DOI: 10.1002/adsc.200800062

Iridium Catalysts with Chiral Imidazole-Phosphine Ligands for Asymmetric Hydrogenation of Vinyl Fluorides and other Olefins

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Received: January 29, 2008; Published online: April 11, 2008

Dedicated to Professor Andreas Pfaltz on his 60th birthday.

Supporting information for this article is available on the WWW under http://asc.wiley-vch.de/home/.

Abstract: New chiral bidentate imidazole-phosphine ligands have been prepared and evaluated for the iridium-catalysed asymmetric hydrogenation of olefins. The imidazole-phosphine-ligated iridium catalysts hydrogenated trisubstituted olefins with the same sense of enantiodiscrimination as known iridium catalysts possessing oxazole and thiazole as N-donors. The imidazole-based catalysts were shown to hydrogenate vinyl fluorides, in some cases with the highest *ee* values published to date.

Keywords: asymmetric hydrogenation; iridium; N,P donating ligand; vinyl fluorides

Introduction

The enantioselective hydrogenation of olefins employing iridium complexes with chiral N,P-chelating ligands has recently emerged as a valuable tool in asymmetric synthesis.[1] Whereas highly enantioselective hydrogenation using rhodium and ruthenium diphosphane complexes is limited to substrates that contain a coordinating polar group next to the carbon-carbon double bond, iridium complexes with chiral N,P-chelating ligands give high enantioselectivities with both non-functionalised and functionalised olefins. Pioneering work by Pfaltz and his co-workers on the first chiral mimic of Crabtree's catalyst[2,3] have been followed by a number of reports describing new chiral N,P-chelating ligands for efficient and substrate-tolerant iridium-catalysed asymmetric hydrogenation of double bonds.[4]

Recently our group undertook a kinetic and computational study of the asymmetric hydrogenation of (*E*)-1,2-diphenyl-1-propene with Pfaltz's iridium-PHOX complex.[5] This led us to develop new chiral N,P-donating oxazole-phosphinite (**A**) ligands, which were successfully employed in the Ir-catalysed asymmetric hydrogenation of olefins (Figure 1).[6] This new class of aromatic heterocyclic ligands was further ex-

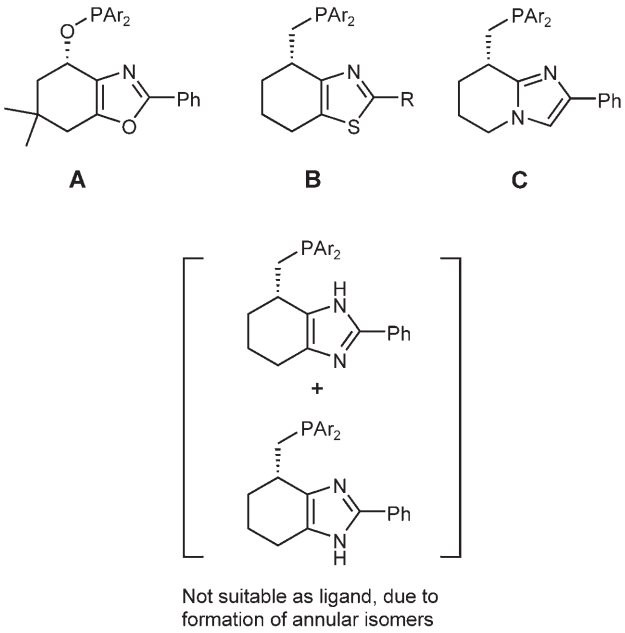


Figure 1. Oxazole-phosphinite (**A**) and thiazole-phosphine (**B**) ligands and the new class of imidazole-phosphine (**C**) ligands.

panded with the introduction of the thiazole phosphines (**B**), which were superior to the oxazole ligands in terms of both selectivity and versatility.[7] The synthetic route to the thiazole-phosphine ligands allowed structural variations in both the phosphine and thiazole moieties.

