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Ir(I) complexes with oxazoline-thioether ligands: nucleophilic attack of pyridine on coordinated 1,5-cyclooctadiene and application as catalysts in imine hydrogenation

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Abstract

Oxazoline-thioether ligands **6–11** react with $[Ir(\eta^4\text{-COD})Py_2]PF_6$ (COD = C_8H_{12} = 1,5-cyclooctadiene) to give $[Ir(\sigma\text{-}\eta^2\text{-}C_8H_{12}Py^+)L]$ PF_6 (L = oxazoline-thioether ligand) **(12a–d)** complexes resulted from the coordination of ligand to the metal and subsequent nucleophilic attack of pyridine to one of the double carbon bond of COD with concomitant iridium–carbon bond formation. When $[Ir(\eta^4\text{-COD})_2]BF_4$ was used as starting material, the reaction with ligands **7**, **9** afforded the complexes $[Ir(\eta^4\text{-COD})L]BF_4$. Application of these iridium complexes to the reduction of *N*-(α-methyl)benzylidenbenzylamine gave low or negligible enantioselectivity.

Keywords: Ir/oxazoline-thioether complexes; Ir/cyclooctenyl complexes; Iridium–carbon bond formation; Hydrogenation of imines

1. Introduction

Chiral metal complexes containing oxazoline derivative ligands (**1a–g**) (Fig. 1) are efficient catalysts in asymmetric reactions [1] such as enantioselective cooper and ruthenium cyclopropanation [2], iron, magnesium, copper-catalysed Diels Alder, copper-catalysed Michael and Mannich reactions [3], rhodium-catalysed hydrosilylation [4], iridium-catalysed hydrogenation [5] and palladium-catalysed allylic substitution [6]. The asymmetry induced by such heterobidentate systems is determined by a combination of steric and electronic interactions. Therefore, these ligands make it possible to control the enantioselectivity in catalytic reactions by creating an asymmetric environment provided by the oxazoline moiety and by combining soft and hard donor atoms (P, S, N) to modify the electronic properties on the metal center. Moreover, modifying the chelate ring size is another way of optimizing the effectiveness of the catalytic system.

The phosphino-oxazoline ligands (P∩N), mainly developed by Williams and co-workers [7], Pfaltz [8] and Helmchen and co-workers [9], proved to be versatile chiral ligands in a wide range of homogeneous catalytic reactions such as imine [10] and olefin [11,12] reductions with Ir(I) complexes as well as in palladium-catalysed allylic substitution and Heck [9] reaction.

Mixed ligands containing nitrogen and sulfur coordinative atoms as oxazoline-thioether ligands were prepared and used mainly by Pfaltz and his colleague [13], Williams and co-workers [7a] and Helmchen and his colleague [9a] in palladium-catalysed allylic alkylation providing a high enantiocontrol [7a,14]. Besides, a group of complexes *fac*-$[ReX(CO)_3(NS)]$ and *fac*-$[PtXMe_3(NS)]$ with oxazoline-thioether ligands have been described showing the presence of four diastereoisomers [15].

In this paper we report the preparation and structural characterization of iridium complexes bearing oxazoline-thioether ligands **6–9** (Scheme 2) and their application in the hydrogenation of *N*-(α-methyl)benzylidenbenzylamine.

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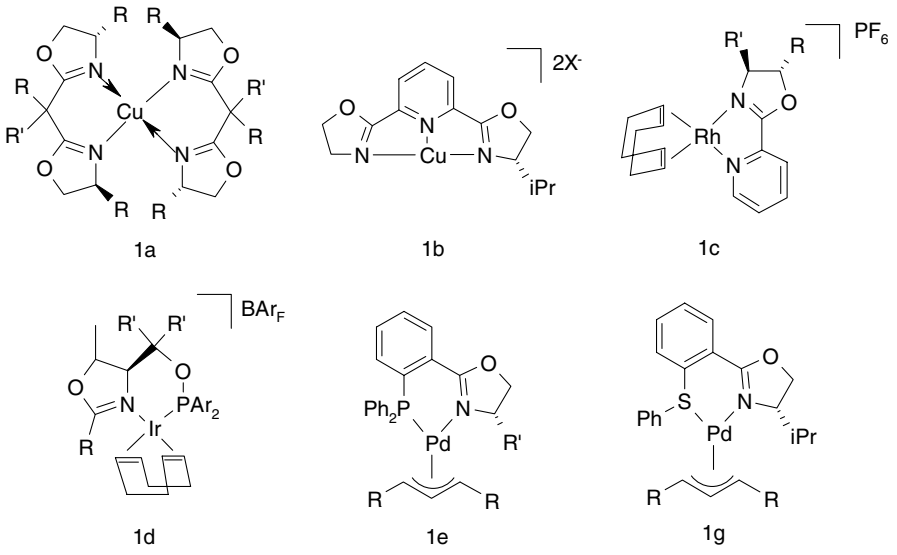


