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Neutral *vs.* cationic rhodium (I) complexes of bulky *N*-phosphino sulfinamide ligands: Coordination modes and its influence in the asymmetric hydrogenation of *Z*-MAC

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ABSTRACT

Here we report the synthesis of a new *N*-di-*tert*-butylphosphino-*tert*-butylsulfinamide (PNSO) ligand and its corresponding *p*-tolylsulfinamide analog. The coordination of these compounds to rhodium to form a neutral and apolar complex is described, followed by the subsequent protonation of said complexes to quantitively form the more orthodox, cationic rhodium species containing a tetrafluoroboric counterion. The crystallographic structure of the *tert*-butylsulfinamide-derived cationic species was obtained and is elucidated. It outlines coordination from the sulfinamide group to the rhodium atom and shows no preference between O- and S-coordination as both complexes can be seen in one unit cell of the crystal. The efficacies of the neutral species and the salt species were tested in the asymmetric hydrogenation of methyl (Z)-α-acetamido cinnamate (*Z*-MAC). The *p*-tolylsulfinamide-derived complexes gave no hydrogenation while the *tert*-butylsulfinamide-derived ones produced hydrogenation with complete conversion but low enantioselectivities. The stereochemical outcome of the reaction was analyzed by means of the quadrant method.

1. Introduction

Chiral bi-dentate ligands have become highly relevant in the field of asymmetric catalysis. These compounds not only increase reactivity but more importantly, they induce the high enantioselectivities currently demanded by the pharmaceutical industry [1]. Thus moving the chiral information of the ligand as close as possible to the catalyzing metal center would be the best way to efficiently confer chirality to and increase enantioselectivities of the catalytic transformations that the catalyst is mediating. This could be achieved by conferring chirality to the metal-coordinating atom. P-stereogenic bidentate diphosphine ligands are extremely proficient in asymmetric transformations [2]. In 2004 Hoge et al. reported the synthesis and efficacy of the three-hindered quadrant chiral ligand trichickenfootphos (TCFP) in the Rh-catalyzed asymmetric hydrogenations of α- and β-acetamido dehydroamino acid substrates [3]. The excellent enantioselectivities obtained suggested the C_1-symmetric, 3-hindered quadrant chiral ligand design was an excellent template to follow. MaxPHOS, an analog of the TCFP ligand, was developed in our laboratory and was first reported in 2010 [4,5]. As with TCFP, it showed excellent enantioselectivity in the asymmetric hydrogenation of α- and β-acetamido dehydroamino acid substrates. Despite the great efficiency of this type of ligand, its synthesis remains somewhat laborious [6]. In this respect, here we addressed the preparation of other cost-effective 3-hindered quadrant ligands that can be readily assembled from commercially available materials (Fig. 1).

We previously showed that the PNSO family of ligands, those containing a sulfinamide moiety bound to a phosphine group through the nitrogen atom where chirality resides on sulfur, can be highly efficient when applied to the intermolecular asymmetric Pauson–Khand reaction [7]. These ligands can be obtained in a very straightforward manner, often involving a one-step, one-pot synthesis using chiral sulfinamides that are commercially available in large amounts [8]. Also, we demonstrated that ligands such as **1** and similar analogs coordinate readily to rhodium and other metals to give either P,O or P,S bidentate coordination [9]. The positive results with these ligands in the Pauson–Khand reaction led us to test their efficacy in rhodium-catalyzed asymmetric hydrogenation of dehydroamino acids. We were willing to test whether the *N*-di-*tert*-butylphosphino-*tert*-butylsulfinamide ligand (PNSO) (**2**) could be another example of the 3-hindered quadrant chiral ligand

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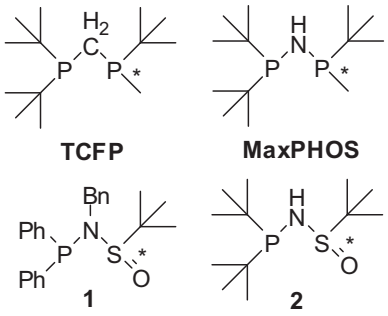


Fig. 1. C_1 symmetric diphosphine and *N*-phosphino sulfinamide (PNSO) ligands.

template, such as the TCFP and MaxPHOS ligands [10]. Thus, here we report on the synthesis of ligand **2** and its *p*-tolylsulfinamide analog, their complexation to rhodium and finally the use of the resulting complexes in asymmetric hydrogenation.

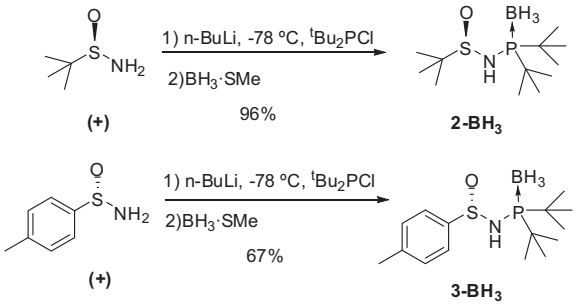
2. Results

2.1. Synthesis of the ligands

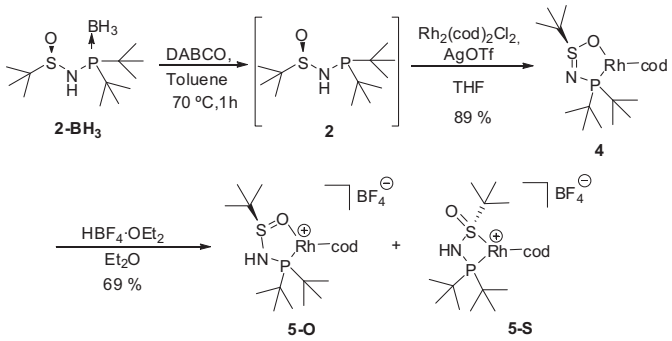
The boron-protected chiral PNSO ligand **2** was synthesized from the commercially available (+)-*tert*-butylsulfinamide in a one-pot reaction (Scheme 1). The anion of the sulfinamide was formed at low temperature with *n*-BuLi. Addition of the $^tBu_2PCl$ electrophile, which was allowed to react to completion at room temperature after warming up from −78 °C, led to total consumption of the sulfinamide starting material (easily monitored by TLC). Finally, the phosphine was protected with borane by addition of the $BH_3{\cdot}SMe_2$ complex. Borane-protected **2** was isolated in an excellent 96% yield after flash chromatography on SiO_2. The analog **3-BH$_3$** was synthesized in exactly the same manner from the commercially available dextrorotatory *p*-tolylsulfinamide. The ligands were not isolated in their borane-free form due to expected oxidation of the phosphine [7a].

2.2. Synthesis of Rh complexes

The compound **2-BH$_3$** was heated to 70 °C in toluene with an excess of DABCO to release the ligand from the boron protecting group (Scheme 2), a process which was easily monitored by TLC. When no protected form remained, the reaction was removed from the heat and allowed to cool. The source of rhodium $Rh_2(cod)_2Cl_2$/AgOTf was then added to the reaction, dissolved in THF The resulting rhodium complex derived from ligand **2** was very apolar, running high on the TLC plate in a 9:1 hexane:ethyl acetate mobile phase and also passing easily through a silica column. This behavior was not expected from a cationic complex. After stirring and later evaporation of solvents, the complex was then be purified by



Scheme 1. Synthesis of bulky BH_3-protected PNSO ligands.



Scheme 2. Synthesis of neutral and cationic rhodium complexes **4** and **5** derived from (+)-*tert*-butylsulfinamide.

column chromatography to give pure complex **4** as an orange oil, which slowly solidified.

^1H NMR analysis of complex **4** revealed a lone signal for the sulfinyl *tert*-butyl group at 1.1 ppm, a pair of overlapping doublets between 1.22 and 1.26 ppm corresponding to the phosphino *tert*-butyl groups, and a set of olefinic proton signals residing between 3.97 ppm and 5.25 ppm. These results led us to believe we had synthesized a monomeric PNSO–Rh complex that probably displayed oxygen to rhodium coordination reminiscent of complex **6**, previously synthesized by our group (Fig. 2). The sulfinyl *tert*-butyl ^1H NMR peak appeared much further downfield than that of complex **6**, which lies at 1.54 ppm and even further downfield than the sulfinyl *tert*-butyl group of complex **7**, found at 1.24 ppm. The ^1H NMR spectrum could not confirm the ligand–metal coordination mode. A reliable structural elucidation was sought by X-ray analysis; however, due to the apolar nature of **4** and its high solubility in a range of solvents from hexane to methanol, our attempts to form crystals suitable for X-ray crystallography failed time and again.

In an attempt to explain the chromatographic behavior of complex **4**, we postulated that it was not a salt but a neutral complex that resulted from deprotonation of the NH functionality in the presence of excess DABCO in the reaction mixture [11]. We hypothesized that by adding 1 eq. of acid to the complex stirring in an apolar solvent we could achieve a complex from which crystals suitable for X-ray crystallography could be formed. This hypothesis was confirmed experimentally; addition of 1 eq. of $HBF_4{\cdot}OEt_2$ to the dissolved complex in Et_2O yielded a bright yellow precipitate. This precipitate was the protonated cationic complex **5** (Scheme 2).

Crystals suitable for X-ray crystallography were formed by dissolution of the salt complex **5** in a small amount of DCM followed by the layering of an excess of Et_2O. Surprisingly, in one unit cell of the crystal (Fig. 3) we detected two distinct structures showing both sulfur coordination (P,S) and at the same time oxygen coordination (P,O) to the metal center. This finding led us to assume that in complex **5** neither O- or S- to metal coordination was greatly favored over the other. Despite of this, the crystallographic data of complex **5** gave us a unique opportunity to compare the effect of the different coordination modes on the bond lengths and bond angles of the molecule and also to analyze them with respect to comparable complexes such as **6** and **7**, previously synthesized by

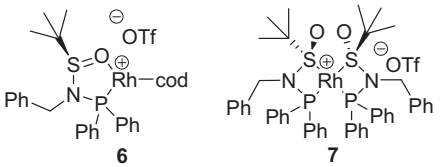


Fig. 2. Previously reported PNSO–Rh complexes.

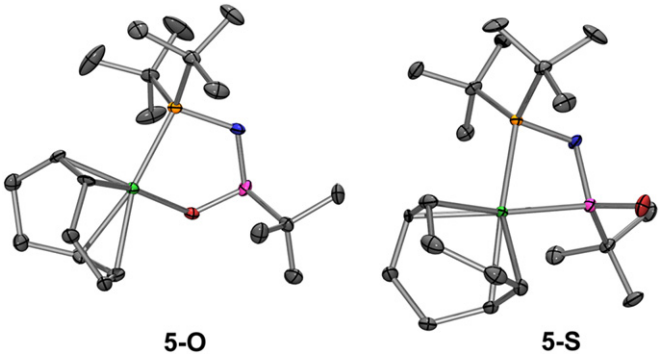


Fig. 3. Ortep drawing for crystal structure of complex **5-O** and **5-S** with 50% probability of ellipsoids. The two different structures coexist in a single unit cell showing P,O and P,S coordinated ligand. Counterions have been omitted for clarity.

our group. The O-coordinated complex **5-O** showed a significant *trans* effect, whereby the olefinic–rhodium bonds were shortened when *trans* to oxygen, from 2.21 Å in the S-coordinated complex to 2.13 Å, comparable with those of the monomeric complex **6** which has an olefinic–rhodium bond of 2.10 Å. The sulfoxide bond also lengthened from 1.46 Å to 1.52 Å when going from S- to O-coordination. S-coordination clearly contracted the S–N–P bond angle from 120° to 104°, showing more similarity to the S–N–P bond angle of the dimeric complex **7** of 102°. We observed that the Rh–O bond had a length of 2.12 Å while that of the Rh–S bond was of 2.32 Å. Also, the Rh–P bond was 2.31 Å in coordination modes **5-O** and **5-S** and clearly longer than the Rh–P bonds of complexes **6** and **7**, which were both 2.25 Å.

The ^{31}P NMR spectrum of the neutral compound **4** showed a very well defined doublet at 138 ppm while the cationic species **5** showed a broad signal pushed slightly downfield at 141 ppm (Fig. 4). The morphology of the ^{31}P NMR signals of the neutral complex **4** versus those of the salt complex **5** suggests that **4** has a more stable, steady structure in $CDCl_3$ solution and favors one of the two possible coordination modes (P,O or P,S) while a fluxional process occurs for the cationic complex **5**. The equilibrium of coordination modes from chalcogen to the rhodium center, which favors neither sulfur coordination nor oxygen coordination, could be responsible for the fluxional behavior of complex **5** in solution.

The syntheses of the *p*-tolyl-substituted sulfinamide-derived complexes **8** and **9** are described in Scheme 3. In analogous fashion with its *tert*-butyl analog, coordination to rhodium in the presence of a base (DABCO) provided the neutral complex **8**, which was easily purified by flash chromatography on silica gel. Addition of HBF_4–OEt_2 over the neutral complex afforded the more conventional cationic species **9** as a yellow solid. Analysis of the ^{31}P NMR showed that the neutral complex **8** had a well defined doublet at 149 ppm while the cationic complex **9** showed a slightly less well defined doublet pushed upfield to 140 ppm. Although the difference in morphology of the peaks was not as apparent as in the previous case, again it suggests that the coordination mode of the cationic species is more fluxional in nature than that of the neutral complex.

2.3. The PNSO–Rh complexes as hydrogenation catalysts

Hydrogenations of methyl (Z)-α-acetamido cinnamate (MAC) 10 were attempted using the given complexes under varying pressures of hydrogen and various solvents (Table 1). The *p*-tolyl complexes **8** and **9** failed to provide any hydrogenation product (Table 1, entries 1 and 2). In contrast, the *tert*-butylsulfinamide-derived complexes **4** and **5** gave hydrogenations with complete