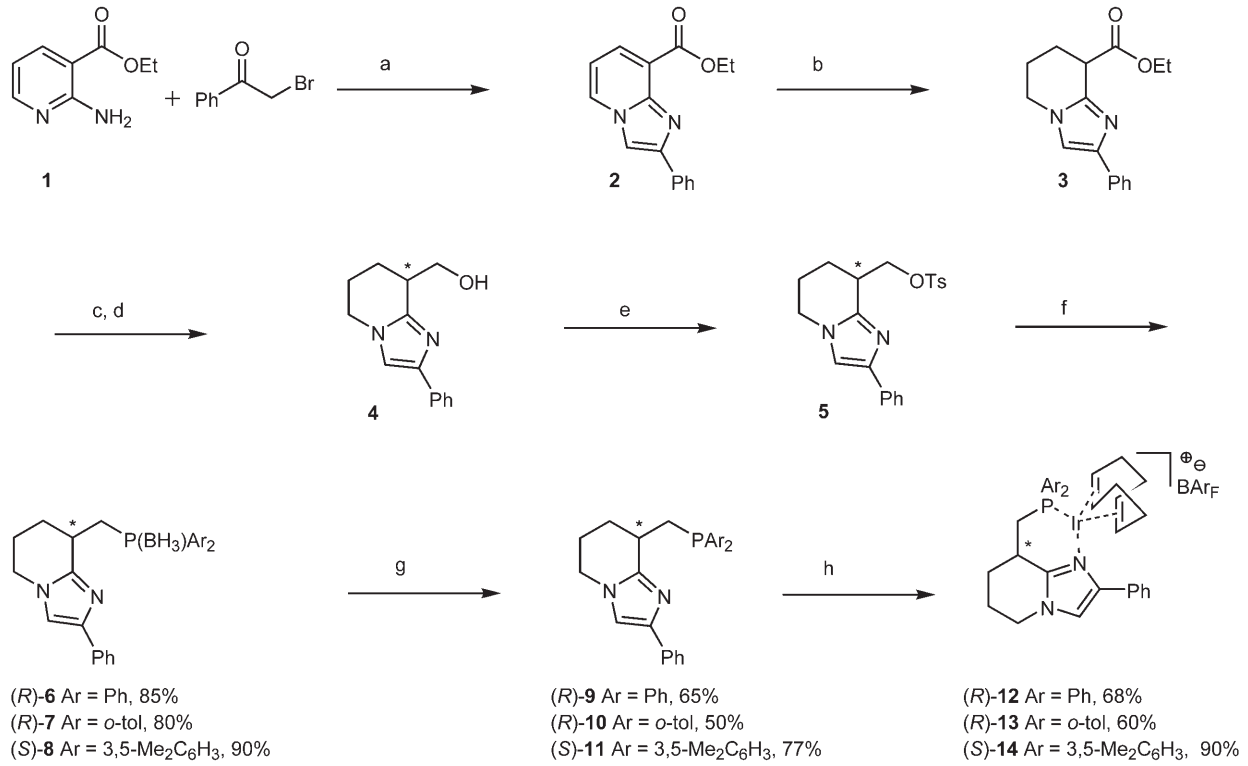
Encouraged by the excellent results accomplished for asymmetric hydrogenation utilising ligands **A** and **B**, we wanted to further develop the heteroaromatic moiety and evaluate imidazoles as chiral ligands. Because annular isomers could be obtained with the imidazole that corresponds to oxazole and thiazole, imidazole (**C**) was chosen as a better alternative for the new ligand structure (Figure 1). Since oxazole- and thiazole-based ligands possess somewhat different substrate scopes, our hope was that this new set of ligands would enable the enantioselective hydrogenation of additional classes of substrates.

In particular, vinyl fluorides are a class of olefins that is difficult to enantioselectively hydrogenate. Organofluorine compounds are increasing in popularity within the pharmaceutical and fine chemical industries, and a growing number of active pharmaceutical products now contain fluorine, such as top selling antidepressants like Fluoxetine and Paroxetine.[8] However, the synthetic methods available for introducing a fluorine-containing stereogenic centre are still scarce.[9] We have recently accomplished this through the iridium-catalysed asymmetric hydrogenation of several vinyl fluorides,[10] and Nelson et al. have reported on the asymmetric hydrogenation of cyclic vinyl fluorides using Rh-Walphos.[11] Extending the scope of asymmetric vinyl fluoride hydrogenation would improve a potentially valuable tool for pharmaceutical industry.

Results and Discussion

Synthesis of the Imidazole-Phosphines and Corresponding Iridium Complexes

As shown in Scheme 1, the imidazole-phosphine ligands are readily accessible from simple, commercially available starting materials. Fischer esterification of 2-aminonicotinic acid gave ester **1**, which underwent condensation with α-bromoacetophenone to give **2** in good yield (84%).[12] The regioselective hydrogenation of **2** was first attempted with PtO_2, but this gave over-reduction of the phenyl ring, leaving only imidazole



Scheme 1. Synthesis of iridium complexes **12–14**: a) 2-butanone, reflux overnight, 84%; b) Pd/C, 100 bar H_2, TFA, room temperature, overnight, 92%; c) $LiAlH_4$, THF, room temperature, overnight, 87%; d) preparative HPLC; Chiracel OD; e) TsCl, pyridine, CH_2Cl_2, 0 °C to room temperature, 70%; f) $Ar_2P(BH_3)H$, *n*-BuLi, THF, DMF, −78 °C; g) Et_2NH, room temperature, overnight; h) $[IrCl(COD)]_2$, CH_2Cl_2, reflux 1 h then H_2O, $NaBAr_F \cdot x H_2O$, room temperature, 1 h.