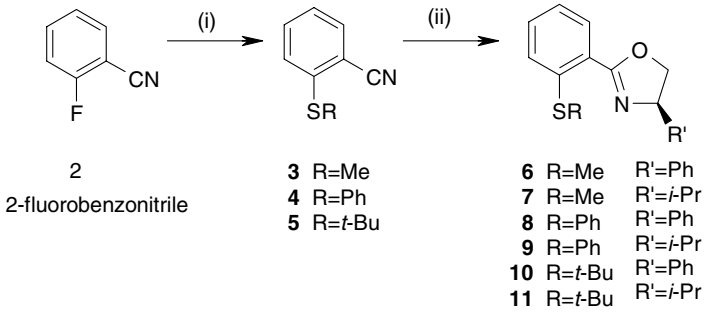
Fig. 1. Chiral metal complexes bearing oxazoline derivative ligands.

2. Results and discussion

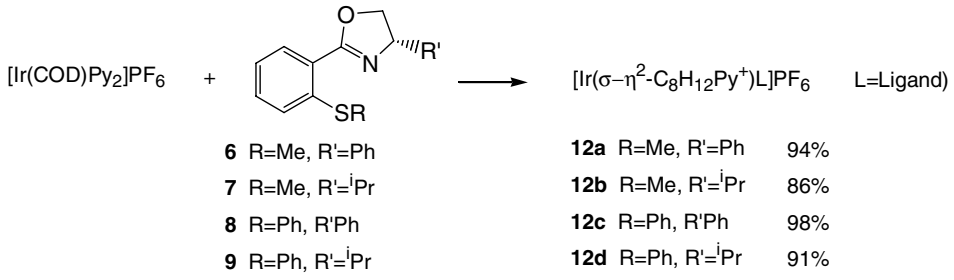
With the aim of exploring the coordination chemistry of the oxazoline-thioether ligands, we decided to prepare ligands **6**–**11**, which have methyl, phenyl or *t*-butyl groups attached to the sulfur atom, and phenyl or isopropyl on the stereogenic center of the oxazoline ring (Scheme 1). Compounds **6**–**9** have already been reported [16] and ligands **10** and **11** have been synthesized and characterized for the first time here following the reported procedure [16].

We initially selected $[Ir(\eta^4\text{-COD})(Py)_2]\,PF_6$(COD = C_8H_{12} = 1,5-cyclooctadiene, Py = pyridine) which had been used as a precursor to prepare several cationic Ir(I) complexes [17]. The reaction of the chiral oxazoline-thioether ligands **6**–**9** with $[Ir(\eta^4\text{-COD})(Py)_2]PF_6$ in anhydrous CH_2Cl_2 at room temperature was expected to occur with the displacement of the two pyridine molecules affording the corresponding cationic Ir(I) complexes $[Ir(\eta^4\text{-COD})L]\,PF_6$ (L = oxazoline-thioether ligands). However, the isolated complexes **12a**–**d** showed the composition depicted in Scheme 2.

Complexes **12a**–**d** were stable in air even in solution. Mass spectroscopy analysis and NMR experiments allow us to elucidate the structure of compound **12a**. The presence of pyridine was confirmed by ^1H and ^{13}C NMR, and also by MS spectroscopy. The highest peak in the FAB spectrum at $m/z = 648.1$ corresponds to the iridium containing cation and another relevant peak appears at $m/z = 570.1$, which corresponds to $M^+ - Py$. The characteristic signals of the PF_6^- anion, which in this case is the counterion of the pyridinium salt, were observed in the $^{31}P\{^1H\}$ spectrum at −144.1 ppm (septuplet, $J_{P-F} = 712.8$ Hz) and in $^{19}F\{^1H\}$ spectrum at −73.6 ppm (doublet, $J_{F-P} = 711.7$ Hz). ^1H and $^{13}C\{^1H\}$ NMR spectra showed signals corresponding to the COD ligand and to the coordinated oxazoline-thioether ligand. The eight signals corresponding to the aliphatic CH_2 protons of COD were unambiguously assigned by COSY and TOCSY experiments and by correlation with their respective carbons. The assignment of the olefinic COD protons revealed that whereas three of these signals appeared at the expected chemical shift (3–5 ppm), a signal corresponding to H3 appeared at 2.59 ppm. The



Scheme 1. (i) RSNa, THF reflux. (ii) L-valinol or L-phenylglycinol, $ZnCl_2$, C_6H_5Cl reflux.



Scheme 2. Synthesis of **12a–d**.

