Dalton Transactions

Accepted Manuscript

ROYAL SOCIETY OF CHEMISTRY

www.rsc.org/dalton

Dalton Transactions

RSCPublishing

ARTICLE

Ruthenium and osmium complexes of hemilabile chiral monophosphinite ligands derived from 1D-pinitol or 1D-*chiro*-inositol as catalysts for asymmetric hydrogenation reactions

Cite this: DOI: 10.1039/x0xx00000x

Received 00th August 2014,
Accepted 00th xxxxx 2014

DOI: 10.1039/x0xx00000x

www.rsc.org/

Angela T. Slade [a], Cornelis Lensink [b], Andrew Falshaw [b], George R. Clark [a], L. James Wright [a*]

The monophosphinite ligands, 1**D**-1,2;5,6-di-*O*-cyclopentylidene-3-*O*-methyl-4-*O*-diphenylphosphino-*chiro*-inositol (**D-P1**), 1**D**-1,2;5,6-di-*O*-isopropylidene-3-*O*-methyl-4-*O*-diphenylphosphino-*chiro*-inositol (**D-P2**), 1**D**-1,2;5,6-di-*O*-cyclohexylidene-3-*O*-methyl-4-*O*-diphenylphosphino-*chiro*-inositol (**D-P3**), and 1**D**-1,2;5,6-di-*O*-cyclopentylidene-3-*O*-ethyl-4-*O*-diphenylphosphino-*chiro*-inositol (**D-P4**), can be conveniently prepared from the chiral natural products 1D-pinitol or 1D-*chiro*-inositol. On treatment of toluene solutions of $RuCl_2(PPh_3)_3$ with two mole equivalents of the ligands **D-PY** (Y = 1 - 4) the complexes $RuCl_2$(D-P1)$_2$ (**1**), $RuCl_2$(D-P2)$_2$ (**4**), $RuCl_2$(D-P3)$_2$ (**5**), or $RuCl_2$(D-P4)$_2$ (**6**), respectively, are formed. Similarly, treatment of $OsCl_2(PPh_3)_3$ with **D-P1** gives $OsCl_2$(D-P1)$_2$ (**7**). The single crystal X-ray structure determination of **1** reveals that each **D-P1** ligand coordinates to ruthenium through phosphorus and the oxygen atom of the methoxyl group. Treatment of **1** with excess LiBr or LiI results in metathesis of the chloride ligands and $RuBr_2$(D-P1)$_2$ (**2**) or RuI_2(D-P1)$_2$ (**3**), respectively, are formed. Exposure of a solution of **1** to carbon monoxide results in the very rapid formation of $RuCl_2(CO)_2$(D-P1)$_2$ (**8**), thereby demonstrating the ease with which the oxygen donors are displaced from the metal and hence the hemilabile nature of the two bidentate D-P1 ligands in **1**. Preliminary studies indicate that **1** - **7** act as catalysts for the asymmetric hydrogenation reactions of acetophenone and 3-quinuclidinone to give the corresponding alcohols in generally high conversions but low enantiomeric excesses.

Introduction

The development and study of homogeneous asymmetric hydrogenation catalysts continue to be actively investigated as these compounds have significant commercial value[1] and continue to reveal fundamental information about the intricate and involved nature of catalytic reactions.[2-4] The synthesis of chiral ligands can be time consuming and therefore utilising starting materials that are enantiopure, readily available, and easily functionalised has considerable merit. In this context chiral ligands that have been derived from natural starting materials such as carbohydrates have become progressively more common over the past 20 years.[5-10] *Chiro*-inositols are important members of this class that display a number of attractive features including availability from natural products of both the D- and L-enantiomers, the presence of six hydroxyl groups that provide extensive scope for selective functionalization, and a chemically robust cyclohexane backbone.

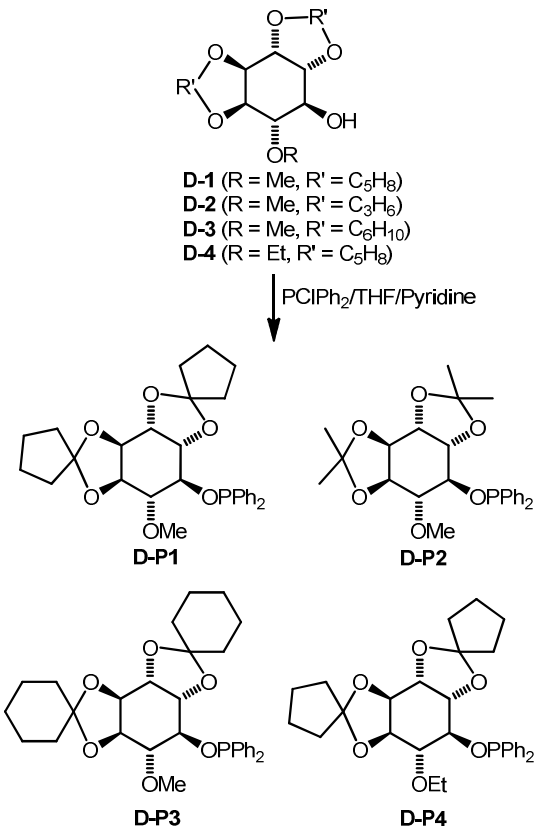
The deployment of chiral phosphinite ligands is well established in transition metal catalysed asymmetric hydrogenation reactions, and usually these ligands take the form of bidentate diphosphinite donors.[5, 7, 9-28] We have demonstrated previously that two of the hydroxyl groups in *chiro*-inositols can be selectively converted into phosphinite donors with ease and the resulting bidentate diphosphinite chiral ligands can be successfully used in catalytic asymmetric hydrogenation reactions.[16, 22, 24] Since recent studies have revealed that monodentate ligands can be important and successful components in asymmetric catalysis we chose to prepare some related monophosphinite ligands that are also constructed from *chiro*-inositiol scaffolds. This would then enable the catalytic activities of the derived metal compounds to be compared with the bidentate diphosphinite analogues. Unexpectedly, it was found that the synthesized monophosphinite ligands coordinated to ruthenium or osmium through both the phosphorus donor and also weakly through the oxygen atom of an adjacent methoxyl group that is attached to the *chiro*-inositiol ring. In this arrangement the monophosphinites behave as classic hemilabile bidentate ligands with the methoxyl groups masking potentially vacant coordination sites at the metal centres.[29-33] In this paper we specifically report: i) the synthesis of the four chiral monophosphinite compounds 1**D**-1,2;5,6-di-*O*-

cyclopentylidene-3-*O*-methyl-4-*O*-diphenylphosphino-*chiro*-inositol (**D-P1**), 1**D**-1,2;5,6-di-*O*-isopropylidene-3-*O*-methyl-4-*O*-diphenylphosphino-*chiro*-inositol (**D-P2**), 1**D**-1,2;5,6-di-*O*-cyclohexylidene-3-*O*-methyl-4-*O*-diphenylphosphino-*chiro*-inositol (**D-P3**), and 1**D**-1,2;5,6-di-*O*-cyclopentylidene-3-*O*-ethyl-4-*O*-diphenylphosphino-*chiro*-inositol (**D-P4**); ii) the use of these hemilabile ligands to prepare $RuCl_2$(D-P1)$_2$ (**1**), $RuBr_2$(D-P1)$_2$ (**2**), RuI_2(D-P1)$_2$ (**3**), $RuCl_2$(D-P2)$_2$ (**4**), $RuCl_2$(D-P3)$_2$ (**5**), $RuCl_2$(D-P4)$_2$ (**6**), $OsCl_2$(D-P1)$_2$ (**7**), and $RuCl_2(CO)_2$(D-P1)$_2$ (**8**) through carbonylation of **1**; iii) the X-ray crystal structure determination of **1**; and iv) investigation of **1**-**7** as precatalysts for homogeneous asymmetric hydrogenation of the prochiral substrates acetophenone and 3-quinuclidinone.

Results and discussion

Syntheses of the monophosphinite ligands (D-PY (Y = 1-4))

D-1, **D-2**, and **D-3** were all prepared from 1D-pinitol using slightly modified versions of a reported procedure as detailed in the Experimental Section.[34, 35] **D-4** was prepared from 1D-*chiro*-inositol again using a modified literature synthesis.[34-36] The new monophosphinite ligands **D-P1** – **D-P4** were prepared in high yield through reaction between the single hydroxyl group in each of the compounds **D-1** – **D-4**, respectively, and $PClPh_2$ (Scheme 1).

