Enantioselective Hydrogenation of Imines with Chiral (Phosphanodihydrooxazole)iridium Catalysts

Patrick Schnider, Guido Koch, Roger Prétôt, Guozhi Wang, Frank Michael Bohnen, Carl Krüger, and Andreas Pfaltz*

Abstract: Cationic iridium(I) complexes of chiral phosphanodihydrooxazoles were used as catalysts for the enantioselective hydrogenation of prochiral *N*-alkyl and *N*-aryl imines. The complexes are air-stable crystalline solids that can be readily prepared and are easy to handle. The structures of two complexes were determined by X-ray analysis. For *N*-alkyl imines of acetophenone, enantiomeric excesses of up to 79% were obtained. Dialkyl ketimines and cyclic imines showed lower reactivity and selectivity. A remarkable dilution effect was observed for the hydrogenation of the *N*-phenyl imine of acetophenone: decreasing the substrate and catalyst concentration led to a significant improvement of the enantioselectivity. Thus, up to 89% *ee* could be achieved using 0.1 mol% of catalyst. The highest enantioselectivities were obtained in weakly coordinating solvents such as CH_2Cl_2. Additives such as halides, imides, or amines were found to poison the catalyst. Hydrogen pressures of 100 bar were usually employed, but in some cases identical results were achieved with only 1 bar H_2.

Keywords
asymmetric catalysis · asymmetric hydrogenation · iridium · nitrogen heterocycles · phosphorus

Introduction

The enantioselective reduction of C=N double bonds has received much attention over the last few years, both in academic and industrial circles.[1] A variety of chiral Rh,[2] Ir,[3] Ru,[4] and Ti[5] complexes have been studied as catalysts for the hydrogenation of imines. A very general, highly selective catalyst system has been reported by Buchwald et al.[5] The catalyst, which is derived from a chiral *ansa*-titanocene complex developed by Brintzinger, gives excellent enantioselectivities for a variety of imines, particularly cyclic derivatives. However, a relatively large amount of catalyst (in general 5 mol%) is required for optimal results. High enantiomeric excesses have also been observed in the Rh-catalyzed hydrogenation of benzylimines of aryl methyl ketones in a two-phase system with water-soluble chiral phosphane ligands.[6] An important new class of catalysts was recently introduced by Noyori and coworkers. They demonstrated that chiral Ru–diamine complexes are highly effective catalysts for the enantioselective transfer hydrogenation of imines with triethylammonium formate.[7] The first technically feasible enantioselective imine hydrogenation was developed by a team at Ciba-Geigy.[8] The catalyst, a chiral ferrocenyldiphosphane–iridium complex, shows extremely high activity and unprecedented productivity (up to 10^6 turnovers) with certain arylimines. It is used to synthesize an important herbicide precursor with 80% *ee* on a technical scale. Despite these impressive achievements, the number of efficient practical methods for the enantioselective reduction of imines is still limited. Further research is necessary in order to expand the scope of this important transformation.

The remarkable catalytic properties of the (pyridine)(phosphane)iridium complexes developed by Crabtree[9] prompted us to evaluate chiral analogues as hydrogenation catalysts with phosphanodihydrooxazoles as ligands. Chiral enantiopure phosphanodihydrooxazoles, which have been developed independently by the groups of Helmchen[10b] and Williams[10c] and also in our laboratory,[10a, d, e] are readily prepared from amino alcohols. They have been successfully employed for enantiocontrol in Pd- and W-catalyzed allylic substitutions,[10a, d, e, 11] in Heck reactions,[12] Ru-catalyzed transfer hydrogenations,[13] and Rh-catalyzed hydrosilylations.[14] Here we report the synthesis of cationic iridium(I) complexes with phosphanodihydrooxazoles **1** and their application as catalysts for the enantioselective hydrogenation of imines.

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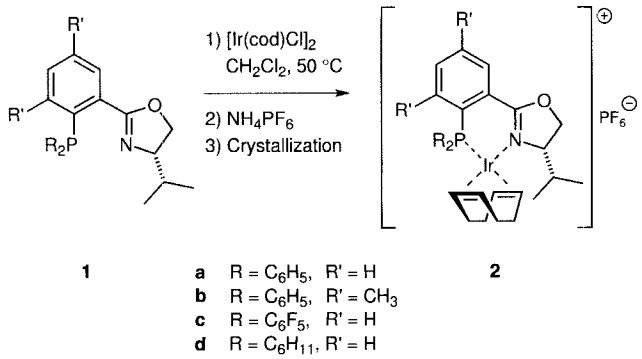
Results and Discussion

Preparation of cationic (phosphanodihydrooxazole)Ir^{I} complexes 2a–d: Ligand **1a** and $[\{Ir(cod)Cl\}_2]$ in CH_2Cl_2 were heated at 50 °C for 1–2 hours under an inert atmosphere (Scheme 1).