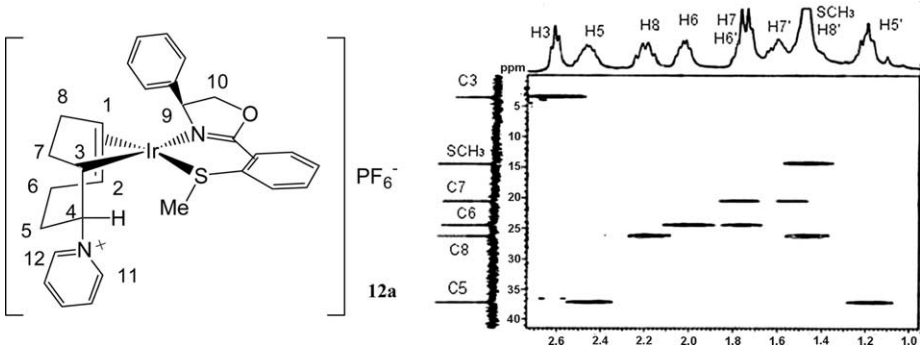


Fig. 2. Proposed structure and a section of the HETCOR spectrum for **12a**.

HETCOR experiment showed a correlation of H3 with the carbon appearing at 3.57 ppm (!) (Fig. 2). This carbon must be directly bonded to the metal and since there are no additional protons in the COD structure, pyridine must be bonded to the neighbouring carbon. In fact, the chemical shift of H4 and C4 are in agreement with the values expected for a carbon bonded to a pyridinium salt.

Two isomers can be obtained for compounds **12a–d** depending on the formation of a C–Ir bond close to the nitrogen of oxazoline ring or to the sulfur atom. Each of them can give 16 diastereomers since three new stereocentres, apart from the one in the oxazoline ring, are formed during the reaction. A NOE experiment carried out in compound **12a** showed a signal enhancement of H11 and H12 of pyridine and H4 when the methyl group was irradiated, confirming that the SMe group is close to the C–Ir bond formed and at the same face as the pyridinium substituent. Thus, considering a *trans* relationship between the C–Ir bond and the pyridinium group, the resulting structure, [Ir(σ-η^2-$C_8H_{12}Py^+$)L] PF_6 (**12a**), consists of monomeric units with an Ir atom coordinated to a pyridinium-cyclooctenyl unit via σ-C and π-C=C bonds and to the oxazoline-thioether ligand (Fig. 2). The relative stereochemistry of phenyl and SMe groups was not determined. The NMR data for **12a** are collected in Table 1.

A reasonable explanation for these observations is that a nucleophilic attack of the pyridine to the C=C of the coordinated cyclooctadiene takes place, resulting in the formation of a pyridinium salt and a C–Ir bond. Olefins, which are usually unreactive to nucleophiles, do react with various nucleophiles such as malonates, acetates, hydroxides, etc, leading to new carbon–carbon or carbon–heteroatom bond formation when they are coordinated to metals [18]. Transition metals such as palladium (II) or platinum (II) [19,20] are most suitable for this reaction, since they withdraw electron density from the olefins. Likewise, several examples were reported with rhodium (I) [21] or iridium (I) [22] complexes, even with NR_nH_{3-n} as nucleophile agents.

Table 1
NMR data of complex [Ir(σ-η^2-$C_8H_{12}Py^+$)**6**]PF_6 (**12a**)

	^{1}H NMR (ppm)		^{13}C NMR (ppm)
H1	4.07	C1	87.1
H2	3.22	C2	67.3
H3	2.59	C3	3.6
H4	4.66	C4	70.9
H5, H5′	2.43, 1.21	C5	37.2
H6, H6′	2.03, 1.74	C6	24.5
H7, H7′	1.74, 1.54	C7	20.6
H8, H8′	2.20, 1.46	C8	26.3
H9	5.81	C9	66.6
H10, H10′	5.13, 4.94	C10	77.9
H11	8.95	C11	154.8
H12	8.54	C12	152.6
Me	1.48	Me	14.5

The ^{1}H NMR spectrum of complex **12b** showed only one species and the presence of pyridine, COD and oxazoline-thioether ligands, as in **12a**, although in this case the signals were broad even at −50 °C and could not be assigned unambiguously. ^{1}H NMR of complexes **12c–d** showed the presence of several species in equilibrium, where pyridine signals were also present. Lowering the temperature did not result in the resolution of one species. The presence of several species may be due to the formation of several regioisomers as a consequence of the nucleophilic attack of the pyridine on either C3 or C4. Moreover, a new stereogenic center is created when the sulfur is coordinated to the metal center, which gives rise to diastereomeric mixtures. This behaviour has previously been described for Rh [23] and Pd [24] complexes with thioether ligands. Attempts to obtain crystals suitable for X-ray diffraction were unsuccessful. The formation of these regioisomeric or diastereomeric complexes seems to be favoured when a phenyl substituent is attached to the sulfur atom.