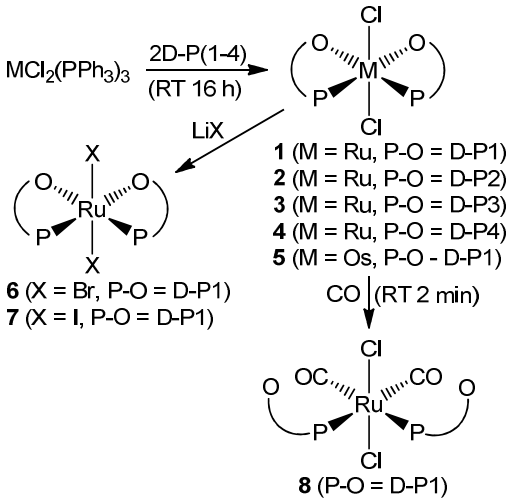


Scheme 1. Syntheses of the ligands **D-PY** (Y = 1-4).

These ligands are all crystalline compounds with moderate air stability. Characterising data for **D-P1** – **D-P4**, and all the other new compounds are collected in the Experimental section. **D-P1** – **D-P4** all have C_1 symmetry and a unique resonance is observed in the ^{13}C NMR spectrum for each of the six carbon atoms of the cyclohexane backbone in all cases. Similarly, separate signals are observed for each carbon atom of the substituent cyclopentylidene rings, cyclohexylidene rings, or isopropylidene groups, apart from the few cases where coincidental overlap of two signals was observed.

Syntheses of the ruthenium and osmium monophosphinite complexes MCl_2(D-PY)$_2$ (Y = 1-4).

Treatment of $RuCl_2(PPh_3)_3$ with two mole equivalents of **D-P1** in toluene under nitrogen at approximately 18 ^oC for 16 hours resulted in the formation of $RuCl_2$(D-P1)$_2$ (**1**) as an orange/red crystalline solid in 85% yield after purification (Scheme 2). Monitoring of the reaction by ^{31}P NMR spectroscopy indicated the reaction was mostly complete after 30 minutes. Compound **1** was purified using column chromatography on alumina, followed by recrystallisation from diethylether/methanol. The same compound could also be obtained by heating $[RuCl_2(COD)]_n$ with four mole equivalents of **D-P1** and excess triethylamine in toluene for 11 hours.[22] However, the yield of **1** obtained by this method was only 42% and so this was not the preferred method of synthesis.



Scheme 2. Synthesis of ruthenium and osmium complexes **1**-**8**.

The geometry of **1** depicted in Scheme 2 is the same as that obtained from a single crystal X-ray structure determination of **1** (see below). The spectroscopic data are consistent with this C_2 symmetric structure being retained in solution, although it should be noted that this is not the only C_2 symmetric possibility for the solution structure. Thus, in the ^{31}P NMR spectrum of **1** a single resonance was observed for the two equivalent phosphorus nuclei at 169.98 ppm. In the ^1H NMR spectrum the resonance of the two –OMe groups appears as a singlet at 4.18 ppm. This shift is considerably down-field compared to the corresponding resonance of the free ligand (3.10 ppm). A similar down-field shift was observed in the ^{13}C NMR spectrum for the single resonance assigned to the two –OMe groups (64.5 vs 59.2 ppm for the free ligand). In contrast, the remaining ^{13}C NMR chemical shifts of the two **D-P1** ligands were very similar to those observed for the free ligand and in addition only one set of signals was observed for the two magnetically equivalent **D-P1** ligands. The pronounced down-field shifts of the –OMe NMR resonances are consistent with these groups making a close approach to the metal centre and

this was confirmed by a single crystal X-ray structure determination of **1**.

The molecular and absolute structure of **1** is shown in Figure 1 and selected bonds and angles are collected in Table 1. The crystal data and refinement details for **1** are available in the Supporting Information. The geometry about the ruthenium centre is approximately octahedral with the two chloride ligands mutually *trans* and the two phosphorus donors mutually *cis*. The oxygen atoms of the two –OMe substituents make close approaches to the ruthenium centre. The Ru–O(4) distance (2.273(3) Å) is close to the average of reported Ru–O(ether) bond lengths (2.270 Å, CCDB) while the Ru–O(3) distance (2.318(3) Å) is significantly longer than this value. Ru–O(ether) bonds are typically very labile,[37] and these distances suggest the –OMe groups are only very weakly bound to ruthenium and hence form part of a hemilabile bidentate ligand system. Not unexpectedly, the Ru–P distances *trans* to these weakly bound Ru–OMe groups are relatively short (Ru–P(1) 2.2217(12) Å, Ru–P(2) 2.2177(12) Å).[22, 24, 38] The remaining bond lengths and angles are normal and do not warrant further discussion.

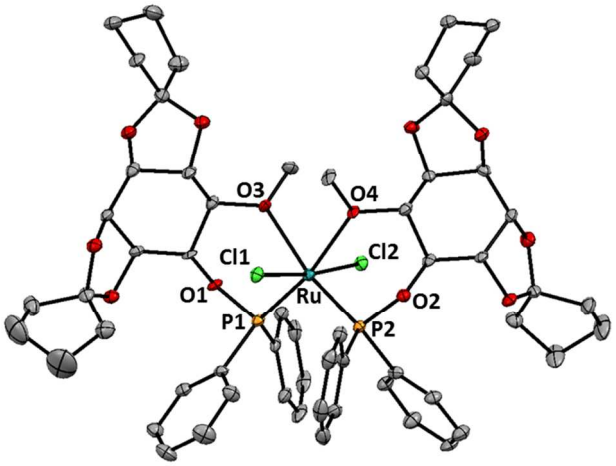


Figure 1. The molecular structure of $RuCl_2$(D-P1)$_2$ (**1**) (hydrogen atoms omitted for clarity and ellipsoids at the 50 % level).

Atoms	Lengths (Å)	Atoms	Angles (°)
Ru–P(2)	2.2177(12)	P(2)–Ru–P(1)	104.49(4)
Ru–P(1)	2.2217(12)	O(4)–Ru–O(3)	78.05(11)
Ru–O(4)	2.273(3)	P(2)–Ru–O(3)	166.34(8)
Ru–O(3)	2.318(3)	P(1)–Ru–O(3)	88.93(9)
Ru–Cl(2)	2.4038(11)	P(1)–Ru–Cl(1)	93.71(4)
Ru–Cl(1)	2.4050(12)	P(2)–Ru–Cl(1)	90.41(4)
		O(3)–Ru–Cl(1)	86.13(9)
		Cl(2)–Ru–Cl(1)	172.81(4)

Table 1. Selected bond lengths and angles for $RuCl_2$(D-P1)$_2$ (**1**).

$RuCl_2$(D-P2)$_2$ (**2**) and $RuCl_2$(D-P3)$_2$ (**3**) were prepared in a manner similar to that used for the preparation of **1** (Scheme 2). However, purification of the crude **2** or **3** obtained after treatment of $RuCl_2(PPh_3)_3$ with two mole equivalents of either **D-P2** or **D-P3**, respectively, proved to be more difficult than was the case for **1**. Two separate chromatographic steps followed by recrystallisation were required to obtain pure samples of **2** or **3** and as a consequence the yields of pure material obtained were low. The NMR spectral data obtained for complexes **2** and **3** are very similar to those obtained for **1** suggesting they have closely related structures. Thus, in the ^{31}P NMR spectra a singlet resonance is observed in each case (at 170.0 and 169.8 ppm for **2** and **3**, respectively) and single downfield shifted resonances are also observed for the –OMe groups in both the ^{1}H NMR (at 4.24 and 4.20 ppm for **2** and **3**, respectively) and ^{13}C NMR spectra (at 64.7 and 64.9 ppm for **2** and **3**, respectively). Also, for both **2** and **3** only one set of signals are observed in the ^{13}C NMR spectra for the two phosphinite ligands signifying that in each case the two phosphinite ligands are magnetically equivalent.

One of the desirable features of the *chiro*-inositol core is that it is readily amenable to modification through the incorporation of different substituent groups. Since the methoxyl substituent of **D-P1** is brought close to the metal centre in complexes of this ligand, it was anticipated changes to the steric bulk of this substituent could substantially influence reactivity. It is for this reason that the monophosphinite ligand **D-P4**, which contains an –OEt in the place of the –OMe group, was synthesised. The complex $RuCl_2$(D-P4)$_2$ (**4**) was subsequently obtained by a procedure analogous to that used for the synthesis of **1** (Scheme 2). Aside from the signals due to the ethyl substituents, the NMR spectral data of **4** are very similar to those of **1** and this indicates the structure of **4** is probably also analogous to that of **1**.

