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Enantioselective Ir-Catalyzed Hydrogenation of Minimally Functionalized Olefins Using Pyranoside Phosphinite-Oxazoline Ligands

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Pyranoside phosphinite-oxazoline ligands prepared from readily available (+)-D-glucosamine were applied to the Ir-catalyzed asymmetric hydrogenation of minimally functionalized olefins. Our results show that the enantioselectivity is dependent on the ozaxoline and the phosphinite moieties and the substrate structure. By carefully selecting the ligand components, enantioselectivities up to 99 % were obtained in the asymmetric reduction of several (*E*)- and (*Z*)-trisubstituted and 1,1-disubstituted olefins. The asymmetric hydrogenation was also performed using propylene carbonate as solvent, which allowed the iridium catalysts to be reused and maintained the high enantioselectivities.

Introduction

Metal-catalyzed asymmetric reactions have become one of the most powerful tools for the production of enantiomerically pure compounds. The permanently growing large number of chemical processes suitable for asymmetric catalysis, as well as the large variety of substrates to which they can be applied represent a permanent need for the discovery of new catalysts.[1] The performance of catalytic enantioselective reactions largely depends on appropriate chiral ligands being selected for the catalyst structure. Most of the research in this area, then, has focused on finding new series of efficient chiral ligands. Although many thousands of chiral ligands have been prepared and tested, very few of them have been found to have general applicability.[1] So, the search for highly efficient and easy-to-synthesize ligands from simple feedstocks is still of great importance. One of the simplest ways of obtaining chiral ligands is to transform or derivatize natural chiral compounds. Carbohydrates have many advantages: they are readily available, they are highly functionalized and they have several stereogenic centers. This enables series of chiral ligands to be synthesized and screened in the search for high activities and selectivities.[2] In this context, Uemura-based pyranoside P-oxazoline ligands (Figure 1) have emerged as privileged ligands that provide excellent results in several metal-catalyzed asymmetric transformations.[3]

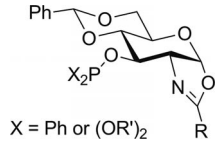

Figure 1. Uemura-based pyranoside P-oxazoline ligands.

Because of its high efficiency, atom economy and operational simplicity, asymmetric hydrogenation that uses molecular hydrogen to reduce prochiral olefins has become one of the most reliable catalytic methods for preparing optically active compounds.[1] Whereas the reduction of olefins containing an adjacent polar group (i.e., dehydroamino acids) by Rh- and Ru-catalyst precursors modified with phosphorus ligands has a long history, the asymmetric hydrogenation of minimally functionalized olefins is less developed, because these substrates have no adjacent polar group to direct the reaction.[1,4] In recent decades, iridium complexes with chiral P,N ligands have become established as one of the most efficient catalyst types for the hydrogenation of minimally functionalized olefins, and they complement Rh– and Ru–diphosphane complexes.[4–6] Most of the successful Ir–P,N catalytic systems contained phosphane/phosphinite-oxazoline-based ligands.[7] Although the number of substrates that can be successfully reduced with these systems was high, there is still a problem of substrate range limitation, since high enantioselectivities were mainly limited to trisubstituted substrates.[8] Research into more versatile phosphane/phosphinite-oxazoline ligand systems from simple starting materials in this reaction is therefore currently of great importance.

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Following our interest in carbohydrates as an inexpensive and highly modular chiral source for preparing ligands and encouraged by the success of the Uemura-based pyranoside phosphorus-oxazoline ligands,[3] we describe here the application of a small but structurally relevant set of phosphinite-oxazoline ligands **L1**–**L4** to the Ir-catalyzed hydrogenation of minimally functionalized olefins (Figure 2). With these ligands we investigate the effect of varying the electronic and steric properties of the oxazoline substituent (**L1**–**L3**), and the substituents at the phosphinite group (**L3**–**L4**), in an attempt to maximize catalyst performance.

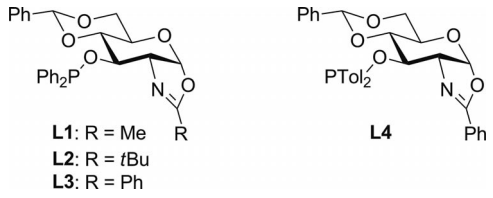
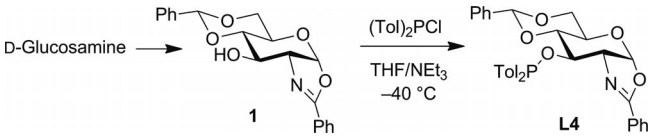


Figure 2. Pyranoside phosphinite-oxazoline ligands **L1**–**L4**.

Results and Discussion

Synthesis of Ligands

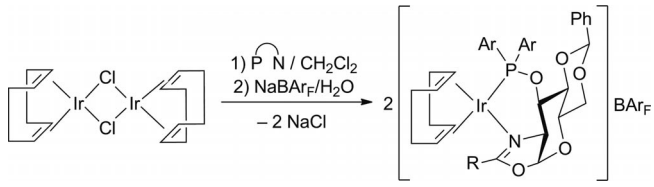
The new pyranoside phosphinite-oxazoline ligand **L4** can be straightforwardly synthesized using the procedure previously described for ligands **L1**–**L3** (Scheme 1).[3a,3b] It was therefore efficiently synthesized in one step by reacting the corresponding sugar oxazoline-alcohol **1** with 1 equiv. of chlorodi(*o*-tolyl)phosphane in the presence of triethylamine. Oxazoline-alcohol **1** is easily prepared from inexpensive D-glucosamine on a large scale.[3a,3b] Ligand **L4** was stable during purification on neutral alumina under argon and isolated in moderate yield as a white solid. It was stable at room temperature and very stable to hydrolysis. The elemental analysis was in agreement with the assigned structure. The ^{1}H, ^{13}C, and ^{31}P NMR spectra were as expected for this C_1 ligand.



Scheme 1. Synthesis of new pyranoside phosphinite-oxazoline ligand **L4**.

Synthesis of the Ir-Catalyst Precursors

The catalyst precursors were prepared by refluxing a dichloromethane solution of the appropriate ligand in the presence of 0.5 equiv. of $[Ir(\mu\text{-}Cl)cod]_2$ for 1 h and then exchanging the counterion with sodium tetrakis[3,5-bis(trifluoromethyl)phenyl]borate ($NaBAr_F$) (1 equiv.), in the presence of water (Scheme 2).



Scheme 2. Synthesis of catalyst precursors $[Ir(cod)(\mathbf{L})]BAr_F$ (**L** = **L1**–**L4**).

All complexes were isolated as air-stable orange solids in pure form, and they were then used without further purification. The complexes were characterized by elemental analysis and ^{1}H, ^{13}C, and ^{31}P NMR spectroscopy. The spectral assignments were based on information from ^{1}H–^{1}H and ^{13}C–^{1}H correlation measurements and were as expected for these C_1 iridium complexes. The elemental analysis of C,H,N matched the stoichiometry $[Ir(cod)(P\text{-}N)]_n(BAr_F)_n$.

For all complexes, the variable-temperature NMR measurements (from +40 °C to –80 °C) indicate that only one isomer was present in solution. In this context, the ^{31}P NMR spectra showed one sharp signal. The ^{13}C NMR showed four signals for the olefinic carbon atoms of the coordinated cyclooctadiene, as expected for C_1-symmetrical complexes. Two of the four signals, those corresponding to the olefinic carbon atoms located *trans* to the phosphorus atom, appeared low-field-shifted. The ^{13}C NMR spectra also showed the expected four signals of the methylene carbon atoms of the cyclooctadiene. The signals from the phosphinite-oxazoline ligands in these complexes produced the expected ^{1}H and ^{13}C NMR pattern for the glucopyranoside nucleus.

Asymmetric Hydrogenation of Minimally Functionalized Olefins

In an initial set of experiments we used the Ir-catalyzed hydrogenation of substrates *trans*-α-methylstilbene (**S1**) and 2-(4-methoxyphenyl)but-1-ene (**S2**) to study the potential of phosphinite-oxazoline ligands **L1**–**L4**. Substrate **S1** was chosen as a model for the hydrogenation of trisubstituted olefins, because it has been reduced with a wide range of ligands, and the efficiency of the various ligand systems can be compared directly.[4d] In order to assess the potential of the ligand library **L1**–**L4** for the more demanding 1,1-disubstituted terminal olefins, which are usually hydrogenated less enantioselectively than the corresponding trisubstituted olefins,[9,10] we chose substrate **S2** as a model.[4e] The lower enantioselectivity obtained with 1,1-disubstituted terminal olefins than that obtained with trisubstituted olefins has been attributed to two main factors.[4e] The first is that enantioface olefin coordination is difficult to control because of the comparable steric size of the alkyl and aryl substituent at the olefinic C atom. The second reason is that the terminal double bond can isomerize to form the more stable

internal *trans*-alkene, which usually leads to the predominant formation of the opposite enantiomer of the hydrogenated product.