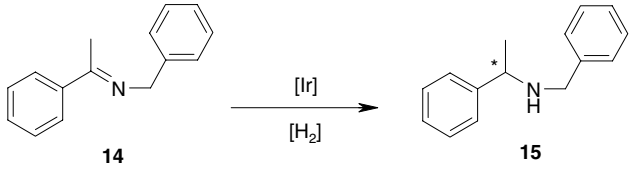
Further investigation of the reaction of [Ir(η^4-COD)Cl]$_2$ with ligand **7** in anhydrous CH_2Cl_2 at 50 °C for 1–2 h under an inert atmosphere afforded the complex [Ir(η^4-COD)**7**]PF_6 (**13a**) after anion exchange by washing with an aqueous solution of $NaPF_6$ and crystallization from CH_2Cl_2/Et_2O. Complex **13b** was synthesized by reacting [Ir(η^4-COD)$_2$]BF_4 with ligand **9** in anhydrous CH_2Cl_2.

Elemental analysis of **13a** and **13b** showed that the composition of these complexes was in agreement with the proposed stoichiometry. The ^{1}H NMR spectra of **13a**,**b** were complex and signals broad, showing the signals corresponding to the coordinated oxazoline-thioether ligand and the η^4-cyclooctadiene appearing at the expected chemical shift.

The hydrogenation of C=N bond presents more points of complexity that the corresponding reduction of alkenes or ketones and most of the catalyst highly efficient in C=C and C=O hydrogenation are ineffective in imines reduction. Recently, the asymmetric hydrogenation of prochiral imines has been received a great deal of attention because it is a useful tool to obtain versatile chiral auxiliaries [25]. Particularly, iridium complexes containing chiral ligands have resulted to be highly efficient in this process [26].

In this context, the Ir/oxazoline-thioether ligands **6–11** and complex **12a** were tested as catalysts for the asymmetric hydrogenation of imines. We focused on reducing the imine *N*-(α-methyl)benzylidenbenzylamine (**14**) (Scheme 3) by systems generated 'in situ' from [Ir(COD)Cl]$_2$/**6–11** and under 50 bar of H_2 pressure. The results are collected in Table 2.

When the catalytic precursor was formed by [Ir(η^4-COD)Cl]$_2$ in the presence of ligands **6–8** (entries 2–4), conversions were lower than 50%. These results were similar or lower than the conversion obtained with the iridium precursor when no ligand was added (entry 1). However, the iridium systems with ligands **9–11** (entries 5–7) provided conversions between 80% and 100% in the same conditions. These results indicate that new catalytic systems are formed at least when the oxazoline-



Scheme 3. Hydrogenation of *N*-(α-methyl)benzylidenbenzylamine.

Table 2
Hydrogenation of **14** catalysed by Ir/oxazoline-thioether ligands **6–11** and complex **12a**[a]

Entry	Precursor/Ligand	Solvent	Additive	Conv [%]
1	[Ir(η^4-COD)Cl]$_2$/–	MeOH/DCE (1:1)	–	48
2	[Ir(η^4-COD)Cl]$_2$/**6**	MeOH/DCE (1:1)	–	50
3	[Ir(η^4-COD)Cl]$_2$/**7**	MeOH/DCE (1:1)	–	32
4	[Ir(η^4-COD)Cl]$_2$/**8**	MeOH/DCE (1:1)	–	34
5	[Ir(η^4-COD)Cl]$_2$/**9**	MeOH/DCE (1:1)	–	80
6	[Ir(η^4-COD)Cl]$_2$/**10**	MeOH/DCE (1:1)	–	99
7	[Ir(η^4-COD)Cl]$_2$/**11**	MeOH/DCE (1:1)	–	100
8	[Ir(η^4-COD)Cl]$_2$/**6**	MeOH/DCE (1:1)	Bu_4NI	73
9	[Ir(η^4-COD)Cl]$_2$/**7**	MeOH/DCE (1:1)	Bu_4NI	44
10	[Ir(η^4-COD)Cl]$_2$/**8**	MeOH/DCE (1:1)	Bu_4NI	28
11	[Ir(η^4-COD)Cl]$_2$/**9**	MeOH/DCE (1:1)	Bu_4NI	64
12	[Ir(η^4-COD)Cl]$_2$/**10**	MeOH/DCE (1:1)	Bu_4NI	99
13	[Ir(η^4-COD)Cl]$_2$/**10**	MeOH	–	95
14	[Ir(η^4-COD)Cl]$_2$/**10**	C_6H_6	–	100
15	[Ir(η^4-COD)Cl]$_2$/**10**	MeOH/C_6H_6(1:1)	–	100
16[b]	**12a**	MeOH/DCE (1:1)	–	13
17	**12a**	MeOH/DCE (1:1)	–	39
18	**12a**	CH_2Cl_2	–	23

[a] 1% mol. [M], 1.25% mol. **6–11**, 1% mol. Bu_4NI, 50 bar H_2, 25 °C, 24 h, DCE, dichloroethane.
[b] 30 bar.

thioether ligands **9–11** are added to the iridium precursor. Conversions were higher when a *t*-butyl group was present at the sulfur atom.