$OsCl_2(PPh_3)_3$ can also be used as a metal substrate for complex formation with **D-P1**. Following the procedure used for the synthesis of **1**, it was found that treatment of $OsCl_2(PPh_3)_3$ with **D-P1** for one hour at 18 ^{o}C under nitrogen gave $OsCl_2$(D-P1)$_2$ (**5**) as a yellow solid in 61% yield after purification (Scheme 2). A singlet signal at 90.0 ppm is observed in the ^{31}P NMR spectrum of **5** for the two phosphorus nuclei. In the ^{1}H NMR spectrum the two –OMe groups appear as a singlet resonance at 4.26 ppm (cf. 4.18 ppm in **1**) and in the ^{13}C NMR spectrum a singlet signal is also observed for these two groups at 64.8 ppm (cf. 64.5 ppm in **1**). The remaining NMR data also closely resemble that of **1** indicating that the structure of **5** is probably analogous to that of **1** with the two –OMe groups forming weak interactions with the metal centre.

The chloride ligands in **1** are labile and can be replaced by other halides using simple metathesis reactions. Thus, treatment of a solution of **1** with excess lithium bromide or lithium iodide gives $RuBr_2$(D-P1)$_2$ (**6**) or RuI_2(D-P1)$_2$ (**7**), respectively. The ^{31}P, ^{13}C, and ^{1}H NMR spectra of pink **6** and purple **7** are closely similar to the spectra obtained for **1**, again suggesting the structures of these compounds mirror that found for **1**.

As discussed above, the data from the X-ray structure determination of **1** suggests that the oxygen atoms of the two –OMe groups are only weakly bound to the ruthenium centre. To test whether these oxygen atoms can be easily displaced from ruthenium, CO gas was bubbled through a solution of **1**. The orange solution immediately turned yellow on exposure to CO and the dicarbonyl derivative, $RuCl_2(CO)_2$(D-P1)$_2$ (**8**), was obtained in high yield (Scheme 2). In the IR spectrum of **8** two ν(CO) bands are observed (at 2020 and 1962 cm^{-1}) indicating the two CO ligands have a mutually *cis* arrangement. The two equivalent –OMe methyl groups are observed as a singlet in the ^{1}H NMR spectrum at 3.32 ppm. This is considerably up-field from the chemical shifts observed for these groups in the

complexes **1-3**, **5-7** (*ca*. 4.2 ppm) where coordination of the oxygen atoms to the metal centres is proposed, but very similar to the shift observed for the free ligand (3.10 ppm). These data provide strong supporting evidence that the oxygen atoms have been displaced from ruthenium in **8**, but are coordinated to the metal in the other complexes. The NMR spectral data of **8** are consistent with this product retaining C_2 symmetry. Only a single resonance is observed in the ^{31}P NMR spectrum for the two equivalent phosphorus nuclei and only one set of signals in the ^{13}C NMR spectrum is observed for the carbon atoms of the two phosphinite ligands.

The very rapid displacement of the two –OMe groups from the ruthenium centre in **1** by CO suggests that the two chiral phosphinite ligands in this complex do indeed act as hemilabile bidentate ligands with the methoxyl groups masking potentially vacant coordination sites at the metal centre.[29-33] On the basis of the similarity of the spectral properties of the closely related complexes **2-7**, it is most likely that the phosphinite ligands in these compounds also act as hemilabile bidentate ligands. The labile donor bond formed between a hemilabile ligand and a metal can provide the metal with the capacity to readily accommodate incoming substrate molecules during catalysis.[39-42] Hemilabile ligands have been studied quite extensively in catalyst development and it has been demonstrated they can favourably influence the regio- and stereoselectivity of reactions.[41-46] The potential of the compounds **1** – **7** to engage in catalytic asymmetric hydrogenation reactions was therefore investigated.

Investigation of the catalytic activity of the new ruthenium and osmium monophosphinite complexes in asymmetric hydrogenation reactions of the prochiral substrates acetophenone and 3-quinuclidinone

Preliminary studies were carried out to determine whether the complexes **1-7** that contain the chiral, hemilabile monophosphinite ligands **D-PY** (Y = 1-4) might act as pre-catalysts for the asymmetric hydrogenation of prochiral ketones. The reaction conditions were selected to match those used in previous studies of related chiral complexes and were as follows: hydrogen pressure, 1000 psi; temperature, 60 ^{o}C; time, 3 hours; solvent, toluene/isopropanol (1:1); KO^{t}Bu (two mole equivalents *vs.* ruthenium complex); substrate:precatalyst mole ratio, 200:1. Reactions were investigated with the prochiral ketones acetophenone and 3-quinuclidinone and the results obtained are collected in Table 2.

Compounds **1**, **3**, **6** and **7** are all effective pre-catalysts for the hydrogenation of acetophenone to give *sec*-phenylethyl alcohol with either complete or near complete conversions achieved under the stated conditions. As might be expected the activity of the osmium complex **5** is low and this also is the case for the ruthenium complex **2** which contains the least sterically demanding phosphinite ligand **D-P2**. For the ruthenium complexes **1**, **3**, **6**, and **7**, the % ee values obtained for this reaction were all very poor and in the range 11-14% (the dominant enantiomer formed was *(R)-sec*-phenylethyl alcohol). Almost no chiral discrimination was observed for **2**, possibly as a result of the smaller size of the substituents on the cyclohexyl rings of the phosphinite ligands. The osmium complex **5** showed no selectivity at all. Changes to the ancillary halide ligands of the pre-catalysts (see results for **1**, **6** and **7**, Table 2) had little effect on the catalytic results.

With respect to the catalytic hydrogenation of 3-quinuclidinone to give 3-quinuclidinol, all the ruthenium complexes were effective pre-catalysts with conversions being either complete or near complete after 3 hours. The osmium compound **5** was not an effective catalyst under these conditions with only 22% conversion observed. The enantioselectivities were poor in all cases, but higher than those obtained in the catalytic hydrogenation of acetophenone discussed above. For the ruthenium compounds **1**, **3**, **6**, and **7,** % ee values were obtained in the range 17-22% (the dominant enantiomer was (*R)*-3-quinuclidinol). Again, the ruthenium complex **2** with the smaller **D-P2** ligands gave a lower % ee value (13%). Somewhat surprisingly, **4** (with the OEt-substituted **D-P4** ligand) gave the lowest % ee value of 5%. A much deeper understanding of the mechanism of this reaction is needed before any meaningful explanation can be offered for the lower enantioselectivity that is observed on replacing the **-**OMe group in **D-P1** by **-**OEt. As noted above, changes to the ancillary halide ligands of the pre-catalysts (see results for **1**, **6** and **7**, Table 2) had little effect on the catalytic results.

These results obtained with **1**, **3**, **6**, and **7** compare favorably with those obtained for analogous reactions that use as pre-catalysts the complexes RuHCl(D-9)$_2$ (**D-9** = 1D-3,4-bis(*O*-diphenylphosphino)-1,2,5,6-tetra-*O*-methyl-*chiro*-inositol)[22, 24] or RuHCl((1*S*,2*S*)-10)$_2$ (**(1*S*,2*S*)-10** = ((1*S*,2*S*)-1,2-*trans*-bis-(*O*-diphenylphosphino)cyclohexane).[24] **D-9** and **(1*S*,2*S*)-10** are both ***bidentate diphosphinite*** ligands that have chiral cyclohexane backbones. Neither of the complexes RuHCl(D-9)$_2$ or RuHCl((1*S*,2*S*)-10)$_2$ are good hydrogenation catalysts for acetophenone (20% and 0% conversion, respectively) and in the former case almost no enantioselectivity (2%) was displayed. However, both of these metal complexes do effectively catalyse the hydrogenation of 3-quinuclidinone (97 and 99%, respectively), although this occurs with very poor enantioselectivity (2% and 10%, respectively). In comparison, **1**, **3**, **6**, and **7** all perform as superior hydrogenation catalysts for both substrates, giving better conversions for acetophenone, similar conversions for 3-quinuclidinone, and enhanced enantioselectivities for both substrates.

Conclusions

The new chiral monophosphinite ligands **D-PY** (Y = 1-4) can be conveniently prepared from the chiral natural products 1D-pinitol or 1D-*chiro*-inositol. These monophosphinite ligands coordinate to ruthenium or osmium in the complexes **1-7** as hemilabile bidentate ligands with the methoxyl (or ethoxyl in the case of **4**) groups masking potentially vacant coordination sites at the metal centre. Although these compounds act as effective hydrogenation catalysts for the prochiral ketones acetophenone and 3-quinuclidinone (up to 99% in both cases), the observed enantioselectivities are poor (up to 14% ee and 22% ee, respectively). Nevertheless, these ketone hydrogenation conversions and enantioselectivities are better than those obtained in analogous catalytic reactions involving the ruthenium complexes RuHCl(D-9)$_2$ or RuHCl((1*S*,2*S*)-10)$_2$ that contain bidentate diphosphinite ligands with related chiral cyclohexane backbones.[22, 24] It is possible that the superior performance of **1**, **3**, **6**, and **7** results, at least in part, from the hemilabile nature of the **D-PY** ligands which allows the reactants better access to the metal centre. From the limited data obtained it appears that increasing the steric bulk of the dioxolane ring substituents of the **D-PY** (Y = 1-4) ligands improves the enantioselectivities of the hydrogenation reactions while increasing the bulk of the lone alkoxy substituent has the opposite effect. Changes to the ancillary halide ligands of the complexes have little effect on the performance of the catalysts.

