Chiral Imidazolylidine Ligands for Asymmetric Hydrogenation of Aryl Alkenes

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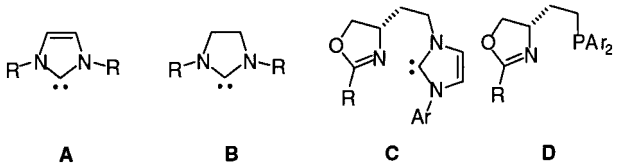
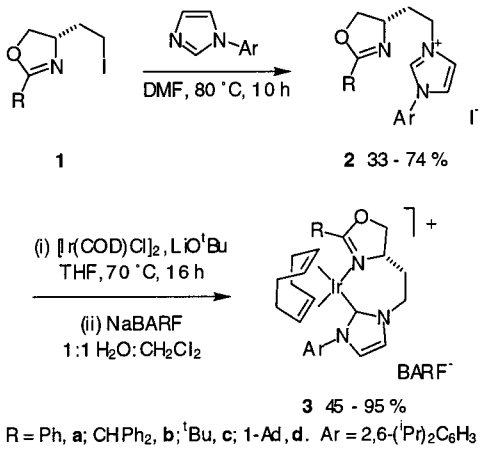
Imidazolylidines **A**, their saturated analogues imidazolinylidines **B**, and related heterocyclic electron-rich carbenes, are useful ligands for transition metals;[1] they stabilize low oxidation states giving robust complexes.[2] Such complexes have been used for several catalytic applications including alkene metathesis,[3] hydrogenations,[4] and C−C[5] and C−N[6] bond construction. These reported transformations do not, however, include useful asymmetric catalysis. Indeed, even though at least 10 different types of chiral carbene ligands of this kind have been prepared and complexed,[2,7] to the best of our knowledge, the best enantioselectivities obtained are less than 76%.[8,9]

Reported here is design and synthesis of the ligand set **C** that can give enantioselectivities of up to 98% in asymmetric hydrogenations of *E*-aryl alkenes. This is especially notable because asymmetric hydrogenations of this kind are difficult and there are only a few practical systems for doing this.[10,11][11] Moreover, the results obtained here indicate that competing mechanistic pathways that could diminish the enantioselectivity of the process, are less prevalent than for analogous phosphine complexes **D**.

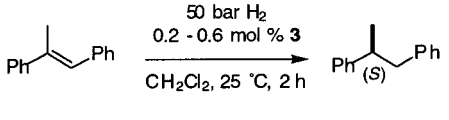


Complexes of the carbenes **C** were prepared by forming the iodides **1** from the corresponding tosylates[12] and then by using these to generate the imidazolium salts **2** (Scheme 1). Salts **2** were reacted with an iridium precursor as shown {the anion exchange was with tetrakis(3,5-bis(trifluoromethyl)phenyl)borate ($BARF^-$)}.

Scheme 1. Synthesis of the Catalysts



Hydrogenation of *E*-1,2-diphenylpropene was chosen as a model reaction to test potential catalysts. Data obtained for the phenyl-, diphenylmethyl-, and *tert*-butyl-substituted oxazoline complexes **3a**−**c** were not encouraging; the maximum enantiomeric excess obtained using these was 40%. However, against expectations, the 1-adamantyl oxazoline complex **3d** gave almost complete conversion and a near perfect enantioselectivity. Even in retrospect, the markedly different enantioselectivities obtained using *tert*-butyl- and 1-adamantyl-substituted ligands seem surprising.



3	E.e (%)	Yield (%)
a	13	25
b	25	12
c	40	33
d	98	99

Data for hydrogenations of trisubstituted alkenes using the adamantyl-derived catalyst **3d** are collected in Table 1. The enantioselectivities for hydrogenations of the *E*-alkenes ranged from 84 to 98%, but *Z*- and 1,1-disubstituted alkenes gave lower values (entries 6 and 7). Comparisons were performed using catalyst **3c**, but in all cases inferior enantioselectivities were obtained (see Supporting Information).

