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Synthesis and Application of Chiral *N*-Heterocyclic Carbene–Oxazoline Ligands: Iridium-Catalyzed Enantioselective Hydrogenation

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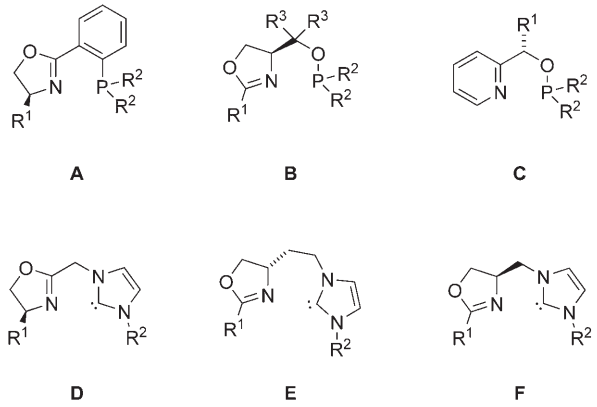
Abstract: Two libraries of enantiomerically pure imidazolium salts bearing an oxazoline unit were synthesized. Deprotonation of the imidazolium salts and complexation of the resulting oxazoline–carbene ligands to iridium(I) was achieved in one step by mixing the imidazolium salts with NaO*t*Bu and $[(\eta^4\text{-cod})IrCl]_2$ in THF at room temperature. The air-stable complexes were purified by flash chromatography. All complexes were analyzed by two-dimensional (2D) NMR methods and one compound from each family was characterized by X-ray structure analysis. The two libraries of iridium complexes were successfully tested in the asymmetric hydrogenation of unfunctionalized and functionalized olefins. Enantioselectivities of up to 90% *ee* were obtained with *trans*-α-methylstilbene. Upon complexation of imidazolium salt **15p** with R^1 = phenyl, C–H bond activation of the phenyl ring gave rise to iridium(III) complex **17**, which was fully characterized by NMR spectroscopy and X-ray structure analysis. Complex **17** proved to be catalytically inactive in the hydrogenation.

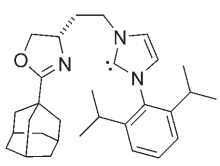
Keywords: asymmetric catalysis · carbene ligands · enantioselectivity · hydrogenation · iridium

Introduction

Chiral phosphino-oxazolines **A** (PHOX ligands) and related compounds such as **B** are highly versatile and efficient ligands for the enantioselective iridium-catalyzed hydrogenation of imines and a wide range of functionalized and unfunctionalized olefins.[1–4] To improve the enantioselectivity and widen the application range, many variants of ligands **A** and **B** have been synthesized, giving rise to a large library of P,N ligands.[5] In addition we developed a series of pyridylphosphinites **C** and related pyridine- and quinoline-derived ligands, which were devised to mimic the coordination sphere of the Crabtree catalyst ($[Ir(PCy_3)(pyridine)(cod)]PF_6$).[6] These ligands also showed high asymmetric induction in iridium-catalyzed hydrogenations.[7] Other groups have also reported efficient P,N ligands containing a pyridine or oxazole as the coordinating unit.[8,9]

Recently, Burgess and co-workers synthesized chiral iridium complexes from ligands **E** containing a seven-membered chelate ring, in which phosphorus was replaced by an *N*-heterocyclic carbene unit (NHC).[10,11] Among the various derivatives tested, one particular structure **1**, with R^1 = 1-adamantyl (1-Ad) and R^2 = 2,6-diisopropylphenyl clearly gave the best enantioselectivities with 98% *ee* for *trans*-α-methylstilbene. Although high enantioselectivities were observed for a range of substrates with this ligand, the overall performance was still inferior to the most efficient P,N ligands. We became interested in evaluating

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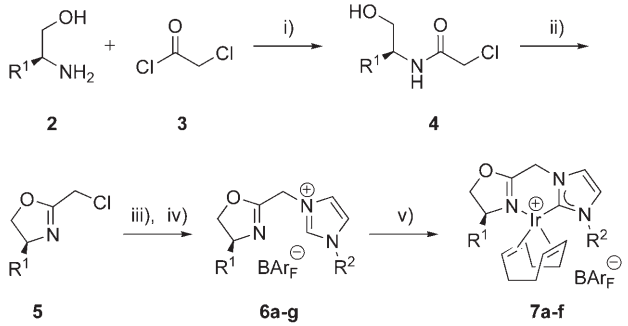
NHC–oxazoline ligands that form a six-membered chelate ring because the most efficient P,N ligands for iridium-catalyzed hydrogenation all form such chelate rings.[12]

Previously reported ligands **D** were thought to be good candidates for this study.[13] In addition, in view of the good results obtained with ligands **B**, we devised a second generation of oxazoline-carbene ligands (structure **F**), in which the R^1 substituents are derived from a carboxylic acid. Therefore, ligand libraries of high structural diversity can be prepared, starting from different carboxylic acid derivatives.

We report herein the synthesis of two libraries of iridium(oxazoline-carbene) complexes Ir-**D** and Ir-**F** and their application in the asymmetric iridium-catalyzed hydrogenation.

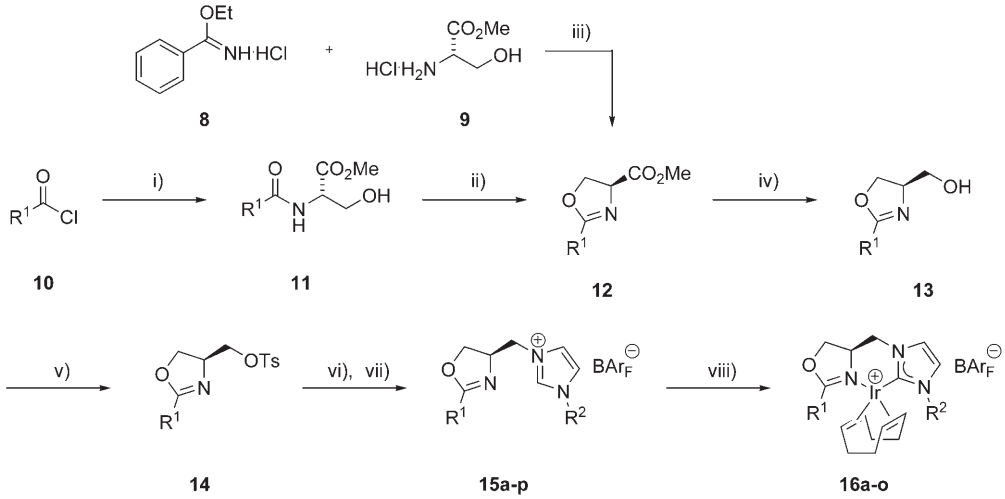


6a R^1 = *t*Bu, R^2 = Me
6b R^1 = *i*Pr, R^2 = Me
6c R^1 = *t*Bu, R^2 = *i*Pr
6d R^1 = *t*Bu, R^2 = 2,4,6-$Me_3C_6H_2$
6e R^1 = *t*Bu, R^2 = Neopentyl
6f R^1 = *t*Bu, R^2 = Isobutyl
6g R^1 = *t*Bu, R^2 = *t*Bu

Scheme 1. Synthesis of iridium complexes **D**: i) NEt_3, CH_2Cl_2, RT, 10 h, (83–99 %); ii) Burgess reagent, THF, reflux, 4 h, (50–66 %); iii) imidazole, DMF, 80 °C, 8 h; iv) $NaBAr_F$ (BAr_F^- = tetrakis[3,5-bis(trifluoromethyl)-phenyl]borate), CH_2Cl_2, RT, 15 min, (58–78 % over two steps); v) [{(η^4-cod)IrCl}$_2$], NaO*t*Bu, THF, RT, 3 h, (44–65 %).