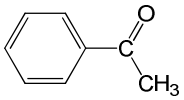
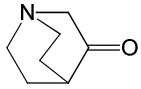
	Acetophenone 		3-Quinuclidinone 	
Precatalyst	**Conversion (%)**	**% ee (*configuration*)**	**Conversion (%)**	**% ee (*configuration*)**
$RuCl_2$(D-P1)$_2$ (**1**)	89	14 (*R*)	97	18 (*R*)
$RuCl_2$(D-P2)$_2$ (**2**)	32	4 (*R*)	95	13 (*R*)
$RuCl_2$(D-P3)$_2$ (**3**)	99	14 (*R*)	99	18 (*R*)
$RuCl_2$(D-P4)$_2$ (**4**)	-	-	96	5 (*R*)
$OsCl_2$(D-P1)$_2$ (**5**)	21	0	22	19 (*R*)
$RuBr_2$(D-P1)$_2$ (**6**)	99	12 (*R*)	99	22 (*R*)
RuI_2(D-P1)$_2$ (**7**)	95	11 (*R*)	99	17 (*R*)

Table 2. Conversion (%), % ee, and configuration of the major enantiomer formed during the catalytic hydrogenation of acetophenone and 3-quinuclidinone. Conditions: substrate: precatalyst ratio, 200: 1; hydrogen pressure, 1000 psi; KO^{t}Bu (2M *vs.* ruthenium complex); temperature, 60 ^{o}C; time, 3 hours; solvent, toluene/isopropanol (1 : 1); estimated error, ±5%.

Experimental

General considerations

Manipulations of air sensitive materials were conducted in an argon atmosphere by using either Schlenk techniques or an Innovative Technology inert atmosphere glove box. Tetrahydrofuran, ether, and toluene were distilled from sodium benzophenone ketyl under nitrogen and stored over activated 4 Å molecular sieves. Dichloromethane was distilled from calcium hydride. *n*-Hexane (>96%) was obtained commercially. All *n*-hexane employed for recrystallisation purposes was cooled to ≤5 ^{o}C. Triethylamine was distilled from calcium hydride and stored over potassium hydroxide. Pyridine was distilled from potassium hydroxide and stored over activated 4 Å molecular sieves. Flash column chromatography was carried out on 230-400 silica (Scharlau) or basic alumina (pH = 10; pore density 0.9 g L^{-1}; granulation 50-150 μm). ^{1}H, ^{13}C, and ^{31}P NMR spectra were obtained on a Bruker Avance 300 at 25 ^{o}C operating at 300.13 (^{1}H), 75.48 (^{13}C), and 121.5 (^{31}P) MHz. Resonances are quoted in ppm and the ^{1}H NMR is referenced to the proteo-impurity in the solvent (7.25 ppm for $CDCl_3$) or TMS (0.00 ppm). ^{13}C NMR spectra were referenced to $CDCl_3$ (77.0 ppm) and ^{31}P NMR spectra to 85% orthophosphoric acid (0.00 ppm) as an external standard. Elemental analyses were obtained from the Microanalytical Laboratory, University of Otago. FAB+ mass spectra were obtained from a VG-70SE machine. 1D-pinitol was obtained from New Zealand Pharmaceuticals Ltd, Palmerston North, New Zealand. 1D-*chiro*-inositol was prepared from 1D-pinitol.[47] 1,2:5,6-Diisopropylidene-3,4-di-*O*-methyl-*chiro*-inositol (**D-2**),[48] 1D-1,2:3,4:5,6-tri-*O*-isopropylidene-*chiro*-inositol,[49] 1D-1,2:5,6-di-*O*-isopropylidene-*chiro*-inositol,[49] $[RuCl_2(COD)]_n$,[50, 51] $RuCl_2(PPh_3)_3$,[52] and $OsCl_2(PPh_3)_3$[53] were all prepared according to literature methods. All other chemicals were obtained commercially.

General procedures and instruments employed for the hydrogenation reactions

Hydrogenations were carried out in 12 mL glass vials equipped with a magnetic stirrer bar. The vials were filled with catalyst (0.005 mmol), substrate (1.0 mmol), KO^{t}Bu (0.01 mmol), and 1 : 1 toluene/isopropanol (3 mL) for both the acetophenone and 3-quinuclidinone substrates inside an inert atmosphere glove box and then placed inside a 300 mL Parr autoclave made from Hastelloy C. In this way, several hydrogenation experiments could be carried out at the same time. The autoclave was sealed, taken outside the glovebox, and heated to 60^{o}C using a thermostatic heating mantle. The autoclave was then flushed with hydrogen three times before being filled with hydrogen (1000 psi). After 3 hours the autoclave was cooled and the pressure reduced to atmospheric pressure. The autoclave was opened and samples of the crude reaction mixture were analysed by GC. The GC analysis, to obtain conversion and enantiomeric excess values, was performed on a HP 6890 Series gas chromatography apparatus with an FID detector using a capillary Supelco GAMMA-DEX 225 (30 m x 0.25 mm x 0.25 mm) column or a SGE CYDEX-B (2 m x 0.32 mm x 0.25 mm) column. The estimated error in each %ee value is ±5%. The GC methods that were established for the two prochiral substrates were (1) acetophenone (80 ^{o}C isothermal): starting material tR (min) 29.4; products tR (min) R 33.3, S 34.2; (2) 3-quinuclidinone (140 ^{o}C for 10 min then ramped up to 220^{o}C at 10 ^{o}C min^{-1}): starting material tR (min) 10.8; products tR (min) R 12.5, S 12.9.

Preparation of 1D-1,2:5,6-di-O-cyclopentylidene-chiro-inositol

1D-1,2:5,6-Di-*O*-cyclopentylidene-*chiro*-inositol was prepared from 1D-*chiro*-inositol and cylcopentanone by the method reported in the literature[54] for the synthesis of di-*O*-cyclohexylidene. Purification was achieved by recrystallisation from ethyl acetate and gave analytically pure material. Anal. Calc. for $C_{16}H_{22}O_6$: C, 61.52; H, 7.74. Found: C, 61.47; H, 7.68. $[\alpha]_D$ = +12.6 ° (*c* 1.00, $CHCl_3$). ^{1}H NMR ($CDCl_3$): δ (ppm) 1.67-1.72 (m, 8H, CH_2), 1.90-1.95 (m, 8H, CH_2), 3.08 (s, 2H, OH), 3.55-3.56 (m, 2H, C*H*), 4.07-4.13 (m, 2H, C*H*), 4.26-

4.30 (m, 2H, C*H*). $^{13}C\{^1H\}$ NMR ($CDCl_3$): δ (ppm) 23.6, 24.1, 37.0, 37.3 (*C*H_2); 72.6, 76.1, 78.7 (*C*H); 119.7 (*C*$(O)_2R_2$).

Preparation of 1D-1,2:5,6-di-O-cyclopentylidene-3-O-methyl-*chiro*-inositol (D-1)

1D-1,2:5,6-di-O-cyclopentylidene-3-O-methyl-*chiro*-inositol was prepared from 1D-pinitol using a modified literature preparation[34, 54] by replacing cyclohexanone with cyclopentanone and purified by column chromatography on silica gel, using hexanes:ethyl acetate (3:2) as eluent. Recrystallisation from ethanol gave the pure product as a white solid (73%). Anal. Calc. for $C_{17}H_{26}O_6$: C, 62.56; H, 8.03. Found: C, 62.82; H, 8.21. ^1H NMR ($CDCl_3$): δ (ppm) 1.68-1.75 (m, 12H, CH_2), 1.93-1.98 (m, 4H, CH_2), 3.04 (d, 1H, $^3J_{HH}$ = 1.5 Hz, O*H*), 3.10-4.22 (m, 9H, C*H*, CH_3). $^{13}C\{^1H\}$ NMR ($CDCl_3$): δ 23.5, 23.6, 24.1, 24.2, 36.8, 37.0, 37.1, 37.2 (*C*H_2); 59.6 (*C*H_3); 71.7, 76.4, 76.7, 78.7, 79.2, 81.6 (*C*H); 112.0, 119.7 (*C*$(O)_2R_2$).