Our catalytic results showed that for both types of substrates the reactions proceeded smoothly at room temperature under standard conditions (50 bar of H_2 for **S1** and 1 bar of H_2 for **S2**).[11] High activities and enantioselectivities (up to 96% for **S1** and 94% for **S2**) were obtained. The results, which are summarized in Table 1, indicate that both activities and enantioselectivities are mainly affected by the oxazoline substituent.

Table 1. Ir-catalyzed asymmetric hydrogenation of **S1** and **S2** using ligands **L1**–**L4**.[a]

Entry	Ligand	Ph, Ph (**S1**)		*p*-MeOC$_6$H$_4$ (**S2**)	
		Conversion [%][b]	*ee* [%][c]	Conversion [%][b]	*ee* [%][c]
1	**L1**	100	91 (*R*)	100	87 (*S*)
2	**L2**	64	95 (*R*)	97	93 (*S*)
3	**L3**	100	95 (*R*)	100	94 (*S*)
4	**L4**	100	96 (*R*)	100	93 (*S*)
5[d]	**L3**	100	95 (*R*)	100	94 (*S*)
6[d]	**L4**	100	96 (*R*)	100	93 (*S*)

[a] Reactions carried out using 0.5 mmol of substrate and 2 mol-% of Ir-catalyst precursor at 50 bar of H_2 for **S1** and 1 bar of H_2 for **S2** with dichloromethane (2 mL) as solvent at room temperature. [b] Conversion measured by ^{1}H NMR spectroscopy after 2 h. [c] Enantiomeric excess determined by HPLC (**S1**) and GC (**S2**). [d] Reaction carried out at 0.25 mol-% of Ir-catalyst precursor.

With ligands **L1**–**L3** we studied the effect of the oxazoline substituent on the catalytic performance. We found that the best trade-off between activity and enantioselectivity was obtained using the Ir/**L3** catalyst precursor (Table 1, Entry 3). The enantiomeric excesses obtained with catalyst precursors Ir/**L2** and Ir/**L3** were comparable and the highest, but the activity obtained with the Ir/**L2** system was the lowest. Conversely, the Ir/**L1** catalyst precursor containing the ligand with the small methyl substituent on the oxazoline provided high relative conversion but the enantioselectivities were the lowest (Table 1, Entry 1).

Finally, we found that the Ir/**L4** catalytic system, which differs from Ir/**L3** in that it contains a bulkier aryl phosphinite moiety, provided similar results (Table 1, Entries 3 and 4).

In summary, the best results were achieved with ligands **L3** and **L4**. Note that at a low catalyst loading (0.25 mol-%), the excellent enantioselectivities and activities were maintained (Table 1, Entries 5 and 6). These results are among the best reported for these types of substrate.[4]

We then studied the potential of [Ir(cod)(**L3**)]BAr_F and [Ir(cod)(**L4**)]BAr_F catalyst precursors in the asymmetric hydrogenation of other minimally functionalized (*E*)- and (*Z*)-trisubstituted (**S3**–**S9**) and 1,1-disubstituted (**S10**–**S20**) olefins. The results are shown in Table 2. Comparing the results obtained using substrates **S1** (Table 1, Entry 3) and **S3**–**S4** (Table 2, Entries 1–4), we found that enantioselectivity is relatively insensitive to the electronic nature of both the phenyl ring (**S3** vs. **S4**) and the substituent *trans* to the aryl group (**S1** vs. **S3**) of the substrate. Interestingly, high enantioselectivities can also be obtained for the more demanding (*Z*) isomers **S5** and **S6** (Table 2, Entries 5–8), which usually react with much lower enantioselectivities than those of the corresponding (*E*) isomers.[4] For this substrate class, we found that the steric hindrance of the phosphinite moiety had a considerable effect. So, the Ir/**L4** catalytic system provided higher enantioselectivity than the Ir/**L3** system (Table 2, Entries 6 and 8). It should also be pointed out that the enantioselectivities obtained in the hydrogenation of trisubstituted olefins containing a neighboring polar group were also high. These substrates are interesting, because they allow for further functionalization and they are therefore important synthons in the synthesis of more complex chiral molecules. High enantioselectivities (up to 99%) have been obtained in the hydrogenation of α,β-unsaturated ester **S7**, allylic alcohol **S8**, and vinylsilane **S9** (Table 2, Entries 9–14).

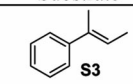
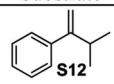
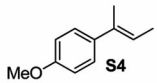
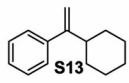
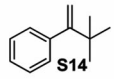
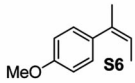
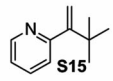
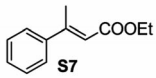
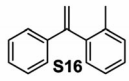
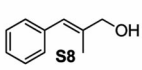
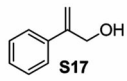
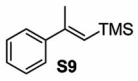
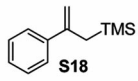
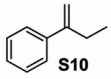
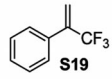
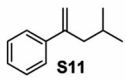
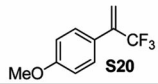
The results indicated that the enantioselectivity of the hydrogenation of several 1,1-disubstituted alkyl-phenyl substrates (**S10**–**S14**) is affected by the nature of the alkyl chain (*ee* 73–99%, Table 2, Entries 15–21). This behavior can be explained by the competition between direct hydrogenation vs. isomerization for the various substrates. This is supported by the fact that the hydrogenation of substrates **S12**–**S13**, which form the most stable isomerized tetrasubstituted olefins, provides the lowest enantioselectivities (Table 2, Entries 18 and 19), while the highest enantioselectivity of the series is found with substrate **S14**, which contains a *t*Bu group and for which isomerization cannot occur (Table 2, Entries 20 and 21). However, the large difference in steric size of Ph vs. *t*Bu may well be the principal factor in this case.

Interestingly, the Ir/**L3** catalyst system was also able to hydrogenate pyridyl-containing substrate **S15** with excellent activities and enantioselectivities (99% *ee*, Table 2, Entry 22). We also obtained excellent levels of enantioselectivities in the reduction of diaryl substrate **S16**, with a steric differentiation between the aryl groups, using the Ir/**L4** catalyst precursor (Table 2, Entry 24). The hydrogenation of 1,1-disubstituted heteroaromatic alkenes and diarylalkenes provides an easy entry point for the preparation of drugs and research materials.[12]

Our results also indicated that the efficiency at transferring the chiral information of these catalyst precursors is highly dependent on the nature of the neighboring polar group in these 1,1-disubstituted substrates. Thus, while the reduction of allylic alcohol **S17** provides lower *ee* values than the best ones reported in the literature (Table 2, Entries 25 and 26), the hydrogenation of vinylsilane **S18** and trifluoromethyl substrates **S19** and **S20** provides fairly good *ee* values (Table 2, Entries 27–32).[3d,8a,13]

Finally, we decided to study the possibility of using propylene carbonate (PC) as an environmentally friendly solvent. PC has recently emerged as an environmentally friendly alternative to standard organic solvents that allows catalysts to be repeatedly recycled by a simple two-phase extraction with an apolar solvent.[14] For this purpose, substrates **S2**, **S12**, and **S14** were hydrogenated in PC with the

Table 2. Asymmetric hydrogenation of several tri- and disubstituted substrates using Ir-pyranoside phosphinite-oxazoline catalyst precursors.[a]

Entry	Substrate	Ligand	*ee* [%][b]	Entry	Substrate	Ligand	*ee* [%][b]
1	 **S3**	**L3**	95 (*R*)	18[c]	 **S12**	**L3**	75 (*S*)
2		**L4**	95 (*R*)				
3	 **S4**	**L3**	96 (*R*)	19[c]	 **S13**	**L3**	73 (*S*)
4		**L4**	95 (*R*)				
5	 **S5**	**L3**	78 (*S*)	20[c]	 **S14**	**L3**	99 (*S*)
6		**L4**	87 (*S*)	21[c]		**L4**	92 (*S*)
7	 **S6**	**L3**	78 (*S*)	22[c]	 **S15**	**L3**	99 (+)
8		**L4**	89 (*S*)				
9	 **S7**	**L3**	99 (*R*)	23	 **S16**	**L3**	44 (+)
10		**L4**	99 (*R*)	24		**L4**	99 (+)
11	 **S8**	**L3**	87 (*R*)	25	 **S17**	**L3**	40 (*R*)
12		**L4**	86 (*R*)	26		**L4**	45 (*R*)
13	 **S9**	**L3**	75 (*R*)	27	 **S18**	**L3**	74 (*S*)
14		**L4**	77 (*R*)	28		**L4**	90 (*S*)
15[c]	 **S10**	**L3**	93 (*S*)	29[c]	 **S19**	**L3**	51 (–)
				30[c]		**L4**	52 (–)
16[c]	 **S11**	**L3**	89 (*S*)	31[c]	 **S20**	**L3**	63 (–)
17[c]		**L4**	87 (*S*)	32[c]		**L4**	62 (–)