Results and Discussion

Synthesis of chiral imidazolium salts: The syntheses of imidazolium salts **6a–g** and **15a–p**, which are precursors of ligands **D** and **F**, are summarized in Schemes 1 and 2. Imidazolium salts **6a–g** were synthesized by using a pathway in which the imidazolium salt moiety is introduced in the last step, thus allowing easy variation of the imidazolin-2-ylidene substituents. This route differs from the previously published synthesis[13] that starts from an imidazole and introduces the oxazoline ring at the end. The key intermediates, chloromethyloxazolines **5**,[14] were prepared by condensation of chloroacetyl chloride **3** with (*S*)-*tert*-leucinol or (*S*)-valinol, followed by ring-closure by using Burgess reagent.[15,16] After purification by distillation, chloromethyloxazolines **5** were allowed to react with a range of imidazoles, which were either commercially available or prepared according to literature procedures.[17–19] The resulting imidazolium chlorides



15a R^1 = *t*Bu, R^2 = Me
15b R^1 = *t*Bu, R^2 = *i*Pr
15c R^1 = *t*Bu, R^2 = 2,4,6-$Me_3C_6H_2$
15d R^1 = *t*Bu, R^2 = Neopentyl
15e R^1 = *t*Bu, R^2 = *t*Bu
15f R^1 = 1-Ad, R^2 = Me
15g R^1 = 1-Ad, R^2 = *i*Pr
15h R^1 = 1-Ad, R^2 = 2,4,6-$Me_3C_6H_2$
15i R^1 = 1-Ad, R^2 = Neopentyl
15j R^1 = 1-Ad, R^2 = *t*Bu
15k R^1 = 2,6-$Me_2C_6H_3$, R^2 = Me
15l R^1 = 2,6-$Me_2C_6H_3$, R^2 = *i*Pr
15m R^1 = 2,6-$Me_2C_6H_3$, R^2 = 2,4,6-$Me_3C_6H_2$
15n R^1 = 2,6-$Me_2C_6H_3$, R^2 = Neopentyl
15o R^1 = 2,6-$Me_2C_6H_3$, R^2 = *t*Bu
15p R^1 = Ph, R^2 = 2,4,6-$Me_3C_6H_2$

Scheme 2. Synthesis of iridium complexes **F**: i) (*S*)-serine methyl ester hydrochloride, NEt_3, CH_2Cl_2, RT, 10 h, (80–93 %); ii) Burgess reagent, THF, reflux, 4 h, (65–72 %); iii) 1,2-dichlorethane, reflux, 20 h, (91 %); iv) DIBAL, THF, RT, 12 h, (52–78 %); v) NEt_3, TsCl, CH_2Cl_2, RT, (50–83 %); vi) imidazole, DMF, 80 °C, 8 h; vii) $NaBAr_F$ (BAr_F^- = tetrakis[3,5-bis(trifluoromethyl)phenyl]borate), acetone, RT, 15 min, (50–78 % over two steps); viii) [{(η^4-cod)IrCl}$_2$], NaO*t*Bu, THF, 3 h, (48–83 %).

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were treated with $NaBAr_F$ (BAr_F^- = tetrakis[3,5-bis(trifluoromethyl)phenyl]borate) to give the corresponding BAr_F^- salts **6a–g** in moderate-to-high yield.

The weakly coordinating BAr_F^- counterion was used for two reasons. First, it allowed simple purification of imidazolium salts **6a–g** by standard chromatography on silica gel, which was not possible with the corresponding chloride salts. Second, the BAr_F^- ion is known to improve the performance of iridium complexes as hydrogenation catalysts compared to other weakly coordinating anions such as hexafluorophosphate, tetrafluoroborate, or triflate anions.[20,21]

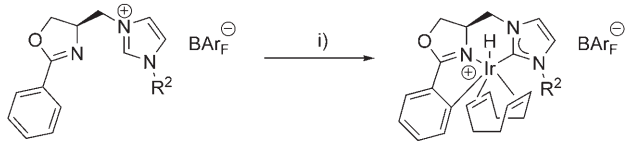
In the synthesis of ligands **F**, the imidazolium moiety was again introduced in the last step (Scheme 2). Oxazolines **12** were obtained by reacting (*S*)-serine methyl ester hydrochloride **9**, either with commercially available benzimidate hydrochloride **8**, or with acyl chlorides **10** followed by ring-closure by using Burgess reagent. Reduction of the ester group by using diisobutylaluminum hydride (DIBAL) in THF gave oxazoline alcohols **13** in moderate-to-good yields. Tosylation and subsequent nucleophilic substitution with a range of imidazoles yielded the corresponding imidazolium tosylates, which were converted into BAr_F^- salts **15a–p** by anion exchange with $NaBAr_F$, followed by flash chromatography on silica gel. By this method, four different sets of ligands (R^1 = *tert*-butyl, adamantyl, 2,6-dimethylphenyl, and phenyl) with various R^2 groups were prepared.

Preparation of the Ir complexes: Cationic iridium(I) complexes **7a–f** and **16a–o** were synthesized in a one-step procedure, starting from the corresponding imidazolium salts **6a–g** and **15a–o** (Schemes 1 and 2). Deprotonation at the imidazolium ring[22] by using sodium *tert*-butoxide in the presence of $[\{(\eta^4\text{-cod})IrCl\}_2]$ allowed simultaneous generation and complexation of the *N*-heterocyclic carbene.[23] The chloride anions were removed from the reaction mixture by precipitation as NaCl. The resulting yellow-orange crystalline BAr_F^- salts were purified by flash chromatography on silica gel.

Whereas complexation of imidazolium salts **6a–f** was successful, no complex formation was observed with imidazolium salt **6g**, even when more forcing conditions with a strong base such as *n*BuLi were applied. In this particular case, steric hindrance by the two *tert*-butyl substituents seems to prevent complexation of imidazolium salt **6g** to the iridium center. However, the analogous imidazolium salt **15e,** which also contains two *tert*-butyl groups, was metalated in respectable yield (59%).

Under the reaction conditions described above, complexation of imidazolium salt **15p** gave an unexpected product **17** as a colorless powder in 84% yield (Scheme 3). Full characterization, including single-crystal X-ray diffraction analysis, allowed the assignment of structure **17**.[24] Apparently, complexation of ligand **15p** was accompanied by insertion of the iridium(I) center into one of the *ortho* C–H bonds of the phenyl substituents at the oxazoline ring.

The presence of an Ir-bound hydride, resulting from C–H activation, was proven by the observation of a hydride



15p **17**

Scheme 3. Synthesis of complex **17**: i) $[\{(\eta^4\text{-cod})IrCl\}_2]$, NaO*t*Bu, THF, RT, 3 h, (84%).

signal at $\delta = -14.6$ ppm in the ^1H NMR spectrum. The crystal structure of compound **17** shows the iridium atom in a pseudo-octahedral coordination environment with the iridium atom lying within 0.02 Å in the best plane fitted through the carbene atom C13, the phenyl C1 atom, and the midpoints of the cyclooctadiene double bonds (Figure 1). This geometry implies that the hydride is located *trans* to the oxazoline ring. Since complex **17** proved to be unreactive in hydrogenation, no other complexes of this type were synthesized.

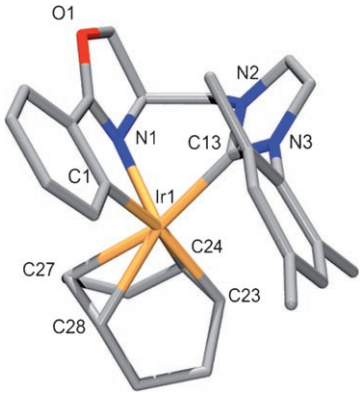


Figure 1. Structure of the cation of **17**. Selected bond lengths [Å] and angles [°]: Ir1–C1 2.029(4), Ir1–N1 2.159(3), Ir1–C13 2.054(4), Ir1–C23 2.281(4), Ir1–C24 2.300(4), Ir1–C27 2.226(4), Ir1–C28 2.248(4), C23–C24 1.380(7), C27–C28 1.373(7); N2-C13-N3 104.3(3), N1-Ir1-C1 78.27(15), C13-Ir1-N1 78.34(14).