Preparation of 1D-1,2:5,6-di-O-cyclohexylidene-3-O-methyl-*chiro*-inositol (D-3)

1D-1,2:5,6-di-O-cyclohexylidene-3-O-methyl-*chiro*-inositol was prepared from 1D-pinitol using a modified literature preparation[34, 54] by replacing the solvent from benzene to a combination of benzene:dimethyl formamide. Recrystallisation from hexanes gave the pure product as a white solid (40%). $[\alpha]_D$ = -29.2 ° (*c* 1.02, $CHCl_3$). ^1H NMR ($CDCl_3$): δ (ppm) 1.40-1.71 (m, 20H, CH_2), 2.85 (s, 1H, OH), 3.10-4.35 (m, 9H, C*H*, CH_3). $^{13}C\{^1H\}$ NMR ($CDCl_3$): δ (ppm) 23.9, 24.1, 24.3, 24.4, 25.4, 25.5, 34.8, 34.9, 37.9, 38.0 (*C*H_2), 59.5 (*C*H_3), 72.1, 76.8, 77.2, 78.4, 78.9, 81.9 (*C*H), 110.7, 110.9 (*C*$(O)_2R_2$).

Preparation of 1D-1,2:5,6-di-O-cyclopentylidene-3-O-ethyl-*chiro*-inositol (D-4)

1D-1,2:5,6-di-O-cyclopentylidene-*chiro*-inositol (1.25 g, 4.00 mmol) and dibutyltin oxide (1.00 g, 4.00 mmol) in a solution of toluene (8 mL) and methanol (8 mL) were heated under reflux for 3 hours. The solvents were removed under reduced pressure and toluene was added to the residue and then removed in the same manner. To the resulting residue a solution of bromoethane (2.99 mL, 4.36 g, 40.0 mmol) in toluene (20 mL) was added to the mixture and heated under reflux. The reaction mixture was partitioned between toluene (50 mL) and water (100 mL) and the aqueous layer separated and extracted with two further 50 mL portions of toluene. The combined toluene extracts were washed with brine (2 x 50 mL), dried ($MgSO_4$) and concentrated under reduced pressure. The resulting oil was purified by column chromatography on silica gel eluting with hexanes:ethyl acetate (2:1). Recrystallisation from ethyl acetate gave the pure product as a white solid (70%). Anal. Calc. for $C_{18}H_{28}O_6$: C, 63.51; H, 8.29. Found: C, 62.29; H, 8.31. $[\alpha]_D$ = -28.6 ° (*c* 0.50, $CHCl_3$). (*m/z*): Calcd for $C_{18}H_{28}O_6$ (MH^+) 341.19641 *m/z*. Found: 341.19614. ^1H NMR ($CDCl_3$): δ (ppm) 1.27 (t, 3H, $^3J_{HH}$ = 7.2 Hz, CH_2CH_3), 1.67-1.97 (m, 16H, CH_2), 2.88 (s, 1H, O*H*), 3.20-4.25 (m, 8H, C*H*, CH_2CH_3). $^{13}C\{^1H\}$ NMR ($CDCl_3$): δ (ppm) 15.8 (*C*H_3), 23.6, 23.6, 24.1, 24.2, 36.9, 37.1, 37.2, 37.3 (*C*H_2), 67.3 (*C*H_2CH$_3$), 71.5, 76.5, 76.9, 78.7, 79.4, 80.0 (*C*H), 119.8, 120.1 (*C*$(O)_2R_2$).

Preparation of 1D-1,2;5,6-di-O-cyclopentylidene-3-O-methyl-4-O-diphenylphosphino-*chiro*-inositol (D-P1)

A solution of $ClPPh_2$ (2.76 g, 12.5 mmol) in tetrahydrofuran (5 mL) was added dropwise to a solution of 1D-3-*O*-methyl-1,2:5,6-dicyclopentylidene-*chiro*-inositol (4.08 g, 12.5 mmol) and pyridine (1.5 g, 18.8 mmol) in tetrahydrofuran (10 mL) which was stirred at room temperature for 1 hour. The reaction mixture was extracted with toluene. The toluene extract was filtered through neutral alumina and the toluene removed under reduced pressure to give pure **D-P1** as a white solid (5.95 g, 93%). Anal. Calc. for $C_{29}H_{35}O_6P$: C, 68.22; H, 6.91. Found: C, 68.02; H, 7.06%. $[\alpha]_D$ = +28.6 ° (*c* 0.50, $CHCl_3$). ^1H NMR ($CDCl_3$): δ (ppm) 1.45-1.95 (m, 16H, CH_2), 3.10 (s, 3H, CH_3), 3.12-4.22 (m, 6H, C*H*), 7.15-7.60 (m, 10H, *Ph*). $^{13}C\{^1H\}$ NMR ($CDCl_3$): δ (ppm) 23.1, 23.2, 23.6, 23.7, 36.8, 36.9 (two signals coincident), 37.1 (*C*H_2); 59.2 (*C*H_3); 75.6, 75.8, 78.4, 79.2, 81.2, 81.5 (*C*H); 119.1, 119.2 (*C*$(O)_2R_2$); 127.9-131.2 (multiple signals, *Ph*). $^{31}P\{^1H\}$ NMR ($CDCl_3$): δ (ppm) 122.17 (s).

Preparation of 1D-1,2;5,6-di-O-isopropylidene-3-O-methyl-4-O-diphenylphosphino-*chiro*-inositol (D-P2)

The same procedure used for the synthesis of **D-P1** was followed. Pure product was obtained as yellow crystals (0.84 g, 87%). Anal. Calc. for $C_{25}H_{31}O_6P$: C, 65.49; H, 6.82. Found: C, 66.06; H, 6.78%. $[\alpha]_D$ = +12.2 ° (*c* 0.50, $CHCl_3$). ^1H NMR ($CDCl_3$): δ (ppm) 1.19 (s, 3H, CH_3), 1.22 (s, 3H, CH_3), 1.39 (s, 3H, CH_3), 1.42 (s, 3H, CH_3), 3.07 (s, 3H, CH_3), 3.10-4.28 (m, 6H, C*H*), 7.09-7.89 (m, 10H, *Ph*). $^{13}C\{^1H\}$ NMR ($CDCl_3$): δ (ppm) 25.4, 27.8 (two signals coincident), 59.1 (*C*H_3); 76.1, 76.2, 78.7, 79.4, 81.3, 81.6 (*C*H); 109.4, 109.5 (*C*$(O)_2Me_2$); 127.9-131.4 (multiple signals, *Ph*). $^{31}P\{^1H\}$ NMR ($CDCl_3$): δ (ppm) 121.84 (s).

Preparation of 1D-1,2;5,6-di-O-cyclohexylidene-3-O-methyl-4-O-diphenylphosphino-*chiro*-inositol (D-P3)

The same procedure used for the synthesis of **D-P1** was followed. Pure product was obtained as yellow crystals (1.55 g, 96%). Anal. Calc. for $C_{31}H_{39}O_6P$: C, 69.13; H, 7.30. Found: C, 69.09; H, 7.44%. $[\alpha]_D$ = +14.9 ° (*c* 0.50, $CHCl_3$). ^1H NMR ($CDCl_3$): δ (ppm) 1.14-1.70 (m, 20H, CH_2), 3.10 (s, 3H, CH_3), 3.12-4.32 (m, 6H, C*H*), 7.02-7.52 (m, 10H, *Ph*). $^{13}C\{^1H\}$ NMR ($CDCl_3$): δ (ppm) 23.5, 23.6, 23.9, 24.0, 25.0, 34.7, 37.6, 37.8 (*C*H_2); 59.1 (*C*H_3); 76.0 (two signals coincident), 78.2, 79.1, 81.8, 81.9 (*C*H); 109.9, 110.1 (*C*$(O)_2R_2$); 125.3-131.3 (multiple signals, *Ph*). $^{31}P\{^1H\}$ NMR ($CDCl_3$): δ (ppm) 122.35 (s).

Preparation of 1D-1,2;5,6-di-O-cyclopentylidene-3-O-ethyl-4-O-diphenylphosphino-*chiro*-inositol (D-P4)

The same procedure used for the synthesis of **D-P1** was followed. Pure product was obtained as yellow crystals (0.27 g, 92%). Anal. Calc. for $C_{30}H_{37}O_6P$: C, 68.69; H, 7.11. Found: C, 68.72; H, 7.19%. ^1H NMR ($CDCl_3$): δ (ppm) 0.77 (apparent t, 3H, $^3J_{HH}$ = 6.8 Hz, CH_2CH_3), 1.40-1.90 (m, 16H, CH_2), 3.19-4.20 (m, 8H, CH_2CH$_3$, C*H*), 7.09-7.51 (m, 10H, *Ph*). $^{13}C\{^1H\}$ NMR ($CDCl_3$): δ (ppm) 14.9 (CH_2CH_3); 23.1, 23.2, 23.6, 23.7, 36.7, 36.9 (two signals coincident), 37.1 (*C*H_2); 67.2 (*C*H_2CH$_3$); 75.6, 75.8, 79.5, 79.7, 81.2, 81.5 (*C*H); 119.0, 119.2 (*C*$(O)_2R_2$); 127.8-130.8 (multiple signals, *Ph*). $^{31}P\{^1H\}$ NMR ($CDCl_3$): δ (ppm) 121.14 (s).