[a] Reactions carried out using 0.5 mmol of substrate and 2 mol-% of Ir-catalyst precursor at 50 bar of H_2 with dichloromethane as solvent at room temperature. Full conversions were obtained in all cases after 2 h. [b] Enantiomeric excess determined by HPLC or GC. [c] Reaction carried out at 1 bar of H_2.

catalyst precursor [Ir(cod)(**L3a**)]BAr_F, and the products were removed by extraction with hexane (Table 3). We were pleased to see that this catalyst can be used up to four times with no significant loss in enantioselectivity, although the reaction time increased.[15] It should be pointed out that the reduction of **S12** proceeds with higher enantioselectivity in PC than in dichloromethane. This behavior has already been observed by Börner and co-workers, and it is in agreement with the reduction in the isomerization when PC was used as a solvent.[16]

Table 3. Recycling experiments with catalyst precursor [Ir(cod)(**L3a**)]BAr_F and **S2**, **S12**, and **S14** as substrates in PC.[a]

Cycle	Substrate	Conversion [%] (time [h])[b]	*ee* [%][c]
1	**S2**	100 (4)	93 (*S*)
2	**S2**	98 (6)	93 (*S*)
3	**S2**	94 (10)	93 (*S*)
4	**S2**	86 (14)	92 (*S*)
5	**S12**	97 (4)	81 (*S*)
6	**S12**	94 (6)	80 (*S*)
7	**S12**	91 (10)	80 (*S*)
8	**S12**	92 (14)	80 (*S*)
9	**S14**	100 (4)	99 (*S*)
10	**S14**	97 (6)	98 (*S*)
11	**S14**	96 (10)	98 (*S*)
12	**S14**	92 (14)	97 (*S*)

[a] Reactions carried out using 0.5 mmol of substrate and 2 mol-% of Ir-catalyst precursor at 50 bar of H_2. [b] Conversion measured by ^1H NMR spectroscopy. [c] Enantiomeric excess determined by GC.

Conclusions

Phosphinite-oxazoline ligands, which contain a pyranoside as a simple but effective backbone, were tested in the asymmetric hydrogenation of a wide range of (*E*)- and (*Z*)-trisubstituted and 1,1-disubstituted terminal olefins, including examples with neighboring polar groups. A small but structurally relevant library of Ir-phosphinite-oxazoline precatalysts has been developed by changing the electronic and steric properties of the oxazoline substituent, and the substituents at the phosphinite group. Although the enantioselectivity is dependent on the oxazoline and phosphinite moieties and the substrate structure, we found that the introduction of a bulky *ortho*-tolyl phosphinite moiety was crucial to achieving the highest enantioselectivities with some of the most elusive substrate types [i.e., (Z)-trisubstituted and diaryl terminal substrates]. By carefully selecting the ligand components, enantioselectivities up to 99% were therefore obtained in the asymmetric reduction of several (*E*)- and (*Z*)-trisubstituted olefins. This good performance extended even to the more challenging class of terminally disubstituted olefins. For this substrate class, our results

indicated that enantioselectivity is dependent on the nature of the alkyl substrate substituent, which has been attributed to the presence of an isomerization process under hydrogenation conditions. Enantioselectivities were therefore best in the asymmetric reduction of aryl and pyridyl/*tert*-butyl substrates as well as in the reduction of diaryl substrates (*ee* up to 99%), for which isomerization cannot occur. The asymmetric hydrogenations were also performed using propylene carbonate as solvent, which allowed the Ir catalyst to be reused and maintained the excellent enantioselectivities.