Structural analysis of the Ir complexes: All ^{13}C and ^1H resonances of complexes **7a–f** and **16a–o** were assigned by standard two-dimensional (2D) NMR techniques. In the ^{13}C NMR spectra, a shift of the N*C*N signal from $\delta = 134(\pm3)$ ppm for the imidazolium salts to $\delta = 173(\pm4)$ ppm for the carbene complexes was observed upon NHC complexation.

Single crystals suitable for X-ray analysis were obtained for complexes **7c** and **16q**, the latter being an analogue of complex **16b** containing PF_6^- instead of BAr_F^- as counterion (Figures 2 and 3).[25] In both crystal structures, the iridium atom adopts a nearly square-planar coordination geometry with the cod double bonds perpendicular to the coordination planes. The bond angles observed at the carbene centers (N2-C14-N3 104.8° for **7c** and N2-C1-N1 104.3° for **16q**) are in good agreement with the value expected for a singlet *N*-heterocyclic carbene.[26]

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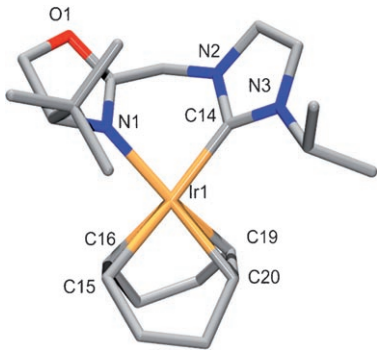


Figure 2. Structure of the cation of **7c**. Selected bond lengths [Å] and angles [°]: Ir1–C14 2.034(4), Ir1–N1 2.089(4) Ir1–C15 2.175(3), Ir1–C16 2.193(4), Ir1–C19 2.105(5), Ir1–C20 2.136(3), C15–C16 1.388(6), C19–C20 1.418(7); N2-C14-N3 104.8(3), N1-Ir1-C14 82.28(15).

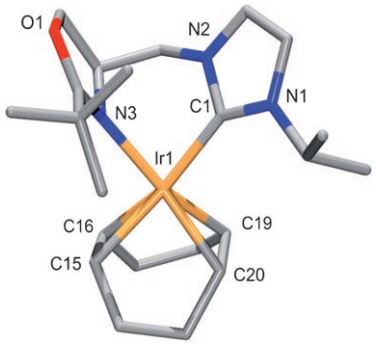


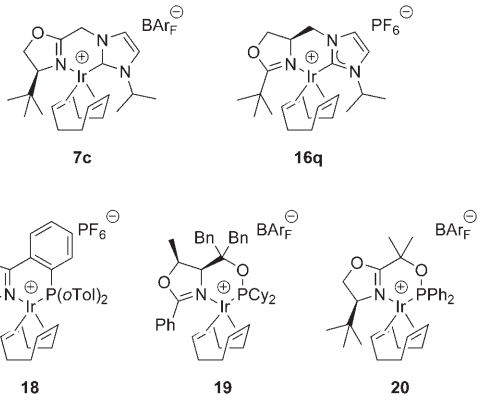
Figure 3. Structure of the cation of **16q**. Selected bond lengths [Å] and angles [°]: Ir1–C1 2.042(3), Ir1–N3 2.094(2), Ir1–C15 2.159(3), Ir1–C16 2.167(3), Ir1–C19 2.115(3), Ir1–C20 2.124(3), C15–C16 1.383(6), C19–C20 1.403(5); N2-C1-N1 104.3(3), N3-Ir1-C1 79.47(11).

The ^{13}C NMR chemical shifts of the cyclooctadiene olefinic C atoms and the Ir–(C=C) distances *trans* to the oxazoline and *trans* to the NHC moiety were compared with those of the most efficient P,N ligands developed in our laboratory (Table 1). According to the observed values, the *trans* influence of the imidazolin-2-ylidene group lies between that of the phosphine and the oxazoline groups. This is reflected by the Ir–(C=C) distances *trans* to the coordinating units, which increase from 200–204 pm for the oxazoline to 205–207 pm for the imidazolin-2-ylidene and 211–212 pm for the phosphine group.

As shown in the crystal structures of complexes **7c** (Figure 2) and **16q** (Figure 3), the ligand arrangement around the iridium atoms in the two complexes is very similar. In both complexes, the six-membered chelate rings give rise to rigid structures with the R^1 and R^2 substituents pointing in the same direction.

Enantioselective hydrogenation: To investigate the potential of these complexes, we tested them in the asymmetric hydrogenation of four different unfunctionalized alkenes (**21**–**24**) and one α,β-unsaturated carboxylic ester (**25**). For each substrate, our complexes were compared with Burgess' best catalyst [Ir(**1**)(cod)]BAr_F with R^1 = 1-adamantyl and R^2 = 2,6-diisopropylphenyl, and one threonine-derived phosphinite-oxazoline iridium complex (**19**). All reactions were set up under inert atmosphere with 1 mol% catalyst and 0.1 mmol of substrate in CH_2Cl_2 (0.5 mL).

Table 1. Structural data of complexes **7c** and **16q** compared with those of complexes **18**,[27] **19**,[28] and **20**.[29]



	Ir–(C=C) distance to the Ir atom [pm][a]		Ir–(C=C) ^{13}C NMR chemical shift [ppm]	
	trans to N	*trans* to P/C	*trans* to N	*trans* to P/C
18	204	211	67.5 67.4	95.0 90.0
19	203	212	69.2 64.9	102.8 96.6
20	201	212	64.5 60.6	99.8 97.4
7c	200	207	65.7 60.1	84.6 82.9
16q	200	205	66.2 56.0	80.8 79.9

[a] Distance calculated from the midpoint of the C=C bond to the iridium atom.

In the hydrogenation of *trans*-α-methylstilbene **21**, up to 90% *ee* was obtained with the best catalysts of type **D** and **F** (**7a** and **16b**; Table 2). For type **D** catalysts (**7a–f**), the choice of R^1 = *tert*-butyl is crucial for activity as well as enantioselectivity; a decrease from 90 to 50% *ee* was observed when R^1 = *tert*-butyl was replaced by an isopropyl group. The strong influence of the oxazoline substituent is consistent with the findings of Burgess and co-workers for ligands of type **E**, which were rationalized by computational studies that suggested a strong steric interaction between the R^1 substituent and the substrate.[30] Although the R^2 substituent at the imidazolin-2-ylidene unit plays a less important role, the asymmetric induction increases when the size of R^2 is reduced (see complexes **7a, 7c**, and **7d**).

Both activity and enantioselectivity of type **F** catalysts strongly depend on the oxazoline substituent. High conversion was obtained for R^1 = *tert*-butyl and 1-adamantyl, with the exception of complexes **16e** and **16j** bearing a *tert*-butyl group at the NHC unit. In these two catalysts, the coordination sphere seems to be too congested to allow high catalytic activity. With R^1 = 2,6-dimethylphenyl, activities were low-to-moderate (**16k–o**). As for the **D** series, the best enantioselectivities were recorded for catalysts with a *tert*-butyl group at the oxazoline ring (**16a–e**). Replacement of R^1 = *tert*-butyl by 1-adamantyl reduced the enantioselectivities by about 20%. With R^1 = 2,6-dimethylphenyl, the asymmetric induction was even lower. Only the catalysts bearing small

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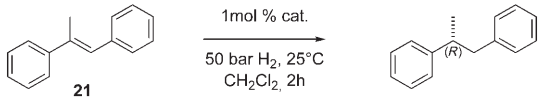
Table 2. Hydrogenation of *trans*-α-methylstilbene **21**.[a]



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Catalyst	Yield [%][b]	*ee* [%][c]
7a	>99	90 (*R*)
7b	25[d]	55 (*R*)
7c	>99	87 (*R*)
7d	76	59 (*R*)
7e	96	84 (*R*)
7f	99	85 (*R*)
16a	>99	89 (*R*)
16b	>99	90 (*R*)
16c	>99	79 (*R*)
16d	>99	87 (*R*)
16e	66	78 (*R*)
16f	97	69 (*R*)
16g	>99	72 (*R*)
16h	>99	61 (*R*)
16i	>99	71 (*R*)
16j	70	66 (*R*)
16k	27	68 (*R*)
16l	92	59 (*R*)
16m	15	*rac*
16n	58	50 (*R*)
16o	7	32 (*R*)
[Ir(**1**)(cod)]BAr_F[11]	>99	98 (*S*)
19[4]	>99	99 (*R*)

[a] See Schemes 1 and 2 for formulae for catalysts. [b] Determined by GC. [c] Determined by HPLC. [d] 5 mol% catalyst.

