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Abnormal N-Heterocyclic Carbene-Phosphine Ruthenium(II) Complexes as Active Catalysts for Transfer Hydrogenation

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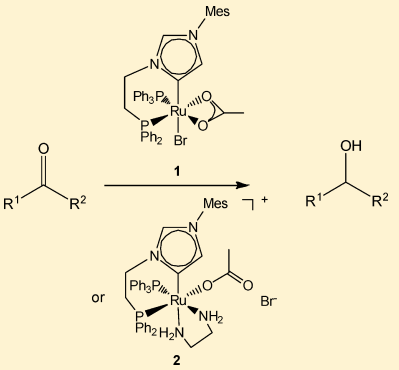
Supporting Information

ABSTRACT: The bifunctional phosphine−abnormal N-heterocyclic carbene ruthenium(II) complex RuBr(OAc)(PPh_3)(P−aNHC) (**1**) has been synthesized in high yield by reaction of $Ru(OAc)_2(PPh_3)_2$ with a phosphine imidazolium bromide (P−NHC × HBr) and characterized by X-ray diffraction. This compound shows high catalytic activity for the transfer hydrogenation of ketones to alcohols in 2-propanol. Rate and efficiency of **1** can be enhanced by the addition of ethylenediamine or benzylamine, affording TOFs up to 140 000 h^{-1}. Reaction of **1** with ethylenediamine leads to the Ru carbene/amine complex [Ru(OAc)(PPh_3)(P−aNHC)-($H_2NCH_2CH_2NH_2$)]Br (**2**), which displays the same activity of the *in situ* generated species.



The reduction of the carbonyl compounds with hydrogen[1] or hydrogen donor molecules[2] mediated by defined homogeneous catalysts is a well-established core process for the preparation of fine chemicals.[3] