Ir/Thioether–Carbene, –Phosphinite and –Phosphite Complexes for Asymmetric Hydrogenation. A Case for Comparison

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ABSTRACT: We studied for the first time the potential of novel and simple Ir/thioether-NHC complexes in the asymmetric hydrogenation of unfunctionalized olefins and cyclic β-enamides. For comparison, we prepared and applied the analogues thioether–phosphinite/phosphite complexes. We found that the efficiency of the new Ir/thioether-NHC catalyst precursors varies with the type of olefin. Thus, while the Ir/thioether-NHC catalyst precursors provided lower catalytic performance than their related Ir/thioether-P complexes in the hydrogenation of olefins lacking a coordinating group, the catalysts had similar good performance for the reduction of functionalized olefins (e.g. tri- and disubstituted enol phosphonate derivatives). Catalytic results together with the studies of the reactivity towards H_2 indicated that the thioether-carbene design favors the formation of inactive trinuclear species, which are responsible of the low activities obtained with this carbene type catalysts. Nevertheless, this catalyst deactivation can be avoided by using functionalized olefins such as enol phosphonates. We also report the discovery of simple-to-synthesize Ir/thioether-P catalysts containing a simple backbone that gave high enantioselectivities for some trisubstituted olefins, some challenging 1,1'-disubstituted olefins and cyclic β-enamides.

INTRODUCTION

Metal-catalyzed asymmetric hydrogenation (AH) offers some of the most sustainable and straightforward processes for producing pharmaceuticals, flavours, fragrances, agrochemicals and fine chemicals.[1] It is estimated that around 10% of all chemical steps in the production of such compounds are hydrogenations. Despite the extensive research dedicated to the AH of alkenes and the important progress reached some problems still need to be solved. Most catalysts only work with a limited number of alkenes and each type of alkene needs a specific catalyst for optimal enantioselectivity. In this area, the AH of functionalized alkenes is mostly carried out by Ru- and Rh-diphosphine catalysts,[2] while the AH of olefins without a coordinative functional group is mainly carried out with Ir-P,N catalysts (P= phosphine, phosphinite and phosphite and N= oxazoline, oxazole, pyridine, thiazole)[3]. The AH of functionalized olefins has been thoroughly studied for decades, there are, however, some substrate types that are still a challenge (e.g. cyclic β-enamides). Compared to the AH of functionalized olefins, the reduction of unfunctionalized alkenes is less mature and has less synthetic utility. Essentially, most catalysts are still specific for a type of olefin geometry and its substitution pattern.[3] For example, the most successful cases have been reported for trisubstituted E-unfunctionalized alkenes and, to a less extend for Z-trisubstituted and 1,1'-disubstituted.[3] To overcome these limitations, research has also studied the replacement of either the P-group by a N-heterocyclic carbene (NHC)[4] moiety or the N-donor group by more stable and accessible O- and S-donor groups[5].

In the last two decades, NHCs have emerged as powerful alternatives for phosphine ligands in catalysis thanks to their strong σ-donor ability, air stability and robustness.[6] In this respect, in 2001, Burgess' group reported for the first time that NHC-oxazoline based Ir-catalysts can also be applied in the AH of unfunctionalized olefins with results comparable to the commonly used Ir-P,N catalysts.[4a,b] However, these catalysts afforded high enantioselectivities (up to 98% ee) in a limited group of unfunctionalized olefins, mainly trisubstituted and for the more challenging disubstituted olefins only one example was reported with low enantioselectivity. Since then, a few more carbene-N ligands have been developed but with less success,[4c-g] except for the family of Ir-NHC-pyridine catalysts[4h] developed in Pfaltz's group that showed similar enantioselectivities to the Burgess ones. Some Ir/carbene-phosphorus catalysts have also been tested but with low success.[7] On the other hand, the combination of the carbene moiety to other heteroatom donor groups have not been applied.[8] In 2011, our group reported the first application of P-thioether ligands in AH of unfunctionalized olefins[5c,d] and further improvements with new generations of P-thiother ligands.[5e-h] Their corresponding Ir-complexes efficiently catalyzed the hydrogenation of 40 cases including a large range of E- and Z-trisubstituted olefins and the more challenging disubstituted olefins. The results were comparable to the best ones catalytic systems found in the literature. In addition, more recently we found that some of these Ir-based P-thioether catalysts could also efficiently reduce cyclic β-enamides.[5h,9]

Inspired by the pioneering work on the AH of unfunctionalized olefins using NHC-based ligands and the success of thioether-containing ligands in the AH,[10] a combination of these scaffolds is a log-

ical field for investigation. Consequently, we here report the first examples of mixed thioether-carbene compounds, **L1**H·Br and **L2**H·Br (Figure 1) for the AH of unfunctionalized olefins and cyclic β-enamides. These ligands combine the advantages of thioether and NHC moieties. For comparison, we also synthesized their related thioether-phosphite **L3**–**L4a**–**b** and thioether-phosphinite **L3**–**L4c**–**e** ligands. For the purpose of this work, only two thioether substituents, phenyl and 2,6-dimethylphenyl, were used because previous work with Ir/P-thioether catalysts showed that these two substituents made it possible to achieve high enantioselectivities.[5d-f]

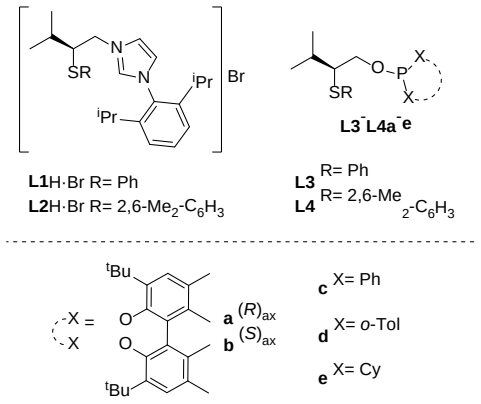


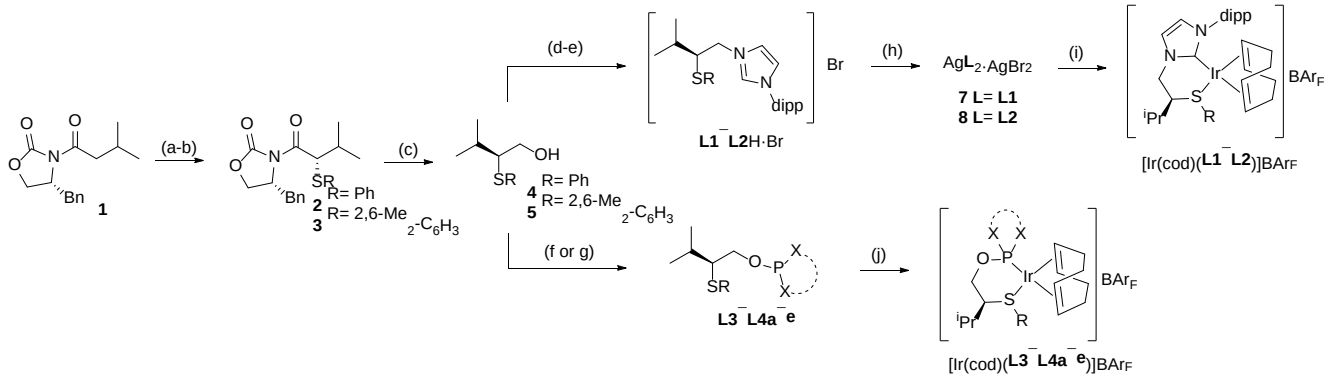
Figure 1. Thioether-carbene (**L1**–**L2**H·Br) and thioether-phosphite/phosphinite (**L3**–**L4a**–**e**) compounds.

RESULTS AND DISCUSSION

Preparation of [Ir(cod)(L1–L4)]BArF catalyst precursors. The preparation of novel thioether-imidazolium salts (**L1**–**L2**H·Br) and thioether-phosphite/phosphinite ligands (**L3**–**L4a**–**e**) was carried out from readily available Evan's *N*-acyl carboximide **1**[11] as depicted in Scheme 1. The stereospecific introduction of the thioether group was carried out after selective α-bromation of **1** using *N*-bromosuccinimide (NBS) and dibutylboryl triflate (step a),[12] followed by treatment with the corresponding *insitu* formed thiolate (step b)[13]. Compounds **2** and **3** were then treated with lithium borohydride to yield the desired hydroxyl-thioether compounds **4** and **5** (step c).[13] From this point the synthesis followed two different pathways depending on the type of ligand. For the preparation of the thioether-imidazolium salts (**L1**–**L2**H·Br), compounds **4** and **5** were treated with tetrabromomethane and triphenylphosphine to yield thioether-bromine intermediates (step d).[14] Reaction of the latter with 1-(2,6-diisopropylphenyl)-1*H*-imidazole **6**[15] gave access to the desired thioether-imidazolium ligand precursors **L1**–**L2**H·Br (step e). For the synthesis of the thioether-phosphite/phosphinite ligands **L3**–**L4a**–**e**, hydroxyl-thioethers **4** and **5** were treated with the corresponding phosphorochloridite (step f) or chlorophosphine (step g). Thioether-imidazolium salts (**L1**–**L2**H·Br) and thioether-phosphite ligands (**L3**–**L4a**–**e**) were isolated as air stable solids whereas the thioether-phosphinite ligands (**L3**–**L4c**–**e**) were isolated as oils that needed to be stored under argon or at low temperature, since they slowly decompose in air at room temperature. In this case, they were immediately used for preparing the Ir-catalyst precursors.[16]

For the preparation of the Ir-catalyst precursors containing the thioether-carbene ligands ([Ir(cod)(**L1**–**L2**)]BAr$_F$), the imidazolium salts were first treated with Ag_2O to form the corresponding silver-carbene complexes **7** and **8** (step h). Then, transmetallation of the latter with 0.5 equivalent of [Ir(μ-Cl)cod]$_2$ followed by in situ Cl$^-$/BAr$_F^-$ counterion exchange led to the desired [Ir(cod)(**L1**–**L2**)]BAr$_F$ (step i). For the preparation of the Ir-catalyst precursors containing the thioether-phosphite/phosphinite ligands ([Ir(cod)(**L3**–**L4a**–**e**)]BAr$_F$), the corresponding ligands were directly coordinated to Ir by reaction with 0.5 equivalent of [Ir(μ-Cl)cod]$_2$ followed by in situ Cl$^-$/BAr$_F^-$ counterion exchange (step j). All complexes, even the phosphinite-based ones, were isolated as air-stable orange solids in pure form. The HRMS-ESI spectra were in agreement with the assigned structures, displaying the heaviest ions at m/z which correspond to the loss of the BAr$_F$ anion from the molecular species. NMR spectra showed the expected pattern for these C_1-complexes (see experimental and Supporting information for characterization details).[17]

Catalytic experiments. To first evaluate de potential of the new catalyst precursors [Ir(cod)(**L1**–**L4**)]BAr$_F$ in the asymmetric hydrogenation of trisubstituted olefins a comparative study using substrates **S1**-**S5** was performed (Table 1). These substrates were chosen because they represent different substitution patterns with



Scheme 1. Preparation of [Ir(cod)(**L1**–**L4**)]BAr$_F$ catalyst precursors. (a) DIPEA, ^{n}Bu$_2$BOTf, NBS, CH_2Cl_2, -78 °C, 3 h;[12] (b) RSH, DBU, THF, -10 °C during 1.5 h and then 2.5 h at rt, 4 h;[13] (c) $LiBH_4$, H_2O, THF, rt, 16 h;[13] (d) CBr_4, PPh_3, CH_2Cl_2, 0 °C, 16 h;[14] (e) 1-(2,6-diisopropylphenyl)-1H-imidazole (**6**), CH_3CN, reflux, 1.5 d; (f) ClP(OR')$_2$ (OR'$_2$= a–b), Py, toluene, 80 °C, 16 h; (g) ClPX$_2$ (X= c–e), NEt_3, DMAP, toluene, rt, 20 min; (h) Ag_2O, CH_2Cl_2, 16 h. (i) [Ir(μ-Cl)(cod)]$_2$, CH_2Cl_2, rt, 4.5 h then NaBAr$_F$, rt, 1 h. (j) [Ir(μ-Cl)(cod)]$_2$, CH_2Cl_2, 50 °C, 1 h then NaBAr$_F$, H_2O, rt, 30 min.