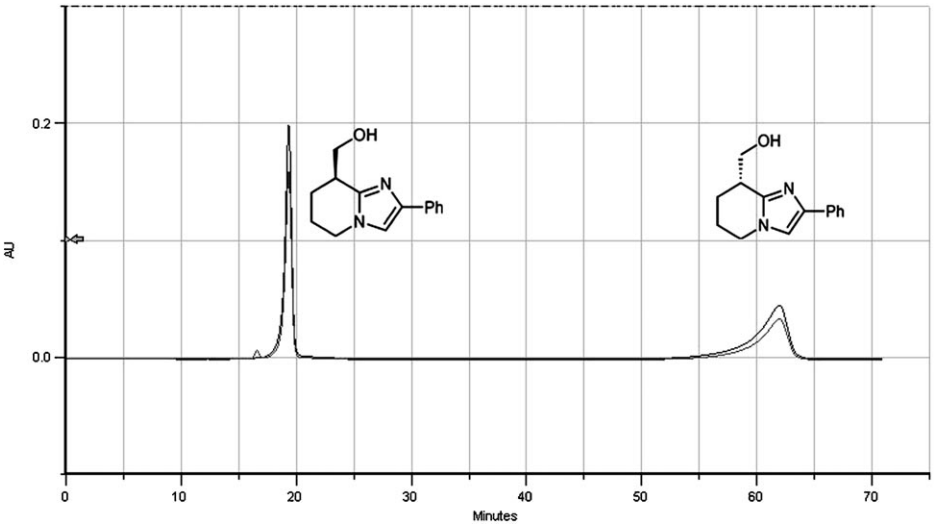


Figure 2. The chromatogram for the chiral separation of the enantiomers of **4** using Chiracel OD-column (20×250 mm) 100% *i*-PrOH, 3 mL min^{-1}. The absolute configurations were assigned by analogy to the corresponding thiazoles, which give the same elution order in chiral HPLC, sign of optical rotation and sense of enantioselection in asymmetric hydrogenation.[7]

unreduced. We next employed Raney nickel, which resulted in a complicated mixture. Finally, Pd/C in TFA afforded **3** in good yield (92%). The imidazole ester derivative **3** was reduced using $LiAlH_4$ to the corresponding alcohol **4**, which could be resolved into pure enantiomers by surprisingly effective chiral HPLC separation (Figure 2). The use of Chiralcel OD as chiral stationary phase resulted in retention times that differed for the two enantiomers by more than 40 min; this permitted the separation of gram quantities of **4**.

The enantiopure alcohol **4** was converted to its tosylate **5** and substitution with $Ar_2P(BH_3)Li$ and subsequent deprotection with Et_2NH gave the free phosphines **9**–**11**. These were complexed to $[IrCl(COD)]_2$ and anion exchange with $NaBAr_F$ gave the iridium complexes **12**–**14** in good yields (60–90%).

Asymmetric Hydrogenation of Olefins

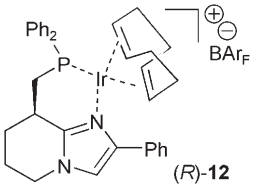
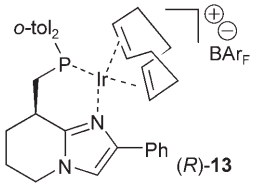
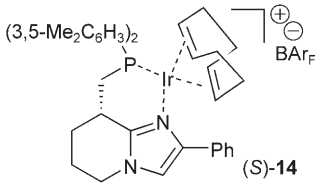
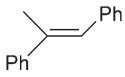
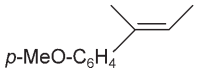
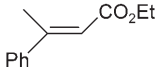
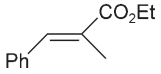
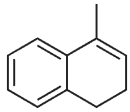
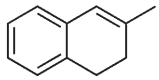
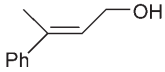
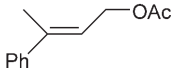
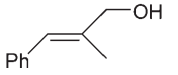
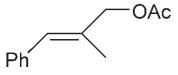
Complexes **12**–**14** were evaluated as catalysts for the asymmetric hydrogenation of some trisubstituted olefins that have been used as standard substrates (Table 1). The new complexes proved to be efficient catalysts with few exceptions and the selectivities were comparable to those obtained with complexes of **A** and **B**. Enantioselectivities varied from good to excellent for olefins that do not contain polar groups next to the carbon-carbon double bond (Table 1, entries 1, 2, 5 and 6). As with ligands **A** and **B**, high *ee* values (93–95%) were achieved for the hydrogenation of ethyl β-methyl-*trans*-cinnamate, whereas the *ee* values were low (33–84%) for the ethyl α-methyl-*trans*-cinnamate (Table 1, entries 3 and 4)

To our surprise the hydrogenation of an allylic alcohol (Table 1, entry 7) gave mixtures of products when catalysed by complexes **12** and **14**, but proceeded smoothly with complex **13**, giving the product in high *ee* (92%). The hydrogenation of the corresponding allylic acetate (Table 1, entry 8) gave low conversions except with complex **13**, and low *ee* values with all complexes. The asymmetric hydrogenation of an isomeric allylic alcohol and the corresponding acetate (Table 1, entries 9 and 10) resulted in varying conversions and only modest enantioselectivities.

A comparison of the iridium-catalysed asymmetric hydrogenation using imidazole, thiazole and oxazole ligands is shown in Figure 3. All the complexes of these three ligand types gave high *ee* values for the hydrogenation of non-functionalised olefin (substrates **15**, **16, 19** and **20**); whereas for functionalised olefins (substrates **17**, **18**, **23** and **24**), both the conversions and enantioselectivities were very ligand-dependent.