R^2 substituents such as methyl and isopropyl in addition to the presence of substituent R^1 = *tert*-butyl reached 90% *ee*, a trend already observed in the **D** series.

Hydrogenation of (*E*)-2-(4-methoxyphenyl)-2-butene **22** and (*Z*)-2-(4-methoxyphenyl)-2-butene **23** showed similar trends (Tables 3 and 4). Contrary to *trans*-α-methylstilbene, the highest enantioselectivity values, 87% *ee* for alkene **22** and 73% *ee* for alkene **23**, were obtained with type **F** catalysts **16b** and **16c**, respectively.

Among type **D** catalysts, complex **7a**, which bears the least bulky substituent on the NHC ring, was again the most selective catalyst with 76% *ee* for substrate **22** and 56% *ee* for substrate **23**.

The results with type **F** catalysts confirmed the trend that the R^1 substituent has a strong influence on both activity and enantioselectivity. Similar to the hydrogenation of *trans*-α-methylstilbene, catalysts with R^1 = *tert*-butyl gave by far the highest enantiomeric excesses followed by catalysts with R^1 = 1-adamantyl and R^1 = 2,6-dimethylphenyl substituents. The R^2 substituent at the NHC unit allowed fine tuning of the enantioselectivity of substrates **22** and **23**. While the highest enantiomeric excesses were obtained for substrate **22** with a small R^2 group such as methyl (**16a**) and isopropyl (**16b**), the best enantioselectivities for substrate **23** were obtained with R^2 = 2,4,6-trimethylphenyl (**16c**).

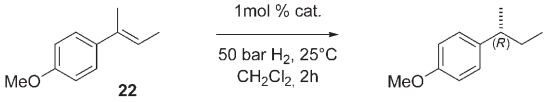
Two further aspects of the hydrogenation of alkene **23** with Ir-**F** catalysts are remarkable. First, the three catalysts **16k, 16l**, and **16n** produce the opposite enantiomer. The observed formation of *R* products starting from both the *E* and *Z* olefins is in contrast to the general trend that *E* and *Z* olefins give products of opposite configuration.[5] A possible explanation of these unexpected results could be that *cis–trans* isomerization takes place during hydrogenation such that the reaction of the less-stable *Z* isomer **23** proceeds mainly through the *E* isomer **22**.[31] Second, catalysts **16e, 16j**, and **16o** with a *tert*-butyl group on the NHC moiety not only gave low conversion but also no asymmetric induction (see Table 4).

The terminal olefin 2-(4-methoxyphenyl)-1-butene **24** is a much more reactive substrate than those discussed so far. Since previous work on substrate **24** showed that low hydrogen pressure increases the asymmetric induction,[5,32] catalyst screening was performed at 1 bar H_2 gas pressure (Table 5).

For type **D** catalysts, R^1 = *tert*-butyl was required for high activity. In this series, the importance of the R^2 substituent was demonstrated by a remarkable inversion of enantioselectivity from 15% *ee* (*R*) to 79% *ee* (*S*) when R^2 = methyl was replaced by an isopropyl group. With a value of 79% *ee*, complex **7c** was the most selective catalyst of both the **7a–f** and the **16a–o** libraries.

Type **F** catalysts gave low-to-moderate enantioselectivities. The best enantiomeric excesses of substrate **24** were again observed with R^1 = *tert*-butyl, even though the difference between the *tert*-butyl and the 1-adamantyl substituent was less pronounced than for substrates **21, 22**, and **23**.

Table 3. Hydrogenation of (*E*)-2-(4-methoxyphenyl)-2-butene **22**.[a]



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Catalyst	Yield [%][b]	*ee* [%][c]
7a	>99	76 (*R*)
7b	5	–
7c	>99	69 (*R*)
7d	>99	9 (*R*)
7e	>99	69 (*R*)
7f	>99	69 (*R*)
16a	>99	85 (*R*)
16b	>99	87 (*R*)
16c	>99	75 (*R*)
16d	>99	84 (*R*)
16e	50	80 (*R*)
16f	>99	69 (*R*)
16g	>99	71 (*R*)
16h	>99	61 (*R*)
16i	>99	73 (*R*)
16j	87	75 (*R*)
16k	83	74 (*R*)
16l	89	59 (*R*)
16m	20	11 (*R*)
16n	84	61 (*R*)
16o	6	*rac*
[Ir(**1**)(cod)]BAr_F[11]	>99	91 (*S*)
19[4]	>99	99 (*R*)

[a] See Schemes 1 and 2 for formulae for catalysts. [b] Determined by GC. [c] Determined by HPLC.

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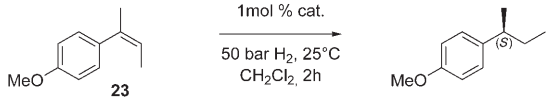
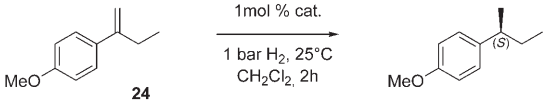
Table 4. Hydrogenation of (*Z*)-2-(4-methoxyphenyl)-2-butene **23**.[a]



Catalyst	Yield [%][b]	*ee* [%][c]
7a	97	56 (*S*)
7b	3	– (*S*)
7c	>99	41 (*S*)
7d	65	27 (*S*)
7e	91	30 (*S*)
7f	97	46 (*S*)
16a	>99	56 (*S*)
16b	>99	66 (*S*)
16c	>99	73 (*S*)
16d	>99	50 (*S*)
16e	68	*rac*
16f	>99	33 (*S*)
16g	>99	43 (*S*)
16h	>99	66 (*S*)
16i	>99	10 (*S*)
16j	79	*rac*
16k	89	25 (*R*)
16l	>99	38 (*R*)
16m	38	17 (*S*)
16n	>99	41 (*R*)
16o	18	*rac*
[Ir(**1**)(cod)]BAr_F[11]	95	78 (*R*)
19[4]	>99	72 (*S*)

[a] See Schemes 1 and 2 for formulae for catalysts. [b] Determined by GC. [c] Determined by HPLC.

Table 5. Hydrogenation of 2-(4-methoxyphenyl)-1-butene **24** at 1 bar H_2 gas pressure.[a]



Catalyst	Yield [%][b]	*ee* [%][c]
7a	>99	15 (*R*)
7b	2	–
7c	>99	79 (*S*)
7d	>99	54 (*S*)
7e	>99	70 (*S*)
7f	>99	78 (*S*)
16a	>99	69 (*S*)
16b	>99	66 (*S*)
16c	>99	55 (*S*)
16d	>99	65 (*S*)
16e	0	–
16f	>99	62 (*S*)
16g	>99	56 (*S*)
16h	>99	56 (*S*)
16i	>99	65 (*S*)
16j	0	–
16k	>99	29 (*S*)
16l	90	20 (*S*)
16m	20	*rac*
16n	>99	27 (*S*)
16o	0	–
[Ir(**1**)(cod)]BAr_F[11]	>99	89 (*R*)
19[4]	>99	94 (*S*)

[a] See Schemes 1 and 2 for formulae for catalysts. [b] Determined by GC. [c] Determined by HPLC.

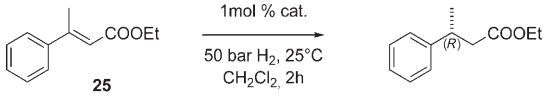
Complexes **16e, 16j**, and **16o**, bearing a *tert*-butyl substituent on the NHC moiety, showed no catalytic activity.