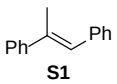
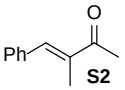
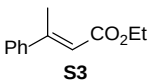
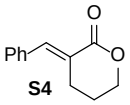
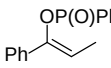
different functional groups with increasing coordinating abilities. They cover from olefin **S1** without a coordinative functional group, to olefin **S5**, which has a coordinative functional group that can also anchor the substrate to the metal. Note that substrates **S2**-**S4**, which contain potentially coordinative functional groups, typically do not coordinate in Rh- and Ir-complexes.[3d] To compare with the state of the art, we used the same optimal reaction conditions found in previous studies with other Ir/P-S systems.[5d]

The results indicate that the Ir/thioether-carbene catalysts are typically less active than the phosphite and phosphinite analogues, except in the hydrogenation of enol phosphonate **S5**. These results can be correlated with the fact that the presence of the bulky dipp group at the N-heterocylic carbene moiety gives the Ir/thioether-carbene catalytic system a higher sterical congestion around the metal center than in the case of the phosphite and phosphinite analogues. Such a steric hindrance hampers the olefin coordination which, at the same time, triggers the deactivation of the Ir-catalyst probably due to the formation of inactive trimeric species (see reactivity studies below).[18] Catalyst deactivation can be avoided in the presence of a good coordinating functional group like for the hydrogenation of **S5**.

Regarding the enantiomeric outcome of the reactions, the use of catalyst precursors with the carbene moiety sharply reduces the enantioselectivity compared with the use of thioether-phosphite/phosphinite analogues. This decrease in enantioselectivity is large for substrates with poorly coordinative or non-coordinative groups (**S1**–**S4**) but less pronounced for the hydrogenation of **S5**. Results also indicate that each substrate requires a different catalyst to maximize the enantioselectivity. The highest enantioselectivities were typically achieved with catalyst precursors with a thioether-phosphinite ligand (ee's between 82-93%), except for **S4** for which ee's were best using phosphite-based catalyst precursor [Ir(cod)(**L4b**)]BAr_F (ee's up to 97% ee).

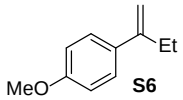
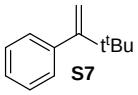
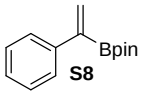
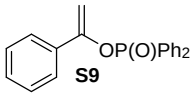
We then focused on the asymmetric hydrogenation of 1,1-disubstituted olefins (substrates **S6**–**S9**; Table 2). These substrates are less hindered than the trisubstituted olefins, so they are more easily hydrogenated but, in turn, face-selectivity is more difficult to control. For this reason, the effective AH of a large range of 1,1-disubstituted olefins was only achieved recently and only with a few catalytic systems.[3e,18] Substrates **S6**–**S9** were chosen because they have different functional groups with increasing coordinating abilities, from non-coordinative (e.g., **S6** and **S7**) to coordinative (e.g. olefin **S9** has a coordinative functional group). Again we used the same optimal reaction conditions found in previous studies with Ir/P-S catalysts. Thus, substrates **S6**–**S8** were reduced at 1 bar of hydrogen while 50 bars were required for **S9**. In contrast to the results reported above, full conversions were achieved with carbene-based catalytic systems, except for the more sterically hindered substrate **S7**. These results are in line with the formation of inactive species when attempting to hydrogenate **S7** with Ir-**L1**/**L2** catalysts. In line with the previous results, the use of phosphite and phosphinite-based catalytic systems (Ir-**L3**/**L4**) provided higher enantioselectivities than Ir-**L1**/**L2** catalytic systems, and the decrease in enantioselectivity with carbene-based catalysts is less pronounced for the hydrogenation of **S9**, with a good coordinative functional group. Again, the correct choice of the catalyst is necessary to maximize enantioselectivities for each substrate type. It is to note the excellent enantioselectivities, comparable to the best one reported, achieved with phosphite-based catalysts in the hydrogenation of **S7** and **S9** (ee's >97%).[19] Like other cases reported in the literature, the hydrogenation of the α-alkylstyrene derivative **S6** proceeded with a much lower enantioselectivity than the analogue **S7**.[19a] This can be due to the fact that either hydrogenation competes with isomerization or that face selectivity is not successfully controlled. To find the explanation, we studied the reduction of **S6** using deuterium, with Ir/S-carbene(**L2**), Ir/S-phosphite(**L4b**) and Ir/S-phosphinite(**L4c**) as catalyst precursors (Scheme 2). With the Ir/S-phosphite/phosphinite catalyst systems,

Table 1. Asymmetric hydrogenation of trisubstituted olefins **S1**–**S5** using [Ir(cod)(**L1**–**L4**)]BAr_F catalyst precursors.[a]

		 **S1**		 **S2**		 **S3**		 **S4**		 **S5**	
Entry	L	% Conv[b]	% ee[c]	% Conv[b]	% ee[c]	% Conv[b]	% ee[c]	% Conv[b]	% ee[c]	% Conv[b]	% ee[c]
1	**L1**	15	2 (*R*)	10	9 (*R*)	20	25 (*R*)	20	20 (*R*)	100	75 (*S*)
2	**L2**	25	4 (*S*)	25	5 (*S*)	30	8 (*S*)	10	28 (*R*)	95	70 (*S*)
3	**L3a**	100	48 (*S*)	80	20 (*R*)	90	80 (*S*)	90	68 (*R*)	25	72 (*S*)
4	**L3b**	85	36 (*S*)	70	60 (*S*)	80	50 (*S*)	100	75 (*S*)	25	9 (*S*)
5	**L3c**	95	61 (*S*)	95	82 (*S*)	100	31 (*S*)	100	70 (*S*)	86	85 (*S*)
6	**L4a**	100	43 (*S*)	95	56 (*R*)	95	13 (*S*)	100	83 (*R*)	15	30 (*R*)
7	**L4b**	95	39 (*S*)	10	65 (*S*)	75	6 (*S*)	100	97 (*S*)	30	17 (*S*)
8	**L4c**	100	90 (*S*)	98	38 (*S*)	100	75 (*S*)	100	85 (*S*)	100	85 (*S*)
9	**L4d**	100	91 (*S*)	100	45 (*S*)	100	89 (*S*)	100	47 (*S*)	95	75 (*S*)
10	**L4e**	100	89 (*S*)	100	55 (*S*)	100	93 (*S*)	95	66 (*S*)	70	10 (*S*)

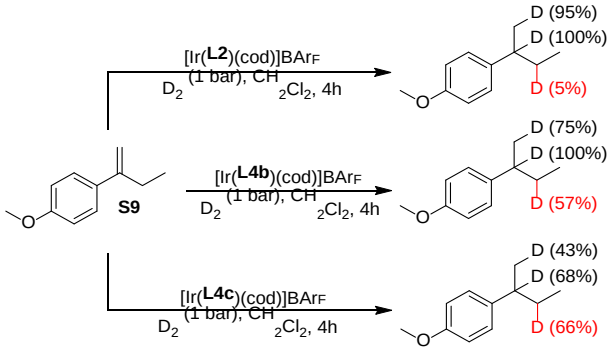
[a] Reaction conditions: 1 mol% Ir-catalyst precursor, substrate (0.5 mmol), DCM, rt for 16 h, P_{H2} = 100 bar. [b] Conversions determined by ^{1}H-NMR. [c] Enantiomeric excesses determined by chiral HPLC or GC.

Table 2. Asymmetric hydrogenation of 1,1'-disusbtitued olefins **S6**–**S9** using [Ir(cod)(**L1**–**L4**)]BArF catalyst precursors[a]

		 **S6**		 **S7**		 **S8**		 **S9**	
Entry	L	% Conv[b]	% ee[c]	% Conv[b]	% ee[c]	% Conv[b]	% ee[c]	% Conv[b]	% ee[c]
1	**L1**	100	2 (*S*)	<5	-	100	10 (*R*)	100	91 (*S*)
2	**L2**	100	3 (*R*)	<5	-	100	9 (*R*)	100	61 (*S*)
3	**L3a**	90	7 (*S*)	100	15 (*R*)	100	44 (*S*)	100	94 (*S*)
4	**L3b**	100	46 (*R*)	100	91 (*R*)	100	1 (*S*)	100	98 (*S*)
5	**L3c**	100	38 (*R*)	100	80 (*R*)	100	74 (*R*)	100	3 (*S*)
6	**L4a**	85	25 (*S*)	100	56 (S)	100	33 (*S*)	100	21 (*R*)
7	**L4b**	100	50 (*R*)	100	97 (*R*)	100	53 (*R*)	100	51 (*S*)
8	**L4c**	100	60 (*R*)	100	88 (*R*)	100	68 (*R*)	95	70 (*S*)
9	**L4d**	100	60 (*R*)	100	91 (*R*)	100	44 (*R*)	100	85 (*S*)
10	**L4e**	100	52 (*R*)	100	65 (*R*)	100	54 (*R*)	95	70 (*S*)

[a] Reaction conditions: 1 mol% Ir-catalyst precursor, substrate (0.5 mmol), DCM, rt for 16 h, P_{H2} = 1bar (for **S6**–**S8**) or 50 bar (for **S9**). [b] Conversions determined by ^{1}H-NMR. [c] Enantiomeric excesses determined by chiral HPLC or GC.

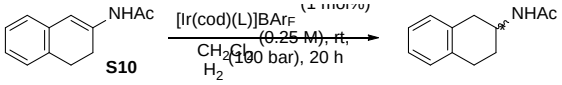
deuterium was found not only at the doubled bond but also at the allylic position. This suggests that the isomerization process[20] is responsible for the low enantioselectivity achieved. On the other hand, isomerization was hardly seen with the Ir/S-carbene catalyst **L2**, which suggest that the low enantioselectivity is due to face-selectivity issues.



Scheme 2. Deuterium labeling studies of substrate **S6** with Ir/**L2**, Ir/**L4b** and Ir/**L4c** catalysts precursors. The percentage of addition of deuterium is illustrated in brackets. The percentage of deuterium added thought isomerization is shown in red.

Finally, we studied the asymmetric hydrogenation of cyclic β-enamides which are a challenging class of functionalized substrates. The AH of these substrates is highly desirable because their hydrogenated products (e.g, rotigotine, robalzotan and alnespirone) have important therapeutic properties.[21] Only a few examples are able to hydrogenate a broad range of these substrates in high enantioselectivities. Most of the catalysts, predominantly based on Rh and Ru, provide unsatisfactory enantioselectivities in reducing cyclic β-enamides.[22] Very recently, it has been shown that Ir-P,X (X= P or S) catalysts can reduce cyclic β-enamides with better enantioselectivities than Rh/Ru catalysts.[9,23] We therefore studied first the Ir-catalyzed asymmetric hydrogenation of the benchmark *N*-(3,4-dihydronaphthalen-2-yl)acetamide **S10** under previously reported conditions.[9] The results are shown in Table 3. Gratifyingly, we found enantioselectivities as high as 96% ee using Ir/phosphinite-thioether **L4d** catalytic system (entry 10). Again P-thioether containing catalysts had a higher catalytic performance than the carbene-thioether based catalysts, being the best results with phosphinite-based catalysts.

Table 3. Asymmetric hydrogenation of *N*-(3,4-dihydronaphthalen-2-yl)acetamide **S10** using [Ir(cod)(**L1**–**L4**)]BArF catalyst precursors[a]



Entry	L	% Conv[b]	% ee[c]
1	**L1**	30	72 (*R*)
2	**L2**	25	69 (*R*)
3	**L3a**	100	69 (*R*)
4	**L3b**	90	57 (*S*)
5	**L3c**	95	92 (*R*)
6	**L4a**	80	61 (*S*)
7	**L4b**	100	80 (*R*)
8	**L4c**	100	85 (*R*)
9	**L4d**	100	96 (*R*)
10	**L4e**	100	88 (*R*)

[a] Reaction conditions: 1 mol% of [Ir(cod)(L)]BArF, 100 bar H_2, CH_2Cl_2, rt for 20 h. [b] Conversions determined by ^{1}H-NMR. [c] Enantiomeric excesses determined by chiral HPLC.

We further studied Ir/**L4d** in the reduction of a range of substituted cyclic β-enamides, which contemplate all possible monosubstitution patterns (Figure 2). We were pleased to see that they were all hydrogenated in enantioselectivities (ee's up to 97%) comparable

to those achieved with substrate **S10**. Among them, it is to note the high enantioselectivity obtained in the AH of **S11** whose hydrogenated product is a key intermediate for the synthesis of rotigotine.