In summary, the reactivity and selectivity of these pyranoside Ir-phosphinite-oxazoline catalysts are high but somewhat lower compared to privileged phosphite-oxazoline analogues.[3d] Nevertheless, these Ir/phosphinite-oxazoline systems represent one of the very few phosphinite-containing P,N catalysts[8a] able to hydrogenate a broad range of terminal disubstituted olefins with high enantioselectivities. Therefore, by appropriate selection of the ligand parameters phosphinite-based P,N ligands can also be successfully applied in the hydrogenation of this challenging substrate class.

Experimental Section

General Considerations: All reactions were carried out using standard Schlenk techniques under argon. Solvents were purified and dried by standard procedures. Ligands **L1**–**L3** were prepared as described previously by Uemura and co-workers.[3a,3b] [Ir(cod)(**L3**)]BArF was prepared as previously reported.[17] ^{1}H, ^{13}C{^{1}H}, and ^{31}P{^{1}H} NMR spectra were recorded with a 400 MHz spectrometer. Chemical shifts are relative to that of $SiMe_4$ (^{1}H and ^{13}C) as internal standard or H_3PO_4 (^{31}P) as external standard. ^{1}H, ^{13}C, and ^{31}P assignments were made on the basis of ^{1}H-^{1}H gCOSY and ^{1}H-^{13}C gHSQC experiments. All catalytic experiments were performed three times.

Synthesis of L4: Chlorodi(*o*-tolyl)phosphane (136.5 mg, 0.55 mmol) was slowly added at –40 °C to a solution of **1** (176.6 mg, 0.5 mmol) and DMAP (5.7 mg, 0.05 mmol) in THF (3.3 mL) and triethylamine (1.7 mL). The reaction mixture was stirred at room temperature for 15 min. Diethyl ether was then added, and the salts were removed by filtration. The residue was purified by flash chromatography (eluent: toluene/NEt_3, 100:2) to produce the corresponding ligand as a colorless oil. Yield: 152 mg (54%). ^{31}P NMR ($CDCl_3$): δ = 106.6 (s) ppm. ^{1}H NMR ($CDCl_3$): δ = 2.25 (s, 3 H, CH_3-Ph), 2.69 (s, 3 H, CH_3-Ph), 3.28 (m, 1 H, 6′-H), 3.45 (m, 2 H, 4-H and 5-H), 3.97 (dd, $^{2}J_{6\text{-}6'}$ = 10.8, $^{3}J_{6\text{-}5}$ = 3.6 Hz, 1 H, 6-H), 4.13 (dd, $^{3}J_{2\text{-}1}$ = 8.0, $^{3}J_{2\text{-}3}$ = 3.6 Hz, 1 H, 2-H), 4.43 (m, 1 H, 3-H), 5.02 (s, 1 H, 7-H), 5.58 (d, $^{3}J_{1\text{-}2}$ = 8.0 Hz, 1 H, 1-H), 6.8–7.2 (m, 12 H, CH=), 7.25 (m, 2 H, CH=), 7.64 (m, 1 H, CH=), 7.88 (m, 1 H, CH=), 8.08 (m, 2 H, CH=) ppm. ^{13}C NMR ($CDCl_3$): δ = 20.8 (d, $J_{C\text{-}P}$ = 21.4 Hz, CH_3-Ph), 21.5 (d, $J_{C\text{-}P}$ = 20.6 Hz, CH_3-Ph), 63.6 (C-5), 68.8 (C-6), 70.1 (d, $J_{C\text{-}P}$ = 4.6 Hz, C-2), 80.2 (C-4), 83.8 (d, $J_{C\text{-}P}$ = 22.1 Hz, C-3), 101.7 (C-7), 103.4 (C-1), 126.9 (CH=), 128.8 (CH=), 128.9 (CH=), 129.0 (CH=), 129.1 (CH=), 129.6 (CH=), 130.2 (CH=), 130.5 (CH=), 130.6 (CH=), 130.8 (CH=), 130.9 (CH=), 131.2 (CH=), 131.3 (CH=), 131.4 (CH=), 131.5 (CH=), 132.1 (CH=), 138.2 (CH=), 140.3 (C), 140.4 (C), 140.6 (C), 141.3 (C), 141.6 (C), 142.2 (C), 142.5 (C), 163.6 (C=N) ppm. $C_{34}H_{32}NO_5P$ (565.60): calcd. C 72.20, H 5.70, N 2.48; found C 72.17, H 5.72, N 2.43.