Finally, our catalyst library was tested in the hydrogenation of (*E*)-2-methylcinnamic acid ethyl ester **25** (Table 6). Type **D** complexes gave moderate enantioselectivities of up to 59% *ee* (**7a**). Complexes with less sterically hindered R^2 substituents such as methyl (**7a**), isopropyl (**7c**), and isobutyl (**7d**) were again the most enantioselective catalysts.

Higher enantioselectivities were obtained with catalysts of type **F**. Contrary to previous substrates **21**–**24**, the R^2 substituent in complexes **16a–j** plays a more important role than the R^1 substituent. The best enantiomeric excesses, 76% and 72% *ee*, were obtained with R^2 = 2,4,6-trimethylphenyl (**16c** and **16h**).

Moreover, in contrast to the results obtained with unfunctionalized alkenes, catalysts with R^1 = 1-adamantyl showed higher *ee* values than their analogues with R^1 = *tert*-butyl. With R^1 = 2,6-dimethylphenyl (**16k–o**), enantioselectivities were moderate. Contrary to catalysts **16a–j**, no positive effect on the asymmetric induction was observed with R^2 = 2,4,6-trimethylphenyl.

Table 6. Hydrogenation of (*E*)-2-methylcinnamic acid ethyl ester **25**.[a]



Catalyst	Yield [%][b]	*ee* [%][c]
7a	>99	59 (*R*)
7b	0	–
7c	>99	54 (*R*)
7d	93	13 (*S*)
7e	>99	48 (*R*)
7f	>99	55 (*R*)
16a	>99	12 (*R*)
16b	>99	38 (*R*)
16c	>99	72 (*R*)
16d	>99	30 (*R*)
16e	>99	*rac*
16f	>99	16 (*R*)
16g	>99	46 (*R*)
16h	>99	76 (*R*)
16i	>99	44 (*R*)
16j	96	36 (*R*)
16k	>99	50 (*R*)
16l	>99	41 (*R*)
16m	>99	30 (*R*)
16n	>99	27 (*R*)
16o	70	*rac*
[Ir(**1**)(cod)]BAr_F[11]	–	–
19[4]	>99	94 (*R*)

[a] See Schemes 1 and 2 for formulae for catalysts. [b] Determined by GC. [c] Determined by HPLC.

Conclusion

Simple and efficient syntheses for two families of chiral iridium(oxazoline-carbene) complexes **D** and **F** with a six-membered chelate ring have been developed. The modular

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nature of these ligands allowed the preparation of a wide range of derivatives.

The complexes were tested in the iridium-catalyzed asymmetric hydrogenation of olefins. Among type **D** complexes, catalyst **7a** gave the highest enantiomeric excesses for all substrates except terminal olefin **24**. Remarkably, catalyst **7a** is the one bearing the least bulky R^2 substituent at the NHC moiety.

The most selective catalysts in the **F** series were found to be equivalent or superior to type **D** complexes. Good enantioselectivities were generally induced by catalysts with a bulky *tert*-butyl or adamantyl–oxazoline unit in combination with a smaller methyl or isopropyl group at the NHC moiety. The functionalized substrate **25** was an exception. Here, the most efficient catalyst was complex **16h** bearing two bulky groups (1-adamantyl and 2,4,6-trimethylphenyl).

The six-membered chelate complexes differ strongly from the seven-membered chelate analogues **E** developed by Burgess. Whereas only one particular complex of type **E** ([Ir(**1**)(cod)]BAr_F with R^1 = 1-adamantyl and R^2 = 2,6-diisopropylphenyl) was found to give high enantioselectivities, several representatives of type **D** and **F** were identified that induced similar *ee* levels. In contrast to the Burgess′ catalysts, which require large substituents both at the NHC and oxazoline units for high enantioselectivity, the six-membered chelate analogues **D** and **F** in general give better results with less sterically demanding ligands. However, despite the wide range of **D** and **F** type catalysts investigated, the enantiomeric excesses are not as high as those obtained with Burgess′ best complex [Ir(**1**)(cod)]BAr_F. Nevertheless, our results indicate that carbene-oxazoline ligands of this type have considerable potential. Their modular nature, which enables easy tuning of the ligand structure, suggests that these ligands could be applied in other areas of asymmetric catalysis.

Experimental Section

General: Reactions with air- or moisture-sensitive compounds were performed under Ar gas by using standard Schlenk techniques or under purified N_2 gas in an MBraun glovebox. Glassware was oven- and flame-dried prior to use. All chemicals were purchased from Fluka Chemie GmbH (Buchs, Switzerland) with the exception of 3,5-bis(trifluoromethyl)-bromobenzene, which was obtained from Fluorochem Ltd (Derbyshire, UK). Diethyl ether, pentane, and tetrahydrofuran were dried over sodium/benzophenone, dichloromethane over CaH_2 and all were freshly distilled under a stream of nitrogen prior to use. Melting points were measured with a Büchi 535 melting point apparatus and were not corrected. Optical rotations: sodium lamp, 1-dm cuvette, *c* in g per 100 mL. HPLC analysis: Shimadzu Systems, SCL-10 A system controller, CTO-10 AC column oven, LC10-AD pump system, DGU-14 A degasser, SPD-M10 A diode-array detector or UV/Vis detector (220 and 254 nm).

General procedure for the preparation of chloroacetamides 4a and 4b: A solution of (*S*)-*tert*-leucinol (3.02 g, 25.8 mmol) and triethylamine (5.2 g, 51.6 mmol) in CH_2Cl_2 (100 mL) was cooled to −20 °C under argon gas. Chloroacetyl chloride (2.91 g, 25.8 mmol) was added dropwise over 5 min. The cooling bath was removed and the mixture was stirred at room temperature for 12 h. After concentration in vacuo, ethyl acetate was added (30 mL). The mixture was filtered and concentrated in vacuo. The crude product was purified by chromatography on silica gel (5 × 20 cm column, R_f = 0.57, AcOEt) eluting with AcOEt to yield a white solid (**4a**, 4.14 g, 83 %).

Compound 4a: M.p. 69–70 °C; $[\alpha]_D^{20} = -18.7$ (c = 1.00, $CHCl_3$); ^{1}H NMR (400.1 MHz, $CDCl_3$, 300 K): δ = 6.75 (br, 1H; NH), 4.10 (mc, 2H; $ClCH_2$), 3.86 (mc, 2H; CH_2OH, CHCC$(CH_3)_3$), 3.62 (mc, 1H; CH_2OH), 2.13 (br, 1H; OH), 0.97 ppm (s, 9H; C$(CH_3)_3$); ^{13}C{^{1}H} NMR (100.6 MHz, $CDCl_3$, 300 K): δ = 167.4 (NHCO), 63.1 (NCH_2OH), 60.5 (NCHC$(CH_3)_3$), 43.3 ($ClCH_2$), 34.0 (C$(CH_3)_3$), 27.2 ppm (C(CH_3)$_3$); IR (KBr): $\tilde{\nu}$ = 3405 (m br), 3277 (m), 2963 (m), 1665 (s), 1636 (s), 1531 (s), 1369 (w), 1276 (w), 1088 (w), 1049 (m), 911 (w), 771 (w), 666 cm^{-1} (w); MS (FAB): *m*/*z* (%): 194 (100) $[M+H]^+$; elemental analysis calcd (%) for $C_8H_{16}ClNO_2$ (193.67): C 49.61, H 8.33, N 7.23, O 16.52; found: C 49.22, H 8.37, N 7.04, O 16.68.

General procedure for the preparation of chloromethyloxazolines 5a and 5b: A solution of chloroacetamide **4a** (1.29 g, 6.65 mmol) and methyl-*N*-triethylammoniosulfonyl-carbamate (1.74 g, 7.32 mmol) in THF (20 mL) was refluxed for 12 h. The mixture was concentrated in vacuo. The residue was diluted with dichloromethane and extracted three times with water. The organic layer was dried over anhydrous magnesium sulfate and concentrated in vacuo. The crude product was purified by distillation (50 °C, 0.1 mbar) to yield a colorless oil (**5a**, 1.45 g, 50 %).