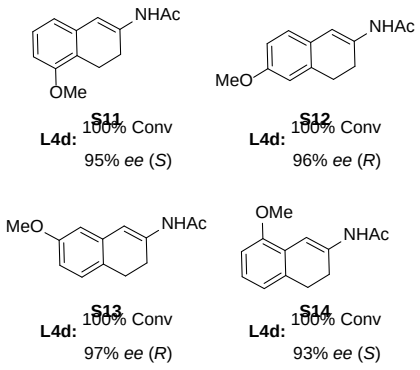
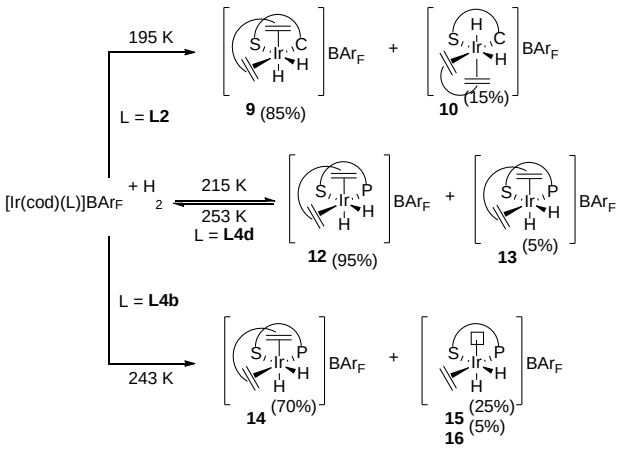


Figure 2. Hydrogenation results for the AH of cyclic β-enamides. Typical reaction conditions: 1 mol% of [Ir(cod)(L)]BAr_F, 100 bar, CH_2Cl_2, rt for 20 h.

Reactivity studies of [Ir(cod)(L)]BAr_F towards H_2. We investigated the reactivity of the iridium catalyst precursors with hydrogen. For comparison purposes we considered compounds [Ir(cod)(L)]BAr_F containing the thioether-carbene ligand **L2**, the thioether-phosphite ligand **L4b** and the thioether-phosphinite ligand **L4d** as models. As expected, the oxidative addition of H_2 to the [Ir(cod)(**L2**)]BAr_F is more favored than with the analogous phosphinite- and phosphite-based compounds. Thus, bubbling H_2 in a CD_2Cl_2 solution of [Ir(cod)(**L2**)]BAr_F at 195 K led to the fast formation of two dihydride species **9** and **10** in a 85:15 ratio, respectively (Scheme 3; Table 4). When the temperature was above -78°C the formation of the stable and catalytically inactive trinuclear iridium hydrido species $[Ir_3(\mu_3\text{-}H)(H)_6(P\text{-}S)_3](BAr_F)_2$ **11** was observed (Figure 3).[24] This behavior is in agreement with our previous catalytic results where Ir/thioether-carbene catalyst precursors had low activities in the reduction of tri- and bulky di-substituted olefins with non-coordinative groups. Therefore, in the absence of a coordinative substrate, the Ir-based-carbene catalyst precursors are prone to the formation of these inactive trinuclear hydrido species.



Scheme 3. Reactivity of [Ir(cod)(L]BAr_F complexes (L= **L2**, **L4b** and **L4d**) with H_2.

Table 4. ^{1}H NMR data at the hydride region of dihydride species **9**, **10**, **12**–**16**.

Compound	H (*trans* to olefin)	H (*trans* to sulfur)
[Ir(H)$_2$(cod)(**L2**)]BAr_F (**9**)	-14.44 (s)	-15.07 (s)
[Ir(H)$_2$(cod)(**L2**)]BAr_F (**10**)	-12.56 (s)	-12.87 (s)
[Ir(H)$_2$(cod)(**L4d**)]BAr_F (**12**)	-12.06 (d, $^2J_{P\text{-}H}$= 16.8 Hz)	-15.47 (d, $^2J_{P\text{-}H}$= 14.8 Hz)
[Ir(H)$_2$(cod)(**L4d**)]BAr_F (**13**)	-12.92 (d, $^2J_{P\text{-}H}$= 15.8 Hz)	-16.63 (d, $^2J_{P\text{-}H}$= 15.4 Hz)
[Ir(H)$_2$(cod)(**L4b**)]BAr_F (**14**)	-11.98 (d, $^2J_{P\text{-}H}$= 19.2 Hz)	-15.37 (s)
[Ir(H)$_2$(coe)(**L4b**)]BAr_F (**15**)	-27.53 (dd, $^2J_{P\text{-}H}$= 28.1 Hz; $^3J_{H\text{-}H}$= 6.0 Hz)	-15.93 (dd, $^2J_{P\text{-}H}$= 20 Hz; $^3J_{H\text{-}H}$= 6.0 Hz)
[Ir(H)$_2$(coe)(**L4b**)]BAr_F (**16**)	-27.68 (dd, $^2J_{P\text{-}H}$= 34.0 Hz; $^3J_{H\text{-}H}$= 6.4 Hz)	-16.06 (dd, $^2J_{P\text{-}H}$= 20 .8 Hz; $^3J_{H\text{-}H}$= 6.4 Hz)

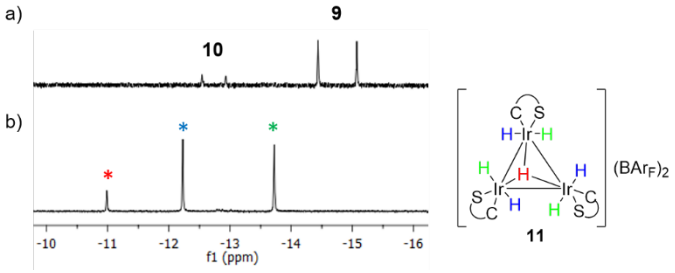


Figure 3. ^{1}H-NMR in the hydride region for (a) dihydride species [Ir(H)$_2$(cod)(**L2**)]BAr_F **9** an **10** and (b) trinuclear iridium hydrido species $[Ir_3(\mu_3\text{-}H)(H)_6(C\text{-}S)_3](BAr_F)_2$ **11**.

The 3D structures of dihydrides **9** and **10** have been elucidated by DFT calculations and NMR studies (see Supporting Information for the full of set of isomers calculated). Figure 4 shows the 3D structures of the two most stable dihydrides. The population of these two dihydridre species obtained by DFT calculation is in good agreement with the experimental ^{1}H-NMR population. The most stable dihydride species **9** has the hydride *trans* to the olefin pointing down, an *S* configuration of the thioether group and a boat-like conformation for the six-membered chelate ring with the methylenic group of the ligand backbone pointing up (Figure 4a).[25] In agreement with this assignment, the hydride *trans* to the olefin of complex **9** showed NOE contacts with the methinic proton of the ligand backbone and also with one of the methyls of the 2,6-dimethylphenyl thioether group. The minor species **10** corresponds to the dihydride species in which the hydride *trans* to the olefin is pointing up, the S atom has an *S* configuration and the chelate ring adopts a boat-like conformation with the methylenic group of the ligand backbone pointing down (Figure 4b).

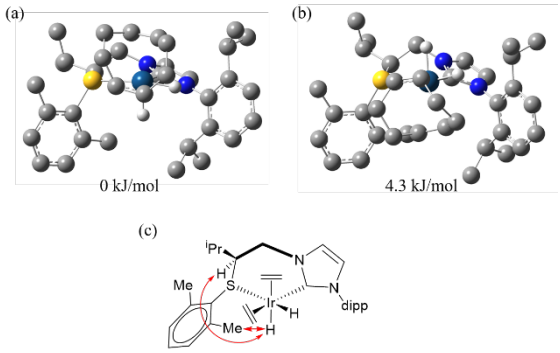


Figure 4. Calculated structures (hydrogen atoms, except metal hydrides, and BAr_F anion have been omitted for clarity) and energies of $[Ir(H)_2(cod)(\mathbf{L2})]BAr_F$ complexes (a) **9** and (b) **10**. (c) Relevant NOE contacts from the NOESY experiment of major dihydride species **9**.

The oxidative addition of H_2 to phosphinite-based $[Ir(cod)(\mathbf{L4d})]BAr_F$ needed to be carried out at 215 K, since it did not took place at lower temperature. Bubbling H_2 to $[Ir(cod)(\mathbf{L4d})]BAr_F$ led to an equilibrium between the starting complex $[Ir(cod)(\mathbf{L4d})]BAr_F$ and two dihydride species $[Ir(H)_2(cod)(\mathbf{L4d})]BAr_F$ (**12** and **13**, Scheme 3). The dihydride species **12** and **13** are not stable upon raising the temperature and, therefore, the equilibrium shifts back to the starting complex $[Ir(cod)(\mathbf{L4d})]BAr_F$ at 253 K. In contrast to the carbene-based catalyst precursor, the analogous inactive trinuclear iridium hydrido species **11** were not detected. Dihydride compounds **12** and **13** showed small phosphorus-hydride coupling constants ($^2J_{P\text{-}H} \leq 16.8$ Hz; Table 4). This indicates that both hydrides are *cis* to the phosphorus atom. DFT calculations and NOESY experiments showed that isomer **12** corresponds to the dihydride complex in which the hydride *trans* to the olefin is pointing down with an *S* configuration at the S atom and a boat-like conformation with the methylenic group of the ligand backbone pointing down (Figure 5a). The minor isomer **13** only differs from **12** in the fact that the methylenic group of the ligand backbone points down (Figure 5b). Therefore, this minor intermediate adopts the same 3D structure as the major dihydride species **9**, formed after the oxidative addition of the carbene-based catalyst precursor.

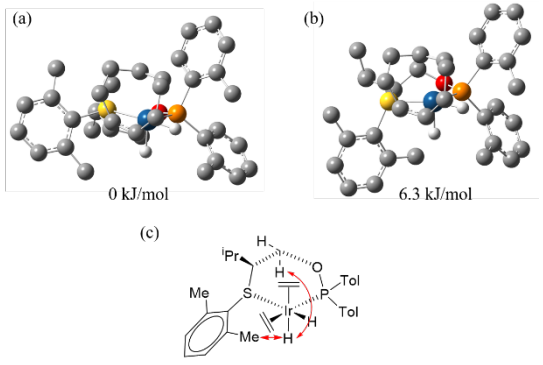


Figure 5. Calculated structures (hydrogen atoms, except metal hydrides, and BAr_F anion have been omitted for clarity) and energies of $[Ir(H)_2(cod)(\mathbf{L4d})]BAr_F$ complexes (a) **12** and (b) **13**. (c) Relevant NOE contacts from the NOESY experiment of major dihydride species **12**.

As expected for compound $[Ir(cod)(\mathbf{L4b})]BAr_F$, that contains the ligand with the stronger π-acceptor ability, its oxidative addition required to bubble H_2 at the highest temperature, 243 K, to drive the equilibrium to the dihydride species. At this temperature, three dihydride species **14**–**16** in a 70:25:5 ratio were observed (Scheme 3). Major species **14** corresponds to the dihydride complex $[Ir(H)_2(cod)(\mathbf{L4b})]BAr_F$ in which both hydrides are *cis* to the phosphite group ($^2J_{P\text{-}H} \leq 19.2$ Hz; Table 4). Similarly to that observed for the analogue complex **12**, the hydride *trans* to the olefin shows NOE interactions with the methylenic protons of the ligand backbone and also with one of the methyls of the 2,6-dimethylphenyl thioether group (Figure 6). These NOE contacts indicated that the dihydride complex **14** has the same structure as the major isomer **12**, with the hydride *trans* to the olefin pointing down, an *S* configuration at the S atom and a boat-like conformation with the methylenic group of the ligand backbone pointing down (Figure 6). DFT calculations not only corroborated the structure of **14**, which is the most stable dihydride, but was also in full agreement with the presence of a single $[Ir(H)_2(\mathbf{L4b})(cod)]BAr_F$ complex since the other calculated isomers were of much higher energy ($\Delta E \geq 28$ kJ/mol).

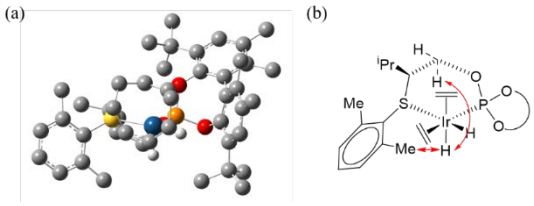


Figure 6. (a) Calculated structure for $[Ir(H)_2(cod)(\mathbf{L4b})]BAr_F$ complex **14** (hydrogen atoms, except metal hydrides, and the BAr_F anion have been omitted for clarity). (b) Relevant NOE contacts from the NOE experiments for dihydride complex **14**.

Minor species **15** and **16** not only show that the hydrides are *cis* to the P-atom atom ($^2J_{P\text{-}H} \leq 28$ Hz; Table 4) but also a very distinct chemical shift for one of the hydrides that appears at high chemical shift (c.a. -27.5 ppm). This is characteristic of a hydride ligand positioned *trans* to a vacant site or to a coordination site involved in a C-H agostic interaction.[26] These species have been therefore assigned to the elusive dihydride intermediate species $[Ir(H)_2(coe)(\mathbf{L4b})]BAr_F$. This indicates that at this temperature not only the oxidative addition of H_2 to $[Ir(cod)(\mathbf{L4b})]BAr_F$ takes place but also the partial hydrogenation of the coordinated cyclooctadiene.