Preparation of $RuCl_2$(D-P1)$_2$ (1)

D-P1 (0.209 g, 0.428 mmol) and $RuCl_2(PPh_3)_3$ (0.030 g, 0.11 mmol) were added to toluene (10 mL) under nitrogen.

The mixture was stirred at 18 °C for 16 hours. The toluene was removed under reduced pressure to give a purple/red residue. This was dissolved in a minimum amount of diethyl ether and purified using column chromatography on basic alumina. A red/orange band was eluted using diethyl ether. The band was collected and recrystallised from dichloromethane/*n*-hexane to give pure **1** as an orange/red solid (0.11 g, 85 %). Anal. Calc. for $C_{58}H_{70}Cl_2O_{12}P_2Ru \cdot 0.5CH_2Cl_2$: C, 56.87; H, 5.79. Found: C, 57.14; H, 5.96 (^{1}H NMR shows the presence of 0.5 equiv of CH_2Cl_2). The crystal for the X-ray structure determination was grown from ethanol/*n*-hexane. MS (*m/z*): Calcd for $C_{58}H_{70}{}^{35}Cl_2O_{12}P_2{}^{102}Ru$ (M^+) 1192.27631 *m/z*. Found: 1192.27696. ^{1}H NMR ($CDCl_3$): δ (ppm) 0.60-2.10 (m, 32H, C*H*$_2$), 3.60-4.85 (m, 12H, C*H*), 4.18 (s, 6H, C*H*$_3$), 6.80-7.50 (m, 20H, *Ph*). ^{13}C{^{1}H} NMR ($CDCl_3$): δ (ppm) 23.0, 23.2, 23.4, 23.8, 35.6, 36.3, 36.6, 36.7 (*C*H$_2$), 64.5 (*C*H$_3$), 73.4, 76.0, 76.2, 77.6, 79.5, 83.9 (*C*H), 119.3, 119.5 (*C*(O)$_2$R$_2$), 126.1-136.5 (multiple signals, *Ph*). ^{31}P{^{1}H} NMR ($CDCl_3$): δ (ppm) 169.98 (s).

Preparation of $RuCl_2$(D-P2)$_2$ (2)

D-P2 (0.400 g, 0.874 mmol) and $RuCl_2(PPh_3)_3$ (0.418 g, 0.437 mmol) were added to toluene (10 mL) under nitrogen. The mixture was stirred at 18 °C for 16 hours. The toluene was removed under reduced pressure to give a purple/red residue. This was dissolved in a minimum amount of diethylether and subjected to column chromatography on basic alumina. A red/orange band was eluted using diethylether, the band was collected and the solvent evaporated under reduced pressure. The resulting solid was dissolved in a minimum amount of diethyl ether and purified using column chromatography on basic alumina. A red/orange band was eluted using diethyl ether. The band was collected and recrystallised from diethylether/methanol to give pure **2** as an orange/red solid (0.071 g, 15%). MS (*m/z*): Calcd for $C_{50}H_{62}{}^{35}Cl_2O_{12}P_2{}^{102}Ru$ (M^+) 1088.21371. *m/z*. Found: 1088.20993. ^{1}H NMR ($CDCl_3$): δ (ppm) 1.32 (s, 6H, C*H*$_3$), 1.37 (s, 6H, C*H*$_3$), 1.53 (s, 6H, C*H*$_3$), 1.57 (s, 6H, C*H*$_3$), 3.12-4.98 (m, 12H, C*H*), 4.24 (s, 6H, C*H*$_3$), 6.78-8.00 (m, 20H, *Ph*). ^{13}C{^{1}H} NMR ($CDCl_3$): δ (ppm) 25.0, 26.3, 27.5, 27.7, 64.7 (*C*H$_3$), 75.7, 76.3, 76.4, 78.4, 79.0, 81.3 (*C*H), 109.5, 109.6 (*C*(O)$_2$R$_2$), 126.2-137.3 (multiple signals, *Ph*). ^{31}P{^{1}H} NMR ($CDCl_3$): δ (ppm) 170.02 (s).

Preparation of $RuCl_2$(D-P3)$_2$ (3)

To a toluene (20 mL) solution of **D-P3** (0.127 g, 0.236 mmol) triethylamine (0.15 mL, 1.2 mmol) and $[RuCl_2(COD)]_n$ (0.033 g, 0.12 mmol) were added giving an opaque brown solution. The mixture was heated under reflux for approximately 9 hours. The resulting red/brown solution was cooled to room temperature and the solvent removed under reduced pressure to give a crude product. This was then purified using column chromatography on basic alumina using dichloromethane as the eluent. This procedure was carried out twice before the material collected was finally recrystallised from dichloromethane/*n*-hexane to give pure **3** as an orange solid (0.020 g, 13%). Anal. Calc. for $C_{62}H_{78}Cl_2O_{12}P_2Ru$: C, 59.61; H, 6.29. Found: C, 59.47; H, 6.42%. MS (*m/z*): Calcd for $C_{62}H_{78}{}^{35}Cl_2O_{12}P_2{}^{102}Ru$ (M^+) 1248.33891 *m/z*. Found: 1248.33828. ^{1}H NMR ($CDCl_3$): δ (ppm) 0.78-1.90 (m, 40H, C*H*$_2$), 3.60-5.00 (m, 12H, C*H*), 4.20 (s, 6H, C*H*$_3$), 6.70-7.50 (m, 20H, *Ph*). ^{13}C{^{1}H} NMR ($CDCl_3$): δ (ppm) 23.5, 23.6, 23.7, 24.0, 24.8, 25.1, 34.2 (two signals coincident), 36.7, 37.5 (*C*H$_2$), 64.9 (*C*H$_3$), 73.7, 76.7, 76.8, 77.7, 78.9, 84.0 (*C*H), 110.6, 110.7 (*C*(O)$_2$R$_2$), 125.3-136.2 (multiple signals, *Ph*). ^{31}P{^{1}H} NMR ($CDCl_3$): δ (ppm) 169.78 (s).

Preparation of $RuCl_2$(D-P4)$_2$ (4)

The same procedure used for the synthesis of **1** was followed except that **D-P4** was used instead of **D-P1**. Pure **4** was obtained as a red/orange solid (0.007 g, 10%). MS (*m/z*): Calcd for $C_{60}H_{74}{}^{35}Cl_2O_{12}P_2{}^{102}Ru$ (M^+) 1220.30760 *m/z*. Found: 1220.30664. ^{1}H NMR ($CDCl_3$): δ (ppm) 0.84 (apparent t, 6H, CH$_2$C*H*$_3$), 0.60-2.10 (m, 32H, C*H*$_2$), 3.20-3.45 (m, 4H, C*H*$_2$CH$_3$), 3.52-5.08 (m, 12H, C*H*), 6.70-7.95 (m, 20H, *Ph*). ^{13}C{^{1}H} NMR ($CDCl_3$): δ (ppm) 14.8 (CH$_2$*C*H$_3$), 22.9, 23.1, 23.3, 23.8, 35.7, 36.2, 36.5, 36.7 (*C*H$_2$), 68.8 (*C*H$_2$CH$_3$), 75.2, 75.5, 75.8, 77.9, 78.1, 82.5 (*C*H), 119.4 (two signals coincident) (*C*(O)$_2$R$_2$), 126.1-137.1 (multiple signals, *Ph*). ^{31}P{^{1}H} NMR ($CDCl_3$): δ (ppm) 169.61 (s).

Preparation of $OsCl_2$(D-P1)$_2$ (5)

The same procedure used for the synthesis of **1** was followed except that $OsCl_2(PPh_3)_3$ was used instead of $RuCl_2(PPh_3)_3$. Pure **5** was obtained as a yellow solid (0.241 g, 61%). Anal. Calc. for $C_{58}H_{70}Cl_2O_{12}P_2Os$: C, 54.28; H, 5.50. Found: C, 54.33; H, 5.48. MS (*m/z*): Calcd for $C_{58}H_{70}{}^{35}Cl_2O_{12}P_2{}^{192}Os$ (M^+) 1282.33345 *m/z*. Found: 1282.33060. ^{1}H NMR ($CDCl_3$): δ (ppm) 0.50-2.10 (m, 32H, C*H*$_2$), 3.65-5.00 (m, 12H, C*H*), 4.26 (s, 6H, C*H*$_3$), 6.70-7.52 (m, 20H, *Ph*). ^{13}C{^{1}H} NMR ($CDCl_3$): δ (ppm) 23.0, 23.2, 23.3, 23.7, 35.5, 36.3, 36.6, 36.7 (*C*H$_2$), 64.8 (*C*H$_3$), 72.8, 75.9 (two signals coincident), 77.6, 80.1, 85.0 (*C*H), 119.2, 119.5 (*C*(O)$_2$R$_2$), 126.0-136.5 (multiple signals, *Ph*). ^{31}P{^{1}H} NMR ($CDCl_3$): δ (ppm) 90.03 (s).