1 **a** R = C_6H_5, R' = H **2**
b R = C_6H_5, R' = CH_3
c R = C_6F_5, R' = H
d R = C_6H_{11}, R' = H

Scheme 1. Preparation of iridium(I) complexes **2a–d** from chiral phosphanodihydrooxazole ligands **1a–d**.

Anion exchange by washing with an aqueous solution of NH_4PF_6 and recrystallization from CH_2Cl_2/Et_2O afforded Ir complex **2a** in 82% yield. Like the Crabtree catalysts, the Ir^{I} complexes **2** are stable in air.

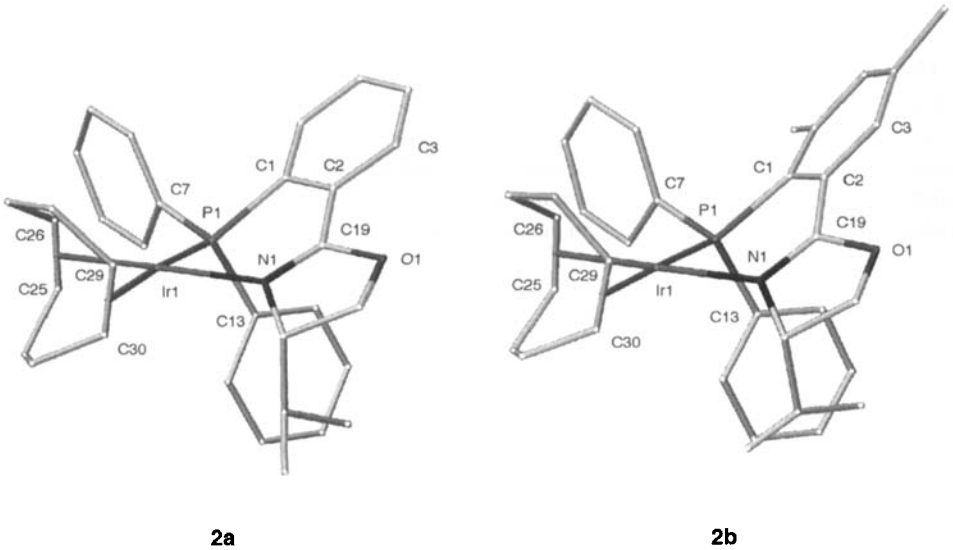
Single crystal X-ray analysis of complexes 2a and 2b: The two complexes have very similar conformations, with a square planar coordination geometry of the iridium atom (Figure 1). The isopropyl group of **2b** is disordered. As in analogous Pd, W, and Zn complexes[11b, 15] the phenyl substituents on the phosphorus adopt a pseudoequatorial and a pseudoaxial position. Another feature, which is also found in other metal complexes of phosphanodihydrooxazole ligands,[11b, 15] is the strong deviation of the chelate ring from planarity. Angles of 39° (**2a**) and 43° (**2b**) were determined between the coordination plane (Ir1-P1-N1-C25-C26-C29-C30) and the ligand plane (P1-C1-C2-C19-N1) (Table 1), whereas in analogous Pd complexes the corresponding values are between 24° and 36° due to the smaller radius of Pd.[15a] Superposition of **2a** and **2b** reveals the effect of steric repulsion between the methyl group *ortho* to phosphorus and the pseudoequatorial phenyl group, resulting in a twist of the aryl moiety attached to the dihydrooxazole ring in **2b** (Figure 2).

Table 1. Selected bond lengths (Å) and angles (°) of **2a** and **2b**.

	2a	**2b**
Ir1–N1	2.097(4)	2.055(9)
Ir1–P1	2.264(2)	2.281(3)
C1-P1-C7	106.6(3)	107.3(5)
C1-P1-C13	103.2(3)	104.0(4)
C7-P1-C13	104.7(3)	107.1(6)
C3-C2-C19-O1	−15.1(8)	−24.1(1.3)
Coordination plane vs. best plane through chelate ligand (Ir1-P1-N1-C25-C26-C29-C30 vs. P1-C1-C2-C19-N1)	38.5(2)	43.3(3)

Figure 2. Superposition of the structures of **2a** (grey) and **2b** (black).

This is reflected in a 9° difference in the torsion angles C3-C2-C19-O1 of **2a** and **2b** (Table 1). Because of this steric repulsion, the pseudoequatorial phenyl group of **2b** is conformationally more restricted and pushed slightly towards the coordination site *trans* to nitrogen.



2a **2b**

Figure 1. Crystal structures of complexes **2a** and **2b**. The H atoms and the PF_6^- ion are omitted for clarity.

Catalytic hydrogenation of imines: Iridium complexes **2** were evaluated as catalysts in the hydrogenation of *N*-phenyl imine **3** and *N*-benzyl imine **5** (Table 2). In the presence of 4 mol% of catalyst in CH_2Cl_2 at room temperature under a pressure of 100 bar H_2, both substrates were fully converted to the secondary amines **4** and **6**. Very similar enantioselectivities and yields were obtained at 1 bar H_2 using ligand **1b**. No side products were detected by ^{1}H NMR and GC–MS analysis of the reaction mixture. Ligands **1a** and **1b** gave similar results with

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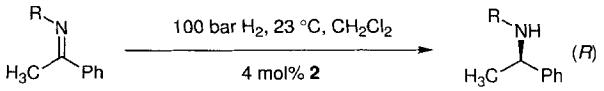
Table 2. Catalytic hydrogenation of imines **3** and **5** with complexes **2**.