Compound 5a: $[\alpha]_D^{20} = -108.5$ (c = 0.94, $CHCl_3$); ^{1}H NMR (400.1 MHz, $CDCl_3$, 300 K): δ = 4.28 (mc, 1H; CH_2O), 4.15 (mc, 1H; CH_2O), 4.10 (mc, 2H; $ClCH_2$), 3.91 (mc, 1H; NCHC$(CH_3)_3$), 0.89 ppm (s, 9H; C$(CH_3)_3$); ^{13}C{^{1}H} NMR (100.6 MHz, $CDCl_3$, 300 K): δ = 162.4 (OCN), 76.1 (NCHCH$(CH_3)_2$), 69.8 (CH_2O), 36.5 ($ClCH_2$), 33.8 (C$(CH_3)_3$), 25.8 ppm (C(CH_3)$_3$); IR (NaCl): $\tilde{\nu}$ = 2957 (s), 2906 (m), 2870 (m), 1671 (s), 1479 (m), 1430 (w), 1395 (w), 1360 (m), 1243 (m), 1155 (w), 983 (s), 944 (w), 892 (w), 733 cm^{-1} (w); MS (FAB, Xe, 8 kV): *m*/*z* (%): 176 (100) $[M+H]^+$; elemental analysis calcd (%) for $C_8H_{14}ClNO$ (175.66): C 54.70, H 8.03, N 7.97; found: C 53.83, H 7.90, N 8.03.

General procedure for the preparation of imidazolium salts 6a–g: A solution of chloromethyloxazoline **5a** (235 mg, 1.33 mmol) and 1-methyl-1*H*-imidazole (93 mg, 1.33 mmol) in DMF (0.4 mL) was heated at 80 °C for 8 h. The mixture was concentrated in vacuo at 80 °C and the residue was diluted in CH_2Cl_2 (5 mL). $NaBAr_F$ (1.18 g, 1.33 mmol) was added to the solution, which was then stirred at room temperature for 30 min. The mixture was filtered and concentrated in vacuo. The crude product was purified by chromatography on silica gel (5 × 8 cm column) eluting with CH_2Cl_2 (1 L) to yield a white solid (**6a**, 1.13 g, 78 %).

Compound 6a: M.p. 103–104 °C; $[\alpha]_D^{20} = -8.2$ (c = 0.50, $CHCl_3$); ^{1}H NMR (400.1 MHz, $CDCl_3$, 300 K): δ = 8.31 (s, 1H; NCHN), 7.69 (mc, 8H; BAr_F *ortho*-CH), 7.53 (mc, 4H; BAr_F *para*-CH), 7.15 (mc, 1H; imid CH), 6.95 (mc, 1H; imid CH), 4.71 (mc, 2H; NCH_2), 4.27 (mc, 1H; oxaz CH_2), 4.14 (mc, 1H; oxaz CH_2), 3.88 (mc, 1H; oxaz CH), 3.70 (s, 3H; NCH_3), 0.82 ppm (s, 9H; *t*Bu CH_3); ^{13}C{^{1}H} NMR (100.6 MHz, $CDCl_3$, 300 K): δ = 162.1 (q, ^1J(B,C) = 49.9 Hz, 4C; BAr_F quat C *ipso* to B), 158.1 (OCN), 135.7 (NCHN), 135.1 (br, 8C; BAr_F *ortho*-CH), 129.3 (qq, ^2J(F,C) = 31.12 Hz, ^3J(B,C) = 2.9 Hz, 8C; BAr_F C *ipso* to CF_3), 124.9 (q, ^1J(F,C) = 272.5 Hz, 8C; BAr_F CF_3), 124.2 (imid CH), 123.8 (imid CH), 117.9 (sept, ^3J(F,C) = 3.8 Hz, 4C; BAr_F *para*-CH), 76.4 (oxaz CH), 71.0 (oxaz CH_2), 46.7 (NCH_2), 37.0 (NCH_3), 33.8 (*t*Bu C), 25.8 ppm (3C; *t*Bu CH_3); IR (KBr): $\tilde{\nu}$ = 3185 (w), 2967 (w), 1686 (w), 1610 (w), 1356 (m), 1277 (s), 1115 (s br), 887 (w), 838 (w), 743 (w), 711 (w), 682 (w), 671 (w), 623 cm^{-1} (w); MS (FAB): *m*/*z* (%): 222 (100) $[M-BAr_F]^+$; elemental analysis calcd (%) for $C_{44}H_{32}BF_{24}N_3O$ (1085.52): C 48.68, H 2.97, N 3.87; found: C 48.72, H 2.99, N 3.84.

General procedure for the preparation of iridium complexes 7a–f and 16a–p: Freshly sublimed NaO*t*Bu (14.3 mg, 0.148 mmol) was added to a solution of imidazolium salt **6a** (161 mg, 0.148 mmol) and [(η^4-cod)IrCl]$_2$ (50 mg, 0.074 mmol) in THF (10 mL). The reaction mixture was stirred at room temperature for 3 h and was then concentrated in vacuo. The crude product was purified by chromatography on silica gel (3 × 20 cm column) eluting with CH_2Cl_2 to yield a yellow/orange solid (**7a**, 134 mg, 65 %).

Compound 7a: $[\alpha]_D^{20} = +48$ (c = 0.159, $CHCl_3$); ^{1}H NMR (500.1 MHz, $CDCl_3$, 295 K): δ = 7.70 (mc, 8H; BAr_F *ortho*-CH), 7.53 (mc, 4H; BAr_F

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para-CH), 6.81 (mc, 1H; imid CH), 6.79 (mc, 1H; imid CH), 4.98 (mc, 1H; NCH_2), 4.61 (mc, 1H; oxaz CH_2), 4.49 (mc, 1H; cod CH), 4.38 (mc, 2H; NCH_2, oxaz CH_2), 4.15 (mc, 2H; cod CH), 3.86 (mc, 1H; cod CH), 3.80 (mc, 1H; oxaz CH), 3.74 (s, 3H; NCH_3), 2.29 (mc, 2H; cod CH_2), 2.11 (mc, 2H; cod CH_2), 2.00 (mc, 2H; cod CH_2), 1.75 (mc, 1H; cod CH_2), 1.63 (mc, 1H; cod CH_2), 0.73 ppm (s, 9H; *t*Bu CH_3); $^{13}C\{^1H\}$ NMR (125.7 MHz, $CDCl_3$, 295 K): $\delta = 174.1$ (NCN), 165.1 (OCN), 161.7 (q, $^1J(B,C) = 49.9$ Hz, 4C; BAr_F quat C *ipso* to B), 134.8 (br, 8C; BAr_F *ortho*-CH), 128.9 (qq, $^2J(F,C) = 31.12$ Hz, $^3J(B,C) = 2.9$ Hz, 8C; BAr_F C *ipso* to CF_3), 124.5 (q, $^1J(F,C) = 272.5$ Hz, 8C; BAr_F CF_3), 123.5 (imid CH), 121.1 (imid CH), 117.5 (sept, $^3J(F,C) = 3.8$ Hz, 4C; BAr_F *para*-CH), 85.4 (cod CH), 81.9 (cod CH), 73.3 (oxaz CH), 72.8 (oxaz CH_2), 64.4 (cod CH), 59.0 (cod CH), 46.8 (NCH_2), 38.0 (NCH_3), 34.0 (cod CH_2), 33.5 (*t*Bu C), 31.1 (cod CH_2), 29.9 (cod CH_2), 28.3 (cod CH_2), 25.1 ppm (3C; *t*Bu CH_3); IR (KBr): $\tilde{\nu} = 2971$ (w), 1648 (w), 1610 (w), 1435 (w), 1355 (m), 1277 (s), 1124 (sbr), 960 (w), 894 (w), 839 (w), 712 (w), 682 (w), 671 cm^{-1} (w); MS (FAB): *m*/*z* (%): 522 (100) $[M-BAr_F]^+$; elemental analysis calcd (%) for $C_{52}H_{43}BF_{24}IrN_3O$ (1384.91): C 45.10, H 3.13, N 3.03; found: C 45.25, H 3.24, N 2.87.