The calculated structures of the ground state of the ligand-Ir-ethene complexes were optimised in the Jaguar program[13] with the B3LYP hybrid density theory functional and the LACVP basis set. The structures are similar and almost overlapping for the complexes of **A**, **B** and **C**, which reflects the similar results for asymmetric hydrogenation of non-functionalised olefins (Figure 4). The more disparate results obtained for hydrogenation of allylic alcohol and acetate and for cinnamate esters may be related to the different heteroaromatic moieties of ligands **A**, **B** and **C**. As well, the mechanisms of hydrogenation for

Table 1. Results of asymmetric hydrogenation with complexes **12–14**.[a]

Entry	Substrate		 (*R*)-**12** Conv.[b] [%]	*ee*[c] [%]	 (*R*)-**13** Conv.[b] [%]	*ee*[c] [%]	 (*S*)-**14** Conv.[b] [%]	*ee*[c] [%]
1		**15**	>99	93 (*R*)	>99	96 (*R*)	>**99**	**98 (*S*)**
2		**16**	>**99**	**94 (*R*)**	>99	89 (*R*)	>99	92 (*S*)
3		**17**	>99	93 (*R*)	>99	93(*R*)	>**99**	**95 (*S*)**
4		**18**	>99	66 (*R*)	>99	33 (*R*)	>**99**	**84 (*S*)**
5		**19**	>99	70 (*S*)	>99	31 (*S*)	>**99**	**72 (*R*)**
6		**20**	>**99**	**90 (*R*)**	>99	89 (*R*)	>99	86 (*S*)
7		**21**	Complex mixture		>**99**	**92 (*R*)**	Complex mixture	
8		**22**	23	37 (*R*)	>99	14 (*R*)	20	18 (*S*)
9		**23**	25	61 (*R*)	**50**	**84 (*R*)**	50	75 (*S*)
10		**24**	68	63 (*R*)	>99	70 (*R*)	>**99**	**73 (*S*)**

[a] Absolute configurations of products in parantheses after *ee* value. *Reactions conditions:* 0.25 M substrate in CH_2Cl_2, 50 bar H_2, 0.5 mol% Ir complex, room temperature, overnight.
[b] Determined by ^1H NMR spectroscopy.
[c] Determined by chiral GC/MS or chiral HPLC.

functionalised and unfunctionalised olefins might be different, as has been discussed.[1c,14]

Asymmetric Hydrogenation of Vinyl Fluorides

We have studied defluorination and enantioselection in the asymmetric hydrogenation of **25** by iridium complexes **a** (oxazole-phosphinite) and **b** (thiazole-phosphine) and found that the electronic properties of the ligand backbone and the phosphorus atom influenced the chemoselectivity of asymmetric hydrogenation of fluoroolefins by N,P-ligated iridium catalysts.[10] Because the complex of the more basic thiazole ligand was shown to give less defluorination than the complex of oxazole-phosphinite, it was interesting to evaluate the complex **12** with the same substrate. Indeed, the complex of imidazole ligand, which has the most basic N-donor, gives less defluorination and more enantioselectivity in the hydrogenation of **25** (Table 2).

Given that catalyst **12**, with a basic imidazole ligand, performed well in the hydrogenation of **25**, we wanted to evaluate this ligand class with other vinyl fluorides (Table 3). The best results, up to 86% *ee*, were achieved with the *Z*-isomers of allylic acetates and alcohols (Table 3, entries 4 and 6). Defluorination was also lowest with these substrates. Remarkably, catalysts **12** and **14** hydrogenated allylic acetates to the same enantiomer of product, regardless of the