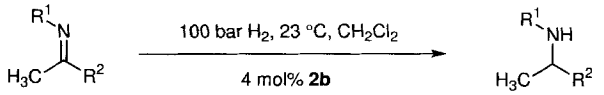
3 R = Ph (100%) **4** R = Ph
5 R = Bn **6** R = Bn

Entry	Complex	*ee* **4** [%]	*ee* **6** [%]
1	**2a**	70	76
2	**2b**	71	76
3	**2c**	73	15
4	**2d**	64	64

the two substrates **3** and **5**. Interestingly, poor enantioselectivity was obtained in the hydrogenation of imine **5** with the Ir complex of the analogous bis(pentafluorophenyl)phosphane ligand **1c**, whereas for imine **3** the *ee* was similar to the results using ligands **1a** and **1b**. The dicyclohexylphosphane ligand **1d** proved to be less effective. Systematic variation of the substituent at the stereogenic center in the dihydrooxazole ring showed the isopropyl group to be optimal for the hydrogenation of imines **3** and **5**. Other substituents, such as *tert*-butyl, *iso*-butyl, and benzyl, gave slightly lower selectivities.

Under standard conditions, a series of imines derived from aryl alkyl ketones was reduced using the Ir^I complex **2b** as the catalyst, producing enantioselectivities of 20–79% *ee* (Table 3).

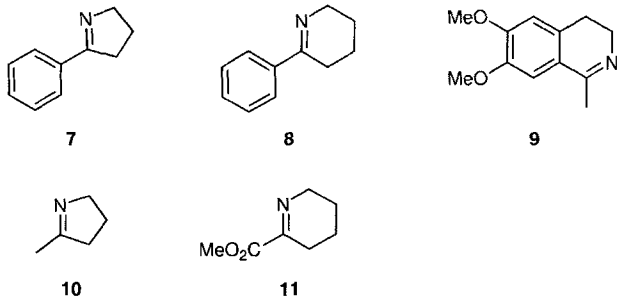
Table 3. Catalytic hydrogenation of imines with complexes **2b**.



Entry	R^1	R^2	Conversion [%]	*ee* [%]
1	Bn	Ph	100	76 [a,b]
2	Bn	2-naphthyl	100	69 [d]
3	Bn	*p*-tolyl	100	79 [b]
4	Bn	*o*-tolyl	100	35 [d]
5	Bn	*i*Pr	30	9 [d]
6	Bn	C_6H_{11} (50 °C)	100	20 [a,b]
7	Me	Ph	100	58 [d]
8	*n*Bu	Ph	100	75 [d]
9	Ph	Ph	100	71 [a,b]
10	Ph	*n*Pr	98	17 [c]
11	Ph	Bn	70	0 [b]
12	2,6-$(Me)_2C_6H_3$	Ph	75	20 [d]

[a] Absolute configuration assigned as (*R*) by comparison of optical rotation with literature values [5c, 16]. [b] Enantiomeric excess determined by HPLC on a Daicel Chiralcel OD or OD-H column (entries 1, 3, 6 and 11: *n*-hexane; entry 9: *n*-heptane/2-propanol 90:10). [c] HPLC on a Daicel Chiralcel OJ column (*n*-heptane/2-propanol 99.99:0.01). [d] Enantiomeric excess determined by ^1H NMR analysis with 2.3 equiv of (−)-mandelic acid (signals of CH_3 or CH at the stereogenic center).

The effect of substituents in the acetophenone moiety of imines **3** and **5** was also investigated. A substituent in the *ortho* position of *N*-benzyl imine **5** lowers the enantiomeric excess, while substituents in the *para* position lead to slightly higher enantioselectivities. The electronic nature of the *para* substituent did not affect the selectivity. The *p*-methoxy-, *p*-chloro, *p*-bromo, and *p*-trifluoromethyl derivatives all gave 79% *ee*. However, enantioselectivities from the hydrogenation of *N*-phenyl imines derived from **3** were decreased by *para* substituents. *p*-Methoxy-, *p*-chloro, and *p*-trifluoromethyl derivatives gave 47%, 60%, and 50% *ee*, respectively. The *N*-benzyl and *N*-(*n*-butyl) imines of acetophenone afforded very similar enantiomeric excesses (entries 1 and 8), whereas the corresponding *N*-methyl imine reacted with somewhat lower enantioselectivity (entry 7). A significant decrease in reactivity and enantioselectivity was observed for the bulkier *N*-2,6-(dimethyl)phenyl derivative (entry 12). Dialkyl ketimines also showed lower reactivity and selectivity (entries 5, 6 and 10). Oximes, oxime ethers, and hydrazones, as well as imines derived from 4-pyridyl methyl ketone and trifluoromethyl phenyl ketone, failed to react. Cyclic imines **7**–**9** afforded enantiomeric excesses of 57%, 64%, and 20%, respectively, from complex **1b**, whereas **10** and **11** proved to be unreactive.