Investigation of the analogous phosphine oxazolines **D** in asymmetric hydrogenations of aryl alkenes provides data for comparison with that obtained in this study.[14] The results shown

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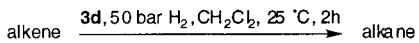
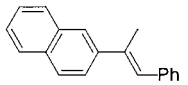
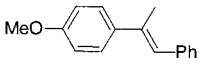
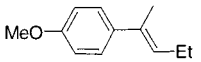
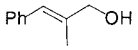
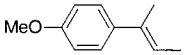
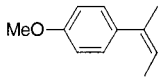
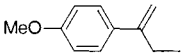
Table 1. Hydrogenations of Trisubstituted Alkenes



Entry	Alkene	**3d** (mol %)	Yield[a] (%)	E.e.[a] (%) (c'fig)
1		1.0	90	93 (*R*)
2		0.6	99	97 (*S*)
3		0.6	94	84[c]
4		1.0	99	93[c]
5		0.6	99	91 (*S*)
6[b]		1.0	95	78 (*R*)
7		0.3	91	31 (*R*)

[a] Determined via GC on a cyclodextrin-based chiral column[13] versus an internal standard. [b] Reaction temperature 0 °C. [c] Absolute configuration not determined.

in Table 1 are comparable with or superior to those obtained by Pfaltz and co-workers[3] and in our laboratories[14] using similar substrates in hydrogenations mediated by chiral phosphine oxazolines.

Our recent studies with analogous iridium complexes of phosphine oxazolines **D** have shown that hydrogenations via other mechanistic pathways can compete with the desired direct hydrogenation process.[14] *Z*- and 1,1-disubstitued alkenes are particularly susceptible to this, whereas such complications are much less prevalent for *E*-alkenes. Competing mechanistic pathways such as double bond migrations make enantioselectivities more difficult to optimize, and they may be a contributing factor if high induction cannot be obtained. Consequently, it is relevant to compare the extent of these reactions leading to "indirect hydrogenations" for analogous carbene **C** and phosphine **D** complexes.

Evidence for indirect introduction of hydrogen was obtained by deuterating, rather than hydrogenating, selected alkenes. Figure 1 shows the relative levels of deuterium incorporation obtained

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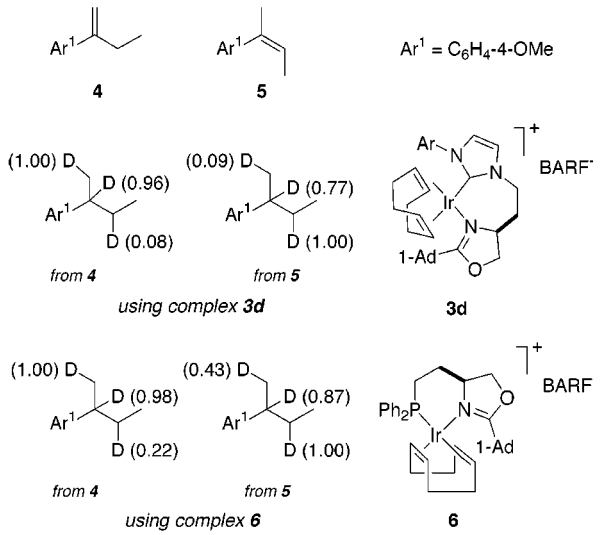

Figure 1. Relative levels of deuteration of alkenes **4** and **5** using catalysts **3d** and **6**, as measured by ^{2}H NMR.

by deuterating alkenes **4** and **5** using an imidazolylidine oxazoline complex **3d** and a similar phosphine oxazoline complex **6**. These preliminary studies show that the carbene complex gave fewer products that may be attributed to competing mechanistic pathways. Indirect addition of hydrogen is a concern when using either catalyst to hydrogenate *Z*- and 1,1-disubstitued alkenes, but this phenomenon is less important for the carbene complex **3d** than for the phosphine **6**.

This research has demonstrated that chiral imidazolylidine complexes can induce high enantioselectivities in catalytic hydrogenations of *E*-aryl alkenes; this is the first report of high induction using electron-rich carbene ligands in any catalytic process. These ligands cannot present edge-face arrays of aryl groups in the same way that many phosphine complexes do, and thus control of enantioselectivities must originate from other topographical features. These might be relatively subtle as indicated by the higher enantioselectivities obtained for the adamantyl complex **3d** relative to the *tert*-butyl analogue **3c**. Studies of the *Z*- and 1,1-disubstituted alkenes **4** and **5**, respectively, indicate that the rate ratio for direct hydrogenation relative to more circumspect pathways is higher for the iridium carbene complex **3d** than it is for the similar phosphine complex **6**. Consequently, subtle mechanistic advantages may be accrued by using imidazolylidenes in preference to the corresponding phosphines. These should be considered along with the more obvious attributes of the carbenes that relate to ease of ligand preparation and catalyst stability.

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Supporting Information Available: Data for hydrogenations with complex **3c**, experimental details for the preparation of compounds **1**−**3**, a general procedure for the hydrogenation (deuteration) experiments, discussion of determination of absolute configurations and on solvent effects in these reactions (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

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