To summarize, the species resulting of the reactivity of the Ir-catalyst precursors towards H_2 depend on the type of ligand in agreement with the catalytic results, where each substrate type requires a different catalyst for maximum catalytic performance. Thus, although the reactivity of carbene-based catalysts with H_2 is more favored than with the analogous P-based catalysts, they are prone to form inactive trinuclear hydrido species that explain their lower activities when hydrogenating tri- and bulky disubstituted olefins with non-coordinative groups. On the other hand, the reactivities with H_2 have in common the formation, for each catalytic precursor, of cis-dihydride intermediates (two for carbene/phosphinite-containing ligands and three for the phosphite-containing ligand) in different ratios, one in major proportion. In all of them the configuration of the thioether moiety is the same. However, while for the phosphinite/phosphite-containing ligands the major species have the

same 3D structures, for the carbene-base precursor the major species shows a different disposition of the six-membered chelate ring with the same disposition of the hydride ligands, which is the same 3D structure of the minor isomer for the phosphinite-based compound. In addition, for the phosphite-containing ligand we detected the presence of two *cis*-dihydride intermediates with one of the hydride ligand in *trans* to a vacant side and with the partial hydrogenation of the cyclooctadiene.

CONCLUSIONS

We studied for the first time the potential of novel and simple Ir/thioether-NHC complexes, with a six-membered chelate, in the asymmetric hydrogenation of unfunctionalized olefins and cyclic β-enamides. For comparison, we also prepared and applied the analogues thioether–phosphinite/phosphite complexes. All these complexes are solid, air stable and easy to synthesize by a simple and efficient synthetic route. We found that the efficiency of the new Ir/thioether-carbene catalyst precursors varies with the type of olefin. Thus, while the Ir/thioether-carbene catalyst precursors provide lower catalytic performance than their related Ir/thioether-P complexes in the hydrogenation of olefins lacking a coordinating group, for the reduction of functionalized olefins (e.g. tri- and disubstituted enol phosphonate derivatives) the catalysts had similar good performance. We have also found that the low activities in the hydrogenation of unfunctionalized tri- and bulky disubstituted olefins with carbene-based catalysts is due to the high steric constrains imposed by the thioether-carbene design, which favors the formation of inactive trinuclear species. This behavior agrees with the reactivity study of the iridium-containing S-carbene/phosphinite/phosphite catalyst precursors toward H_2 that shows the formation of inactive trinuclar hydrido species in the case of the carbene-based catalysts. Interestingly, in the hydrogenation of challenging 1,1'-disubstituted olefins, the deuterogenation studies indicate that carbene-based catalyst favors the hydrogenation vs the competing isomerization process, which is one important problem in the reduction of this type of olefins. It is also interesting to note the discovery of simple-to-synthesize Ir/thioether-P complexes containing a simple backbone that gave high enantioselectivities for some tri- and the challenging 1,1'-disubstituted olefins and cyclic β-enamides (ee's up to 98%).

Finally, we want to stress the high potential of thioether-carbene ligands. Although the enantioselectivities achieved with these ligands are not as high as those obtained with their phosphite/phosphinite analogues, their promising results in the reduction of functionalized substrates (ee values up to 91%, including the challenging cyclic β-enamides) together with their potential modularity make thioether/carbene-based ligands an interesting field for future research.

EXPERIMENTAL SECTION

General considerations. All reactions were carried out using standard Schlenk techniques under an argon atmosphere. Commercial chemicals were used as received. Solvents were dried by means of standard procedures and stored under argon. ^{1}H, ^{13}C{^{1}H} and ^{31}P{^{1}H} NMR spectra were recorded using a Varian Mercury-400 MHz spectrometer. Chemical shifts are relative to that of $SiMe_4$ (^{1}H and ^{13}C{^{1}H}) as an internal standard or H_3PO_4 (^{31}P) as an external standard. ^{1}H and ^{13}C assignments were made on the basis of ^{1}H-^{1}H gCOSY, ^{1}H-^{13}C gHSQC and NOESY experiments. The compounds **1**,[11] **2**,[13] **4**,[13] **6**,[15] (*R*)-4-benzyl-3-((*S*)-2-bromo-3-methyl butanoyl)oxazolidin-2-one[12] and (*S*)-(1-bromo-3-methylbutan-2-yl)(phenyl)sulfane[14] and phosphorochloridites[27] were prepared in accordance with the corresponding methods published in the literature.

(*R*)-4-Benzyl-3-((*S*)-2-((2,6-dimethylphenyl)thio)-3-methylbutanoyl)oxazolidin-2-one (3). DBU (15.6 mmol) was added to a cooled solution (-10 °C) of 2,6-dimethylphenyl)thiol (2 mL, 15.6 mmol) in anhydrous THF (3 M). After 20 min a white suspension was formed. To the suspension, a THF (90 mL) solution of (*R*)-4-benzyl-3-((*S*)-2-bromo-3-methylbutanoyl)oxazolidin-2-one (4.0 g, 13 mmol) was added and the reaction was stirred for an additional 90 min at -10 °C. Then, it was stirred for 2.5 h at room temperature. After that, the reaction mixture was quenched with water (25 mL), extracted with diethyl ether (3 x 25mL) and then the organic phase was washed with water (25 mL) and brine (25 mL). The diethyl ether solution was dried with $MgSO_4$, filtered and concentrated under vacuum. For purification column chromatography was needed (SiO_2, hexane/ethyl acetate – 90:10). Yield: 3.2 g (68%) as a colourless oil. ^{1}H NMR (400 MHz, $CDCl_3$) *δ*: 1.03 (d, 3H, $^3J_{H\text{-}H}$= 6.8 Hz, CH_3, ^{i}Pr), 1.23 (d, 3H, $^3J_{H\text{-}H}$= 6.8 Hz, CH_3, ^{i}Pr), 2.27 (m, 1H, CH, ^{i}Pr), 2.44 (s, 6H, CH_3, Ar), 2.54 (dd, 1H, $^2J_{H\text{-}H}$= 13.4 Hz, $^3J_{H\text{-}H}$= 9.9 Hz, CH_2-Ph), 3.14 (dd, 1H, $^2J_{H\text{-}H}$= 13.4 Hz, $^3J_{H\text{-}H}$= 3.6 Hz, CH_2-Ph), 3.44 (t, 1H, $^2J_{H\text{-}H}$= 8.3 Hz, CH_2-O), 3.80 (dd, 1H, $^2J_{H\text{-}H}$= 8.3 Hz, $^3J_{H\text{-}H}$= 1.8 Hz, CH_2-O), 4.20 (m, 1H, CH-N), 4.91 (d, 1H, $^3J_{H\text{-}H}$= 9.3 Hz, CH-S), 6.96-7.25 (m, 8H, CH=). ^{13}C NMR (100.6 MHz, $CDCl_3$) *δ*: 20.1 (CH_3, ^{i}Pr), 21.1 (CH_3, ^{i}Pr), 21.9 (CH_3, Ar), 30.5 (CH, ^{i}Pr), 37.8 (CH_2-Ph), 52.1 (CH-S), 56.4 (CH-N), 65.8 (CH_2-O), 127.3-173.3 (aromatic carbons). Anal. calcd. (%) for $C_{23}H_{27}NO_3S$: C 69.49, H 6.85, N 3.52, S 8.06; found: C 69.17, H 6.81, N 3.49, S 8.01. MS HR-ESI [found 420.1601, $C_{23}H_{27}NO_3S$ $(M+Na)^+$ requires 420.1604].

(*S*)-2-((2,6-Dimethylphenyl)thio)-3-methylbutan-1-ol (5). To a solution of **3** (1.0 g, 1 mmol) in anhydrous THF (8 mL) a solution of $LiBH_4$ (2 mmol, 2.0 M in THF) and H_2O (90 μL, 2 mmol) were added and stirred overnight at room temperature. The solution was quenched with HCl 1 M, until no gas release is observed, and diluted with ethyl acetate (15 mL). The organic layer was washed with HCl 1 M (20 mL), water (20 mL) and brine (20 mL). Afterwards it was dried over $MgSO_4$, filtered and concentrated under vacuum. For purification column chromatography was needed (SiO_2, hexane/ethyl acetate – 90:10). Yield: 240 mg (85%) as a pale yellow oil. ^{1}H NMR (400 MHz, $CDCl_3$) *δ*: 1.11 (d, 3H, $^3J_{H\text{-}H}$= 6.8 Hz, CH_3, ^{i}Pr), 1.13 (d, 3H, $^3J_{H\text{-}H}$= 6.8 Hz, CH_3, ^{i}Pr), 1.91 (m, 1H, OH), 2.07 (m, 1H, CH, ^{i}Pr), 2.54 (s, 6H, CH_3, Ar), 2.82 (m, 1H, CH- S), 3.57 (m, 2H, CH_2-OH), 7.08-7.12 (m, 3H, CH=). ^{13}C NMR (100.6 MHz, $CDCl_3$) *δ*: 19.8 (CH_3, ^{i}Pr), 20.1 (CH_3, ^{i}Pr), 22.3 (2 CH_3, Ar), 29.5 (CH, ^{i}Pr), 58.8 (CH-S), 62.4 (CH_2-OH), 128.3-143.3 (aromatic carbons). Anal. calcd. (%) for $C_{13}H_{20}OS$: C 69.59, H 8.99, S 14.29; found: C 69.16, H 8.93, S 14.18. MS HR-ESI [found 247.1122, $C_{13}H_{20}OS$ $(M+Na)^+$ requires 247.1127].

(*S*)-(1-Bromo-3-methylbutan-2-yl)(2,6-dimethylphenyl)sulfane. To a solution of the corresponding thioether-alcohol **5** (3.1 eq) in dry DCM (6 mL), tetrabromomethane (1.2 g, 3.7 mmol) and triphenylphosphine (0.98 g, 3.7 mmol) were added. Then, it was stirred overnight at 0 °C. The reaction mixture was then diluted with DCM (15 mL) and washed with water (15 mL) and brine (15 mL). The products were further purified by column chromatography (SiO_2, hexane/ethyl acetate – 80:20). Yield: 695 mg (77%) as a pale yellow oil. ^{1}H NMR (400 MHz, $CDCl_3$) *δ*: 0.84 (d, 3H, $^3J_{H\text{-}H}$= 6.8 Hz, CH_3, ^{i}Pr), 0.94 (d, 3H, $^3J_{H\text{-}H}$= 6.8 Hz, CH_3, ^{i}Pr), 2.08 (m, 1H, CH, ^{i}Pr), 2.46 (s, 6H, CH_3, Ar), 3.05 (m, 2H, CH_2-Br), 3.97 (m, 1H, CH-S), 7.00-7.04 (m, 3H, CH=). ^{13}C NMR (100.6 MHz, $CDCl_3$) *δ*: 15.5 (CH_3, ^{i}Pr), 20.7 (CH_3, ^{i}Pr), 21.1 (2CH_3, Ar), 30.5 (CH, ^{i}Pr), 40.6 (CH_2-Br), 62.7 (CH-S), 127.2-141.8 (aromatic carbons). Anal. calcd. (%) for $C_{13}H_{19}BrS$: C 54.36, H 6.67, S 11.16; found: C 54.06, H 6.64, S 11.08. MS HR-ESI [found 309.0279, $C_{13}H_{19}BrS$ $(M+Na)^+$ requires 309.0283].

General procedure for the preparation of thioether–imidazolium derivatives L1H·Br–L2H·Br. To a solution of the corresponding thioeter-bromine compounds (1 eq) in anhydrous MeCN (3 mL), **6** (1.2 eq) was added. The mixture was refluxed for 1.5 days after that the solution was cooled to room temperature and the solvent was evaporated and purified by flash chromatography (SiO_2, DCM/MeOH – 20:1 → 10:1).

