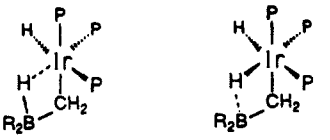

A B

The formation of **3a,b** likely results from oxidative addition of the organoborane B–H bond to the unsaturated Ir center, followed by B–C bond reductive elimination and β-H abstraction from the resulting B–Me group.[15] While an analogous reductive elimination process has been proposed[2] as the B–C-bond-forming step in rhodium-catalyzed alkene hydroboration, the additional β-H abstraction process observed here likely results from the increased basicity of the iridium center, which retains the BR_2Me Lewis acid in the metal coordination sphere. The reactivity of complexes **2** and **3** with unsaturated organic substrates is under investigation.

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Supplementary Material Available: Typical preparation of **2** and **3**, X-ray experimental details, and tables of bond distances and angles, atomic coordinates, and temperature factors for complexes **2b** and **3b** (10 pages); complete listings of observed and calculated structure factors for complexes **2b** and **3b** (16 pages). Ordering information is given on any current masthead page.

(15) Analogous β-H abstraction from Ru-coordinated Si–Me moieties has recently been reported. Procopio, L. J.; Berry, D. H. *Abstracts of Papers*, 199th National Meeting of the American Chemical Society, Boston, MA; American Chemical Society: Washington, DC, 1990; INOR 36. Tilley, T. D.; Campion, B. K.; Grumbine, S. K.; Heyn, R. H.; Quimbita, G.; Straus, D.; Chang, C. *Abstracts of Papers*, 199th National Meeting of the American Chemical Society, Boston, MA; American Chemical Society: Washington, DC, 1990; INOR 136.

Iridium(III) Hydride Complexes for the Catalytic Enantioselective Hydrogenation of Imines

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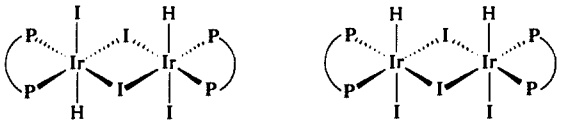
Considerable research during the past 20 years has produced remarkable catalysts based on Rh and Ru for enantioselective homogeneous hydrogenation of olefins and ketones where in many cases optical yields >95% have been observed.[1] On the other hand, few publications have appeared that deal with asymmetric hydrogenation of the C=N bond of imines to form chiral amines,[2] the greatest success having been obtained by using in situ mixtures of M/chiral diphosphine/X (M = Rh^I or Ir^I, X = NEt_3 or halide) but the nature and the mechanism of action of the catalyst is not well-defined.

We report herein the discovery of a new class of iridium(III)–diphosphine–monohydrido complexes, $[Ir(P\text{–}P)HI_2]_2$, **1a–d** (e.g., P–P = DIOP, BDPP, NORPHOS, BINAP),[3] that are effective for asymmetric reduction of prochiral imines to the corresponding amine with high turnover numbers and moderate to good enantioselectivity.

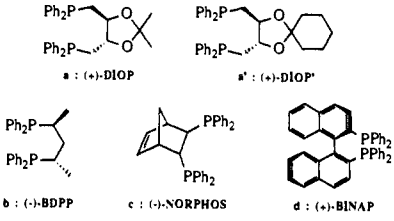
We have previously reported[4] that when $[Ir(P\text{–}P)(COD)]BF_4$ (P–P = dppe, dpe, R-prophos) is refluxed with excess LiI (>30 equiv) in acetone, the complexes $Li[Ir(P\text{–}P)I_4]$ were isolated and found to be chemoselective catalysts for the hydrogenation of imines. Under similar conditions,[5] complexes **1** are prepared and isolated as air-stable pale yellow powders that can be recrystallized from CH_2Cl_2/Et_2O or CH_2Cl_2/hexane in 50–60% yield. In solution the ^1H and ^{31}P NMR spectra show that **1** exists as a mixture of two geometrical isomeric dimers,[5b] where the hydride ligands are either transoid or cisoid to each other. The structure of the transoid isomer has been confirmed by an X-ray determination.[6]



transoid-**1** *cisoid*-**1**

Some preliminary results on the enantioselective hydrogenation of selected imines (≥1000 equiv) catalyzed by complexes **1a–d** are compiled in Table I. Reactions were carried out at ambient temperature and >10 bar of H_2 pressure and proceeded smoothly to completion. The reduction of imine I by catalysts **1a** and **1b** (entries 1 and 2) occurred rapidly but with modest ee (11–40%). However, II (entries 3–5) could be hydrogenated conveniently, and an ee of 80% was obtained by using $[Ir((-)\text{-BDPP})HI_2]_2$ as catalyst. The asymmetric reduction of a model herbicide precursor, III (entries 6–10), shows **1a**, $[Ir((-)\text{-DIOP})HI_2]_2$, to yield the highest ee (63%), but extensive screening of other chiral diphosphine ligands for this substrate reduction has not been carried out. Interestingly, the BINAP complex **1d** is ineffective