General procedure for the preparation of compounds 11a,f,k: A solution of (*S*)-serine methyl ester hydrochloride (6.00 g, 38.6 mmol) and triethylamine (11.7 g, 115.7 mmol) in CH_2Cl_2 (150 mL) was cooled to −10 °C under argon gas. Pivaloyl chloride (4.65 g, 38.6 mmol) was added dropwise over 5 min. The mixture was stirred at room temperature for 12 h and was then diluted with water (100 mL). The dichloromethane layer was separated, dried over magnesium sulfate, and concentrated in vacuo to yield a yellow oil. The crude product was purified by chromatography on silica gel (7×30 cm column, $R_f = 0.43$) eluting with a mixture of AcOEt and hexane (4:1) to yield a colorless oil (**11a**, 5.90 g, 80%).

Compound 11a: $[\alpha]_D^{20} = +24.6$ ($c = 1.00$, $CHCl_3$); ^1H NMR (400.1 MHz, $CDCl_3$, 300 K): $\delta = 6.61$ (br, 1H; NH), 4.63 (mc, 1H; NHC*H*CO_2CH_3), 3.93 (mc, 2H; C*H*$_2$OH), 3.78 (s, 3H; CO_2CH_3), 2.68 (br, 1H; OH), 1.23 ppm (s, 9H; $C(CH_3)_3$); $^{13}C\{^1H\}$ NMR (100.6 MHz, $CDCl_3$, 300 K): $\delta = 179.7$ (NCO), 171.6 (*C*O_2CH_3), 64.1 (*C*H_2OH), 55.2 (NH*C*HCO$_2$), 53.2 (CO_2CH_3), 39.2 ($C(CH_3)_3$), 27.8 ppm ($C(CH_3)_3$); IR (NaCl): $\tilde{\nu} = 3396$ (sbr), 2960 (s), 2878 (m), 1744 (s), 1645 (s), 1521 (s), 1438 (m), 1368 (m), 1204 (s), 1081 (m), 979 (w), 938 (w), 857 cm^{-1} (w); MS (FAB): *m*/*z* (%): 204 (100) $[M+H]^+$, 57 (66); elemental analysis calcd (%) for $C_9H_{17}NO_4$ (203.24): C 53.19, H 8.43, N 6.89; found: C 52.88, H 8.54, N 7.00.

General procedure for the preparation of esters 12a,f,k: A solution of amide **11a** (2.40 g, 12.6 mmol) and methyl *N*-triethylammoniosulfonylcarbamate (3.29 g, 13.8 mmol) in THF (40 mL) was refluxed for 12 h. The mixture was concentrated in vacuo and the residue was diluted in dichloromethane. The organic layer was extracted three times with water, dried over magnesium sulfate, and concentrated in vacuo to give an oil that was purified by distillation (45 °C, 0.08 mbar) to yield a colorless oil (**12a**, 1.51 g, 65%).

Compound 12a: $[\alpha]_D^{20} = +150.9$ ($c = 0.94$, $CHCl_3$); ^1H NMR (400.1 MHz, $CDCl_3$, 300 K): $\delta = 4.67$ (mc, 1H; oxaz CH), 4.42 (mc, 1H; oxaz CH_2), 4.34 (mc, 1H; oxaz CH_2), 3.74 (s, 3H; CO_2CH_3), 1.20 ppm (s, 9H; $C(CH_3)_3$); $^{13}C\{^1H\}$ NMR (100.6 MHz, $CDCl_3$, 300 K): $\delta = 177.3$ (NCO), 172.3 (*C*O_2CH_3), 69.8 (oxaz CH_2), 68.5 (oxaz CH), 52.9 (CO_2CH_3), 33.8 ($C(CH_3)_3$), 28.1 ppm ($C(CH_3)_3$); IR (NaCl): $\tilde{\nu} = 2975$ (s), 1742 (s), 1651 (s), 1482 (m), 1438 (m), 1396 (w), 1363 (m), 1300 (m), 1144 (s), 1061 (w), 981 (m), 785 (w), 728 cm^{-1} (w); MS (FAB): *m*/*z* (%): 186 (100) $[M+H]^+$; elemental analysis calcd (%) for $C_9H_{15}NO_3$ (185.22): C 58.36, H 8.16, N 7.56; found: C 58.17, H 7.98, N 7.61.

Preparation of ester 12p: Ethyl benzimidate hydrochloride (5.00 g, 26.9 mmol) was dissolved in dichloromethane (100 mL). The solution was extracted three times with an aqueous solution of $NaHCO_3$ and concentrated in vacuo to yield an oil (3.77 g). The oil was dissolved in 1,2-dichlorethane (150 mL) and (*S*)-serine methyl ester hydrochloride (4.32 g, 27.8 mmol) was added. The suspension was refluxed for 20 h, then was filtered and concentrated in vacuo to remove the solvent. The crude product was purified by chromatography on silica gel (7×30 cm column, $R_f = 0.57$) eluting with a mixture of AcOEt and hexane (3:1) to yield a colorless oil (**12p**, 5.02 g, 91%).

Compound 12p: $[\alpha]_D^{20} = +99.3$ ($c = 1.36$, $CHCl_3$); ^1H NMR (400.1 MHz, $CDCl_3$, 300 K): $\delta = 7.97$ (mc, 2H; arom CH), 7.49 (mc, 1H; arom CH), 7.40 (mc, 2H; arom CH), 4.95 (mc, 1H; oxaz CH), 4.69 (mc, 1H; oxaz CH_2), 4.59 (mc, 1H; oxaz CH_2), 3.81 ppm (s, 3H; OCH_3); $^{13}C\{^1H\}$ NMR (100.6 MHz, $CDCl_3$, 300 K): $\delta = 172.0$ (*C*O_2CH_3), 166.7 (NCO), 132.3 (arom CH), 129.0 (2C; arom CH), 128.8 (2C; arom CH), 127.3 (arom C), 70.0 (oxaz CH_2), 69.0 (oxaz CH), 53.1 ppm (CO_2CH_3); IR (NaCl): $\tilde{\nu} = 2953$ (w), 1742 (s), 1642 (m), 1450 (w), 1362 (m), 1210 (m), 1090 (m), 1026 (w), 971 (w), 779 (w), 697 cm^{-1} (m); MS (FAB): *m*/*z* (%): 206 (100) $[M+H]^+$; elemental analysis calcd (%) for $C_{11}H_{11}NO_3$ (205.21): C 64.38, H 5.40, N 6.83; found: C 64.26, H 5.66, N 7.06.

General procedure for the preparation of oxazoline alcohols 13p,a,f,k: Ester **12p** (11.0 g, 53.9 mmol) and dried THF (300 mL) were added under argon gas to a 2 L round-bottomed flask equipped with a thermometer and an addition funnel. A solution of DIBAL in THF (170 mL, 1.0 mmol mL^{-1}) was added dropwise at −10 °C. The mixture was stirred overnight at room temperature. A solution of the Seignette salt (400 mL, 20% w/w) was carefully added with stirring and the mixture was extracted three times with ethyl acetate. The combined organic layers were dried over magnesium sulfate and concentrated in vacuo to yield a yellow oil. The crude product was purified by chromatography on silica gel (7×20 cm column, $R_f = 0.33$) eluting with AcOEt to yield a white solid (**13p**, 6.4 g, 67%).