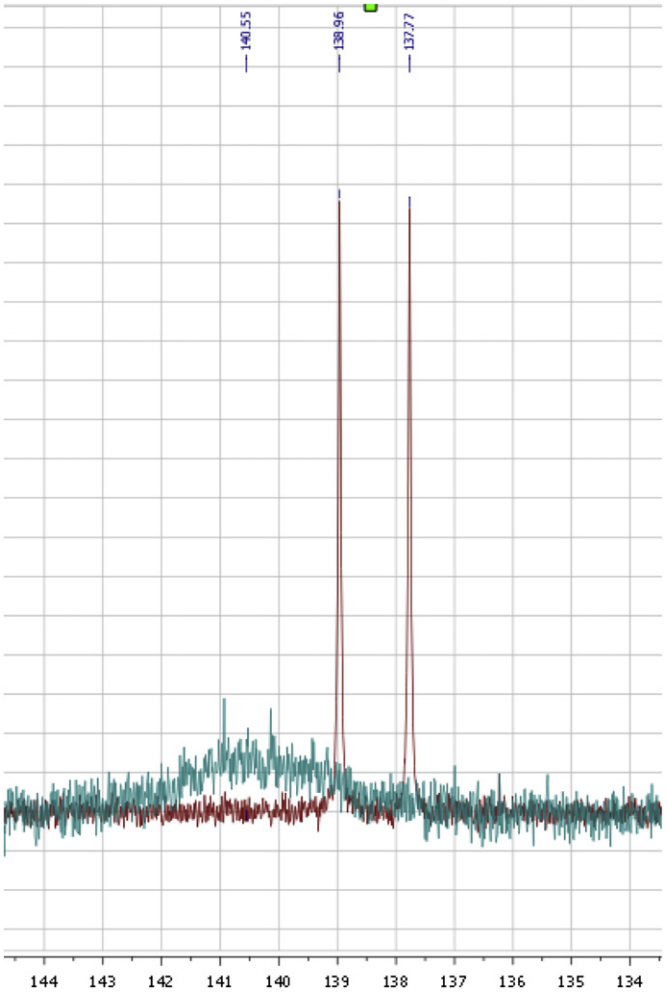
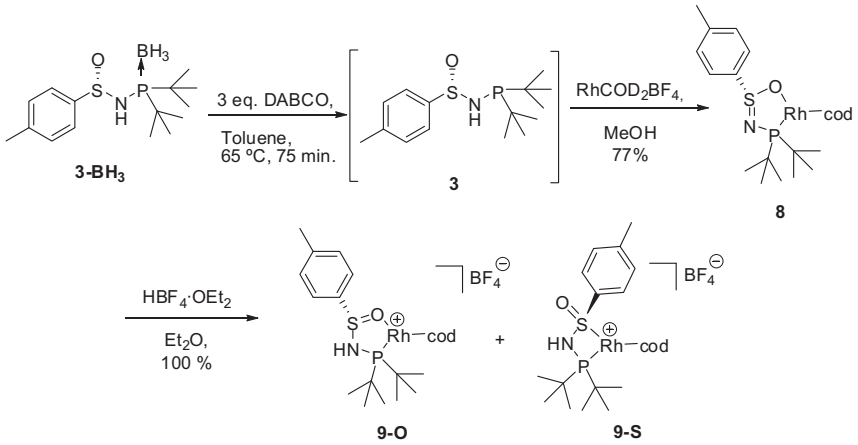


Fig. 4. Overlapping of ^{31}P NMR spectra of complexes **4** (red) and **5** (green). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

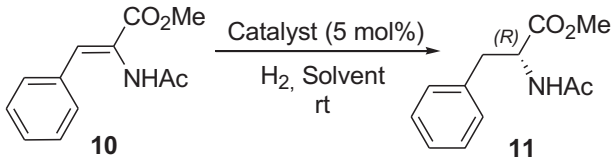
conversion as determined by ^{1}H NMR (Table 1, entries 3–6). The best selectivity was observed for the neutral complex **4** at room temperature with a 38% enantiomeric excess, yielding the *R* enantiomer of **11** when the reaction was run in dichloromethane with 4 bar of H_2 (Table 1, entry 6). The selectivity was improved to 42% enantiomeric excess by running the hydrogenation at 0 °C in methanol (Table 1, entry 7). Most interestingly, the more conventional cationic Rh complex **5** consistently yielded lower enantioselectivities [12]. This observation again suggested that the neutral species in solution is more tightly coordinated than the cationic one, thereby resulting in higher selectivity during the hydrogenation. To test whether a specific solvent or an additive could be used to induce a more selective coordination mode and thereby give a better enantiomeric excess, we applied various solvents. The results obtained varied greatly, THF for example, slowed the reaction dramatically and gave no selectivity. We thought that the addition of a base would give favorable results; however, addition of Et_3N or *tert*-butylamine only impaired the enantiomeric excesses obtained (Table 1, entries 11 and 12). The pressure of hydrogen had a key effect on the reaction outcome. We found high pressures gave poor excesses while the lower the pressure the better the performance. However, reducing the pressure to 1–2 bars of H_2 led to no conversion. The optimum pressure was found to be 4–5 bars.



Scheme 3. Synthesis of neutral and cationic rhodium complexes **8** and **9** derived from (+)-*p*-tolylsulfinamide.

The quadrant diagram method has been widely applied to correlate the steric demand surrounding the metal center and the absolute configuration of hydrogenation products [13]. In this respect, Hoge and co-workers demonstrated that the (*R*)-(TCFP) ligand hydrogenates MAC (**10**) to give the product (*R*) enantiomer with 99% enantiomeric excess [3]. According to the quadrant-analysis method, in complexes **4** and **5**, switching from an S- to O-coordination modifies the non-hindered quadrant available for the substrate coordination (Fig. 5). This phenomenon can be clearly observed in the X-ray structures of **5**-**O** and **5**-**S** (Fig. 3). The predomination of O- or S-coordination should ultimately determine the absolute configuration of the final hydrogenation product. Thus, for both the (*R*)-TCFP ligand and our S-bonded ligand (*R*)-**2**, the lower-left quadrant is the non-hindered one, and therefore, these compounds should provide the same hydrogenated enantiomer. In contrast, the O-bonded ligand (*R*)-**2** should provide the opposite enantiomer, since now the free quadrant is the upper-left one. Since the major enantiomer found in the hydrogenation using **4** as catalyst had the *R* configuration, we assumed that the S-coordination mode was the most abundant for the neutral complex during hydrogenation [14]. However, the low enantiomeric bias observed during the hydrogenation indicates that the hemilabile nature of the S–Rh linkage is detrimental to attain high selectivity in the hydrogenation catalysis.

Table 1
Hydrogenation of (Z)-α-acetamido cinnamate using PNSO–Rh complexes.



10 11

Entry	Catalyst	Solvent	Bar (H_2)	Conversion (%)[a]	ee (%)[b]
1	**8**	MeOH	3	0	0
2	**9**	MeOH	3	0	0
3	**5**	MeOH	3	100	11
4	**5**	CH_2Cl_2	4	100	12
5	**4**	MeOH	5	100	35
6	**4**	CH_2Cl_2	4	100	38
7[c]	**4**	MeOH	4	100	42
8	**4**	MeOH	30	100	8
9	**4**	CH_2Cl_2	25	100	6
10	**4**	THF	5	90	0
11	**4**	TFE	5	100	13
12[d]	**4**	MeOH	5	100	32
13[e]	**4**	MeOH	5	100	11

[a] Conversions to hydrogenated product determined by ^{1}H NMR.
[b] Enantiomeric excess determined by chiral HPLC analysis on a Chiralpak AD-H column.
[c] Reaction was carried out at 0 °C.
[d] 10 mol % of Et_3N were added.
[e] 10 mol % of *tert*-butylamine were added.

2.4. Conclusions

Here we have reported the synthesis of two new di-*tert*-butylphosphino PNSO ligands and their subsequent coordination to a rhodium(I) center. The secondary amine nature of these ligands together with the basic nature of their borane deprotection before metal coordination gave rise to neutral rhodium complexes with more interesting properties than normal salt-like rhodium species. These complexes are apolar and soluble in solvents such as hexane and diethyl ether as well as in more polar solvents such as methanol. The neutral complexes can be easily protonated to form their more standard salt counterparts. NMR and X-ray studies have shown that the coordination mode of ligand **2** to rhodium *via* either sulfur or oxygen is ill-defined for the cationic species, where there is an equally balanced equilibrium between the two possible coordination modes. In contrast, the neutral complexes display a more stable coordination mode to the metal center. In this respect, the absolute configuration of the hydrogenation products along with the quadrant analysis method indicates that the sulfur coordination is preferred for the neutral complex **4**. Although the neutral complex **4** is active as a hydrogenation catalyst, the hemilabile nature of the S–Rh is detrimental to attain high enantiomeric excess.

3. Experimental

3.1. (+)-(R)-N-(di-tert-butylphosphino)-2-methylpropane-2-sulfinamide borane (2-BH_3)

n-BuLi (1.5 mL, 3.85 mmol) was added dropwise to a solution of (+)-*tert*-butylsulfinamide (0.423 g, 3.5 mmol) stirring in THF (30 mL) at −78 °C under N_2 and the mixture was allowed to stir. After 30 min di-*tert*-butylchlorophosphine (0.731 mL, 3.85 mmol) was slowly added over approximately 10 min with the temperature maintained at −78 °C. The temperature was allowed to rise to 0 °C, the reaction was then stirred for 5 h at 0 °C. Upon consumption of the sulfinamide starting material, as monitored by TLC, $BH_3 \cdot SMe_2$ (0.405 mL, 3.85 mmol) was added to the reaction, which was allowed to heat up to room temperature and stirred for 17 h

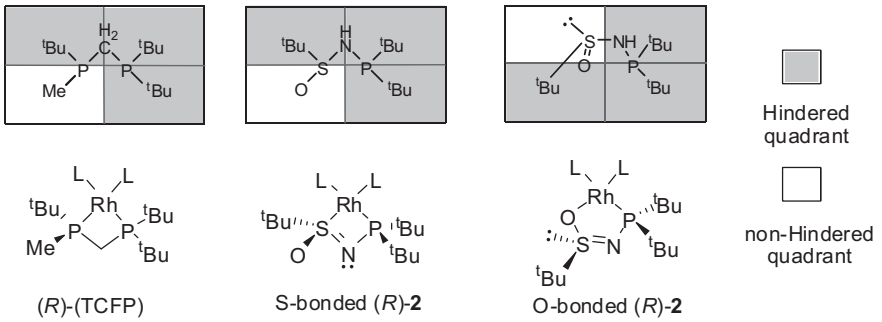


Fig. 5. Quadrant analysis for S- and O-bonded ligand (*R*)-**2**, and comparison with (*R*)-TCFP ligand. Absolute configurations refer to the free ligand.