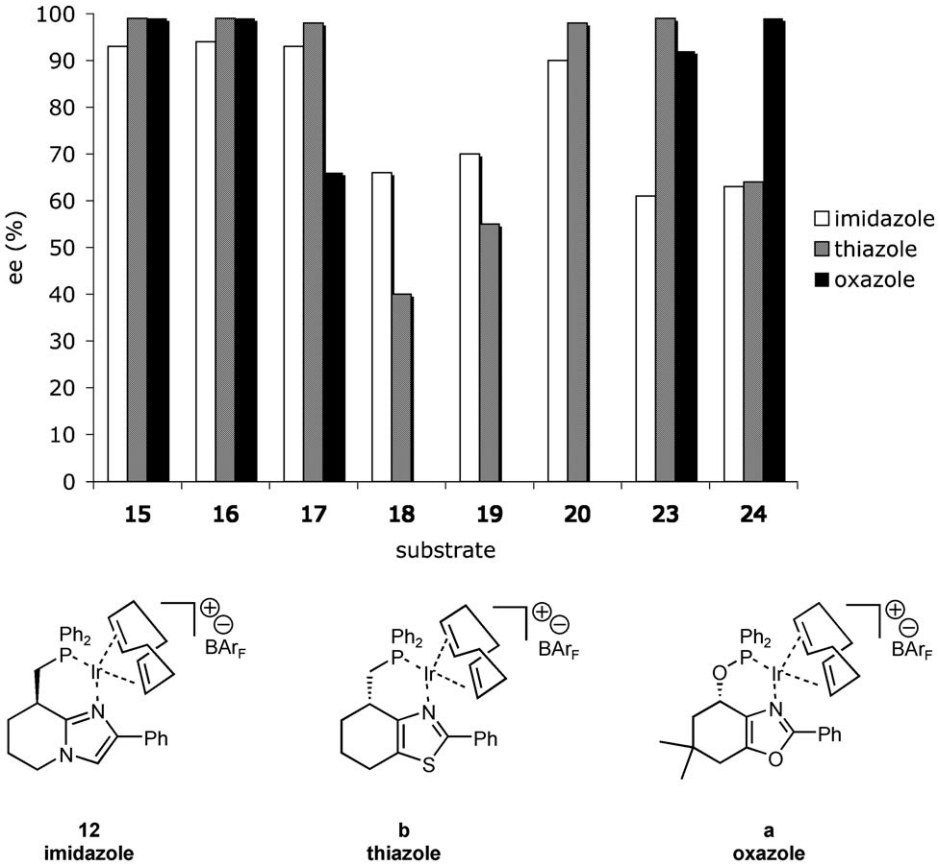
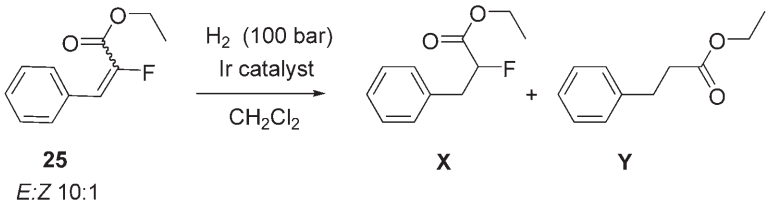
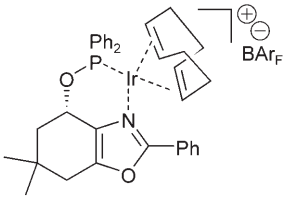
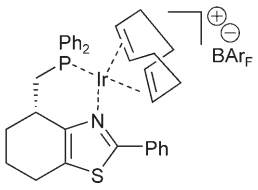
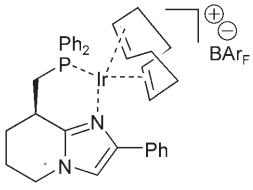


Figure 3. Comparision of imidazole, thiazole and oxazole ligands in iridium-catalysed asymmetric hydrogenation of trisubstituted olefins. The results for the hydrogenations with **a** and **b** are found in previous reports.[6,7] The hydrogenation of substrates **18**–**20** has not been evaluated with catalyst **a**.

Table 2. The pK_a values of the ligand backbone nitrogen in **a**, **b**, and **12** compared to the defluorination ratio, conversion and enantiomeric excess of the product after hydrogenation of **25**.[a]



			
pK_a[b]	0.8	2.5	7.0
X:**Y**	60:40	68:32	79:21
Conv. [%]	43	31	16
ee [%]	4 (*S*)	12 (*R*)	72 (*S*)

[a] *Reaction conditions:* 100 bar H_2, 72 h, 40 °C in CH_2Cl_2.
[b] pK_a values correspond to the unsubstituted heterocycles.[15]

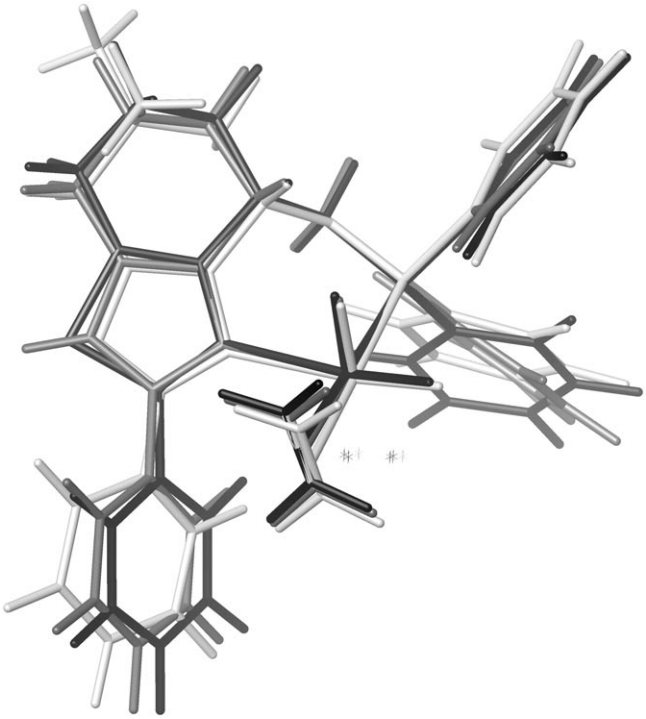


Figure 4. The calculated structures of the ground state of the ligand-Ir-ethene complex (B3LYP/LACVP). **a (oxazole)**: light grey, **b (thiazole)**: black, **12 (imidazole):** dark grey.

E/Z configuration of the starting material (Table 3, entries 3 and 4). The hydrogenations of the unsaturated esters (Table 3, entries 1 and 2) by both **12** and **14** gave better enantioselectivities than previously published. The *E*-isomer of the unsaturated ester gave higher *ee* than the *Z*-isomer. The tetrasubstituted vinyl fluorides were hydrogenated with modest *ee* values (Table 3, entries 7 and 8).

