133. An Unexpectedly Stable Chiral Hydrido-Solvent Complex of Ru^{II}: A Mechanistic Link in the Enantioselective Hydrogenation of Pyrones

Preliminary Communication

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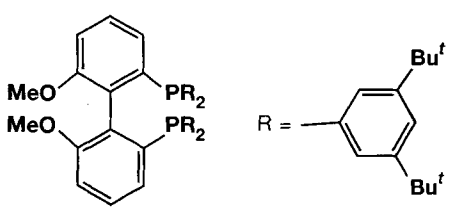
The ligand (6,6′-dimethoxybiphenyl-2,2′-diyl)bis[3,5-di(*tert*-butyl)phenylphosphine] (**1**) forms an unexpectedly stable hydrido-bis-solvento complex of composition $[RuH(isopropanol)_2(\mathbf{1})]BF_4$, (**2**) under the conditions used in the enantioselective hydrogenation of pyrones. The structure of **2**, determined by X-ray diffraction, represents the first well-characterized chiral five-coordinate bis-phosphine ruthenium-hydride complex stable as a solvento complex, and provides a structural link in the enantioselective pyrone hydrogenation cycle catalyzed by $[Ru(OAc)_2(\mathbf{1})]$. Using the arene complex $[RuH(p\text{-cymene})(\mathbf{1})]BF_4$ (**3**), the chiral pocket of coordinated **1** is shown to be relatively rigid, *via* NMR spectroscopy. This is reflected in restricted rotation about one of the four *P*–[3,5-di(*tert*-butyl)phenyl] P–C_{ipso} bonds *at room temperature*.

Introduction. – Enantioselective homogeneous hydrogenation using Ru^{II} is now a well established tool [1–4] with successful catalysts often containing chiral bidentate phosphine ligands such as binap [5] [6] or biphep [1]. Although both chloride and acetate precursors are readily available, little is known with respect to the hydride complexes which are generated during the hydrogenation, *in situ*. It is generally assumed that the hydrogen activation is heterolytic [6] [7], and that many of the intermediates are six-coordinate [5–7].

Results and Discussion. – In the course of hydrogenation studies on prochiral pyrones [1] using the chiral biphep complex $[Ru(OAc)_2(\mathbf{1})]$ which contains the bulky 3,5-di(*tert*-butyl)aryl-phosphorus substituents shown, we isolated the novel bis-solvento five-coordi-



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nate hydride $[RuH(i\text{-}PrOH)_2(\mathbf{1})]^+$ (**2**) in good yield as a red crystalline solid from the i-PrOH reaction mixture (*Eqn. 1*).

$$[Ru(OAc)_2(\mathbf{1})] + 2\,HBF_4 \xrightarrow[333\ K,\ i\text{-}PrOH]{H_2\ (60\ atm)} [RuH(i\text{-}PrOH)_2(\mathbf{1})]\,BF_4 + 2\,HOAc + HBF_4 \quad (1)$$

Once removed from the autoclave, complex **2** is relatively air-sensitive. The i-PrOH filtrates from the autoclave, both in the presence and in the absence of pyrone substrate, were shown by ^{31}P-NMR to be qualitatively the same, consisting of **2** and three, as yet, unidentified compounds. In the presence of substrate, many of the resonances are somewhat broader. When used as a catalyst in the enantioselective pyrone hydrogenation, complex **2** is exactly as effective as $[Ru(OAc)_2(\mathbf{1})]$. Consequently, **2** is either an intermediate in the hydrogenation cycle, or it reacts to form an active species. As suggested previously [6a], for a different catalyst based on binap, it is clear[2]) that the hydrogen is activated before coordination of the olefin in the chemistry of *Eqn. 1*.