(overnight). To quench the reaction, 30 mL of water was added, the residue was then extracted with ether (3 × 30 mL). Organic extracts were combined and dried over $MgSO_4$, and solvents were extracted *in vacuo* and pure product (0.581 g, 96%) was obtained as a white solid after purification by flash column chromatography (SiO_2, Hexanes/EtOAc, 80:20 to 1:1). $[\alpha]_D = -40.8$ (c 1.0, CH_2Cl_2). IR (KBr): υ_{max}: 2382, 1366 cm^{-1} ^1H NMR (400 MHz, $CDCl_3$): δ 3.74 (s, N–H), 1.36 (d, J = 13.7 Hz, 9H), 1.32 (d, J = 13.6 Hz, 9H), 1.28 (s, 9H) ppm. ^{13}C NMR (400 MHz, $CDCl_3$): δ 58.19 (d, J = 4.7 Hz, C), 35.28 (d, J = 4.4 Hz, C), 35.02 (d, J = 1.8 Hz, C), 27.40 (dd, J = 3.9, 2.6 Hz, CH_3 X 6), 22.49 (s, CH_3 X 3) ppm. ^{31}P NMR (300 MHz, $CDCl_3$): δ 76.41–75.88 (m) ppm. MS ESI: 581($[M + M + Na]^+$, 100%).

3.2. *[Rh(PNSO)(COD)]* (***4***)

AgOTf (0.138 g, 0.537 mmol) and $[RhCl(COD)]_2$ (0.133 g, 0.269 mmol) were added to a round-bottomed flask under nitrogen, THF (2 mL) was added on top and this was allowed to stir, covered in aluminum foil. The ligand **2-BH$_3$** (0.15 g, 0.537 mmol) was added to a flame-dried Schlenk tube, followed by DABCO (0.181 g, 1.61 mmol) and toluene (5 mL), under nitrogen. The reaction was stirred at 70 °C and monitored by TLC. Stirring and heating was stopped after 1 h and it was allowed to cool. After the rhodium had been stirred for 2 h it was filtered through a pad of celite under N_2, washed with dry THF and concentrated *in vacuo*. The solution of rhodium was quickly added to the deprotected ligand **2** stirring in the schlenk tube, this solution was allowed to stir for 1 h at room temperature before the residue was concentrated *in vacuo*. The residue was purified by flash column chromatography (SiO_2, Hexanes/EtOAc, 80:20) to give an orange solid (0.226 g, 89%). $[\alpha]_D$ = +48 (c 0.7, CH_2Cl_2). IR (KBr): υ_{max} 2936 (broad), 1472, 1358, 1046, 1014, 852 cm^{-1} ^1H NMR (400 MHz, $CDCl_3$): δ 5.32–5.21 (m, 1H), 5.15 (dd, J = 7.8, 2.1 Hz, 1H), 4.09 (td, J = 7.2, 2.8 Hz, 1H), 3.96 (d, J = 2.4 Hz, 1H). 2.48 (ddd, J = 16.1, 8.1, 6.0 Hz, 1H), 2.35–2.10 (m, 4H), 2.05–1.74 (m, 3H), 1.25 (d, J = 20 Hz, 9H), 1.24 (d, J = 20 Hz, 9H), 1.10 (s, 9H) ppm. ^{13}C NMR (400 MHz, $CDCl_3$): δ 99.21 (dd, J = 10.3, 7.9 Hz, CH), 95.98 (dd, J = 11.4, 7.2 Hz, CH), 65.24 (d, J = 15.2 Hz, CH), 61.52 (d, J = 13.9 Hz, CH), 42.62 (d, J = 13.0 Hz, C), 38.14 (d, J = 22.0 Hz, C), 34.72 (s, CH_2) 32.78 (s, CH_2) 30.17 (d, J = 50.1 Hz, C), 29.70 (d, J = 6.3 Hz, CH_3 X 3), 29.29 (d, J = 4.8 Hz, CH_3 X 3), 28.18 (s, CH_2), 27.28 (s, CH_2), 22.47 (s, CH_3 X 3) ppm. ^{31}P NMR (300 MHz, $CDCl_3$): δ:138.4 (d, J = 145 Hz) ppm. MS ESI: 476 ($[M + H]^+$, 100%).