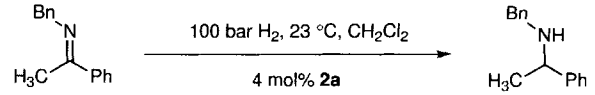
7 **8** **9**

10 **11**

In contrast to the *ansa*-titanocene catalyst system,[5] no correlation was found between the enantioselectivities in the hydrogenation of the imines listed in Table 3 and the (*E*)/(*Z*) ratios measured by ^1H NMR spectroscopy. Also, acetophenone *N*-benzylimine **5**, which exists as a 13:1 (*E*)/(*Z*) mixture in $CDCl_3$, reacts with higher enantioselectivity than its cyclic analogue **8** with fixed geometry.

Additives such as iodide,[3a–e] phthalimide,[3f] and amines[3g] are known to strongly influence the enantioselectivity and the rate of Ir-catalyzed hydrogenations. In our case too, addition of iodide to catalyst **2a** had a dramatic effect (Table 4). In the presence of 1 equiv iodide/Ir the enantioselectivity dropped to 10% and the configuration of the product was reversed from (*R*) to (*S*). This is in contrast to earlier findings with Ir-diphosphano complexes where much higher enantioselectivity was observed after addition of 2 equiv iodide/Ir.[3a] On the other hand,

Table 4. Effect of iodide in the catalytic hydrogenation of imine **5**.



5 **6**

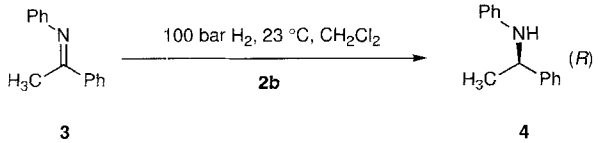
Entry	$nBu_4N^+I^-$ [equiv/Ir]	*ee* [%]
1	—	72 (*R*)
2	0.5	72 (*R*)
3	1.0	10 (*S*)
4	1.5	18 (*S*)
5	2.0	20 (*S*)
6	25	7 (*S*)

the Ir–BINAP catalyst system developed by Tani et al.[3g] was not affected by the addition of iodide.

Addition of acetate or 1,2-diaminoethane resulted in complete inhibition of the catalyst. Replacing PF_6^- by other non-coordinating counterions such as SbF_6^-, BPh_4^-, or BF_4^- had no apparent effect, whereas the corresponding trifluoroacetate salt was much less active and led to the opposite enantiomer with low *ee*. The highest enantioselectivities were achieved in CH_2Cl_2 and 1,2-dichloroethane, but other weakly coordinating aprotic solvents such as ethyl acetate can also be used; in acetonitrile conversion was very low.

The best enantioselectivities and highest turnover numbers were achieved in the reduction of imine **3**. A remarkable concentration effect was observed in this case. Decreasing the substrate and catalyst concentration led to a significant enhancement of enantioselectivity (Table 5). Under optimized conditions using

Table 5. Concentration effects in the catalytic hydrogenation of imine **3**.



3 **4**

Entry	[**3**] [M]	[Catalyst] [mol%]	Conversion [%]	*ee* [%]
1	0.22	3.7	100	71
2	0.24	0.1	100	81
3	0.035	0.1	100	86
4	0.035 (5 °C)	0.1	99	89
5	0.035	0.01	50	87

0.1 mol% of catalyst at 5 °C, amine **4** could be obtained in 89% *ee* and 99% yield. These numbers compare favorably to the best results reported to date for this substrate.[3a–e] The *N*-benzyl derivative **5** was also cleanly hydrogenated using only 0.1 mol% of catalyst under diluted conditions, although no increase of enantioselectivity was observed in this case.

Under standard conditions the reactions were run overnight. However, we observed that the reactions are generally very fast. In the presence of 4 mol% of catalyst (Table 5, entry 1) the hydrogenation was complete after pressurizing the autoclave and immediate release of pressure. In more dilute solutions (entry 3) 38% conversion was observed after 2 min.

Conclusions

In summary, we have shown that cationic Ir^I complexes of phosphanodihydrooxazoles are efficient catalysts for the enantioselective hydrogenation of imines. The complexes are readily synthesized, air-stable, and easily handled. Up to 89% *ee* and turnover numbers approaching 5000 could be achieved with the *N*-phenyl imine of acetophenone. Although the enantioselectivities are lower in other cases, our results indicate a considerable potential for this class of catalysts, which merits further investigation. We have recently found that (phosphanodihydrooxazole)Ir complexes are also promising catalysts for the enantioselective hydrogenation of C–C double bonds. The results of these studies will be reported in due course.