Typical Procedure for the Preparation of [Ir(cod)(L)]BAr$_F$: The corresponding ligand (0.074 mmol) was dissolved in CH_2Cl_2 (2 mL), and [Ir(μ-Cl)cod]$_2$ (25 mg, 0.037 mmol) was added. The mixture was refluxed at 50 °C for 1 h. After 5 min at room temperature, $NaBAr_F$ (77.1 mg, 0.082 mmol) and water (2 mL) were added and the reaction mixture was stirred vigorously at room temperature for 30 min. The phases were separated, and the aqueous phase was extracted twice with CH_2Cl_2. The combined organic phases were filtered through a Celite plug, dried with $MgSO_4$, and the solvent was evaporated to give the product as an orange solid.

[Ir(cod)(L1)]BAr$_F$: Yield 110 mg (91%). ^{31}P NMR ($CDCl_3$): δ = 106.8 (s) ppm. ^{1}H NMR ($CDCl_3$): δ = 1.7–2.0 (br., 4 H, CH_2, cod), 2.08 (m, 2 H, CH_2, cod), 2.14 (s, 3 H, CH_3), 2.21 (br., 2 H, CH_2 cod), 3.32 (br., 1 H, CH=, cod), 3.73 (m, 2 H, 4-H and 6′-H), 3.95 (m, 1 H, 5-H and CH = cod), 4.17 (m, 1 H, 3-H), 4.31 (dd, $^{2}J_{6\text{-}6'}$ = 10.0, $^{3}J_{6\text{-}5}$ = 4.8 Hz, 1 H, 6-H), 4.46 (m, 1 H, 2-H), 4.58 (m, 1 H, CH=, cod), 5.02 (br., 1 H, CH=, cod), 5.39 (s, 1 H, 7-H), 5.99 (d, $^{3}J_{1\text{-}2}$ = 6.4 Hz, 1 H, 1-H), 7.0–8.4 (m, 27 H, CH=, aromatic H) ppm. ^{13}C NMR ($CDCl_3$): δ = 16.8 (CH_3), 25.7 (br., CH_2, cod), 29.6 (br., CH_2, cod), 30.7 (br., CH_2, cod), 34.6 (br., CH_2 cod), 65.3 (br., CH=, cod), 66.9 (C-5), 67.3 (C-2), 67.9 (C-6), 70.2 (br., CH=, cod), 74.9 (d, $J_{C\text{-}P}$ = 7.4 Hz, C-4), 79.2 (C-3), 96.4 (d, $J_{C\text{-}P}$ = 19.7 Hz, CH=, cod), 100.9 (d, $J_{C\text{-}P}$ = 12.9 Hz, CH=, cod), 101.7 (s, C-7), 104.5 (s, C-1), 117.7 (br., CH=BAr$_F$), 120–134 (aromatic C), 135.0 (br., CH=BAr$_F$), 135.5–150 (aromatic C), 161.9 (q, $^{1}J_{C\text{-}B}$ = 50 Hz, C-B BAr$_F$), 173.6 (C=N) ppm. $C_{67}H_{50}BF_{24}IrNO_5P$ (1639.09): calcd. C 49.10, H 3.07, N 0.85; found C 49.03, H 3.01, N . 0.82.

[Ir(cod)(L2)]BAr$_F$: Yield 119 mg (96%). ^{31}P NMR ($CDCl_3$): δ = 106.7 (s) ppm. ^{1}H NMR ($CDCl_3$): δ = 1.49 (s, 9 H, CH_3, *t*Bu), 1.6–2.3 (m, 8 H, CH_2 cod), 3.61 (m, 1 H, 4-H), 3.76 (m, 2 H, 6′-H and 5-H), 4.02 (m, 1 H, 3-H), 4.19 (m, 1 H, CH=, cod), 4.27 (m, 1 H, 6-H), 4.39 (m, 1 H, H2), 4.53 (br., 1 H, CH=, cod), 4.79 (br., 1 H, CH=, cod), 5.37 (s, 1 H, 7-H), 5.45 (br., 1 H, CH=, cod), 6.03 (d, $^{3}J_{1\text{-}2}$ = 6 Hz, 1 H, CH, H1), 7.1–8.2 (m, 27 H, CH=, aromatic H) ppm. ^{13}C NMR ($CDCl_3$): δ = 23.8 (br., CH_2, cod), 26.5 (br., CH_2, cod), 29.1 (CH_3, *t*Bu), 32.1 (br., CH_2, cod), 32.4 (C, *t*Bu), 33.4 (br., CH_2, cod), 65.9 (C-5), 67.7 (C-6), 68.9 (C-2), 69.9 (CH=, cod), 70.4 (CH=, cod), 74.5 (C-4), 80.4 (C-3), 90.8 (CH=, cod), 101.3 (C-7), 103.4 (C-1), 104.2 (d, $J_{C\text{-}P}$ = 15.6 Hz, CH=, cod), 117.7 (br., CH=BAr$_F$), 120–134 (aromatic C), 135.0 (br., CH=BAr$_F$), 135.5–147 (aromatic C), 161.9 (q, $^{1}J_{C\text{-}B}$ = 50 Hz, C-B, BAr$_F$), 175.3 (s, C=N) ppm. $C_{86}H_{86}BF_{24}IrNO_7P$ (1935.58): calcd. C 53.37, H 4.48, N 0.72; found C 53.42, H 4.53, N 0.69.