(3) Abbreviations defined:



a : (+)-DIOP a' : (+)-DIOP' b : (-)-BDPP c : (-)-NORPHOS d : (+)-BINAP

(4) Ng Cheong Chan, Y.; Meyer, D.; Osborn, J. A. *J. Chem. Soc., Chem. Commun.* **1990**, 869.

(5) (a) For example, the $[Ir(DIOP)HI_2]_2$ complex is synthesized as follows: $[Ir(DIOP)(COD)]BF_4$ (600 mg; 0.68 mmol) was refluxed with LiI (900 mg; 6.7 mmol) in acetone (10 mL) for 20 h, whereby a yellow precipitate was slowly formed. After cooling to room temperature, the yellow solid was separated by centrifuge, then washed two times with acetone (5 mL), and dried. The crude product thus obtained was extracted with dichloromethane (10 mL) to remove insoluble LiI. Ether (10 mL) was then added to the solution, and after 1 day at room temperature, pale yellow crystals had formed (375 mg; 58%). All new complexes have been characterized by elemental analyses, ^1H and ^{31}P NMR, and FAB mass spectroscopy. (b) Ratio of isomers and corresponding hydride shifts (200 MHz, CD_2Cl_2, δ in ppm and $^2J_{PH}$ in Hz): P–P = DIOP (same with DIOP'), major/minor = 9/1 (δ = −16.2 (t), J = 11, and −16.7 (t), J = 11); P–P = BDPP, major/minor = 7/3 (δ = −16.2 (dd), $\sum J$ = 21.5, and −16.9 (dd), $\sum J$ = 21.4); P–P = NORPHOS, major/minor = 7/3 (δ = −11.9 (dd), J = 17.0, and −12.3 (dd) $\sum J$ = 18.0); P–P = BINAP, major/miinor = 10/0 (δ = −19.5 (dd), $\sum J$ = 21.5). In all cases, the major isomer is probably transoid. (c) GC–MS analysis of the solution after reaction shows the presence of free COD and an excess of $CH_3COCH{=}C(CH_3)_2$, the product of an aldol condensation of acetone catalyzed by Li^+. The hydride source is thus probably H_2O. Further synthesis using wet acetone (0.2% H_2O) gave similar results. Synthesis using acetone-d_6 yielded the corresponding dideuteride complex.

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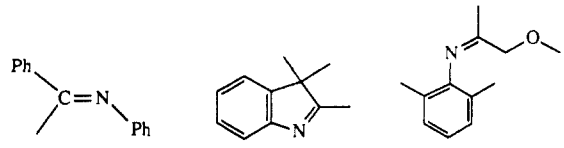
Table I. Hydrogenation of Imines **1-3** Catalyzed by $[Ir(P-P)HI_2]_2$

entry	S	P-P	$S/[Ir_2]$	H_2(bar), T (°C)	time (h)	ee (%)
1	I	(-)-BDPP	1000	40, 30	2	40 (*S*)
2	I	(+)-DIOP	1000	28, 30	5	11 (*S*)
3	II	(-)-BDPP	1000	40, 30	43	80 (+)
4	II	(+)-DIOP	1000	40, 30	21	51 (-)
5	II	(-)-NORPHOS	1000	40, 30	13	47 (-)
6	III	(+)-DIOP	1000	40, 30	8	54 (*S*)
7	III	(+)-DIOP	4000	100, 20	40	63 (*S*)
8	III	(-)-BDPP	1000	40, 30	6.5	34 (*R*)
9	III	(-)-NORPHOS	1000	40, 30	4	25 (*S*)
10	III	(+)-BINAP	1000	40, 30	145	22 (*S*)