Experimental Section

General: Dichloromethane, Merck p.a. [{Ir(cod)Cl}$_2$], Strem 99%. Specific rotation: Perkin Elmer 241 polarimeter; 1 dm, 23 °C, concentration in g/100 mL of solution, estimated error: ±5%. NMR: ^{1}H: δ relative to TMS as internal reference; ^{13}C: δ relative to $CDCl_3$ (77.0 ppm); ^{31}P: triphenylphosphate as external reference (18.0 ppm). MS: Varian VG-70-250 (NBA = 4-nitrobenzylalcohol).

General procedure for the preparation of complexes 2a–d: A solution of **1a** (191 mg, 0.511 mmol) and {[Ir(cod)Cl}$_2$] (171 mg, 0.255 mmol) in dichloromethane (10 mL) was heated for 1 h at 50 °C in a sealed tube under Ar. 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). Anion exchange was monitored by TLC (silica gel, CH_2Cl_2/CH_3OH 20:1; [Ir(cod)(**1a**)]Cl: R_f 0.2; [Ir(cod)(**1a**)]PF_6: R_f 0.5). The red dichloromethane solution was washed with water and dried over Na_2SO_4. Crystallization from CH_2Cl_2/Et_2O and drying at 0.04 mbar afforded **2a**·(0.6 CH_2Cl_2)·(0.1 Et_2O) (369 mg, 82%) as a bright red powder. Analytical data were obtained from a different sample containing 1 molar equivalent of CH_2Cl_2 as a crystal solvent.

Complex 2a·CH_2Cl_2: Purple crystals; m.p. 194–196 °C; $[\alpha]_D = -361$ ($c = 0.20$ in $CHCl_3$, 23 °C); ^{1}H NMR (300 MHz, $CDCl_3$): $\delta = -0.06$ (d, $J = 6.8$ Hz, 3H, CH_3), 0.90 (d, $J = 7.0$ Hz, 3H, CH_3), 1.41–1.52 (m, 1H, $CH(CH_3)_2$), 1.64–1.74 (m, 1H, H_2C of cod), 1.96–2.07 (m, 2H, H_2C of cod), 2.12–2.22 (m, 1H, H_2C of cod), 2.43–2.70 (m, 4H, H_2C of cod), 2.92–2.97 (m, 1H, HC of cod), 3.21–3.49 (m, 1H, HC of cod), 4.28–4.33 (m, 1H, HC(4)), 4.46 (dd, $J = 9.6$ and 3.5 Hz, 1H, $H_2C(5)$), 4.68 (t, $J = 9.0$ Hz, 1H, $H_2C(5)$), 5.01–5.29 (m, 1H, HC of cod), 5.30–5.37 (m, 1H, HC of cod), 7.09–7.14 (m, 2H, arom. CH), 7.36–7.75 (m, 11H, arom. CH), 8.23–8-27 (m, 1H, arom. CH); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta = 12.6$ ($CH(CH_3)_2$), 18.7 ($CH(CH_3)_2$), 26.6 (H_2C of cod), 28.5 (H_2C of cod), 32.2 (H_2C of cod), 32.9 ($CH(CH_3)_2$), 36.2 (d, J(C,P) = 5 Hz, H_2C of cod), 62.3 (HC of cod), 63.1 (HC of cod), 68.8 ($H_2C(5)$), 70.4 (HC(4)), 94.3 (d, J(C,P) = 13 Hz, HC of cod), 98.9 (d, J(C,P) = 11 Hz, HC of cod), 128.7 (d, J(C,P) = 11 Hz), 129.7 (d, J(C,P) = 11 Hz), 131.8 (d, J(C,P) = 2 Hz), 132.4, 132.5, 133.2 (d, J(C,P) = 10 Hz), 133.6 (d, J(C,P) = 7 Hz), 133.8, 134.1 (d, J(C,P) = 8 Hz), 134.8 (d, J(C,P) = 12 Hz) (arom. CH), 122.8 (d, $J = 57$), 128.1, 129.0, 129.2, 130.4 (arom. C), 163.7 (d, J(C,P) = 7 Hz, C(2)); ^{31}P NMR (121 MHz, $CDCl_3$): $\delta = 15.4$; IR ($CHCl_3$): $\tilde{\nu}$ = 3593 w, 3042 m, 2968 m, 2925 m, 2889 m, 2838 w, 1601 s, 1567 m, 1485 s, 1464 w, 1436 s, 1397 w, 1380 s, 1331 w, 1284 w, 1259 m, 1178 w, 1115 m, 1098 s, 1000 w, 962 m, 909 s, 844 s, 694 s, 558 s cm^{-1}; MS (FAB, NBA): *m/z* (%): 674 (100) [M^+, ^{193}Ir], isotope cluster 672–676; calcd (obsd): 57(62), 21(27), 100(100), 36(36), 6(7); Anal. calcd for $C_{33}H_{38}Cl_2F_6IrNOP_2$ (903.74): calcd C 43.86, H 4.24, N 1.55; found C 43.93, H 4.19, N 1.49.