Preparation of $RuBr_2$(D-P1)$_2$ (6)

$RuCl_2$(D-P1)$_2$ (0.209 g, 0.428 mmol) and lithium bromide (0.147 g, 1.69 mmol) were added to a solvent mixture of dichloromethane (5 mL) and methanol (10 mL) under nitrogen. The mixture was stirred at 18 °C for 1 hour. The solvent was removed under reduced pressure, to approximately 5 mL, until a solid precipitated out of solution. The crude material was filtered and washed with methanol to give pure **6** as a pink solid (0.033 g, 86%). Anal. Calc. for $C_{58}H_{70}Br_2O_{12}P_2Ru$: C, 54.34; H, 5.50. Found: C, 54.26; H, 5.75. MS (*m/z*): Calcd for $C_{58}H_{70}{}^{79}Br_2O_{12}P_2{}^{102}Ru$ (M^+) 1280.17527 *m/z*. Found: 1280.17311. ^{1}H NMR ($CDCl_3$): δ (ppm) 0.55-2.10 (m, 32H, C*H*$_2$), 3.60-5.10 (m, 12H, C*H*), 4.21 (s, 6H, C*H*$_3$), 6.70-7.50 (m, 20H, *Ph*). ^{13}C{^{1}H} NMR ($CDCl_3$): δ (ppm) 23.1, 23.2, 23.4, 23.7, 35.6, 36.3, 36.7, 36.8 (*C*H$_2$), 60.3 (*C*H$_3$), 73.4, 76.0, 76.3, 77.8, 79.5, 83.8 (*C*H), 119.4, 119.6 (*C*(O)$_2$R$_2$), 126.0-136.7 (multiple signals, *Ph*). ^{31}P{^{1}H} NMR ($CDCl_3$): δ (ppm) 171.27 (s).

Preparation of RuI_2(D-P1)$_2$ (7)

The same procedure used for the synthesis of **6** was followed except that lithium iodide (0.216 g, 1.61 mmol) was used instead of lithium bromide. Pure **7** was obtained as purple solid (0.071 g, 87 %). Anal. Calc. for $C_{58}H_{70}I_2O_{12}P_2Ru$: C, 50.63; H, 5.13. Found: C, 50.77; H, 5.43. MS (*m/z*): Calcd for $C_{58}H_{70}IO_{12}P_2{}^{102}Ru$ (M-I)$^+$ 1249.24308 *m/z*. Found: 1249.24275. ^{1}H NMR ($CDCl_3$): δ (ppm) 0.50-2.10 (m, 32H, C*H*$_2$), 3.60-5.26 (m, 12H, C*H*), 4.27 (s, 6H, C*H*$_3$), 6.70-7.50 (m,

20H, *Ph*). $^{13}C\{^1H\}$ NMR ($CDCl_3$): δ (ppm) 23.2, 23.5, 23.6, 23.7, 35.9, 36.1, 36.7, 37.0 (*C*H_2), 65.4 (*C*H_3), 73.5, 75.0, 75.3, 77.7, 79.2, 84.2 (*C*H), 119.6, 119.8 (*C*$(O)_2R_2$), 125.0-134.8 (multiple signals, *Ph*). $^{31}P\{^1H\}$ NMR ($CDCl_3$): δ (ppm) 175.28 (s).

Preparation of $RuCl_2$(D-P1)$_2(CO)_2$ (8)

To a dichloromethane (10 mL) solution of $RuCl_2$(D-P1)$_2$ (0.051 g, 4.2 x 10^{-2} mmol) CO gas was slowly bubbled through the clear red/orange solution for 2 minutes. A colour change was observed from red/orange to yellow within the first 10 seconds. The solvent was removed under reduced pressure to give the crude product as a yellow/brown solid. The crude product was purified by column chromatography on alumina using dichloromethane as the eluent. The product was recrystallised from dichloromethane/*n*-hexane to give pure **8** as a cream solid (0.050 g, 95%). Anal. Calc. for $C_{60}H_{70}Cl_2O_{14}P_2Ru$: C, 57.69; H, 5.65. Found: C, 57.87; H, 5.94%. MS (*m/z*): Calcd for $C_{59}H_{70}Cl_2O_{13}P_2{}^{102}Ru$ $(M\text{-}CO)^+$ 1221 *m/z*. Found: 1221. IR (cm^{-1}): 1962, 2020 ν(CO). ^1H NMR ($CDCl_3$): δ (ppm) 1.10-2.00 (m, 32H, CH_2), 3.20-4.86 (m, 12H, C*H*), 3.32 (s, 6H, CH_3), 7.10-8.20 (m, 20H, *Ph*). $^{13}C\{^1H\}$ NMR ($CDCl_3$): δ (ppm) 23.1, 23.2, 23.7, 23.8, 36.1, 36.3, 36.7, 36.8 (*C*H_2), 58.5 (*C*H_3), 76.0, 76.2, 77.7, 78.1, 79.1, 80.3 (*C*H), 119.4, 119.5 (*C*$(O)_2R_2$), 125.3-137.8 (multiple signals, *Ph*), 194.26 (*C*O) (coupling to phosphorus not observed). $^{31}P\{^1H\}$ NMR ($CDCl_3$): δ (ppm) 116.36 (s).

Summary of X-ray crystal structure data for $RuCl_2$(D-P1)$_2$ (1)

A suitable crystal of **1** was isolated from ethanol/*n*-hexane. Crystal data for $C_{58}H_{70}Cl_2O_{12}P_2Ru.C_2H_6O$. M = 1239.12, triclinic, $P1$, a = 11.5760(2) Å, b = 11.9927(2), c = 12.0811(2), α = 104.793(1) °, β = 115.370(1), γ = 91.577(1), V = 1447.10(4) $Å^3$, Z = 1, D_x = 1.422 Mg m^{-3}, μ = 0.482 mm^{-1}, T = 85(2) K, measured 14202 reflections (10839 unique) in θ range 1.78-26.42 °. R_{int} = 0.0257. Final R indices (for 10282 reflections with $I>2\sigma(I)$) R_1=0.0475, wR_2= 0.1189.

Acknowledgements

We thank the Tertiary Education Commission, administered by Auckland UniServices Limited, for granting an Enterprise Scholarship to A. T. Slade and Industrial Research Limited New Zealand for partial support of this work. We also thank The University of Auckland Research Committee for partial support of this work through grants-in-aid.

Notes and references

[a] School of Chemical Sciences, University of Auckland, Private Bag 92019, Auckland 1142, New Zealand. E-mail: lj.wright@auckland.ac.nz; Fax: +64 9 373 7422; Tel: +64 9 373 7599
[b] A Industrial Research Limited, PO Box 31-310, Lower Hutt, New Zealand.

† Electronic Supplementary Information (ESI) available: Crystal and refinement data for compound $RuCl_2$(D-P1)$_2$ (**1**) in CIF format. This data is also available from the Cambridge Crystallographic Data Centre as supplementary publication number CCDC 884602.