Conclusions

In conclusion, we have shown that imidazole-phosphine ligands are selective and efficient in the asymmetric iridium-catalysed hydrogenation of olefins. The imidazole ligand class resulted in high enantioselectivities for a range of non-functionalised olefins. In addition, the imidazole-phosphine based catalysts were found to hydrogenate vinyl fluorides efficiently, in some cases giving the highest *ee* values published so far.

Experimental Section

General Remarks

All the reactions were run with dry glassware and under a nitrogen atmosphere unless other conditions are stated. THF was freshly distilled under N_2 from a deep-blue solution of sodium-benzophenone ketyl prior to use. CH_2Cl_2 was freshly distilled under N_2 from powdered CaH_2 prior to use. Flash chromatography was performed using silica gel 60 Å (37–70 μm). Analytical TLC was carried out utilising 0.25 mm plates precoated with silica gel 60 UV_{254} and spots were visualised by the use of UV light or ethanolic phosphomolybdic acid (5%) followed by heating. For NMR spectroscopy, samples were dissolved in $CDCl_3$ and analysed at room temperature. ^1H (300, 400 or 500 MHz), ^{13}C (75 or 100 MHz) and ^{19}F (282 or 376 MHz) NMR spectra were recorded on a 300, 400 or 500 MHz spectrometer whereas ^{31}P (121 MHz) NMR spectra were recorded on a 300 MHz spectrometer in C_6D_6. The relative shifts for phosphorus are reported relative to external H_3PO_4. Chemical shifts for protons are reported using the residual $CHCl_3$ as internal reference ($\delta = 7.26$). Carbon signals are referenced to the shift from the ^{13}C signal of $CDCl_3$ ($\delta = 77.0$). The chemical shifts for fluorine are reported relative to external $CFCl_3$. Mass spectra were measured at 70 eV (EI). IR spectra was measured using an FT-IR apparatus. Optical rotation was measured using a sodium lamp (589 nm). The samples were directly infused into an orthogonal acceleration time-of-flight mass spectrometer Agilent LC/MSD TOF (AgilentTechnologies, Santa Clara, CA, USA). Detection was performed in positive ion mode. The voltage applied at the sampling capillary at the entrance of the mass spectrometer was 4.0 kV. Nitrogen at 300 °C and 7 L min^{-1} was used as drying gas. Nebuliser gas at 15 L min^{-1} was used. Voltages fixed at fragmentor, skimmer and octopole guides were 215 V, 60 V and 250 V, respectively. The ion pulser at the TOF analyser was set up to a measurement a frequency of 0.5 cycles/s. Agilent TOF software and Agilent TM QS software were used to record and analyse mass spectra, respectively. Standard autotune of masses was performed in the TOF-MS instrument before the experimental runs, and typical mass errors of 1–3 ppm were achieved in the calibration. Melting points are reported as their uncorrected values. Substrates **25–32** were synthesised according to published procedures.[10]

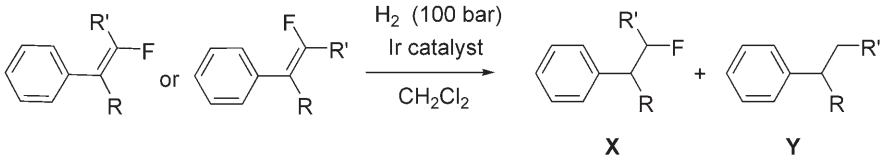
Ethyl 2-Phenylimidazo[1,1-*a*]pyridine-8-carboxylate (2)

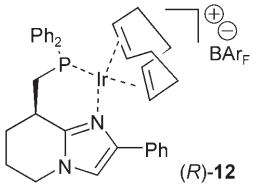
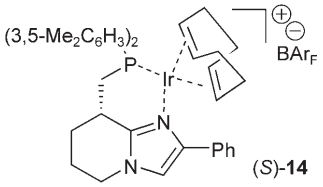
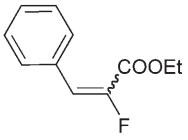
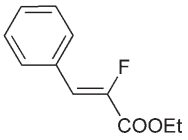
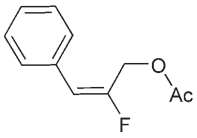
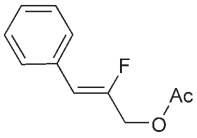
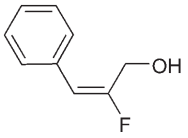
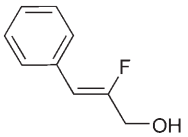
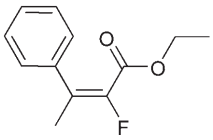
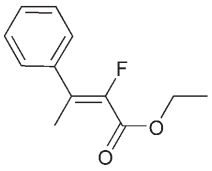
2-Aminonicotinic acid ethyl ester (6.0 g, 36.13 mmol), phenacyl bromide (7.19 g, 36.16 mmol) and 2-butanone (90 mL) were weighed into a 250-mL round-bottomed flask equipped with a condenser, and the mixture was heated to reflux and stirred for 18 h. The mixture was allowed to cool to room temperature, and the formed white precipitate was filtered off. The precipitate was then dissolved in H_2O (150 mL) and 10% Na_2CO_3 (aqueous) was added until pH 12. Thereafter the aqueous solution was extracted with CH_2Cl_2 (3× 200 mL) and the combined organic phases were dried over Na_2SO_4, filtered and concentrated under vacuum to give the product as yellow oil; yield: 8.14 g (84%).