Complex 2b: Purple crystals; m.p. 239 °C; $[\alpha]_D = -254$ ($c = 0.17$ in $CHCl_3$); ^{1}H NMR (300 MHz, $CDCl_3$): $\delta = -0.13$ (d, $J = 6.9$ Hz, 3H, CH_3), 0.77 (d, $J = 7.1$, 3H, CH_3), 1.40–1.47 (m, 1H, H_2C of cod), 1.59–1.77 (m, 2H, $CH(CH_3)_2$, H_2C of cod), 1.64 (s, 3H, arom. CH_3), 1.94–2.17 (m, 2H, H_2C of cod), 2.40–2.67 (m, 4H, H_2C of cod), 2.43 (s, 3H, arom. CH_3), 2.72–2.84 (m, 1H, HC of cod), 3.12–3.19 (m, 1H, HC of cod), 4.22–4.27 (m, 1H, HC(4)), 4.38 (dd, $J = 9.6$ and 3.6 Hz, 1H, $H_2C(5)$), 4.67 (t, $J = 9.6$ Hz, 1H, $H_2C(5)$), 4.92–4.98 (m, 1H, HC of cod), 5.18–5.23 (m, 1H, HC of cod), 7.14–7.21 (m, 2H, arom. CH), 7.28 (s, 1H, arom. CH), 7.41–7.43 (m, 3H, arom. CH), 7.55–7.60 (m, 3H, arom. CH), 7.67–7.74 (m, 2H, arom. CH), 7.97 (brs, 1H, arom. CH); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta = 12.5$ ($CH(CH_3)_2$), 18.4 ($CH(CH_3)_2$), 21.0 (arom. CH_3), 24.5 (d, J(C,P) = 4 Hz, arom. CH_3), 26.8 (H_2C of cod), 28.8 (H_2C of cod), 31.9 (H_2C of cod), 32.9 ($CH(CH_3)_2$), 35.6 (d, J(C,P) = 5 Hz, H_2C of cod), 62.9 (HC of cod), 65.1 (HC of cod), 68.6 ($H_2C(5)$), 70.0 (HC(4)), 92.8 (d, J(C,P) = 13 Hz, HC of cod), 97.1 (d, J(C,P) = 12 Hz, HC of cod), 128.8 (d, J(C,P) = 11 Hz), 129.9 (d, J(C,P) = 11 Hz), 131.0 (d, J(C,P) = 11 Hz), 131.1, 132.2 (d, J(C,P) = 5 Hz), 133.2 (d, J(C,P) = 9 Hz), 134.0 (d, J(C,P) = 12 Hz), 139.2 (d, J(C,P) = 10 Hz) (arom. CH), 119.4 (d, J(C,P) = 48 Hz), 125.2 (d, J(C,P) = 55 Hz), 128.1 (d, J(C,P) = 51 Hz), 131.4 (d, J(C,P) = 17 Hz), 143.3 (d, J(C,P) = 66 Hz), 143.4 (d, J(C,P) = 70 Hz) (arom. C), 164.9 (d, J(C,P) = 9 Hz, C(2)); ^{31}P NMR (121 MHz, $CDCl_3$): $\delta = 10.2$; IR ($CHCl_3$): $\tilde{\nu}$ = 3032 m, 2971 m, 2889 m, 2838 m, 1592 m, 1482 m, 1437 m, 1386 m, 1372 m, 1162 m, 1098 m, 849 s cm^{-1}; MS (FAB, NBA): *m/z* (%): 702(100) [M^+, ^{193}Ir], isotope cluster 700–705; calcd (obsd): 57(64), 22(29), 100(100), 38(38), 7(7), 1(1); $C_{34}H_{40}F_6IrNOP_2$ (846.84): calcd C 48.22, H 4.76, N 1.65, found C 48.04, H 4.59, N 1.69.

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Crystal structure determinations: Crystals of compound **2a** and **2b** were mounted in a glass capillary and transfered into the cold stream of N_2 on an Enraf-Nonius CAD4 diffractometer. Accurate unit-cell parameters and an orientation matrix were determined from the accurate settings of 25 reflections. Intensity data were collected at 100 K. Crystal data are shown in Table 6. Absorption corrections were performed by ψ-scans (**2a**) and numerical methods (**2b**).[17a] The structures were solved by Patterson methods.[17b,c] Refinement on F^2 was carried out by full-matrix least-squares techniques.[17d] All non-hydrogen atoms were refined anisotropically except the disordered isopropyl group of **2b**. All hydrogen positions were calculated.

Table 6. Crystal data of **2a** and **2b** [18].