It has been shown that in several Rh(I) [27] and Ir(I) [28] systems, the presence of a co-catalyst improves the catalytic activity and the enantioselectivity. Among the most widely used co-catalysts are iodides and amines [29]. The experiments with ligands **6** and **7** (Table 2, entries 8 and 9) provided higher conversion when Bu_4NI was used as co-catalyst. The results obtained in the experiments carried out with ligands **9** and **10** in the presence of Bu_4NI were maintained or were slightly lower than in the absence of additive. No enantioselectivity was observed with these catalytic systems in the asymmetric hydrogenation of imine **14**. Only ligand **6** provided 15% of ee (determined by ^1H NMR using mandelic acid). Such solvents as $MeOH/C_2H_4Cl_2$, MeOH, C_6H_6 and $MeOH/C_6H_6$ (Table 2, entries 12–15) have been tested, and total conversion was obtained in all cases.

The complex $[Ir(\sigma\text{-}\eta^2\text{-}C_8H_{12}Py^+)\mathbf{6}]PF_6$ (**12a**) was active in reducing imine **14** into the corresponding amine (Table 2, entries 16–18). Conversions were similar to those obtained with systems prepared in situ from $[Ir(\eta^4\text{-COD})Cl]_2$/**7** and **8** (entries 3, 4 and 17). It has been reported [30] that diolefin ligands in cationic iridium complexes are hydrogenated before the substrate. However, when we studied the hydrogenation of imine **14** in the presence of the complex **12a** by HP ^1H NMR at 298 K, we observed signals corresponding to the coordinated Py-cyclooctenyl ligand after 24 h at 50 bar of H_2 pressure. That can be a reason of the low activity of this catalytic system.

3. Conclusions

In the preparation of iridium complexes containing oxazoline-thioether ligands starting from the iridium precursor $[Ir(\eta^4\text{-COD})Py_2]PF_6$, an unexpected nucleophilic attack of the pyridine on the coordinated cyclooctadiene with concomitant σ-Ir–C bond formation takes place, leading to the $Ir(\sigma\text{-}\eta^2\text{-}C_8H_{12}Py^+)L]PF_6$ (**12a–d**). When $[Ir(\eta^4\text{-COD})Cl]_2$, followed by anion exchange, or $[Ir(\eta^4\text{-COD})_2]BF_4$ were used as precursors the expected $[Ir(\eta^4\text{-COD})L]A$ ($A = PF_6$, BF_4) complexes were obtained.

Hydrogenation of imine **14** with the catalytic systems formed in situ from $[Ir(\eta^4\text{-COD})Cl]_2$/**6–11** provided conversions of 30–100% in 24 h, although no enantioselectivity was achieved. The new stereogenic center formed by the coordination of sulfur to the metal center may be responsible for the existence of different diastereomers during the catalytic cycle, which does not favour the stereoselectivity.

Complex **12a** was also active in the hydrogenation of imine **14** although only in one instance, some enantioselectivity (15%) was achieved.

4. Experimental

All reactions were carried out in an argon atmosphere using standard Schlenk techniques. Solvents were distilled and degassed prior to use.

^1H, $^{13}C\{^1H\}$, $^{31}P\{^1H\}$ and $^{19}F\{^1H\}$ NMR spectra were recorded on a Varian Gemini spectrometer at 300 and 400 MHz. Chemical shifts were reported relative to tetramethylsilane for ^1H and $^{13}C\{^1H\}$ as internal reference, H_3PO_4 85% for $^{31}P\{^1H\}$ and trichlorofluoromethane for $^{19}F\{^1H\}$ as external references. Optical rotations were measured on a Perkin–Elmer 241 MC polarimeter. Elemental analyses were carried out on a Carlo Erba Microanalyser EA 1108. VG-Autospect equipment was used for FAB mass spectral analyses with 3-nitrobenzylalcohol as matrix. EI mass spectra were obtained on an HP 5989 A spectrometer at an ionizing voltage of 70 eV. The catalytic reactions were monitored by GC on a Hewlett–Packard 5890A. Conversion was measured in an Ultra-2 column (5% diphenylsilicone/95% dimethylsilicone, 25 m × 0.2 mm ∅). The enantiomeric excess of *N*-(α-methyl)phenylidenbenzylamine (**14**) was determined by ^1H NMR, using mandelic acid as resolution agent.

4.1. 2-tert-Butylsulfanyl-benzonitrile (5)

A solution of 2-methyl-2-propanethiol (9 mmol) in THF (2 ml) was added to a stirred mixture of sodium hydride (9 mmol) in THF (5 ml). To the resulting white precipitate, a solution of 2-fluorobenzonitrile (8 mmol) in THF (2 ml) was added. The mixture was stirred under reflux for 48 h. The reaction mixture was poured into dichloromethane (20 ml) and washed with 15% aqueous NaOH (20 ml) and then with water (20 ml). The aqueous layers were extracted with dichloromethane (2 × 30 ml) and the combined extracts were dried ($MgSO_4$), concentrated under reduced pressure and purified by column chromatography using hexane/ethyl acetate 3:1 as solvent to give 1.3 g (86%) of compound **5**.