The crystals, which slowly precipitate from i-PrOH, were of sufficient quality such that the structure could be determined, and an ORTEP plot of the cationic part is shown in *Fig. 1*. The Ru^{II} is five-coordinate with the immediate coordination sphere consisting of

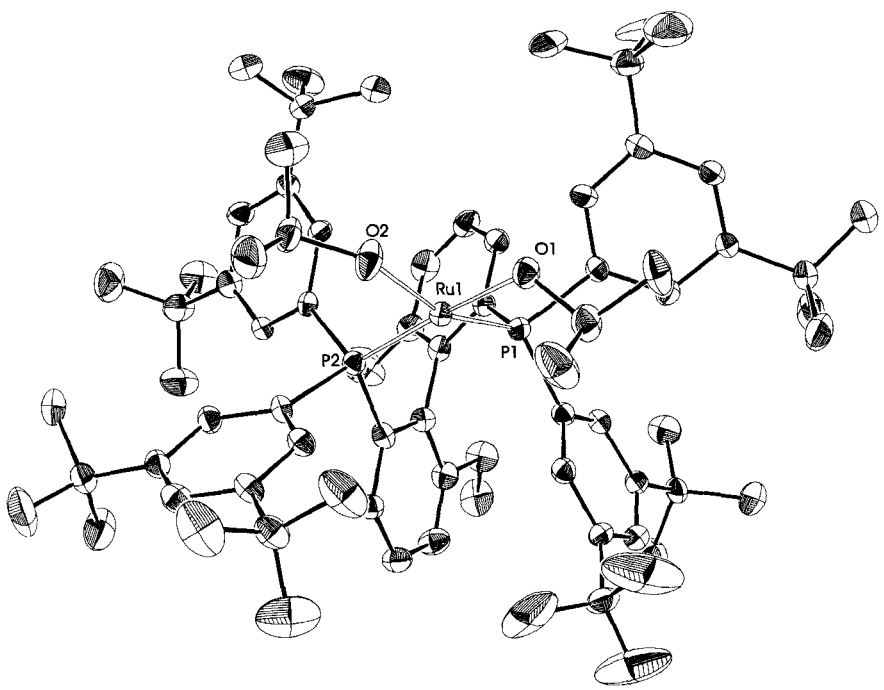

Fig. 1. *ORTEP View of the cation of* **2**. Selected bond lengths [Å] and bond angles [°] are: Ru(1)–O(1), 2.201(4); Ru–O(2), 2.192(5), Ru–P(1), 2.217(2), Ru–P(2), 2..228(2), O(1)–Ru–O(2), 78.0(2), P(1)–Ru–O(2), 161.4(2), P(1)–Ru–O(1), 94.6(1), P(2)–Ru–O(1), 172.1(1), P(1)–Ru–P(2), 91.0(1).

[2]) We have shown, separately, that heterolytic hydrogen activation by $Ru(OAc)_2(\mathbf{1})$ in the presence of HBF_4 occurs readily at room temperature with 1 atm. of H_2; however, for high yields of **2** the conditions given in the experimental part are best.

the two P-atoms of the chiral bidentate ligand, two solvent O-donors and, as shown from NMR spectroscopy, a single hydride ligand. Assuming an apical hydride ligand, the local coordination sphere is best described as a distorted square-pyramid. There are a number of interesting structural aspects; however, the O–Ru–O angle, *ca* 78°, is noteworthy as this provides a hint as to the effective size of coordinated **1**. The structure of **2** represents the first well-characterized chiral five-coordinate bis-phosphine ruthenium-hydride complex stable as a solvento complex, and provides a structural link in terms of the [Ru(OAc)$_2$(**1**)]-catalyzed pyrone hydrogenation mechanism.

Ru Complexes of **1** and related biphep complexes are known [8], and these afford excellent enantiomeric excesses (> 95%) in homogeneous hydrogenation [1] [8]. We believe that the high ee's, observed for **1**, in the hydrogenation of moderately large organic substrates is partly related to the relative rigidity of its chiral pocket. The arene complex [RuH(*p*-cymene)(**1**)]BF_4 (**3**), which we arbitrarily take as model for a coordinated substrate, reflects this rigidity in that, *at room temperature,* there is restricted rotation about one of the four P–C_{ipso} bonds (*Fig. 2*).