	2a	**2b**
empirical formula	$C_{32}H_{36}F_6IrNOP_2 \cdot CH_2Cl_2$	$C_{34}H_{40}F_6IrNOP_2$
T [K]	100	100
λ [Å]	0.71069	0.71069
crystal system	monoclinic	orthorhombic
space group	$P2_1$	$P2_12_12_1$
a [Å]	9.4697(10)	11.731(3)
b [Å]	18.688(2)	15.551(5)
c [Å]	9.8823(10)	17.454(5)
α [°]	90	90
β [°]	103.419(6)	90
γ [°]	90	90
V [Å^3]	1701.1(3)	3184.2(16)
Z	2	4
ρ_{calcd} [Mg m^{-3}]	1.764	1.766
μ [mm^{-1}]	4.237	4.360
F_{000}	892	1680
crystal size [mm]	$21 \times 21 \times 10$	$65 \times 54 \times 48$
θ range [°]	2.12–29.98	1.75–29.97
index ranges	$-13 \le h \le 12$	$0 \le h \le 16$
	$0 \le k \le 26$	$0 \le k \le 21$
	$0 \le l \le 13$	$0 \le l \le 24$
absorption correction	ψ scans	numeric (DATAP)
no. of reflns collected	5087	5123
no. of independent reflns	5087	5123
no. of observed reflns	4833	4259
refinement method	full-matrix least-squares on F^2	
data/restraints/parameter	5087/1/415	5123/7/373
Flack x parameter	0.010(8)	−0.022(17)
GoF on F^2	1.049	1.055
final R indices	$R1 = 0.0292$;	$R1 = 0.0526$;
	$wR2 = 0.0772$	$wR2 = 0.1449$
largest diff. peak/hole	+2.41/−3.62	+3.48/−2.32

The disorder at the isopropyl group in **2b** could not be resolved accurately. One of the C–C bond lengths showed a shrinkage effect due to large thermal movement. The opposite fluorines of the PF_6^- anion in **2b** were refined with the same anisotropic displacement parameters, and C20 and C21 were refined with similar anisotropic displacement parameters. In both structures, residual electron density appeared perpendicular to the coordination plane of the iridium atoms.

General procedure for the preparation of imines: To a solution of acetophenone (12.0 g, 100 mmol) and freshly distilled aniline (11.2 g, 120 mmol) in benzene (40 mL) were added 3 Å molecular sieves (50 g) that had been activated in a microwave oven. After being stirred at room temperature for 2 h, the reaction mixture was filtered. Evaporation of the solvent *in vacuo* and distillation afforded *N*-(1-phenylethylidene)aniline **3** (18.0 g, 92%) as a pale yellow solid. B.p. 125 °C/0.04 mbar; m.p. 38–39 °C; GC (Restek Rtx® 1701 column (30 m, 0.6 bar H_2), 100 °C for 5 min, 3 °C min^{-1}, 250 °C): t_R = 31.4 min; ^{1}H NMR (300 MHz, $CDCl_3$): δ = 2.22 (s, 3H, CH_3), 6.77–6.81 (m, 2H, arom. CH), 7.05–7.10 (m, 1H, arom. CH); 7.31–7.36 (m, 2H, arom. CH), 7.40–7.45 (m, 3H, arom. CH), 7.89–7.93 (m, 2H, arom. CH); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 17.3 (CH_3), 119.3, 123.2, 127.1, 128.3, 128.9, 130.4 (arom. CH), 139.4, 151.7 (arom. C), 165.4 (C=N); IR ($CHCl_3$): $\tilde{\nu}$ = 1639 cm^{-1} (C=N); MS (70 eV, EI): *m/z* (%): 195(55) [M^+], 180(100) [$(M - CH_3)^+$], 118(11) [$(M - C_6H_5)^+$], 77(61) [$C_6H_5^+$]; $C_{14}H_{13}N$ (195.26): calcd C, 86.12 H 6.71 N 7.17; found C 86.06, H 6.72, N 7.16.

***N*-(1-Phenylethylidene)benzylamine (5)**: $C_{15}H_{15}N$ (209.29): pale yellow solid; m.p. 39–41 °C; GC (Restek Rtx 1701 column (30 m, 0.6 bar H_2), 100 °C for 2 min, 7 °C min^{-1}, 250 °C): t_R = 19.3 min; ^{1}H NMR (300 MHz, $CDCl_3$): δ = 2.31 (s, 3H, CH_3 (major isomer)), 2.37 (t, J = 1.2 Hz, 3H, CH_3 (minor isomer)), 4.42 (s, 2H, H_2CPh (minor isomer)), 4.73 (s, 2H, H_2CPh (major isomer)), 7.20–7.45 (m, 8H, arom. CH), 7.82–7.91 (m, 2H, arom. CH); (*E*)/(*Z*) isomer ratio 13:1; ^{13}C NMR (75 MHz, $CDCl_3$): δ = 15.9 (CH_3), 55.7 (CH_2), 126.6, 126.8, 127.7, 128.2, 128.4, 129.6 (arom. CH), 140.6, 141.7 (arom. C), 166.0 (C=N); IR ($CHCl_3$): $\tilde{\nu}$ = 1631 cm^{-1} (C=N); MS (70 eV, EI): *m/z* (%): 209(14) [M^+], 194(2) [$(M - CH_3)^+$], 91(100) [$C_7H_7^+$].