Ethyl 2-Phenyl-5,6,7,8-tetrahydroimidazo[1,2-*a*]pyridine-8-carboxylate (3)

Pd/C (10% on activated carbon, 0.6 g), **2** (4.90 g, 22.53 mmol) and TFA (50 mL) were added to a glass liner (size: 100 mL) and placed into a high-pressure autoclave.

Table 3. Hydrogenation of fluorine-containing olefins.[a]



Entry	Substrate		 (*R*)-**12**				 (*S*)-**14**			
			Conv. [%]	**X**:**Y**	*ee* [%]	Abs. Conf.	Conv. [%]	**X**:**Y**	*ee* [%]	Abs. Conf.
1	 *E*:*Z* 10:1	**25**	16	83:17	72	*(S)*	82	72:28	55	*(R)*
2		**26**	99	66:34	46	*(R)*	93	65:35	29	*(S)*
3		**27**	99	50:50	17	*(R)*	99	57:43	11	*(S)*
4		**28**	99	84:16	85	*(R)*	99	87:13	85	*(S)*
5		**29**	99	43:57	52	*(S)*	99	51:49	60	*(R)*
6		**30**	99	92:8	80	*(R)*	99	93:7	86	*(S)*
7		**31**	-	-	-	-	97	58:42	59	(+)-(2*S**,3*S**)
8		**32**	-	-	-	-	35	46:54	25	(+)-(2*R**,3*S**)

[a] *Reaction conditions:* 0.5–1.5 mol% catalyst, room temperature to 40 °C, dry CH_2Cl_2, 30–100 bar H_2.

The autoclave containing the reaction mixture was sealed, pressurised to 100 bar H_2 and the mixture was stirred for 18 h at room temperature. The pressure was released and the mixture was filtered through Celite and rinsed with CH_2Cl_2. The filtrate was concentrated under vacuum to give the product as a yellow oil; yield: 4.6 g (92%).

(*R*)-(2-Phenyl-5,6,7,8-tetrahydroimidazo[1,2-*a*]pyridin-8-yl)methanol (4)

Compound **3** (3.4 g, 12.5 mmol) dissolved in THF(30 mL) was added slowly to a slurry of $LiAlH_4$ (0.95 g, 25 mmol) in THF (30 mL) at 0 °C. The mixture was allowed to warm to room temperature and stirred for 18 h. The mixture was thereafter cooled to 0 °C and quenched by addition of H_2O, 2 M NaOH and H_2O. The resulting mixture was stirred at room temperature for 4 h and then filtered through Celite and rinsed with THF. The filtrate was concentrated under vacuum to give the crude product as a white oil; yield: 2.5 g (87%).

The racemic alcohol was resolved into its enantiomers by chiral HPLC: Chiracel OD (5×19 cm), EtOH 100%, 80 mL min^{-1}, 0.4 g loading, t_{R1} = 3.5 min (*R*), t_{R2} = 7.2 min (*S*). Analytical chiral HPLC: Chiracel OD (20× 250 mm), 100% *i*-PrOH, 3.0 mL min^{-1}, t_{R1} = 19.5 min (R), t_{R2} = 61.6 min (*S*). The absolute configurations were assigned by analogy to the corresponding thiazoles, which give the same elution order in chiral HPLC, sign of optical rotation and sense of enantioselection in asymmetric hydrogenation.[7]

(*R*)-(2-Phenyl-5,6,7,8-tetrahydroimidazo[1,2-*a*]pyridin-8-yl)methyl 4-Methylbenzenesulfonate (5)

The optically pure alcohol **4** (0.70 g, 3.1 mmol) was dissolved in CH_2Cl_2 (10 mL) and pyridine (10 mL) was added. The reaction mixture was cooled to 0 °C (ice/water bath) and a solution of TsCl (1.75 g, 9.2 mmol) in CH_2Cl_2 (10 mL) was added dropwise. The temperature was allowed to rise to room temperature and the mixture was stirred overnight. The mixture was poured into a 10% Na_2CO_3 (aqueous) (30 mL) solution and the two phases were separated. The aqueous phase was extracted with CH_2Cl_2 (2×20 mL) and the combined organic phases were washed with water (50 mL) and brine (50 mL) followed by drying over $MgSO_4$, filtration and removal of the solvent to give the crude material as slightly purple oil; yield: 1.36 g.

Purification by flash column chromatography on silica gel using EtOAc:toluene (1:4) as eluent gave pure compound as slightly purple white solid; yield: 0.83 g (70%).