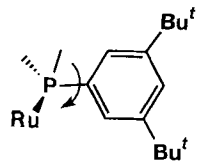

Fig. 2. *Fragment showing the site of restricted rotation*

As seen in *Fig. 3, a*, the two *ortho*-protons are nonequivalent and sharp at ambient temperature. This is the first report of such a relatively high rotational barrier in a coordinated tertiary aryl-phosphine not having *ortho*-substituents. Indeed, variable-temperature ^{1}H-NMR measurements show that there are four distinct barriers to rotation with all eight *ortho*-protons sharp and identified at 193 K, as shown in *Fig. 3, b*. The 3-D solution structure of **3** has been determined using ^{1}H-ROESY (and not NOESY) measurements, in combination with our usual methodology [9], and will be described subsequently.

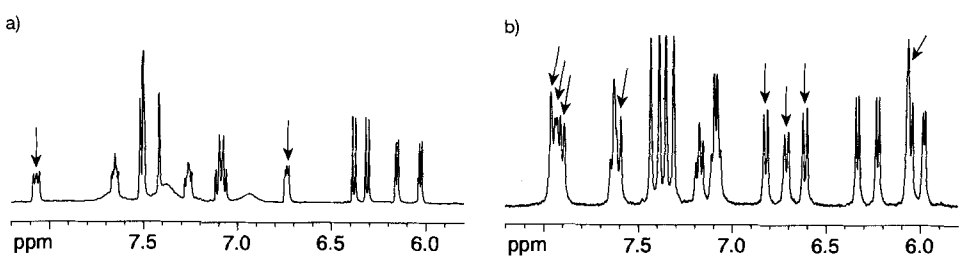

Fig. 3. a) *^{1}H-NMR Spectrum at ambient temperature for* **3** *indicating,* via *arrows, the two nonequivalent* ortho-*protons of one of the P-aryl substituents and* b) *the same region at 193 K indicating the eight nonequivalent* ortho-*protons* (500 MHz, CD_2Cl_2). Chemical shifts for these eight protons are given in [12].

Since **2** has coordinated i-PrOH solvent molecules, we attempted and succeeded in preparing the bis-acetone complex $[Ru(OAc)(acetone)_2(\mathbf{1})]BF_4$ (**4**). Complex **4** exists in solution as a mixture of *cis*- and *trans*-isomers, and can be prepared by addition of HBF_4 and acetone to a solution of $[Ru(OAc)_2(\mathbf{1})]$ in CH_2Cl_2. Obviously, the ease with which one can prepare these chiral Ru^{II} complexes, containing weakly coordinated solvent ligands, has led us to a series of new derivatives, and we shall report on these shortly.

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Experimental Part

General. Solution NMR spectra were measured using *Bruker AC-200* and *AMX-500* spectrometers. Referencing is to H_3PO_4 (^{31}P) and TMS (^1H and ^{13}C). FAB-MS and microanal. measurements were performed in the anal. laboratories of the ETH-Zurich.

X-Ray Crystal Structure of **2**. An orange crystal of **2** was measured on a scanner (STOE IPDS) at 200 K. The complex crystallizes in the orthorhombic space group $P2_12_12_1(19)$ with $a = 18.388(3)$ Å, $b = 19.375(3)$ Å, $c = 21.252(3)$ Å, $V = 7521(2)$ Å^3, $Z = 4$. Refinement of 11890 independent reflections ($R_{int} = 0.0693$) with 775 parameters gave $wR2 = 0.1450$ (based on F^2) and a conventional $R^1 = 0.0607$ (based on F) for 10089 reflections with $|F|^2 > 2\sigma(|F|^2)$. The hydride was not localized.