^1H NMR (300 MHz, $CDCl_3$, ppm) 7.7–7.5 (m, 4H, arom.), 1.35 (s, 9H, $C(CH_3)_3$). ^{13}C NMR (74.5 MHz, $CDCl_3$, ppm) 138.8 (arom., CH), 136.3 (arom., C), 133.6, 132.3, 129.3, 121.0 (arom., CH), 118.1 (C≡N), 48.8 ($C(CH_3)_3$), 30.9 ($C(CH_3)_3$).

4.2. General procedure for the synthesis of oxazoline-thioether ligands 6–11

In a 50-ml Schlenk flask, zinc chloride (0.5 mmol) was melted under high vacuum and cooled under nitrogen to room temperature. Chlorobenzene (25 ml) was then

added followed by the corresponding thiobenzonitrile (10 mmol) and the aminoalcohol (15 mmol L-valinol or L-phenylglycinol). The mixture was heated under reflux for 48 h. The solvent was removed under reduced pressure to give an oily residue, which was dissolved in dichloromethane (30 ml). The solution was extracted with aqueous solution of NaCl (3×20 ml) and the aqueous phase with dichloromethane (30 ml). The combined organic extracts were dried ($MgSO_4$) and evaporated under reduced pressure.

4.3. (4S)-2-(2-tert-Butylsulfanyl-phenyl)-4-phenyl-4,5-dihydro-oxazole (**10**)

A total of 0.5 mmol (68 mg) of $ZnCl_2$ reacted with 10 mmol (1.91 g) of 2-*tert*-butylthio-benzonitrile (**5**) and 15 mmol (1.37 g) of L-phenylglycinol by following the general procedure described above. The residue was purified by column chromatography using CH_2Cl_2/Et_3N as solvent to give 1.5 g (49% yield) of compound **10** as a yellow oil was obtained. Compound **10** decomposed slightly during the purification.

^{1}H NMR (300 MHz, $CDCl_3$, ppm) 7.7–7.1 (m, arom., 9H), 5.40 (dd, $^3J = 8.4$ Hz, $J = 1.8$ Hz 1H, CH), 4.81, (dd, $^3J = 8.4$ Hz, $J = 1.8$ Hz, 1H, CH_2), 4.30 (t, $J = 8.4$ Hz, 1H, CH_2), 1.25 (s, 9H, $CH_3 \times 3$). ^{13}C NMR (75.4 MHz, $CDCl_3$, ppm) 166.1 (C=N), 142.5 (arom., C), 138.6 (arom., CH), 135.6, 130.4 (arom., C), 130.2, 128.9, 128.8, 128.6, 127.7, 127.1, 126.8, 126.8 (arom., CH), 75.2 (CH_2–O), 70.5 (CH–N), 47.6 ($C(CH_3)_3$), 31.4 ($C(CH_3)_3$).

4.4. (4S)-2-(2-tert-Butylsulfanyl-phenyl)-4-isopropyl-4,5-dihydro-oxazole (**11**)

A total of 0.25 mmol (68 mg) of $ZnCl_2$ reacted with 5 mmol (950 g) of 2-*tert*-butylthio-benzonitrile (**5**) and 7.5 mmol (685 mg) of L-valinol following the general procedure described above. The residue was purified by column chromatography using CH_2Cl_2/Et_3N as solvent to obtain 85.5 mg (55% yield) of compound **11** as a yellow oil.

$[\alpha_D]^{20} = -28.0°$ ($c = 0.33$, CH_3COCH_3). ^{1}H NMR (300 MHz, $CDCl_3$, ppm) 7.7–6.8 (m, arom., 4H), 4.37 (dd, $^3J = 6.8$ Hz, $J = 1.5$ Hz, 1H, CH), 4.18 (t, $^3J = 6.8$ Hz, CH_2), 4.13 (m, 1H, CH_2), 1.84 (m, $^3J = 6.6$ Hz, 1H, CH), 1.35 (s, 9H, $CH_3 \times 3$), 1.04 (d, 3H, CH_3), 0.96 (d, 3H, CH_3). ^{13}C NMR (75.4 MHz, $CDCl_3$, ppm) 161.6 (C=N), 137.6–125.0 (arom., C, CH), 73.3 (CH_2–O), 69.7 (CH–N), 48.85 ($C(CH_3)_3$), 32.7 (CH), 30.68 ($C(CH_3)_3$), 18.6 (CH_3), 18.2 (CH_3). IR (NaCl, cm^{-1}) 3059, 2957 (=CH), 1648 (C=N).