L1H·Br: Yield: 230 mg (42%, reaction carried out using 1.1 mmol of (*S*)-(1-bromo-3-methylbutan-2-yl)(phenyl)sulfane as dark orange oil. ^{1}H NMR ($CDCl_3$) *δ*: 1.01 (m, 3H, CH_3 ^{i}Pr-Ar), 1.08 (m, 3H, CH_3, ^{i}Pr-Ar), 1.10 (m, 3H, CH_3, ^{i}Pr-Ar), 1.13 (m, 3H, CH_3, ^{i}Pr-Ar), 1.15 (m, 3H CH_3, ^{i}Pr), 1.17 (m, 3H, CH_3, ^{i}Pr), 2.15 (m, 2H, CH, ^{i}Pr-Ar), 2.38 (m, 1H, CH, ^{i}Pr), 3.81 (m, 1H, CH-S), 4.63 (dd, 1H, $^2J_{H\text{-}H}$= 14.0 Hz, $^3J_{H\text{-}H}$= 11.3 Hz, CH_2-N), 5.40 (dd, 1H, $^2J_{H\text{-}H}$= 14.0 Hz, $^3J_{H\text{-}H}$= 3.6 Hz, CH_2-N), 7.15 (ps, 1H, CH=, NHC), 7.20-7.35 (m, 7H, CH=), 7.52 (t, 1H, $^3J_{H\text{-}H}$= 7,5 Hz, CH=), 8.43 (ps, 1H, CH=, NHC), 10.10 (s, 1H, CH=, NHC). ^{13}C NMR (100.6 MHz, $CDCl_3$) *δ*: 18.3 (CH_3, ^{i}Pr-Ar), 20.7 (CH_3, ^{i}Pr-Ar), 24.1 (CH_3, ^{i}Pr), 24.2 (CH_3, ^{i}Pr-Ar), 24.2 (CH_3, ^{i}Pr), 24.4 (CH_3, ^{i}Pr-Ar), 28.6

(CH, ^{i}Pr-Ar), 28.6 (CH, ^{i}Pr-Ar), 31.6 (CH, ^{i}Pr), 53.2 (CH_2-N), 57.9 (CH-S), 123.5 (CH=, NHC), 124.5 (CH=, NHC), 124.7-145.5 (aromatic carbons), 138.7 (CH=, NHC). Anal. calcd. (%) for $C_{26}H_{35}BrN_2S$: C 64.05, H 7.24, N 5.75, S 6.58; found: C 63.81, H 7.20, N 5.71, S 6.53. MS HR-ESI [found 407.2507, $C_{26}H_{35}N_2S$ $(M)^+$ requires 407.2515].

L2H·Br**:** Yield: 600 mg (46%, reaction carried out using 2.4 mmol of (*S*)-(1-bromo-3-methylbutan-2-yl)(2,6-dimethylphenyl)sulfane as light brown foam. ^{1}H NMR ($CDCl_3$) δ: 1.05 (m, 3H, CH_3, ^{i}Pr), 1.07 (m, 3H, CH_3, ^{i}Pr), 1.10 (m, 3H, CH_3, ^{i}Pr-Ar), 1.12 (m, 3H, CH_3, ^{i}Pr-Ar), 1.17 (m, 3H, CH_3, ^{i}Pr-Ar), 1.18 (m, 3H, CH_3, ^{i}Pr-Ar), 1.81 (m, 1H, CH, ^{i}Pr), 2.23 (m, 1H, CH, ^{i}Pr-Ar), 2.30 (m, 1H, CH, ^{i}Pr-Ar), 2.40 (s, 6H, CH_3, Ar), 3.31 (m, 1H, CH-S), 4.42 (dd, 1H, $^2J_{H\text{-}H}$= 14.3 Hz, $^3J_{H\text{-}H}$= 9.3 Hz, CH_2-N), 5.29 (dd, 1H, $^2J_{H\text{-}H}$= 14.3 Hz, $^3J_{H\text{-}H}$= 4.3 Hz, CH_2-N), 7.03-7.09 (m, 3H, CH=) 7.15 (ps, 1H, CH=, NHC), 7.20-7.25 (m, 2H, CH=), 7.47 (m, 1H, CH=), 7.89 (ps, 1H, CH=, NHC), 10.36 (s, 1H, CH=N, NHC). ^{13}C NMR (100.6 MHz, $CDCl_3$) δ: 18.8 (CH_3, ^{i}Pr), 19.5 (CH_3, ^{i}Pr), 22.1 (CH_3, Ar), 24.3 (CH_3, Ar), 24.3 (CH_3, ^{i}Pr-Ar), 24.4 (CH_3, ^{i}Pr-Ar), 24.4 (CH_3 ^{i}Pr-Ar), 24.4 (CH_3, ^{i}Pr-Ar), 28.7 (CH, ^{i}Pr-Ar) 28.7 (CH, ^{i}Pr-Ar), 30.7 (CH, ^{i}Pr), 51.4 (CH_2-N), 55.1 (CH-S), 123.8 (CH=, NHC), 123.9 (CH=, NHC), 124.6-145.5 (aromatic carbons), 139.0 (CH=, NHC). Anal. calcd. (%) for $C_{28}H_{39}BrN_2S$: C 65.23, H 7.62, N 5.43, S 6.22; found: C 64.95, H 7.60, N 5.40, S 6.18. MS HR-ESI [found 435.2822, $C_{28}H_{39}N_2S$ $(M)^+$ requires 435.2828].

General procedure for the preparation of thiother-phosphite ligands L3–L4a–b. The corresponding phosphorochloridite (0.55 mmol) produced *in situ* was dissolved in toluene (5 mL) and pyridine (1.9 mmol, 0.15 mL) was added. Then, the corresponding hydroxyl-thioether (0.5 mmol) compound was azeotropically dried with toluene (3x1 mL) and dissolved in toluene (5 mL) to which pyridine (1.9 mmol, 0,15 mL) was added. The solution was transferred slowly at 0 °C to the phosphorochloridite solution. The reaction mixture was stirred overnight at 80 °C, and the pyridine salts were removed by filtration. The evaporation of the solvent yielded a white foam, which was purified by flash chromatography in alumina (100:1 - toluene/NEt_3) to produce the corresponding ligand as a white solid.

L3a: Yield: 208 mg (72%). ^{31}P (161.9 MHz, C_6D_6), δ: 128.8. ^{1}H (400 MHz, C_6D_6), δ: 0.90 (m, 3H, CH_3, ^{i}Pr), 1.03 (m, 3H, CH_3, ^{i}Pr), 1.51 (s, 9H, CH_3, ^{t}Bu), 1.51 (s, 9H, CH_3, ^{t}Bu), 1.64 (s, 3H, CH_3), 1.67 (s, 3H, CH_3), 2.01 (s, 6H, CH_3), 2.36 (m, 1H, CH, ^{i}Pr), 3.28 (m, 1H, CH-S), 3.68 (m, 1H, CH_2-O), 4.12 (m, 1H, CH_2-O), 6.75-7.27 (m, 7H, CH=). ^{13}C (100.6 MHz, C_6D_6), δ: 16.1 (CH_3), 16.4 (CH_3), 16.8 (CH_3) 20.0 (CH_3), 20.1 (CH_3, ^{i}Pr), 20.6 (CH_3, ^{i}Pr), 27.4 (CH, ^{i}Pr), 30.9 (CH_3, ^{t}Bu), 31.2 (CH_3, tBu), 34.5 (C, ^{t}Bu), 34.5 (C, ^{t}Bu), 56.2 (CH-S), 64.8 (CH_2-O), 125.9-145.7 (aromatic carbons). Anal. calcd. (%) for $C_{35}H_{47}O_3PS$: C 72.63, H 8.19, S 5.54; found: C 72.76, H 8.18, S 5.50. MS HR-ESI [found 601.2875, $C_{35}H_{47}O_3PS$ $(M+Na)^+$ requires 601.2876].

L3b: Yield: 176 mg (61%). ^{31}P (161.9 MHz, C_6D_6), δ: 127.7. ^{1}H (400 MHz, C_6D_6), δ: 0.89 (m, 3H, CH_3, ^{i}Pr), 1.03 (m, 3H, CH_3, ^{i}Pr), 1.38 (s, 9H, CH_3, ^{t}Bu), 1.52 (s, 9H, CH_3, ^{t}Bu), 1.62 (s, 3H, CH_3), 1.75 (s, 3H, CH_3), 2.01 (s, 3H, CH_3), 2.07 (s, 3H, CH_3), 2.32 (m, 1H, CH, ^{i}Pr), 3.19 (m, 1H, CH-S), 3.43 (m, 1H, CH_2-O), 4.27 (m, 1H, CH_2-O), 6.93-7.31 (m, 7H, CH=). ^{13}C (100.6 MHz, C_6D_6), δ: 16.1 (CH_3), 16.3 (CH_3), 16.6 (CH_3), 20.0 (CH_3, ^{i}Pr), 20.5 (CH_3), 27.4 (CH, ^{i}Pr), 30.6 (CH_3, ^{t}Bu), 31.2 (CH_3, ^{t}Bu), 34.4 (C, ^{t}Bu), 34.5 (C, ^{t}Bu), 56.9 (CH-S), 64.0 (CH_2-O), 126.8-146.4 (aromatic carbons). Anal. calcd. (%) for $C_{35}H_{47}O_3PS$: C 72.63, H 8.19, S 5.54; found: C 72.68, H 8.18, S 5.51. MS HR-ESI [found 601.2873, $C_{35}H_{47}O_3PS$ $(M+Na)^+$ requires 601.2876].

L4a: Yield: 171 mg (56%). ^{31}P (161.9 MHz, C_6D_6), δ: 126.9. ^{1}H (400 MHz, C_6D_6), δ: 1.37 (m, 3H, CH_3, ^{i}Pr), 1.51 (m, 3H, CH_3, ^{i}Pr), 1.77 (s, 9H, CH_3, ^{t}Bu), 1.87 (s, 9H, CH_3, ^{t}Bu), 1.98 (s, 3H, CH_3), 2.10 (s, 3H, CH_3), 2.37 (s, 3H, CH_3), 2.48 (s, 3H, CH_3), 2.71 (s, 6H, CH_3), 2.80 (m, 1H, CH, ^{i}Pr), 3.44 (m, 1H, CH-S), 3.99 (m, 1H, CH_2-O), 4.37 (m, 1H, CH_2-O), 7.18-7.54 (m, 5H, CH=). ^{13}C (100.6 MHz, C_6D_6), δ: 16.4 (CH_3, ^{i}Pr), 16.7 (CH_3), 20.3 (CH_3, ^{i}Pr), 20.5 (CH_3), 20.8 (CH_3), 22.1 (2xCH_3), 28.2 (CH, ^{i}Pr), 31.2 (CH_3, ^{t}Bu), 31.3 (CH_3, ^{t}Bu), 34.7 (C, ^{t}Bu), 34.9 (C, ^{t}Bu), 56.4 (CH-S), 64.2 (CH_2-O), 127.7-146.0 (aromatic carbons). Anal. calcd. (%) for $C_{37}H_{51}O_3PS$: C 73.23, H 8.47, S 5.28; found: C 73.32, H 8.46, S 5.26. MS HR-ESI [found 629.3184, $C_{37}H_{51}O_3PS$ $(M+Na)^+$ requires 629.3189].

L4b: Yield: 144 mg (47%). ^{31}P (161.9 MHz, C_6D_6), δ: 122.9. ^{1}H (400 MHz, C_6D_6), δ: 0.98 (m, 3H, CH_3, ^{i}Pr), 1.15 (m, 3H, CH_3, ^{i}Pr), 1.23 (s, 9H, CH_3, ^{t}Bu), 1.51 (s, 9H, CH_3, ^{t}Bu), 1.61 (s, 3H, CH_3), 1.77 (s, 3H, CH_3), 2.00 (s, 3H, CH_3), 2.13 (s, 3H, CH_3), 2.28 (s, 6H, CH_3), 2.44 (m, 1H, CH, ^{i}Pr), 3.04 (m, 1H, CH-S), 3.16 (m, 1H, CH_2-O), 4.36 (m, 1H, CH_2-O), 6.91-7.16 (m, 5H, CH=). ^{13}C (100.6, MHz, C_6D_6), δ: 15.2 (CH_3, ^{i}Pr), 15.3 (CH_3), 15.6 (CH_3), 19.3 (CH_3, ^{i}Pr), 19.6 (CH_3), 19.7 (CH_3), 21.1 (2xCH_3), 26.7 (CH, ^{i}Pr), 29.3 (CH_3, ^{t}Bu), 30.6 (CH_3, ^{t}Bu), 33.5 (C, ^{t}Bu), 33.8 (C, ^{t}Bu), 54.1 (CH-S), 62.8 (CH_2-O), 124.4-144.9 (aromatic carbons). Anal. calcd. (%) for $C_{37}H_{51}O_3PS$: C 73.23, H 8.47, S 5.28; found: C 73.41, H 8.46, S 5.23. MS HR-ESI [found 629.3188, $C_{37}H_{51}O_3PS$ $(M+Na)^+$ requires 629.3189].

General procedure for the preparation of thioether-phosphinite ligands L3–L4c–e. The corresponding hydroxyl-thioether (0.5 mmol) and DMAP (0.055 mmol, 6.7 mg) were dissolved in toluene (1 mL), and triethylamine was added (0.65 mmol, 0.09 mL) at r.t. Followed by the addition of the corresponding chlorophosphine (0.55 mmol) via syringe. The reaction was stirred 20 min at r.t. The solvent was removed *in vacuo*, and the product was purified by flash chromatography on alumina (100:1 - toluene/NEt_3) to produce the corresponding ligands as colorless oils.