Typical Procedure for Preparation of Compounds 6–8

(*R*)-8-[(Diphenylphosphino)methyl]-2-phenyl-5,6,7,8-tetrahydroimidazo[1,2-*a*]pyridine·borane adduct (6): Diphenylphosphine·borane adduct (0.35 g, 1.77 mmol) was dissolved in dry THF (2.5 mL) and cooled to −78 °C under N_2. *n*-BuLi (1.6 M in hexane, 1.18 mL) was added dropwise. The reaction mixture was stirred for 10 min at −78 °C and then 30 min at 0 °C. A solution of tosylate (*R*)-**5** (0.45 g, 1.18 mmol) in anhydrous DMF (2.5 mL) was added dropwise and the mixture was stirred overnight at room temperature. The reaction mixture was poured into aqueous $NaHCO_3$ (10%,15 mL) and extracted with CH_2Cl_2 (3× 20 mL). The combined organic phases were washed with H_2O, brine, dried over $MgSO_4$ and concentrated under vacuum to give the crude product.

The crude product was purified by flash column chromatography on silica gel using EtOAc:toluene 1:19 as eluent resulting in a white foam; yield: 0.41 g (85%).

Typical Procedure for Preparation of Compounds 9–11

(*R*)-(8)-[(Diphenylphosphino)methyl]-2-phenyl-5,6,7,8-tetrahydroimidazo[1,2-*a*]pyridine (9): Compound **6** (0.15 g, 0.37 mmol) was dissolved in dry Et_2NH (15 mL)and the mixture was evacuated and backfilled by N_2 (×3). The mixture was stirred at room temperature overnight. The solvent was removed under reduced pressure and the residue was purified by flash column chromatography on silica gel using 3% Et_3N in toluene as eluent. The flash chromatography afforded the product as a clear oil; yield: 0.094 g (65%).

Typical Procedure for Preparation of Iridium Complexes 12–14

Complex (*R*)-12: Compound **9** (0.07 g, 0.18 mmol) was dissolved in CH_2Cl_2 (5 mL) and $[IrCl(COD)]_2$ (0.06 g, 0.09 mmol) was added. The mixture was stirred under reflux for 1 h and then allowed to cool down to room temperature. H_2O (4 mL) was added followed by $NaBAr_F$ (0.20 g, 0.21 mmol) and the mixture was stirred vigorously for 30 min. The two phases were separated and and the organic phase was dried over $MgSO_4$, filtered and concrentrated under vacuum. The crude product was dissolved in absolute EtOH and H_2O was added until a precipitate was formed. The precipitate was filtered and washed with ice cold aqueous EtOH (80%). After drying under reduced pressure, was analytically pure complex afforded as an orange solid; yield: 0.19 g (68%).

General Procedure for the Hydrogenation of Olefins (Table 1)

A vial was charged with a substrate (0.25 mmol) and catalyst (0.5 mol%) and 1 mL of anhydrous CH_2Cl_2 was added. The vial was placed in a high-pressure equipment which was purged with three times with H_2 before it was pressurised to 50 bars. The mixture was stirred at room temperature overnight. The pressure was released and solvent was removed under vacuum. The residue was dissolved in Et_2O:pentane (1:5) and filtered through short plug of silica. The solvent was evaporated and the conversion was determined by ^1H NMR and enantiomer excess by GC/MS (G-TA) or chiral HPLC.

General Procedure for the Hydrogenation of Vinyl Fluorides

A vial was charged with substrate and catalyst (0.5–1.5 mol%) and CH_2Cl_2 (1–2 mL) was added. *For 100 bar hydrogenations* the vial was placed in high-pressure steel equipment, which was purged three times with H_2 before it was pressurised to 100 bar, heated to working temperature and held at this pressure for 63–72 h. One hour before the end

of the reaction, the heating was turned off. The pressure was released and the solvent was evaporated off.

For hydrogenations at pressures up to 30 bar the vial was placed in a Endeavor™ Catalyst screening system. Vessels were purged three times with Ar (10 atm), and then flushed and pressurised with H_2 to working pressure and stirred at 700 rpm for 24 h. In all cases, conversions were measured by ^{1}H NMR after evaporation of solvent. 1.5 mL of Et_2O:pentane (1:1) were added, the solution was filtered through a short plug of silica. The silica plug was rinsed with 3 mL Et_2O:pentane (1:1). The solvent was evaporated and the *ee* was determined by GC-MS (G-TA or B-DM, 90 °C 30 min, 1 °C min^{-1} 130 °C, 20 °C min^{-1} 175 °C, 14.5 psi, 1.5 mL min^{-1}) or HPLC (*Chiralcel* OB-H, i.d. 4.6 mm × 25 cm 3% *i*-PrOH: 97% *n*-hexane 0.5 mL min^{-1}, 220 nm).

Supporting Information

Characterisation data for all compounds and separation data for the hydrogenated olefins are given in the Supporting Information.

Acknowledgements

We would like to thank The Swedish Research Council (VR), AstraZeneca and Ligbank (Activity 3, contract FP6–505267–1) for support of this work. We would also like to thank AstraZeneca Discovery Chemistry (Södertälje) and Tanja Larsson for resolving the imidazole alcohol and Dr. T. L. Church for carefully reading of the manuscript.

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