3.3. *[Rh(PNSO)(COD)][BF$_4$]* (***5***)

The rhodium complex **4** (50 mg, 0.105 mmol) was stirred in anhydrous Et_2O (3 mL) under N_2 in a round-bottomed flask and $HBF_4 \cdot OEt_2$ (0.014 mL, 0.105 mmol) was added dropwise. A precipitate instantly fell out of solution. The supernatant was removed by syringe. The precipitate was washed with dry diethyl ether (3 × 2 mL). Solvent was removed *in vacuo* and later by high vacuum to afford product as a bright yellow powder (0.041 g, 69%). $[\alpha]_D$ = +27.9 (c 0.32, CH_2Cl_2). IR (KBr): υ_{max}: 2919, 1471, 1076 cm^{-1} ^1H NMR (400 MHz, $CDCl_3$): δ 5.97 (s, 1H), 5.44–5.33 (m, 1H), 5.15 (s, 1H), 4.27 (s, 1H), 2.61–2.47 (m, 1H), 2.47–2.33 (m, 3H), 2.28–2.18 (m, 1H), 2.14–1.97 (m, 3H), 1.81 (s, 1H, NH), 1.50 (d, J = 14.6 Hz, 9H), 1.40 (s, 9H), 1.35 (d, J = 14.9 Hz, 9H) ppm. ^{13}C NMR (400 MHz, $CDCl_3$): δ:105.54 (s, CH), 102.09 (d, J = 18.7 Hz, CH), 67.12 (d, J = 211.0 Hz, CH), 60.09 (d, J = 91.0 Hz, CH), 42.74 (d, J = 6.2 Hz, C), 39.62 (dd, J = 14.7, 3.0 Hz, C), 33.40 (s, CH_2), 33.12 (s, CH_2), 29.65 (s, CH_3 X 3), 28.98 (s, CH_3 X 3), 27.61 (s, CH_2 X 2), 21.92 (s, CH_3 X 3) ppm. ^{31}P NMR (300 MHz, $CDCl_3$): δ:140.4 (br) ppm. MS ESI: 476 ($[M - BF_4]^+$, 100%).

3.4. *(+)-(S)-N-(Di-tert-butylphosphino)-4-methylphenylsulfinamide borane (**3-BH$_3$**)*

n-BuLi (0.43 mL, 1.06 mmol) was added dropwise to the (+)-(*S*)-*p*-toluenesulfinamide stirring in THF (10 mL) under N_2 at −78 °C. After 50 min of stirring, P^tBu_2Cl (0.2 mL, 1.06 mmol) was slowly added. The solution was allowed to warm up to 0 °C and the temperature was maintained at 0 °C for 4.5 h. $BH_3 \cdot SMe_2$ (0.1 mL, 1.06 mmol) was added and the reaction was allowed to stir overnight for 17 h at room temperature. The reaction was quenched with NH_4Cl (aq.). The organic layer was washed with water, and the aqueous fractions were combined and washed with EtOAc 3 times. The organic fractions were then combined and dried over $MgSO_4$, and the solvents were removed *in vacuo*. Pure product was obtained as a white solid (0.20 g, 67%) after flash column chromatography (SiO_2, Hexanes/EtOAc, 80:20 to 6:4). $[\alpha]_D$ = + 79.9 (c 1.0, CH_2Cl_2). IR (KBr): υ_{max}: 2975, 2385, 1469, 1341, 1059, 861 cm^{-1} ^1H NMR (400 MHz, $CDCl_3$): δ 7.64 (d, J = 8.3 Hz, 2H), 7.32 (d, J = 7.9 Hz, 2H), 4.45 (s, 1H, NH), 2.42 (s, 3H), 1.36 (d, J = 13.9 Hz, 9H), 1.28 (d, J = 13.7 Hz, 9H) ppm. ^{13}C NMR (400 MHz, $CDCl_3$): δ 151.70 (s, C), 139.58 (s, C), 128.71 (s, CH), 124.62 (s, CH), 99.82 (d, J = 8.1 Hz, CH), 96.01 (s, CH), 67.67 (d, J = 14.7 Hz, CH), 61.51 (d, J = 15.6 Hz, CH), 40.75 (d, J = 22.3 Hz, C), 37.22 (dd, J = 17.4, 3.8 Hz, C), 33.64 (s, CH_2), 33.27 (s, CH_2), 29.48 (d, J = 5.4 Hz, CH_3 X 3), 28.51 (d, J = 5.6 Hz, CH_3 X 3), 27.82 (s, CH_2), 27.49 (s, CH_2), 21.31 (s, CH_3) ppm. ^{31}P NMR (300 MHz, $CDCl_3$): δ 94.2 (m) ppm. MS ESI: 649 ($[M + M + Na]^+$, 100%).