L3c: Yield: 118 mg (62%). ^{31}P NMR (161.9 MHz, C_6D_6), δ: 114.5. ^{1}H (400 MHz, C_6D_6), δ: 0.91 (m, 3H, CH_3, ^{i}Pr), 0.98 (m, 3H, CH_3, ^{i}Pr), 2.20 (m, 1H, CH-^{i}Pr), 3.24 (m, 1H, CH-S), 4.01 (m, 2H, CH_2-O), 6.85-7.57 (m, 15H, CH=). ^{13}C (100.6 MHz, C_6D_6), δ: 18.6 (CH_3, ^{i}Pr), 21.2 (CH_3, ^{i}Pr), 29.5 (CH-^{i}Pr), 58.0 (d, CH-S, $J_{C\text{-}P}$= 19.1 Hz), 71.1 (d, CH_2-O, $J_{C\text{-}P}$= 19.1 Hz), 126.0-143.2 (aromatic carbons). Anal. calcd. (%) for $C_{23}H_{25}OPS$: C 72.61, H 6.62, S 8.43; found: C 72.74, H 6.63, S 8.37. MS HR-ESI [found 403.1261, $C_{23}H_{25}OPS$ $(M+Na)^+$ requires 403.1256].

L4c: Yield: 87 mg (43%). ^{31}P NMR (161.9 MHz, C_6D_6), δ: 114.7. ^{1}H (400 MHz, C_6D_6), δ: 0.97 (m, 3H, CH_3, ^{i}Pr), 1.02 (m, 3H, CH_3, ^{i}Pr), 2.24 (m, 1H, CH-^{i}Pr), 2.42 (s, 6H, CH_3), 3.03 (m, 1H, CH-S), 3.81 (m, 1H, CH_2-O), 3.99 (m, 1H, CH_2-O), 6.87-7.48 (m, 13H, CH=). ^{13}C (100.6 MHz, C_6D_6), δ: 17.8 (CH_3, ^{i}Pr), 20.2 (CH_3, ^{i}Pr), 22.1 (2xCH_3), 28.9 (CH-^{i}Pr), 56.3 (CH-S), 69.8 (CH_2-O), 125.3-143.3 (aromatic carbons). Anal. calcd. (%) for $C_{25}H_{29}OPS$: C 73.50, H 7.16, S 7.85; found: C 73.72, H 7.15, S 7.72. MS HR-ESI [found 431.1572, $C_{25}H_{29}OPS$ $(M+Na)^+$ requires 431.1569].

L4d: Yield: 152 mg (70%). ^{31}P (161.9 MHz, C_6D_6), δ: 101.7. ^{1}H (400 MHz, C_6D_6), δ: 0.98 (m, 3H, CH_3, ^{i}Pr), 1.03 (m, 3H, CH_3, ^{i}Pr), 2.23 (s, 3H, CH_3, *o*-Tol), 2.25 (m, 4H, CH_3, *o*-Tol and CH-^{i}Pr), 2.40 (s, 6H, CH_3), 3.02 (m, 1H, CH-S), 3.78 (m, 1H, CH_2-O), 4.03 (m, 1H, CH_2-O), 6.84-7.12 (m, 9H, CH=), 7.48 (m, 1H, CH=), 7.60 (m, 1H, CH=). ^{13}C (100.6 MHz, C_6D_6), δ: 17.5 (CH_3, ^{i}Pr), 20.05 (CH_3, *o*-Tol), 20.1 (CH_3, *o*-Tol), 20.3 (CH_3, ^{i}Pr), 22.1 (2xCH_3), 28.8 (CH, ^{i}Pr), 56.5 (CH-S), 70.1 (CH_2-O), 125.9-147.3 (aromatic carbons). Anal. calcd. (%) for $C_{27}H_{33}OPS$: C 74.28, H 7.62, S 7.34; found: C 74.53, H 7.64, S 7.23. MS HR-ESI [found 459.1881, $C_{27}H_{33}OPS$ $(M+Na)^+$ requires 459.1882].

L4e: Yield: 146 mg (69%). ^{31}P NMR (C_6D_6), δ: 101.7. ^{1}H NMR (C_6D_6), δ: 0.98 (m, 3H, CH_3, ^{i}Pr), 1.03 (m, 3H, CH_3, ^{i}Pr), 1.22-1.82 (m, 22H, CH, Cy), 2.29 (m, 1H, CH, CH-^{i}Pr), 2.50 (s, 6H, CH_3-Ar), 3.07 (m, 1H, CH-S), 3.66 (m, 1H, CH_2-O), 3.93 (m, 1H, CH_2-O), 6.90-7.12 (m, 3H, CH=). ^{13}C NMR (C_6D_6), δ: 17.7 (CH_3, ^{i}Pr), 20.3 (CH_3, ^{i}Pr), 22.1 (CH_3-Ar), 25.3-28.9 (CH_2, Cy), 35.6 (d, $^1J_{C\text{-}P}$= 20.2 Hz, CH, Cy), 36.2 (d, $^1J_{C\text{-}P}$= 20.2 Hz, CH, Cy), 56.6 (CH-S), 72.6 (CH_2-O), 132.6-143.1 (aromatic carbons).

Preparation of silver carbene compounds 7 and 8. Ag_2O (55.6 mg. 0.24 mmol) was added into a solution of the corresponding imidazolium salt derivative (0.48 mmol) in dichloromethane (30 mL) and kept in the dark with vigorous stirring overnight. After that, the reaction crude was passed through a dry celite plug and evaporated affording the silver carbene complexes **7** and **8** as a dark brown foam.

7: Yield: 104.2 mg (63%). ^{1}H NMR (400 MHz, $CDCl_3$), δ: 1.06-1.20 (m, 18H, CH_3, ^{i}Pr-Ar and CH_3, ^{i}Pr), 2.10 (m, 1H, CH, ^{i}Pr), 2.21 (m, 1H, CH, ^{i}Pr-Ar), 2.51 (m, 1H, CH, ^{i}Pr-Ar), 3.50 (m, 1H, CH-S), 4.20 (m, 1H, CH_2-N), 4.59 (m, 1H, CH_2-N), 6.94-7.47 (m, 10H, CH=). Anal. calcd. (%) for $C_{52}H_{70}Ag_2Br_2N_4S_2$: C 52.45, H 5.93, N 4.70, S 5.38; found: C 52.27, H 5.91, N 4.68, S 5.32. MS HR-ESI [found 919.3919, $C_{52}H_{68}AgN_4S_2$ $(M\text{-}AgBr_2)^+$ requires 919.3931].

8: Yield: 120 mg (70%). ^{1}H NMR (400 MHz, $CDCl_3$), δ: 1.44 (m, 18H, CH_3, ^{i}Pr and CH_3, ^{i}Pr-Ar), 2.08 (m, 1H, CH, ^{i}Pr), 2.61 (m, 2H, CH, ^{i}Pr-Ar), 2.75 (s, 6H, CH_3, Ar), 3.54 (m, 1H, CH-S), 4.21 (m, 1H, CH_2-N), 4.84 (m, 1H, CH_2-N), 7.20-7.72 (m, 8H, CH=). Anal. calcd. (%) for $C_{56}H_{78}Ag_2Br_2N_4S_2$: C 53.92, H 6.31, N 4.49, S 5.148; found: C 53.67, H 6.28, N 4.46, S 5.10. MS HR-ESI [found 975.4559, $C_{56}H_{76}AgN_4S_2$ $(M\text{-}AgBr_2)^+$ requires 975.4564].

Preparation of [Ir(cod)(L1–L2)]BAr_F compounds. Into a solution of the corresponding silver carbene (0.074 mmol) and dichloromethane (5 mL), [Ir(μ-Cl)(cod)]$_2$ (0.037 mmol, 25 mg) was added and stirred for 4.5 h in the dark. Subsequently, $NaBAr_F$ (0.080 mmol, 77.2 mg) was added and stirred for an additional

hour at r.t. Then, the solvent is evaporated in vacuo and the crude product purified via column chromatography with neutral silica (75:25 – dichloromethane/hexane) to yield the corresponding complexes as orange solids.

[Ir(cod)(L1)]BAr$_F$: Yield: 38 mg (46%). ^{1}H NMR (400 MHz, $CDCl_3$), δ: 1.00 (m, 3H, CH_3, ^{i}Pr-Ar), 1.04 (m, 6H, CH_3, ^{i}Pr), 1.08 (m, 3H, CH_3, ^{i}Pr-Ar), 1.10 (m, 3H, CH_3, ^{i}Pr-Ar), 1.43 (m, 3H, CH_3, ^{i}Pr-Ar), 1.60-1.88 (m, 8H, CH_2, cod), 1.99 (m, 1H, CH, ^{i}Pr) 2.31 (m, 1H, CH, ^{i}Pr-Ar), 2.40 (m, 1H, CH, ^{i}Pr-Ar), 3.21 (m, 1H, CH-S), 3.67 (b, 2H, CH=, cod), 3.85 (b, 1H, CH=, cod), 4.12 (b, 1H, CH=, cod), 4.57 (dd, 1H, $^2J_{H\text{-}H}$= 14.2 Hz, $^3J_{H\text{-}H}$= 6.3 Hz, CH_2-N), 4.82 (m, 1H, CH_2-N), 6.99 (d, 1H, $^3J_{H\text{-}H}$= 2.9 Hz, CH=, NHC), 7.13 (d, 1H, $^3J_{H\text{-}H}$= 2.9 Hz, CH=, NHC), 7.25-7.75 (m, 20H, CH=). ^{13}C NMR (100.6 MHz, $CDCl_3$), δ: 19.8 (CH_3, ^{i}Pr), 20.4 (CH_3, ^{i}Pr), 22.6 (CH_3, ^{i}Pr-Ar), 23.4 (CH_3, ^{i}Pr-Ar), 24.0 (CH_3, ^{i}Pr,-Ar), 25.1 (CH_3, ^{i}Pr-Ar), 25.3 (CH, ^{i}Pr), 28.7 (CH, ^{i}Pr-Ar), 29.3 (CH, ^{i}Pr), 29.7 (2xCH_2, cod), 31.1 (CH_2, cod), 31.9 (CH_2, cod), 54.7 (CH_2-N), 57.9 (CH-S), 71.5 (CH=, cod), 83.3 (CH=, cod), 83.9 (CH=, cod), 122.2 (CH=, NHC), 125.9 (CH=, NHC), 117.5-145.9 (aromatic carbons), 161.4 (q, C, $^1J_{C\text{-}B}$= 49.6 Hz, BAr$_F$), 169.6 (C, NHC). Anal. calcd. (%) for $C_{66}H_{58}BF_{24}IrN_2S$: C 50.46, H 3.78, N 1.78, S 2.04; found: C 50.31, H 3.70, N 1.75, S 2.02. MS HR-ESI [found 707.2986, $C_{34}H_{46}IrN_2S$ (M-BAr$_F$)$^+$ requires 707.3005].