[Ir(cod)(L4)]BAr$_F$: Yield: 122 mg (96%). ^{31}P NMR ($CDCl_3$): δ = 116.2 (s) ppm. ^{1}H NMR ($CDCl_3$): δ = 1.6–1.8 (m, 4 H, CH_2, cod), 1.89 (s, 3 H, CH_3-Ph), 1.8–2.2 (br., 4 H, CH_2, cod), 2.48 (m, 1 H, CH=, cod), 2.99 (s, 3 H, CH_3-Ph), 3.6–3.8 (m, 4 H, 3-H, 4-H, 5-H, 6′-H), 3.86 (m, 1 H, CH=, cod), 4.28 (dd, $^{2}J_{6\text{-}6'}$ = 10.0, $^{3}J_{6\text{-}5}$ = 4.0 Hz, 1 H, 6-H), 4.58 (m, 1 H, 2-H), 5.02 (m, 1 H, CH=), 5.47 (m, 1 H, 7-H), 6.28 (d, $^{3}J_{1\text{-}2}$ = 6.0 Hz, 1 H, 1-H), 6.5 (m, 1 H, CH= aromatic H), 7.0–7.8 (m, 26 H, CH= aromatic H), 8.32 (m, 2 H, CH= aromatic H), 8.73 (m, 1 H, CH= aromatic H) ppm. ^{13}C NMR ($CDCl_3$): δ = 21.6 (CH_3-Ph), 23.0 (d, $J_{C\text{-}P}$ = 6.0 Hz, CH_3), 25.6 (br., CH_2, cod), 29.0 (br., CH_2, cod), 29.9 (br., CH_2, cod), 32.3 (br., CH_2, cod), 65.9 (CH), 66.4 (CH), 67.7 (CH), 69.3 (CH=, cod), 75.1 (CH=, cod), 80.7 (CH), 93.0 (d, $J_{C\text{-}P}$ = 13.8 Hz, CH=cod), 101.8 (d, $J_{C\text{-}P}$ = 12.6 Hz, CH=cod), 102.2 (C-7), 104.4 (C-1) 117.7 (br., CH=, BAr$_F$), 120–134 (aromatic C), 135.0 (br., CH=, BAr$_F$), 136–145 (aromatic C), 161.9 (q, $^{1}J_{C\text{-}B}$ = 49.6 Hz, C-B, BAr$_F$), 170.5 (C=N) ppm. $C_{74}H_{56}BF_{24}IrNO_5P$ (1729.22): calcd. C 51.40, H 3.26, N 0.81; found C 51.35, H 3.24, N 0.77.

Typical Procedure for the Hydrogenation of Olefins: The alkene (0.5 mmol) and Ir complex (2 mol-%) were dissolved in CH_2Cl_2 (2 mL) in a high-pressure autoclave, which was purged four times with hydrogen. Subsequently, it was pressurized at the desired pressure. After the required reaction time, the autoclave was depressurized and the solvent evaporated. The residue was dissolved in Et_2O (1.5 mL) and filtered through a short Celite plug. The enantiomeric excess was determined by chiral GC or chiral HPLC, and conversions were determined by ^1H NMR spectroscopy. The enantiomeric excesses of hydrogenated products were determined using the conditions previously described.[17,18]

Typical Procedure for Catalyst Recycling: After each catalytic run, the autoclave was depressurized. The colorless propylene carbonate solution was then extracted with dry/deoxygenated hexane under argon in order to remove the substrate and the hydrogenated product. Upon extractions, the corresponding amount of substrate was then added to start a new run.

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