[a] All reactions were performed in a stainless steel autoclave using 7.83×10^{-3} mmol of complex in 10 mL of THF/CH_2Cl_2 (3/1, v/v). Reaction time given above corresponds to 99-100% conversion (GC analysis). The enantiomeric excesses of purified amines are measured by optical activity for reduced I (ref 7) and III (ref 2a) and by ^1H NMR (300 MHz) for reduced II (the absolute configuration of this compound has not been determined) using (*S*)-(+)-2,2,2-trifluoro-1-(9-anthryl)ethanol as chiral shift reagent; the sign of optical rotation ($[\alpha]_D$ Na, 20 °C) indicated here was measured in hexane.

in both the rate and enantioselectivity of this hydrogenation. **1a** can be recovered unchanged after reduction of III and has been recycled, and further, the catalysts show high chemoselectivity (similar to that found for $Li[Ir(P-P)I_4]$[3]), notably not reducing ketones or simple olefins.



I II III

When catalytic hydrogenation (40 bar, THF/CH_2Cl_2) of 200 equiv of III is carried out with a 1/1 catalyst mixture of **1a** and **1a'**, recovery and analysis of the dimers after completion of the reaction shows that extensive but, importantly, *incomplete* scrambling has occurred. Crossed dimer formation also occurs at the same rate in the absence of imine and/or hydrogen and is *first order* in **1a** ($t_{1/2} \simeq 11$ h). This observation is concentration independent and thus is only consistent with a dissociative mechanism. However, the initial rate of reduction in the catalytic reaction shows a dependence on $[\mathbf{1a}]^{1/2}$. This indicates that the dimer is equilibrating with a small quantity of monomer and monomer/imine complex, which are the active species on the hydrogenation catalytic cycle, and that this cycle turns more rapidly than the reconversion of monomer back into dimer. However we have been as yet unable to isolate the postulated monomer/imine complexes, perhaps because of their low formation constants, but similar compounds have been synthesized by using chelating imines.[8]

The hydride ligands of **1a** do not directly exchange with D_2. Further, no discernible isotope effect is observed in deuteration experiments under the catalytic conditions described above, and **1a** is recovered with partial but not total deuteride incorporation. These observations confirm that only a small quantity of monomer is active during catalysis at a given instant. The ^1H and ^2H NMR spectra of deuterated III show that addition has occured almost exclusively (>95%) on the C=N bond, indicating that reduction does not pass by the enamine tautomer.

$$|IrH|_2 \rightleftharpoons 2|IrH|$$

$$|IrH| + \text{Imine} \rightleftharpoons |IrH\text{-(Imine)}|$$

$$|IrH\text{-(Imine)}| \rightleftharpoons |Ir\text{-(ImineH)}|$$

$$|Ir\text{-(ImineH)}| + H_2 \longrightarrow |IrH| + \text{Amine}$$

In summation we note that (1) an equilibrium is established between the dimer, the monomer, and the Ir-imine complex with the dimer predominating; (2) in the catalytic cycle, the hydride transfer[9] and the heterolytic activation of hydrogen[10] are undoubtedly both slow steps, accounting for the fractional kinetic dependence found both on substrate concentration and hydrogen pressure; and (3) the enantioselectivity results from either imine complexation or insertion (or both), the effect of H_2 pressure (>25 bar) not being significant. Attempts to understand the origin of enantioselection in this well-defined catalytic system and further details of the mechanism are under study so that higher chiral discrimination may be achieved.

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(8) Ng Cheong Chan, Y.; Osborn, J. A., unpublished results.

(9) Slow H/D exchange has been observed when $[Ir(DIOP)D1_2]_2$ was mixed with benzylideneaniline, which is also a reducible imine; IrD + $PhCH{=}NPh \rightarrow IrH + PhCD{=}NPh$.

(10) An Ir(III)-amido 16e complex was found to react with molecular hydrogen to give Ir(III)-H and amine, respectively: Fryzuk, M. D.; MacNeil, P. A.; Rettig, S. J. *J. Am. Chem. Soc.* **1987**, *109*, 2803.

Atom Transfer Addition, Annulation, and Macrocyclization Reactions of Iodomalononitriles

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Iodomalonic esters are members of a growing class of reagents that can be used as precursors in atom transfer addition,[2,3] cyclization,[4] and annulation[3] reactions. However, a detailed study[4] revealed at least two significant limitations of iodomalonic esters: (1) they add efficiently only to mono- and 1,1-disubstituted olefins and (2) they are not suitable for simple radical macrocyclizations. The first limitation is especially frustrating because it blocks radical annulations with cyclic alkenes (the addition step fails), and thus fused rings cannot be prepared. We now report preliminary results

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