4.5. General procedure for the synthesis of [Ir(σ-η²-$C_8H_{12}Py^+$)L]PF_6 (**12a–d**)

A solution of the corresponding ligand (0.40 mmol) and [Ir(η^4-COD)(Py)$_2$]PF_6 (0.30 mmol) in 1 ml of anhydrous dichloromethane was stirred for 2 h. Then cold degassed diethylether was added and a precipitate appeared. The solid was filtered off and washed with cold degassed diethylether.

4.6. [Ir(σ-η²-$C_8H_{12}Py^+$)**6**]PF_6 (**12a**)

Complex [Ir(η^4-COD)Py$_2$]PF_6 (181 mg, 0.30 mmol) was treated with **6** (107 mg, 0.40 mmol) following the general procedure to obtain 221 mg (94% yield) of complex **12a**. Elemental Anal. Calc. for $C_{29}H_{32}F_6IrN_2OPS$: C, 43.88; H, 4.06; N, 3.53; S, 4.04. Found: C, 43.97; H, 4.19; N, 3.40, S, 3.49%. MS FAB: *m/z* (%): 648.1 (8.5, M^+), 572.1 (19.8, $M^+ - C_6H_5$), 570.1 (63.5, $M^+ - Py$), 462 (2.20, $M^+ - C_{13}H_{17}N$), 136 (100, $C_8H_{10}NO$). HRMS L-SIMS: *m/z* $[C_{24}H_{27}NOSIr]^+$: 570.14425. Found: 570.14537. ^{1}H NMR (400 MHz, $CDCl_3$, ppm) 8.95 (m, 1H, arom.), 8.54 (m, 1H, arom.), 7.79 (m, 4H, arom.), 7.52 (m, 2H, arom.), 7.41 (m, 2H, arom.), 7.30 (m, 3H, arom.), 7.05 (m 1H, arom.), 5.81 (m, 1H, CH), 5.13 (m, 1H, CH_2), 4.96 (m, 1H, CH_2), 4.66 (m, 1H, CH), 4.07 (m, 1H, CH), 3.22 (m, 1H, CH), 2.59 (m, 1H, CH), 2.43 (m, 1H, CH_2), 2.22 (m, 1H, CH_2), 2.03 (m, 1H, CH_2), 1.74 (m, 1H, CH_2), 1.51 (s, 3H, CH_3–S), 1.21 (m, 1H, CH_2). ^{13}C NMR (100.6 MHz, $CDCl_3$, ppm) 176.5 (C=N), 154.7 (arom., CH), 152.6 (arom., CH), 147.8–123.4 (arom.), 87.13 (=*C*H), 77.94 (*C*H$_2$–O), 70.93 (=*C*H), 67.3 (=*C*H), 66.63 (*C*H–N), 37.21 (*C*H$_2$), 26.29 (*C*H$_2$), 24.50 (*C*H$_2$), 20.57 (*C*H$_2$), 14.47 (*C*H$_3$–S), 3.57 (=*C*H). ^{31}P NMR (161.9 MHz, CDCl3, ppm) −144.1 (sept, $J_{P-F} = 712.8$ Hz). ^{19}F NMR (376 MHz, $CDCl_3$, ppm) −73.6 (d, $J_{F-P} = 711.7$ Hz).

4.7. [Ir(σ-η²-$C_8H_{12}Py^+$)**7**]PF_6 (**12b**)

Complex [Ir(η^4-COD)Py$_2$]PF_6 (90.5 mg, 0.15 mmol) was treated with **7** (47 mg, 0.20 mmol) following the general procedure to obtain 98 mg (86% yield) of complex **12b**. ^{1}H NMR (300 MHz, $CDCl_3$, ppm) 8.68 (m, 1H, arom.), 8.48 (m, 1H, arom.), 7.70 (m, 3H, arom.), 7.19 (m, 3H, arom.), 6.94 (m, 1H, arom.), 4.68 (m, 2H, CH), 4.54 (m, 3H, CH), 4.33 (m, 1H, CH), 2.65 (m, 1H, CH), 2.51–0.82 (m, 8H, CH_2), 1.43 (s, 3H, CH_3–S), 1.07 (d, 3H, CH_3, $^3J = 6.9$ Hz), 0.64 (d, 3H, CH_3, $^3J = 6.9$ Hz). ^{13}C NMR (74.5 MHz, $CDCl_3$, ppm) 197.5 (C=N), 154.7 (arom., CH), 152.7 (arom., CH), 138.9–123.7 (arom.), 87.53 (=*C*H), 71.6 (*C*H$_2$–O), 70.78 (=*C*H), 68.5 (=*C*H), 65.95 (*C*H–N), 37.49 (*C*H$_2$), 30.32 (*C*H), 29.90 (*C*H$_2$), 26.84 (*C*H$_2$), 24.94 (*C*H$_2$), 20.90 (CH_3), 19.43 (CH_3), 14.93 (*C*H$_3$–S), 3.75 (=*C*H).