[Ir(cod)(L2)]BAr$_F$: Yield: 50 mg (42%). ^{1}H NMR (400 MHz, $CDCl_3$), δ: 0.85 (m, 3H, CH_3, ^{i}Pr-Ar), 0.92 (m, 3H, CH_3, ^{i}Pr-Ar), 0.94 (m, 3H, CH_3, ^{i}Pr), 1.09 (m, 6H, CH_3, ^{i}Pr-Ar), 1.50 (m, 3H, CH_3, ^{i}Pr-Ar), 1.68 (m, 2H, CH_2, cod), 1.90 (m, 3H, CH_2, cod), 2.12 (m, 3H, CH_2, cod) 2.33 (m, 2H, CH, ^{i}Pr-Ar), 2.47 (s, 3H, CH_3, Ar), 2.53 (m, 1H, CH, ^{i}Pr), 2.67 (s, 3H, CH_3, Ar), 2.77 (m, 2H, CH-S an CH=, cod), 2.94 (m, 1H, CH=, cod), 3.96 (m, 1H, CH=, cod), 4.22 (m, 1H, CH=, cod), 4.42 (dd, 1H, $^2J_{H\text{-}H}$= 14.6 Hz, $^3J_{H\text{-}H}$= 2.6 Hz, CH_2-N), 5.02 (dd, 1H, $^2J_{H\text{-}H}$= 14.6 Hz, $^3J_{H\text{-}H}$= 3.5 Hz, CH_2-N), 6.89 (s, 1H, CH=, NHC), 6.97 (s, 1H, CH=, NHC), 7.09-7.64 (m, 18H, CH=). ^{13}C NMR (100.6 MHz, $CDCl_3$), δ: 20.6 (CH_3, ^{i}Pr), 21.1 (CH_3, ^{i}Pr-Ar), 21.9 (CH_3, Ar), 22.3 (CH_3, Ar), 22.7 (CH_3, ^{i}Pr-Ar), 24.2 (CH_3, ^{i}Pr), 24.9 (CH_3, ^{i}Pr-Ar), 25.9 (CH_3, ^{i}Pr-Ar), 28.4 (CH, ^{i}Pr-Ar), 28.5 (CH, ^{i}Pr-Ar) 29.3 (CH, ^{i}Pr), 31.2 (CH_2, cod), 31.5 (CH_2, cod) 32.9 (CH_2, cod), 36.5 (CH_2, cod), 55.0 (CH_2-N), 55.1 (CH-S), 68.2 (CH=, cod), 72.3 (CH=, cod), 83.3 (CH=, cod), 84.9 (CH=, cod), 123.2 (CH=, NHC), 125.9 (CH=, NHC), 117.4-145.7 (aromatic carbons), 161.7 (q, C, $^1J_{C\text{-}B}$= 49.6 Hz, BAr$_F$), 168.5 (C, NHC). Anal. calcd. (%) for $C_{68}H_{62}BF_{24}IrN_2S$: C 51.10, H 3.91, N 1.75, S 2.00; found: C 51.01, H 3.89, N 1.73, S 1.98. MS HR-ESI [found 735.3324, $C_{36}H_{50}IrN_2S$ (M-BAr$_F$)$^+$ requires 735.3318].

General procedure for the preparation of [Ir(cod)(L3–L4a–e)]BAr$_F$. The corresponding ligand (0.074 mmol) was dissolved in CH_2Cl_2 (5 mL) and $[Ir(\mu\text{-}Cl)(cod)]_2$ (0.037 mmol, 25 mg) was added. The reaction mixture was refluxed at 50 °C for 1 hour. After 5 min at room temperature, $NaBAr_F$ (0.080 mmol, 77.2 mg) and water (5 mL) were added and the reaction mixture was stirred vigorously for 30 min at r.t. The phases were separated and the aqueous phase was extracted twice with CH_2Cl_2. The combined organic phases were dried with $MgSO_4$ and purified, if necessary, with neutral silica resulting in orange solids.

[Ir(cod)(L3a)]BAr$_F$: Yield 110 mg (87%). ^{31}P NMR (161.9 MHz, $CDCl_3$), δ: 96.4. ^{1}H NMR (400 MHz, $CDCl_3$), δ: 1.01 (d, 3H, CH_3, ^{i}Pr, $^3J_{H\text{-}H}$= 6.6 Hz), 1.11 (d, 3H, CH_3, ^{i}Pr, $^3J_{H\text{-}H}$= 6.6 Hz) 1.47 (s, 9H, CH_3, ^{t}Bu) 1.75 (s, 9H, CH_3, ^{t}Bu), 1.81 (s, 3H, CH_3), 1.85 (s, 3H, CH_3), 1.98 (b, 4H, CH_2, cod), 2.20 (m, 5H, CH, ^{i}Pr and CH_2, cod), 2.27 (m, 6H, 2CH_3), 3.05 (b, 1H, CH=, cod), 3.26 (b, 1H, CH=, cod) 4.34 (b, 1H, CH=, cod), 4.56 (m, 2H, CH_2-O and CH-S), 4.95 (m, 2H, CH_2-O and CH=, cod), 7.22-7.71 (m, 19H, CH=). ^{13}C NMR (100.6 MHz, $CDCl_3$), δ: 14.5 (CH_3), 14.6 (CH_3), 17.3 (CH_3, ^{i}Pr), 18.3 (CH_3), 18.5 (CH_3), 18.9 (CH_3, ^{i}Pr), 25.7 (CH_2, cod), 27.0 (CH, ^{i}Pr), 27.5 (CH_2, cod), 29.6 (CH_3, ^{t}Bu), 30.2 (d, CH_2, cod, $^2J_{C\text{-}P}$=3.8 Hz), 30.6 (CH_3, ^{t}Bu), 31.4 (CH_2, cod, $J_{C\text{-}P}$ =3.8 Hz), 32.9 (C, ^{t}Bu), 33.2 (C, ^{t}Bu), 60.6 (CH=, cod), 66.9 (CH=, cod), 67.8 (CH_2-O), 75.5 (CH-S), 100.0 (CH=, cod, $J_{C\text{-}P}$= 14.9 Hz), 104.3 (CH=, cod, $J_{C\text{-}P}$= 14.9 Hz), 115.5-141.9 (aromatic carbons) 159.7 (q, C-B, BAr$_F$ $J_{C\text{-}B}$= 49.7Hz). Anal. calcd. (%) for $C_{75}H_{71}BF_{24}IrO_3PS$: C 51.67, H 4.11, S 1.84; found: C 51.49, H 4.07, S 1.81. MS HR-ESI [found 879.3557, $C_{43}H_{59}IrO_3PS$ (M-BAr$_F$)$^+$ requires 879.3546].

[Ir(cod)(L3b)]BAr$_F$, Yield 102 mg (72%). ^{31}P NMR (161.9 MHz, $CDCl_3$), δ: 98.2. ^{1}H NMR (400 MHz, $CDCl_3$), δ: 0.89 (d, 3H, $^3J_{H\text{-}H}$= 6.6 Hz, CH_3, ^{i}Pr), 1.02 (d, 3H, $^3J_{H\text{-}H}$= 6.6 Hz, CH_3, ^{i}Pr) 1.43 (s, 9H, CH_3, ^{t}Bu) 1.63 (s, 9H, CH_3, ^{t}Bu), 1.78 (b, 7H, CH_3 and CH, ^{i}Pr), 1.95 (m, 6H, CH_2, cod), 2.18 (m, 2H, CH_2, cod), 2.27 (m, 6H, CH_3), 3.02 (b, 1H, CH=, cod), 3.41 (b, 1H, CH=, cod) 4.33 (m, 1H, CH_2-O), 4.67 (m, 3H, CH_2-O, CH-S and CH=, cod), 5.09 (b, 1H, CH=, cod) 7.23-7.71 (m, 19H, CH=). ^{13}C NMR (100.6 MHz, $CDCl_3$) δ: 14.4 (CH_3), 14.4 (CH_3), 14.6 (CH_3, ^{i}Pr), 18.3 (CH_3), 18.5 (CH_3, ^{i}Pr), 25.8 (CH_2, cod), 26.6 (CH_2, cod), 27.3 (CH, ^{i}Pr), 27.8 (CH_3r), 29.7 (CH_3, ^{t}Bu), 30.4 (d, $^2J_{C\text{-}P}$ =3,8 Hz CH_2, cod), 30.6 (CH_3, ^{t}Bu), 31.4 (d, $J_{C\text{-}P}$=3,8 Hz, CH_2, cod), 32.9 (C, ^{t}Bu), 33.1 (C, ^{t}Bu), 54.8 (CH=, cod), 65.1 (CH=, cod), 65.4 (CH_2-O), 76.9 (CH-S), 102.9 (d, $J_{C\text{-}P}$= 14.9 Hz, CH=, cod), 104.1 (d, $J_{C\text{-}P}$= 14.9 Hz, CH=, cod), 115.5-142.4 (aromatic carbons), 159.7 (q, C-B, BAr$_F$ $J_{C\text{-}B}$= 49.7Hz). Anal. calcd. (%) for $C_{75}H_{71}BF_{24}IrO_3PS$: C 51.67, H 4.11, S 1.84; found: C 51.52, H 4.09, S 1.82. MS HR-ESI [found 879.3542, $C_{43}H_{59}IrO_3PS$ (M-BAr$_F$)$^+$ requires 879.3546].

[Ir(cod)(L3c)]BAr$_F$: Yield: 99 mg (87%). ^{31}P NMR (161.9 MHz, $CDCl_3$), δ: 103.7. ^{1}H NMR (400 MHz, $CDCl_3$), δ: 0.91 (d, 3H, $^3J_{H\text{-}H}$= 6.8 Hz, CH_3, ^{i}Pr), 1.01 (d, 3H, $^3J_{H\text{-}H}$= 6.8 Hz, CH_3, ^{i}Pr,), 1.95 (m, 5H, CH, ^{i}Pr and CH_2, cod), 2.28 (m, 4H, CH_2, cod), 3.28 (b, 1H, CH=, cod), 3.36 (m, 1H, CH-S), 3.55 (b, 1H, CH=, cod), 4.33 (m, 2H, CH_2-O and CH=, cod) 4.61 (m, 1H, CH_2-O), 4.98 (b, 1H, CH=, cod), 7.26-7.73 (m, 27H, CH=). ^{13}C NMR (100.6 MHz, $CDCl_3$), δ: 17.5 (CH_3, ^{i}Pr), 20.4 (CH_3, ^{i}Pr), 28.8 (d, $J_{C\text{-}P}$= 2.0 Hz, CH_2, cod), 29.0 (d, $J_{C\text{-}P}$= 2.0 Hz, CH_2, cod), 29.6 (CH_2, cod), 30.3 (CH, ^{i}Pr), 32.2 (d, $J_{C\text{-}P}$= 6.9 Hz, CH_2, cod,), 59.0 (CH-S), 68.9 (CH_2-O), 73.2 (CH=, cod), 73.3 (CH=, cod), 99.7 (d, $J_{C\text{-}P}$= 11.4 Hz, CH=, cod), 100.6 (d, $J_{C\text{-}P}$= 11.9 Hz, CH=, cod), 117.4-134.8 (aromatic carbons), 161.6 (q, C-B, BAr$_F$, $^1J_{C\text{-}B}$= 49.9 Hz). Anal. calcd. (%) for $C_{63}H_{49}BF_{24}IrOPS$: C 49.01, H 3.20, S 2.07; found: C 48.88, H 3.17, S 2.05. MS HR-ESI [found 681.1932, $C_{31}H_{37}IrOPS$ (M-BAr$_F$)$^+$ requires 681.1926].

[Ir(cod)(L4a)]BAr$_F$: Yield: 56 mg (42%). ^{31}P NMR (161.9 MHz, $CDCl_3$), δ: 97.5. ^{1}H NMR (400 MHz, $CDCl_3$), δ: 0.95 (m, 3H, CH_3, ^{i}Pr), 1.01 (m, 3H, CH_3, ^{i}Pr), 1.44 (s, 9H, CH_3, ^{t}Bu), 1.63 (s, 9H, CH_3, ^{t}Bu), 1.73 (s, 3H, CH_3), 1.81 (s, 3H, CH_3), 1.84-2.16 (m, 9H, CH, ^{i}Pr and CH_2, cod), 2.26 (s, 3H, CH_3), 2.28 (s, 3H, CH_3), 2.54 (s, 3H, CH_3), 2.85 (m, 4H, CH_3 and CH=, cod), 3.30 (m, 1H, CH-S), 3.91 (m, 1H, CH=, cod), 4.49 (m, 2H, CH_2-O and CH=, cod), 4.78 (m, 1H, CH_2-O), 4.93 (m, 1H, CH=, cod), 7.16-7.70 (m, 17H, CH=). ^{13}C NMR (100.6 MHz, $CDCl_3$), δ: 16.3 (CH_3, ^{i}Pr), 16.5 (CH_3, ^{i}Pr), 17.9 (CH_3), 20.3 (CH_3), 20.4 (CH_3), 22.1 (CH_3), 22.6 (CH_3), 22.9 (CH_3), 27.0 (CH_2, cod), 29.5-29.7 (2xCH_2, cod), 30.9 (CH, ^{i}Pr), 31.5 (CH_3, ^{t}Bu), 32.6 (CH_3, ^{t}Bu), 33.7 (CH_2, cod), 34.8 (C, ^{t}Bu), 35.2 (C, ^{t}Bu), 57.6 (CH-S), 66.6 (CH_2-O), 67.0 (CH=, cod), 75.9 (CH=, cod), 102.8 (d, $J_{C\text{-}P}$= 13.7 Hz CH=, cod), 106.1 (d, $J_{C\text{-}P}$= 14.2 Hz, CH=, cod), 117.4-143.5 (aromatic carbons), 161.4 (q, $^1J_{C\text{-}B}$= 49.9 Hz, C-B, BAr$_F$). Anal. calcd. (%) for $C_{77}H_{75}BF_{24}IrO_3PS$: C 52.24, H 4.27, S 1.81; found: C 52.01, H 4.24, S 1.79. MS HR-ESI [found 907.3865, $C_{45}H_{63}IrO_3PS$ (M-BAr$_F$)$^+$ requires 907.3859].

