederiksen, M. T. Rudd, *Angew. Chem.* **2005**, *117*, 6788; *Angew. Chem. Int. Ed.* **2005**, *44*, 6630–6666.
[14] B. T. Trost, F. D. Toste, A. B. Pinkerton, *Chem. Rev.* **2001**, *7*, 2067–2096.
[15] C. Bruenau, P. H. Dixneuf (Eds.), *Topics in Organometallic Chemistry*, vol. 11 ("Ruthenium Catalysts and Fine Chemistry"), Springer-Verlag, Berlin, Heidelberg, New York, **2004**.
[16] W. McKay, G. R. Proctor, *J. Chem. Soc. Perkin Trans. 1* **1981**, *9*, 2435–2442.
[17] H. Dai, X. Lu, *Tetrahedron Lett.* **2009**, *50*, 3478–81.
[18] X. Hao, Q. Chen, K. Yamada, Y. Yamamoto, K. Tomioka, *Tetrahedron* **2011**, *67*, 6469–6473.
[19] a) P. M. P. Gois, A. F. Trindade, L. F. Veiros, V. André, M. T. Duarte, C. A. M. Afonso, S. Caddick, F. G. N. Cloke, *Angew. Chem.* **2007**, *119*, 5852; *Angew. Chem. Int. Ed.* **2007**, *46*, 5750–5753; b) A. V. Moro, E. R. T. Tiekink, J. Z. Schpector, D. S. Lüdtke, C. R. D. Correia, *Eur. J. Org. Chem.* **2010**, 3696–3703; c) C. M. Marques, A. J. Burke, *Tetrahedron* **2012**, submitted.
[20] a) Y. Yamamoto, K. Kurihara, N. Miyaura, *Angew. Chem.* **2009**, *121*, 4478; *Angew. Chem. Int. Ed.* **2009**, *48*, 4414–4416; b) Y. Yamamoto, T. Shirai, M. Wantanaber, K. Kurihara, N. Miyaura, *Molecules* **2011**, *16*, 5020–5034.
[21] X. Hao, Q. Chen, M. Kuriyama, K. Yamada, Y. Yamamoto, K. Tomioka, *Catal. Sci. Technol.* **2011**, *1*, 62–64.
[22] L. Cavallo, A. Correa, C. Costabile, H. Jacobsen, *J. Organomet. Chem.* **2005**, *690*, 5407–5413.
[23] T. Strassner, *Top. Organomet. Chem.* **2004**, *13*, 1–20.
[24] D. Bourissou, O. Guerret, F. P. Gabbai, G. Bertrand, *Chem. Rev.* **2000**, *100*, 39–91.
[25] H. Jacobsen, A. Correa, A. Poater, C. Costabile, L. Cavallo, *Coord. Chem. Rev.* **2009**, *253*, 687–703.
[26] W. A. Herrmann, *Angew. Chem.* **2002**, *114*, 1342; *Angew. Chem. Int. Ed.* **2002**, *41*, 1290–1309.
[27] K. Mikami, M. Lautens in *New Frontiers in Asymmetric Catalysis*, John Wiley & Sons, Inc., New Jersey, **2007**.
[28] C. S. Marques, A. J. Burke, *Tetrahedron: Asymmetry* **2007**, *18*, 1804–1808.

[29] J. C. Martins, P. C. Barrulas, C. S. Marques, A. J. Burke, *Synth. Commun.* **2008**, *38*, 1365–1374.
[30] G. Yong-En, E. P. Carreiro, A. J. Burke, *J. Mol. Catal. A: Chem.* **2005**, *235*, 285–292.
[31] C. S. Marques, A. J. Burke, *Synth. Commun.* **2008**, *38*, 4207–4214.
[32] U. Berens, R. Selke, *Tetrahedron: Asymmetry* **1996**, *7*, 2055–2064.
[33] W. Li, J. P. Waldkirch, X. Zhang, *J. Org. Chem.* **2002**, *67*, 7618–7623.
[34] U. Berens, D. Leckel, S. C. Oepen, *J. Org. Chem.* **1995**, *60*, 8204–8208.
[35] W. Hems, G. Patrick, A. Gabriela, WO2005/007662, **2005**.
[36] M. T. Barros, A. M. F. Phillips, *Molecules* **2006**, *11*, 177–196.
[37] M. T. Barros, C. D. Maycock, A. M. F. Phillips, *Tetrahedron: Asymmetry* **2005**, *16*, 2946–53.
[38] B. Linclau, P. J. Clarke, M. E. Light, *Tetrahedron Lett.* **2009**, *50*, 7144–7147.
[39] J. Lemke, N. Metzler-Nolte, *Eur. J. Inorg. Chem.* **2008**, 3359–3366.
[40] A. R. Chianese, X. Li, M. C. Janzen, J. W. Faller, R. H. Crabtree, *Organometallics* **2003**, *22*, 1663–1667.
[41] H. M. J. Wang, I. J. B. Lin, *Organometallics* **1998**, *17*, 972–975.
[42] X. Hao, M. Kuriyama, Q. Chen, Y. Yamamoto, K. Yamada, K. Tomioka, *Org. Lett.* **2009**, *11*, 4470–4473.
[43] F.-X. Chen, A. Kina, T. Hayashi, *Org. Lett.* **2006**, *8*, 341–344.
[44] I. J. B. Lin, C. S. Vasam, *Comments Inorg. Chem.* **2004**, *25*, 75–129.
[45] I. J. B. Lin, C. S. Vasam, *Coord. Chem. Rev.* **2007**, *251*, 642–670.
[46] J. C. Garrison, W. J. Youngs, *Chem. Rev.* **2005**, *105*, 3978–4008.
[47] W. L. F. A. Perrin, *Purification of Laboratory Chemicals*, 4th ed., Butterworth Heinemann, Oxford, **1996**.
[48] H.-F. Duan, Y.-X. Jia, L.-X. Wang, Q.-L. Zhou, *Org. Lett.* **2006**, *8*, 2567–2569.

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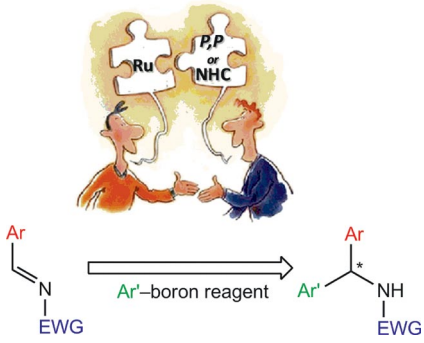
Arylation Reactions

A new method is presented for the synthesis of chiral substituted amines by employing Ru catalysts along with known chiral phosphane ligands and a new NHC-type chiral ligand. Organoboron reagents were applied as the aryl transfer agents. High enantioselectivities were achieved with this new method, and some mechanistic insights are provided.



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