3.5. *[Rh(PNSO)(COD)]* (***8***)

The PNSO ligand **3-BH$_3$** (0.06 g, 0.192 mmol), DABCO (0.065 g, 0.575 mmol) and toluene (3 mL) were added to a flame-dried Schlenk tube under N_2 and this solution was heated to 65 °C while stirring. It was stirred for 1.25 h and then allowed to cool to room temperature. After 45 min, $[Rh(COD)_2][BF_4]$ (0.078 g, 0.192 mmol) in anhydrous MeOH (2 mL) was added to the Schlenk flask. After 2 h of stirring, the solvents were removed *in vacuo* and pure product (80 mg, 77%) was obtained after flash column chromatography (SiO_2, Hexanes/EtOAc, 9:1). $[\alpha]_D$ = +68.4 (c 0.55,

CH_2Cl_2). IR (KBr): υ_{max}: 2944 (large), 1588, 1471, 1037 cm^{-1} ^1H NMR (400 MHz, $CDCl_3$): δ 7.84 (d, $J = 8.1$ Hz, 2H), 7.22 (d, $J = 7.9$ Hz, 2H), 5.40–5.25 (m, 2H), 4.20–4.02 (m, 2H), 2.51–2.40 (m, 1H), 2.37 (s, 3H), 2.40–2.26 (m, 4H), 2.19–1.88 (m, 3H), 1.34 (d, $J = 13.2$ Hz, 9H), 0.92 (d, $J = 13.3$ Hz, 9H) ppm. ^{13}C NMR (400 MHz, $CDCl_3$): δ 151.70 (s, C), 139.58 (s, C), 128.71 (s, CH), 124.62 (s, CH), 99.82 (d, $J = 8.1$ Hz, CH), 96.01 (s, CH), 67.67 (d, $J = 14.7$ Hz, CH), 61.51 (d, $J = 15.6$ Hz, CH), 40.75 (d, $J = 22.3$ Hz, C), 37.22 (dd, $J = 17.4$, 3.8 Hz, C), 33.64 (s, CH_2), 33.27 (s, CH_2), 29.48 (d, $J = 5.4$ Hz, CH_3 X 3), 28.51 (d, $J = 5.6$ Hz, CH_3 X 3), 27.82 (s, CH_2), 27.49 (s, CH_2), 21.31 (s, CH_3) ppm. ^{31}P NMR (300 MHz, $CDCl_3$): δ 148.74 (d, $J = 149.4$ Hz) ppm. MS ESI: 701 $[(PNSO)Rh(PNSO)]^+$.

3.6. *[Rh(PNSO)(COD)][BF_4] (**9**)*

The complex **8** (0.042 g, 0.078 mmol) was stirred in anhydrous Et_2O (3 mL) under N_2 and $HBF_4 \cdot OEt_2$ (0.11 mL of a 1:10, $HBF_4 \cdot OEt_2$:Et_2O solution, 0.078 mmol) was then added A yellow precipitate quickly formed and fell out of solution. This precipitate was washed several times with anhydrous Et_2O to yield pure product in quantitative yield (0.051 g, 99%). $[\alpha]_D = +55.6$ (c 0.85, CH_2Cl_2). IR (KBr): υ_{max} 3506, 3199, 2940 (broad), 1482, 1051 cm^{-1} ^1H NMR (400 MHz, $CDCl_3$): δ 8.19 (d, $J = 8.2$ Hz, 2H), 7.43 (d, $J = 8.0$ Hz, 2H), 5.57–5.47 (m, 1H), 5.34–5.23 (m, 1H), 4.25 (d, $J = 49.5$ Hz, 2H), 2.64–2.47 (m, 4H), 2.46 (s, 3H), 2.28–2.03 (m, 4H), 1.56 (d, $J = 14.6$ Hz, 9H), 0.90 (d, $J = 15.0$ Hz, 9H) ppm. ^{13}C NMR (400 MHz, $CDCl_3$): δ 143.96 (s, C), 130.00 (s, CH), 125.10 (s, CH), 109.98 (s, C), 105.87 (s, CH), 100.54 (dd, $J = 12.0$, 7.3 Hz, CH), 73.82 (s, CH), 64.58 (s, CH), 38.10 (s, C) 34.26 (s, CH_2), 32.12 (s, CH_2), 29.50 (d, $J = 5.9$ Hz, CH_3 X 3), 28.35 (s, CH_2), 27.77 (d, $J = 6.1$ Hz, CH_3 X 3), 26.71 (s, CH_2), 21.60 (s, CH_3) ppm. ^{31}P NMR (300 MHz, $CDCl_3$): δ 140.11 (d, $J = 150.2$ Hz) ppm. MS ESI: 701 $[(PNSO)Rh(PNSO)]^+$.

3.7. *General procedure for hydrogenations*

A glass sample tube fitted with a stirring bar was loaded with the MAC substrate and the catalyst (5 mol %). The sample tube was placed in a pressure vessel. In open air, anhydrous degassed MeOH was added to the sample tube to a substrate concentration of 0.228×10^{-3} M. The reaction vessel was sealed tightly and, with the aid of vacuum, purged with nitrogen. The vessel was then connected to a hydrogen gas manifold where with the aid of vacuum was filled with hydrogen at the designated pressure. The closed vessel was left to stir for 24 h. Then, the pressure was released from the vessel and the reaction mixture was diluted EtOAc and filtered through a short pad of silica. The solvent was removed *in vacuo* to yield an off-white solid. **HPLC**: CHIRALPAK AD-H, 90% Heptane-10% IPA, 1 mL/min, $\lambda = 220$ nm, t_R isomer = 8.8, t_S isomer = 12.3 min.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jorganchem.2012.07.008.

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