Acyclic imines (Table 3) were prepared according to the general procedure. For analytical data of *N*-alkyl imines, see ref. [5c]. Cyclic imines were prepared as described in the literature.[5b,19]

General procedure for the Ir-catalyzed enantioselective hydrogenation of imines: A glass flask (200 mL) with a magnetic stirring bar was charged in air with *N*-(1-phenylethylidene)aniline (**3**) (1.00 g, 5.12 mmol), complex **2b** (4.5 mg, 5.3 μmol, 0.1 mol%), and CH_2Cl_2 (50 mL) and placed in a steel autoclave (500 mL). The reaction mixture was stirred overnight at room temperature under 100 bar H_2. After evaporation of the solvent, hexane was added to the residue effecting precipitation of the catalyst. The resulting slurry was filtered through a sintered glass funnel (Por. 4). GC analysis indicated complete conversion. Kugelrohr distillation afforded (*R*)-*N*-phenyl-1-phenylethylamine (**4**) (0.98 g, 97%) as a colorless oil. $C_{14}H_{15}N$ (197.28); b.p. 110 °C/0.09 mbar; GC (Restek Rtx 1701 column (30 m, 0.6 bar H_2), 100 °C for 5 min, 3 °C min^{-1}, 250 °C): t_R = 31.7 min; HPLC (Daicel Chiralcel OD-H column, 220 nm, 0.5 mL min^{-1}, *n*-heptane/2-propanol 90:10; t_R = 9.8 (*S*) and 12.0 (*R*) min): 84% *ee*; ^{1}H NMR (300 MHz, $CDCl_3$): δ = 1.51 (d, J = 6.7 Hz, 3H, CH_3), 4.01 (brs, 1H, NH), 4.48 (q, J = 6.7 Hz, 1H, CH), 6.49–6.52 (m, 2H, arom. CH), 6.61–6.66 (m, 1H, arom. CH), 7.05–7.11 (m, 2H, arom. CH), 7.18–7.38 (m, 5H, arom. CH); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 25.0 (CH_3), 53.4 (CH), 113.3, 117.2, 125.8, 126.8, 128.6, 129.1 (arom. CH), 145.2, 147.3 (arom. C); IR ($CHCl_3$): $\tilde{\nu}$ = 3431 cm^{-1} (N–H); MS (70 eV, EI): *m/z* (%): 197(46) [M^+], 182(100) [$(M - CH_3)^+$], 105(69) [$C_8H_9^+$], 77(40) [$C_6H_5^+$].

Experiments under standard conditions were usually conducted on a 0.1 mmolar scale of imine.

(*R*)-*N*-Benzyl-1-phenylethylamine (6): $C_{15}H_{17}N$ (211.31); colorless oil; b.p. 85 °C/0.1 mbar; GC (Restek Rtx 1701 column (30 m, 0.6 bar H_2), 100 °C for 2 min, 7 °C min^{-1}, 250 °C): t_R = 16.5 min; HPLC (Daicel Chiralcel OD column, 220 nm, 0.5 mL min^{-1}, *n*-hexane; t_R = 31 (*R*) and 40 (*S*) min); ^{1}H NMR (300 MHz, $CDCl_3$): δ = 1.36 (d, J = 6.6 Hz, 3H, CH_3), 1.60 (s, 1H, NH), 3.59 (d, J = 13.2 Hz, 1H, H_2CPh), 3.66 (d, J = 13.2 Hz, 1H, H_2CPh), 3.80 (q, J = 6.6 Hz, 1H, HC), 7.23–7.35 (m, 10H, arom. CH); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 24.5 (CH_3), 52.0 (CH_2), 57.8 (CH), 126.7, 126.8, 126.9, 128.1, 128.4, 128.5 (arom. CH), 140.7, 145.6 (arom. C); IR ($CHCl_3$): $\tilde{\nu}$ = 3320 cm^{-1} (N–H); MS (70 eV, CI(NH_3)): *m/z* (%): 212(100) [$(M+1)^+$], 196 [$(M - CH_3)^+$], 91(11) [$C_7H_7^+$].

General procedure for the preparation of racemic amines: To a solution of sodium cyanoborohydride (0.17 g, 2.3 mmol) in methanol (1.5 mL) was added dropwise at room temperature a solution of *N*-(1-phenylethylidene)aniline (**3**) (0.61 g, 3.1 mmol) in methanol (1.5 mL). The mixture was stirred overnight under N_2. The reaction was quenched by the addition of 6 N HCl (6 mL). After dilution with water and washing with *tert*-butyl methyl ether, the aqueous phase was neutralized with a saturated solution of Na_2CO_3 and extracted three times with CH_2Cl_2. Drying over $MgSO_4$ and kugelrohr distillation afforded *N*-phenyl-1-phenylethylamine (**4**) (0.34 g, 55%) as a colorless oil.

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[18] Crystallographic data (excluding structure factors) for the structures reported in this paper have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication no. CCDC-100075. Copies of the data can be obtained free of charge on application to The Director, CCDC, 12 Union Road, Cambridge CB21EZ, UK (Fax: Int. code +(1223)336-033; e-mail: deposit@chemcrys.cam.ac.uk).

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