[Ir(cod)(L4b)]BAr$_F$: Yield: 77 mg (59%). ^{31}P NMR (161.9 MHz, $CDCl_3$), δ: 96.3. ^{1}H NMR (400 MHz, $CDCl_3$), δ: 0.90 (m, 6H, CH_3, ^{i}Pr), 1.46 (s, 9H, CH_3, ^{t}Bu), 1.62 (s, 9H, CH_3, ^{t}Bu), 1.72 (s, 3H, CH_3), 1.74 (s, 3H, CH_3), 1.90-2.15 (m, 7H, CH_2, cod), 2.24 (s, 6H, CH_3), 2.34 (m, 2H, CH, ^{i}Pr and CH_2, cod), 2.62 (s, 3H, CH_3), 2.73 (s, 3H, CH_3), 3.10 (m, 1H, CH=, cod), 3.35 (m, 1H, CH-S), 4.48 (m, 2H, CH_2-O and CH=, cod), 4.60 (m, 2H, CH_2-O and CH=, cod), 4.77 (m, 1H, CH=, cod), 7.17-7.70 (m, 17H, CH=). ^{13}C NMR (100.6 MHz, $CDCl_3$), δ: 16.4 (CH_3, ^{i}Pr), 16.6 (CH_3, ^{i}Pr), 20.3 (CH_3), 20.4 (CH_3), 20.6 (CH_3), 22.6 (CH_3), 23.5 (2CH_3), 26.6 (CH_2, cod), 29.6 (CH, ^{i}Pr), 29.7 (CH_2, cod) 30.2 (CH_2, cod), 31.0 (CH_2, cod), 31.8 (CH_3, ^{t}Bu), 32.2 (CH_3, ^{t}Bu), 34.9 (C, ^{t}Bu), 35.0 (C, ^{t}Bu), 54.9 (CH-S), 64.8 (CH=, cod), 66.9 (CH_2-O), 77.7 (CH=, cod), 101.7 (d, $J_{C\text{-}P}$= 13.4 Hz, CH=, cod), 107.1 (d, $J_{C\text{-}P}$= 11.5 Hz, CH=, cod), 110.0-143.2 (aromatic carbons), 161.4 (q, $^1J_{C\text{-}B}$= 49.9 Hz, C-B, BAr$_F$). Anal. calcd. (%) for $C_{77}H_{75}BF_{24}IrO_3PS$: C 52.24, H 4.27, S 1.81; found: C 51.99, H 4.25, S 1.79. MS HR-ESI [found 907.3862, $C_{45}H_{63}IrO_3PS$ (M-BAr$_F$)$^+$ requires 907.3859].

[Ir(cod)(L4c)]BAr$_F$: Yield: 47 mg (41%). Major isomer (53%): ^{31}P NMR ($CDCl_3$) δ: 107.7. ^{1}H NMR ($CDCl_3$) δ: 0.96 (m, 6H, CH_3, ^{i}Pr), 1.75-2.33 (m, 9H, CH_2, cod and CH, ^{i}Pr), 2.55 (s, 3H, CH_3-Ar), 2.60 (s, 3H, CH_3-Ar), 3.10 (m, 1H, CH=, cod), 3.43 (b, 1H, CH=, cod), 3.56 (m, 1H, CH-S), 3.79 (m, 1H, CH_2-O), 4.45 (m, 1H, CH_2O), 4.56 (b, 1H, CH=, cod), 5.09 (b, 1H, CH=, cod), 6.92-7.97 (m, 25H, CH=). ^{13}C NMR ($CDCl_3$) δ: 14.1 (CH_3, ^{i}Pr), 16.3 (CH_3, ^{i}Pr), 20.6 (CH_3-Ar), 20.8 (CH_3-Ar), 22.4-36.4 (CH_2, cod), 33.1 (CH, ^{i}Pr), 54.9 (CH-S), 66.0 (CH_2-O), 75.4 (CH=, cod), 81.9 (CH=, cod), 95.6 (d, $J_{C\text{-}P}$= 13.9 Hz, CH=, cod), 99.4 (d, $J_{C\text{-}P}$= 14.6 Hz, , CH=, cod), 117.4-155.3 (aromatic carbons), 161.4 (q, $^1J_{C\text{-}B}$= 49.9 Hz, C-B, BAr$_F$). Minor isomer (47%): ^{31}P NMR ($CDCl_3$) δ: 85.6. ^{1}H NMR ($CDCl_3$) δ: 1.38 (m, 3H, CH_3, ^{i}Pr), 1.75-2.33 (m, 8H, CH-S, CH_2, cod and CH, ^{i}Pr), 2.89 (m, 2H, CH_2, cod), 2.99 (s, 6H, CH_3-Ar), 3.43 (b, 2H, CH=, cod), 3.69 (m, 1H, CH=, cod), 3.79 (m, 1H, CH_2-O), 4.62 (m, 1H, CH_2-O), 5.09 (m, 1H, CH=, cod), 6.92-7.97 (m, 20H, CH=). ^{13}C NMR ($CDCl_3$) δ: 20.2 (CH_3, ^{i}Pr), 22.2 (CH_3, ^{i}Pr), 23.8 (CH_3-Ar), 22.2 (CH_3-Ar), 31.7 (CH-iPr), 22.6-36.4 (CH_2, cod), 55.1 (CH-S), 66.2 (CH_2-O), 68.02 (CH=, cod), 91.8 (CH=, cod), 98.5 (d, $J_{C\text{-}P}$= 13.0 Hz CH=, cod), 103.0 (d, $J_{C\text{-}P}$= 9.47 Hz, CH=, cod), 117.4-

155.3 (aromatic carbons), 161.4 (q, $^1J_{C\text{-}B}$= 49.9 Hz, C-B, BAr_F). Anal. calcd. (%) for $C_{65}H_{53}BF_{24}IrOPS$: C 49.66, H 3.40, S 2.03; found: C 49.71, H 3.42, S 2.01. MS HR-ESI [found 709.2245, $C_{33}H_{41}IrOPS$ $(M\text{-}BAr_F)^+$ requires 709.2239].

[**Ir(cod)(L4d)**]**BAr$_F$**: Yield: 90 mg (77%). ^{31}P NMR (161.9 MHz, $CDCl_3$), δ: 110.7. ^{1}H NMR (400 MHz, $CDCl_3$), δ: 0.72 (m, 3H, CH_3, ^{i}Pr), 0.87 (m, 3H, CH_3, ^{i}Pr), 1.44 (m, 1H, CH, ^{i}Pr), 1.85-2.00 (m, 6H, CH_2, cod), 2.12 (s, 3H, CH_3, *o*-Tol), 2.18-2.85 (m, 2H, CH_2, cod), 2.55 (s, 3H, CH_3, *o*-Tol), 2.72 (m, 1H, CH=, cod), 2.88 (s, 3H, CH_3), 2.97 (s, 3H, CH_3), 3.17 (m, 1H, CH=, cod), 3.70 (m, 1H, CH=, cod), 3.78 (b, 2H, CH_2-O and CH-S), 4.54 (m, 1H, CH_2-O), 4.87 (m, 1H, CH=, cod), 6.68-8.95 (m, 23H, CH=). ^{13}C NMR (100.6 MHz, $CDCl_3$), δ: 16.2 (CH_3, ^{i}Pr), 20.2 (CH_3, ^{i}Pr), 21.6 (CH_3, *o*-Tol), 22.2 (CH_3, *o*-Tol), 22.3 (CH_3); 23.0 (CH_3), 27.6 (CH, ^{i}Pr) 28.7 (CH_2, cod), 30.6 (CH_2, cod), 30.9 (CH_2, cod), 33.3 (CH_2, cod), 54.7 (CH-S), 66.2 (CH_2-O), 67.6 (CH=, cod), 76.1 (CH=, cod), 97.1 (d, $J_{C\text{-}P}$= 9.2 Hz, CH=, cod), 98.4 (d, $J_{C\text{-}P}$= 11.5 Hz, CH=, cod), 117.4-143.2 (aromatic carbons), 161.9 (q, $^1J_{C\text{-}B}$= 49.9 Hz, C-B, BAr_F). Anal. calcd. (%) for $C_{67}H_{57}BF_{24}IrOPS$: C 50.29, H 3.59, S 2.00; found: C 50.34, H 3.58, S 1.98. MS HR-ESI [found 737.2554, $C_{35}H_{45}IrOPS$ $(M\text{-}BAr_F)^+$ requires 737.2552].

[**Ir(cod)(L4e)**]**BAr$_F$**: Yield: 45 mg (39%). ^{31}P NMR (161.9 MHz, $CDCl_3$), δ: 129.7. ^{1}H NMR (400 MHz, $CDCl_3$), δ: 1.11 (m, 3H, CH_3, ^{i}Pr), 1.20 (m, 3H, CH_3, ^{i}Pr), 1.47-2.56 (m, 31 H, CH, Cy, CH_2, Cy, CH, ^{i}Pr and CH_2, cod), 2.80 (s, 3H, CH_3), 2.93 (s, 3H, CH_3), 3.13 (m, 1H, CH-S), 3.77 (m, 1H, CH=, cod), 4.01 (m, 1H, CH=, cod), 4.24 (m, 1H, CH=, cod), 4.59 (m, 2H, CH_2-O), 4.75 (m, 1H, CH=, cod), 7.33-7.92 (m, 15H, CH=). ^{13}C NMR (100.6 MHZ, $CDCl_3$), δ: 19.1 (CH_3, ^{i}Pr), 20.9 (CH_3, ^{i}Pr), 22.2 (CH_3), 23.0 (CH_3), 25.8-34.0 (CH_2, Cy andCH, ^{i}Pr and CH_2, cod,), 40.0 (d, $^1J_{C\text{-}P}$= 29.9 Hz, CH, Cy), 41.5 (d, $^1J_{C\text{-}P}$= 30.0 Hz, CH, ^{i}Pr), 57.8 (CH-S), 66.3 (CH=, cod), 70.0 (CH=, cod), 71.3 (CH_2-O), 94.9 (d, $J_{C\text{-}P}$= 10.2 Hz, CH=, cod), 96.9 (d, $J_{C\text{-}P}$= 10.2 Hz, CH=, cod), 117.4-142.2 (aromatic carbons), 161.9 (q, $^1J_{C\text{-}B}$= 49.9 Hz, C-B, BAr_F). Anal. calcd. (%) for $C_{65}H_{65}BF_{24}IrOPS$: C 49.28, H 4.14, S 2.02; found: C 49.17, H 4.11, S 1.99. MS HR-ESI [found 721.3180, $C_{33}H_{53}IrOPS$ $(M\text{-}BAr_F)^+$ requires 721.3178].

General procedure for the asymmetric hydrogenation. The alkene (0.5 mmol) and Ir complex (1 mol %) were dissolved in CH_2Cl_2 (2 mL) and placed in a high-pressure autoclave. The autoclave was purged 4 times with hydrogen. Then, it was pressurized at the desired pressure. After the desired reaction time, the autoclave was depressurized and the solvent evaporated off. The residue was dissolved in Et_2O (1.5 mL) and filtered through a short plug of celite. The enantiomeric excess was determined by chiral GC or chiral HPLC (see Supporting Information for details) and conversions were determined by ^{1}H NMR.

Reactivity studies of [Ir(cod)(L)]BAr$_F$ towards H$_2$. In a typical experiment hydrogen was bubbled through a CD_2Cl_2 solution of the desired [Ir(cod)(L)]BAr_F catalyst precursor (5 mmol) to the desired temperature for 15-30 min. The reaction mixture was analyzed by NMR spectroscopy at the desired temperature. All attempts to isolate the *cis*-dihydride iridium complexes **9**, **10**, **12**, **13** and **14** were unsuccessful even at -70 ºC under a hydrogen atmosphere.

Computational Details. The geometries of all intermediates were optimized using the Gaussian 09 program,[28] employing the B3LYP-D3[29] density functional and the LANL2DZ[30] basis set for iridium and the 6-31G*[31] basis set for all other elements.[32] Solvation correction was applied in the course of the optimizations using PCM model with the default parameters for dichloromethane.[33] The complexes were treated with charge +1 and in the single state. No symmetry constraints were applied. All energies reported are Gibbs free energies.

ASSOCIATED CONTENT

Supporting Information

Copies of $^{31}P\{^1H\}$, ^{1}H and $^{13}C\{^1H\}$ NMR spectra, enantiomeric excess determination and characterization details of hydrogenated products and ^{1}H NMR and mass spectra of the deuterium experiments (PDF).

Calculated energies and coordinates for all computational structures (PDF).

The supplemental file CartCoord contains the computed Cartesian coordinates of all of the molecules reported in this study (xyz).

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Notes

The authors declare no competing financial interest.

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