4.8. [Ir(σ-η²-$C_8H_{12}Py^+$)**8**]PF_6 (**12c**)

Complex [Ir(η^4-COD)Py$_2$]PF_6 (71.3 mg, 0.118 mmol) was treated with **8** (50.6 mg, 0.15 mmol) following the general procedure to obtain 99 mg (98% yield) of com-

plex **12c**. Elemental Anal. Calc. for $C_{34}H_{34}F_6IrN_2OPS$: C, 47.71; H, 4.00; N, 3.27; S, 3.75. Found: C, 47.44; H, 4.08; N, 2.92; S, 3.75%. ^{1}H NMR (400 MHz, $CDCl_3$, ppm) 8.33–6.81 (m, arom.), 5.89–4.22 (m, CH_2–O, CH–N, COD), 2.97–1.37 (m, COD).

4.9. *[Ir(σ-η²-$C_8H_{12}Py^+$)**9**]PF_6 (**12d**)*

Complex [Ir(η⁴-COD)Py_2]PF_6 (181 mg, 0.3 mmol) was treated with **9** (118.8 g, 0.4 mmol) following the general procedure to obtain 224 mg (91% yield) of complex **12d**. Elemental Anal. Calc. for $C_{31}H_{36}F_6IrN_2OPS$: C, 45.30; H, 4.41; N, 3.41, S, 3.9. Found: C, 45.12; H, 4.42; N, 3.59; S, 3.61%. MS FAB: *m/z* (%) 598.1 (7.01, $M^+ - Py$), 147 (100, C_9H_9NO). HRMS L-SIMS *m/z* $[C_{26}H_{31}NOSIr]^+$: 598.1755. Found: 598.1752 ^{1}H NMR (400 MHz, $CDCl_3$, ppm) 10.59–6.84 (m, arom.), 5.51–3.81 (m, CH2–O, CH–N, COD), 2.50–0.45 (m, COD, CH, CH_3). ^{31}P NMR (161.9 MHz, $CDCl_3$, ppm) −143.9 (sept, $J_{P-F} = 712.7$ Hz). ^{19}F NMR (376 MHz, $CDCl_3$, ppm) −73.26 (d, $J_{F-P} = 713.3$ Hz).

4.10. *[Ir(η⁴-COD)**7**]PF_6 (**13a**)*

A solution of ligand **7** (71.4 mg, 0.3 mmol) and $[Ir(COD)Cl]_2$ (101.6 mg, 0.132 mmol) in dichloromethane (5 ml) was heated for 2 h at 50 °C in a sealed tube under argon. After cooling to room temperature, the solution was washed twice with an aqueous solution of NH_4PF_6 (0.4 M, two 10 ml portions). The red dichloromethane solution was washed with water and dried over Na_2SO_4. Crystallization from CH_2Cl_2/Et_2O and drying afforded 65.6 mg (73% yield) of complex **13a**. Elemental Anal. Calc for $C_{21}H_{29}F_6IrNOPS$: C, 37.05; H, 4.26; N, 2.06; S, 4.70. Found: C, 38.30; H, 4.13; N, 1.96; S, 4.46%.

4.11. *[Ir(η⁴-COD)**9**]BF_4 (**13b**)*

A solution of **9** (60.6 mg, 0.204 mmol) with dry and degassed dichloromethane (5 ml) was added dropwise to a chilled (−80 °C) solution of $[Ir(COD)_2]BF_4$ (101 mg, 0.204 mmol) with dry and degassed dichloromethane (4 ml).The solution was allowed to warm to 0 °C and stirred for 15 min. Then ethyl ether (30 ml) was added until a yellow solid precipitated, which was filtered off, washed with ether and dried affording 118.5 mg (85% yield) of complex **13b**. Elemental Anal. Calc. for $C_{26}H_{31}F_4IrNOBS$: C, 45.61; H, 4.56; N, 2.05; S, 4.68. Found: C, 45.92; H, 4.31; N, 1.92; S, 4.81%.

4.12. General procedure for hydrogenation process

In a typical experiment, $[Ir(\eta^4\text{-COD})Cl]_2$ (0.022 mmol) was dissolved in 10 ml of dry, degassed solvent (usually MeOH/CH_2Cl_2 1:1) in a Schlenk tube. The oxazoline-thioether ligand (0.055 mmol) was then added, followed by imine (4.4 mmol for a 100:1 imine:Ir ratio). The solution was transferred under argon to the autoclave via syringe.

4.13. In situ HP NMR hydrogenation of **14**

In a typical experiment, a sapphire tube ($\phi = 10$ mm) was filled under argon with a solution of [Ir(σ-η²-$C_8H_{12}Py^+$)**7**]PF_6 (**12b**) (0.05 mmol) and imine 14 (0.52 mmol) in CH_2Cl_2-d_8 (1.5 ml). The HP NMR tube was purged twice with H_2 and pressurized to the appropriate pressure of H_2 (50 bar). After shaking the sample for 24 h, the solution was analysed.

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