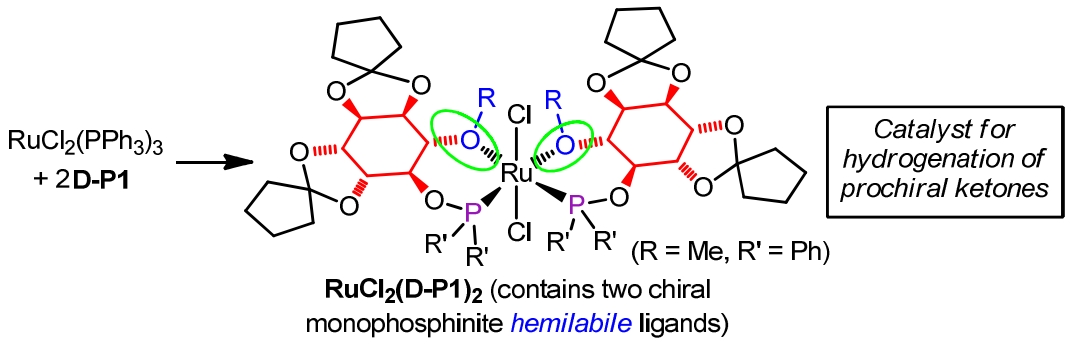
1. H. U. Blaser and E. Schmidt, *Asymmetric Catalysis on Industrial Scale*, Wiley-VCH GmbH & Co. KGaA, Weinheim, 2004.
2. R. Noyori and S. Hashiguchi, *Accounts of Chemical Research*, 1997, **30**, 97-102.
3. M. Yamakawa, H. Ito and R. Noyori, *Journal of the American Chemical Society*, 2000, **122**, 1466-1478.
4. K. Abdur-Rashid, S. E. Clapham, A. Hadzovic, J. N. Harvey, A. J. Lough and R. H. Morris, *Journal of the American Chemical Society*, 2002, **124**, 15104-15118.
5. S. Castillon, C. Claver and Y. Diaz, *Chemical Society Reviews*, 2005, **34**, 702-713.
6. Y. K. Chen, M. Yoshida and D. W. C. MacMillan, *Journal of the American Chemical Society*, 2006, **128**, 9328-9329.
7. M. Dieguez, O. Pamies and C. Claver, *Chemical Reviews*, 2004, **104**, 3189-3215.
8. I. Ojima, N. Clos and C. Bastos, *Tetrahedron*, 1989, **45**, 6901-6939.
9. T. V. RajanBabu, B. Radetich, K. K. You, T. A. Ayers, A. L. Casalnuovo and J. C. Calabrese, *Journal of Organic Chemistry*, 1999, **64**, 3429-3447.
10. R. Selke, M. Ohff and A. Riepe, *Tetrahedron*, 1996, **52**, 15079-15102.
11. A. Zhang, Y. Feng and B. Jiang, *Tetrahedron: Asymmetry*, 2000, **11**, 3123-3130.
12. B. Saha and T. V. RajanBabu, *Organic Letters*, 2006, **8**, 4657-4659.
13. M. T. Reetz and X. Li, *Tetrahedron*, 2004, **60**, 9709-9714.
14. L. Qiu, J. Wu, S. Chan, T. T.-L. Au-Yeung, J.-X. Ji, R. Guo, C.-C. Pai, Z. Zhou, X. Li, Q.-H. Fan and A. S. C. Chan, *PNAS*, 2004, **101**, 5815-5820.
15. S. Kaiser, S. P. Smidt and A. Pfaltz, *Angewandte Chemie International Edition*, 2006, **45**, 5194-5197.
16. K. Ishii, C. Lensink, J. B. Hart and A Falshaw, *Japan Patent*, JP003155293, 2003.
17. D. Hobuβ, C. Thone, S. Laschat and A. Baro, *Synthesis*, 2003, **13**, 2053-2056.
18. E. Guiu, B. Munoz, S. Castillon and C. Claver, *Advanced Synthesis and Catalysis*, 2003, **345**, 169-171.
19. E. Guimet, M. Dieguez, A. Ruiz and C. Claver, *Tetrahedron: Asymmetry*, 2004, **15**, 2247-2251.
20. I. Gergely, C. Hegedus, A. Szollosy, A. Monsees, T. Riermeier and J. Bakos, *Tetrahedron Letters*, 2003, **44**, 9025-9028.
21. P. W. Galka and H.-B. Kraatz, *Journal of Organometallic Chemistry*, 2003, **674**, 24-31.
22. A. Falshaw, G. J. Gainsford, C. Lensink, A. T. Slade and L. J. Wright, *Polyhedron*, 2007, **26**, 329-337.
23. E. Duliere, M. Devillers and J. Marchand-Brynaert, *Organometallics*, 2002, **22**, 804-811.
24. G. R. Clark, A. Falshaw, G. J. Gainsford, C. Lensink, A. T. Slade and L. J. Wright, *Journal of Coordination Chemistry*, 2010, **63**, 373-393.
25. R. B. Bedford, S. L. Hazelwood and M. E. Limmert, *Organometallics*, 2003, **22**, 1364-1371.
26. M. S. Balakrishna, P. P. George and S. M. Mobin, *Polyhedron*, 2005, **24**, 475-480.
27. T. T.-L. Au-Yeung and A. S. C. Chan, *Coordination Chemistry Reviews*, 2004, **248**, 2151-2164.
28. M. Aghmiz, A. Aghmiz, Y. Diaz, A. Masdeu-Bulto, C. Claver and S. Castillon, *Journal of Organic Chemistry*, 2004, **69**, 7502-7510.
29. J. C. Jeffrey and T. B. Rauchfuss, *Inorganic Chemistry*, 1979, **18**, 2658.

30. P. Braunstein and F. Naud, *Angewandte Chemie International Edition*, 2001, **40**, 680-699.
31. V. V. Grushin, *Chemical Reviews*, 2004, **104**, 1629-1662.
32. A. D. Burrows, *Science Progress*, 2002, **85**, 199-217.
33. S. C. N. Hsu, S.-C. Hu, Z.-S. Wu, M. Y. Chiang and M.-Y. Hung, *Journal of Organometallic Chemistry*, 2009, **694**, 1912-1917.
34. S. J. Angyal, G. C. Irving, D. Rutherford and M. E. Tate, *Journal of the Chemical Society*, 1965, 6662-6664.
35. T. Akiyama, H. Nishimoto, T. Kuwata and S. Ozaki, *B Chem Soc Jpn*, 1994, **67**, 180-188.
36. A. B. C. Simas, K. C. Pais and A. A. T. d. Silva, *Journal of Organic Chemistry*, 2003, **68**, 5426-5428.
37. E. Lindner, S. Pautz and M. Haustein, *Coordination Chemistry Reviews*, 1996, **155**, 145-162.
38. G. R. Clark, C. Lensink, A. T. Slade and L. J. Wright, *Acta Crystallographica Section E*, 2009, **65**, m804-m805.
39. R. Lindner, B. v. d. Bosch, M. Lutz, J. N. H. Reek and J. I. v. d. Vlugt, *Organometallics*, 2011, **30**, 499-510
40. L. J. Hounjet, R. McDonald, M. J. Ferguson and M. Cowie, *Inorganic Chemistry*, 2011, **50**.
41. M. Fessler, S. Eller, C. Bachmann, R. Gutmann, B. Trettenbrein, H. Kopacka, T. Mueller and P. Brueggeller, *Dalton Transactions*, 2009, 1383-1395.
42. M. McConville, O. Saidi, J. Blacker and J. Xiao, *Journal of Organic Chemistry*, 2009, **74**, 17.
43. M. Nandi, J. Jin and T. V. RajanBabu, *Journal of the American Chemical Society*, 1999, **121**, 2.
44. J. L. Ruiz, T. Flor and J. C. Bayon, *Inorganic Chemistry Communications*, 1999, **2**, 3.
45. P. Braunstein, *Journal of Organometallic Chemistry*, 2004, **689**, 15.
46. M. H. Chisholm, J. C. Gallucci and G. Yaman, *Inorganic Chemistry*, 2007, **46**, 8.
47. S. J. Angyal and N. K. Matheson, *Journal of the American Chemical Society*, 1955, **77**, 4343.
48. A. P. Kozikowski, A. H. Fauq, G. Powis and D. C. Melder, *Journal of the American Chemical Society*, 1990, **112**, 4528-4531.
49. G. Cousins, A. Falshaw and J. O. Hoberg, *Carbohydrate Research*, 2003, **338**, 995-998.
50. M. A. Bennett and G. Wilkinson, *Chemistry and Industry*, 1959, 1516.
51. J. Chatt and L. M. Venzanzi, *Journal of the Chemical Society*, 1957, 4735.
52. L. A. Ortiz-Frade, L. Ruiz-Ramirez, I. Gonzalez, A. Marin-Becerra, M. Alcarazo, J. G. Alvarado-Rodriguez and R. Moreno-Esparza, *Inorganic Chemistry*, 2003, **42**, 1825.
53. G. P. Elliott, N. M. McAuley and W. R. Roper, *Inorgnic Syntheses*, 1989, **26**, 184.
54. T. Akiyama, H. Nishimoto, T. Kuwata and S. Ozaki, *Bulletin of the Chemical Society of Japan*, 1994, **67**, 180-188.

Ruthenium and osmium complexes of hemilabile chiral monophosphinite ligands derived from 1D-pinitol or 1D-*chiro*-inositol as catalysts for asymmetric hydrogenation reactions

Angela T. Slade [a], Cornelis Lensink [b], Andrew Falshaw [b], George R. Clark [a], L. James Wright [a*]

Text and graphic for Table of Contents Entry



$RuCl_2$(D-P1)$_2$ (contains two chiral monophosphinite *hemilabile* ligands)

Chiral monophosphinite ligands derived from 1D-pinitol or 1D-*chiro*-inositol (e.g. **D-P1**) coordinate to ruthenium as bidentate hemilabile lignds to produce complexes that are excellent hydrogenation catalysts for prochiral ketones (with conversions up to 99%) but give products with poor enantioselectivities (≤ 22% ee).