*Improved Preparation of [RuH(i-PrOH)$_2$(***1***)]BF$_4$* (**2**). To a soln. of $[Ru(OAc)_2(\mathbf{1})]$ (235.7 mg, 0.189 mmol) in 4.0 ml of i-PrOH were added 2.0 equiv. of $HBF_4 \cdot H_2O$ (46 µl of a 8.2M soln. in H_2O, 0.38 mmol). After stirring for 90 min the mixture was transferred to an autoclave. The Ar atmosphere was then replaced by an atmosphere of H_2 (quality: 6.0, *i.e.*, 99.9999%) in three cycles. The initial pressure was set at 60 atm. The autoclave was heated in an oil-bath for 2 h at 60°. After cooling to r.t., the mixture (without stirring) was allowed to stand in the autoclave for one week. Subsequently, the soln. was transferred to a *Schlenk* tube and evaporated to dryness. After washing with cold i-PrOH and drying *in vacuo*, the product was isolated as a red powder in a yield of 86%. Selected NMR data: ^1H-NMR: −26.0 ppm (hydride). ^{31}P-NMR: 87.9, 75.0, $^2J(P,P) = 52$. The crystals which grew from an earlier autoclave run amounted to a *ca.* 45% yield.

*Preparation of [RuH(*p*-cymene)(***1***)]BF$_4$* (**3**). To a soln. of $[Ru(OAc)_2(\mathbf{1})]$ (68.4 mg, 0.0547 mmol) in 1 ml of i-PrOH were added 2.1 equiv. of $HBF_4 \cdot H_2O$ (14 µl of a 8.2M soln. in H_2O, 0.11 mmol) followed by the addition of 1.2 equiv. (10 µl, 0.066 mmol) of *p*-cymene. The mixture was then heated until refluxing started. After cooling to r.t., the Ar atmosphere was replaced by an atmosphere of H_2 (*ca.* 1.2 atm.). The soln. was heated again until it started to reflux. The pale-yellow soln. then stood overnight at r.t. under an atmosphere of H_2. After transferring to a *Schlenk* tube, the mixture was taken to dryness *in vacuo*, the residue washed twice with 3 ml of hexane and then redissolved in 4 ml of CH_2Cl_2. The resulting soln. was extracted twice with 4 ml of H_2O, to remove inorganics, and the CH_2Cl_2 dried ($MgSO_4$). After filtration and drying *in vacuo*, removal of solvent affords the anal. pure product as a yellow powder in 81% yield. IR (KBr): 2030*w* (Ru–H), 1125–1045*s* (br. BF_4^-). Selected NMR data: ^{31}P-{^1H}-NMR (CD_2Cl_2, 193 K): 54.0, 52.6, $^2J(P,P) = 46$. ^1H-NMR (500 MHz, CD_2Cl_2): −9.80 (hydride); 7.95 (3 H), 7.61, 6.82, 6.71, 6.61. 6.06, 8 H_2, *Fig. 3,b*); 3.12, 2.97 (2 MeO). FAB-MS: found: 1267.8 (M^+). Anal. calc.: C 70.94; H 8.26; found: C 70.19; H 8.26.

*Preparation of [Ru(OAc)(acetone)$_2$(***1***)]BF$_4$* (**4**). To a soln. of $[Ru(OAc)_2(\mathbf{1})]$ (29.2 mg, 0.0237 mmol) in 1 ml CH_2Cl_2 were added 2.1 equiv. of $HBF_4 \cdot Et_2O$ (6.7 µl of a 7.3M soln. in Et_2O, 0.050 mmol). The soln. colored instantaneously to dark-orange. Subsequently, 8.6 equiv. of acetone (25 µl, 0.20 mmol) were added. After stirring for 30 min at r.t., the mixture was taken to dryness and washed twice with hexane. Subsequently, the soln. was washed three times with 1 ml of H_2O. After drying ($MgSO_4$) and evaporation to dryness, the product was washed twice with 2 ml of hexane. Drying *in vacuo* afforded a pale-green powder in 78% yield. IR (KBr): 1623, 1531 (C=O, acetone), 1130–1049*s* (br. BF_4^-). Selected NMR data: ^{31}P-{^1H}-NMR (CD_2Cl_2, 298 K): 66.8 (*s*, 74% *trans*-isomer); 59.9, 57.3 ($^2J(P,P) = 43$, 26% *cis*-isomer). ^{19}F-{^1H}-NMR (CD_2Cl_2), 298 K: −153.4 (*s*, BF_4^-). FAB-MS: found: 1248.8 (M^+). Anal. calc.: C 67.18; H 8.03; found: C 67.25; H 7.77.

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