Compound 13p: M.p. 99–100 °C; $[\alpha]_D^{20} = +89.0$ ($c = 1.00$, $CHCl_3$); ^1H NMR (400.1 MHz, $CDCl_3$, 300 K): $\delta = 7.97$ (mc, 2H; arom CH), 7.42 (mc, 1H; arom CH), 7.31 (mc, 2H; arom CH), 4.30–4.50 (m, 3H; 2× oxaz CH_2, 1× oxaz CH), 3.99 (mc, 1H; C*H*$_2$OH), 3.65 (mc, 1H; C*H*$_2$OH), 3.53 ppm (br, 1H; OH); $^{13}C\{^1H\}$ NMR (100.6 MHz, $CDCl_3$, 300 K): $\delta =$ 166.0 (NCO), 131.9 (arom CH), 128.7 (2C; arom CH), 128.6 (2C; arom CH), 127.5 (arom C), 69.5 (oxaz CH_2), 68.5 (oxaz CH), 64.1 ppm (*C*H_2OH); IR (KBr): $\tilde{\nu} = 3266$ (sbr), 2928 (m), 1652 (s), 1500 (m), 1363 (m), 1276 (m), 1098 (m), 958 (m), 783 (w), 693 cm^{-1} (m); MS (FAB): *m*/*z* (%): 178 (100) $[M+H]^+$; elemental analysis calcd (%) for $C_{10}H_{11}NO_2$ (177.20): C 67.78, H 6.26, N 7.90, O 18.06; found: C 67.60, H 6.28, N 7.87, O 17.80.

General procedure for the preparation of tosylate 14p,a,f,k: Triethylamine (3.98 g, 39.4 mmol) was added dropwise to a solution of alcohol **13p** (6.35 g, 35.8 mmol) and tosyl chloride (13.65 g, 71.6 mmol) in dichloromethane (40 mL). The mixture was stirred at room temperature for 8 h and was then concentrated in vacuo to remove the solvent. The crude product was purified by chromatography on silica gel (7×25 cm column, $R_f = 0.48$, AcOEt/hexane 1:1) eluting with a mixture of AcOEt and hexane (from 3:7 to 7:3) to yield a colorless oil that crystallized on standing (**14p**, 8.41 g, 71%).

Compound 14p: M.p. 109–110 °C; $[\alpha]_D^{20} = +96.5$ ($c = 1.00$, $CHCl_3$); ^1H NMR (400.1 MHz, $CDCl_3$, 300 K): $\delta = 7.86$ (mc, 2H; tos CH), 7.77 (mc, 2H; tos CH), 7.49 (mc, 1H; arom CH), 7.40 (mc, 2H; arom CH), 7.30 (mc, 2H; arom CH), 4.49 (mc, 2H; oxaz CH, oxaz CH_2), 4.34 (mc, 1H; oxaz CH_2), 4.27 (mc, 1H; C*H*$_2$OH), 4.04 (mc; C*H*$_2$OH), 2.43 ppm (s, 3H; tos CH_3); $^{13}C\{^1H\}$ NMR (100.6 MHz, $CDCl_3$, 300 K): $\delta = 145.4$ (tos C), 132.9 (tos C), 132.3 (arom CH), 130.3 (2C; tos CH), 128.8 (2C; arom CH), 128.8 (2C; arom CH), 128.4 (2C; tos CH), 127.3 (arom C), 71.1 (CH_2), 70.3 (CH_2), 65.4 (oxaz CH), 22.1 ppm (tos CH_3), 1 quat C not detected; IR (NaCl): $\tilde{\nu} = 2976$ (w), 1648 (m), 1452 (w), 1366 (s), 1269 (w), 1176 (s), 1023 (m), 969 (m), 837 (m), 690 (m), 555 cm^{-1} (m); MS (FAB): *m*/*z* (%): 332 (100) $[M+H]^+$; elemental analysis calcd (%) for $C_{17}H_{17}NO_4S$ (331.39): C 61.61, H 5.17, N 4.23, O 19.31; found: C 61.56, H 5.20, N 4.19, O 19.50.

General procedure for the preparation of imidazolium salts 15a–p: A solution of tosylate **14a** (400 mg, 1.28 mmol) and 1-methyl-1*H*-imidazole (105 mg, 1.28 mmol) in DMF (0.5 mL) was heated at 80 °C for 8 h. The mixture was concentrated in vacuo at 80 °C and the residue was diluted in acetone (5 mL). $NaBAr_F$ (1.13 g, 1.28 mmol) was added to the solution that was stirred at room temperature for 30 min. The mixture was filtered and concentrated in vacuo to remove the solvent. The crude product was purified by chromatography on silica gel (5×10 cm column) eluting with CH_2Cl_2 (1 L) to yield a white solid (**15a**, 1.06 g, 0.973 mmol, 76%).

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Compound 15a: M.p. 120–121 °C; $[\alpha]_D^{20} = +35.5$ ($c = 1.00$, $CHCl_3$); ^{1}H NMR (500.1 MHz, $CDCl_3$, 295 K): $\delta = 8.45$ (s, 1H; NCHN), 7.69 (mc, 8H; BAr_F *ortho* CH), 7.52 (mc, 4H; BAr_F *para* CH), 7.07 (mc, 1H; imid CH), 6.92 (mc, 1H; imid CH), 4.40 (mc, 1H; oxaz CH_2), 4.30 (mc, 1H; oxaz CH), 4.05 (mc, 1H; NCH_2), 3.81 (mc, 2H; oxaz CH_2, NCH_2), 3.72 (s, 3H; NCH_3), 1.16 ppm (s, 9H; *t*Bu CH_3); ^{13}C{^{1}H} NMR (125.7 MHz, $CDCl_3$, 295 K): $\delta = 178.0$ (OCN), 161.7 (q, ^1J(B,C) = 49.9 Hz, 4C; BAr_F quat C *ipso* to B), 135.3 (NCHN), 134.7 (br, 8C; BAr_F *ortho* CH), 129.0 (qq, ^2J(F,C) = 31.12 Hz, ^3J(B,C) = 2.9 Hz, 8C; BAr_F C *ipso* to CF_3), 124.5 (q, ^1J(F,C) = 272.5 Hz, 8C; BAr_F CF_3), 123.7 (imid CH), 122.9 (imid CH), 117.5 (sept, ^3J(F,C) = 3.8 Hz, 4C; BAr_F *para* CH), 69.2 (oxaz CH_2), 64.7 (oxaz CH), 54.1 (NCH_2), 36.5 (NCH_3), 33.5 (*t*Bu C), 27.4 ppm (3C; *t*Bu CH_3); IR (KBr): $\tilde{\nu} = 3163$ (w), 3098 (w), 2980 (w), 1655 (w), 1610 (w), 1577 (w), 1562 (w), 1482 (w), 1356 (m), 1282 (s), 1122 (s br), 932 (w), 889 (w), 839 (w), 745 (w), 713 (w), 682 (w), 671 (w), 624 cm^{-1} (w); MS (FAB): *m/z* (%): 222 (100) $[M-BAr_F]^+$; elemental analysis calcd (%) for $C_{44}H_{32}BF_{24}N_3O$ (1085.52): C 48.68, H 2.97, N 3.87; found: C 48.63, H 3.15, N 3.64.

General procedure for catalytic hydrogenation at elevated pressure: In a glovebox, 0.1 mmol substrate, 1 mol% iridium complex, and 0.5 mL CH_2Cl_2 were added to a 60-mL autoclave (Premex AG, Lengnau, Switzerland) with four glass inserts (1.5 mL) and magnetic stirrer bars. The autoclave was pressurized to 50 bar H_2 gas (Carbagas, Switzerland, 99.995%) and the mixture was stirred for 2 h. After pressure release, the solvent was evaporated and heptane (3 mL) was added. The resulting suspension was filtered through a short plug of silica gel (0.5 × 6 cm) eluting with a mixture of hexane and Et_2O (1:1) and the filtrate was analyzed by GC and chiral HPLC to determine conversion and enantioselectivity (for analytical procedures and data, see reference [3]).

General procedure for catalytic hydrogenation at low pressure (1 bar H_2): A solution of 0.1 mmol substrate with 1 mol% iridium complex in dry CH_2Cl_2 (2–3 mL) was prepared under inert atmosphere in a 20 mL Schlenk flask (∅ ~ 1.5 cm). The mixture was stirred for 0.5–2 h with slow bubbling of hydrogen gas through the solution introduced through a stainless-steel needle. The temperature was kept constant at 25 °C by using a water bath. Work-up and analyses were performed as described for the hydrogenation at high pressure.

Crystal structure analysis: CCDC-288265 (**7c**), CCDC-288267 (**16q**), and CCDC-288266 (**17**) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from the Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

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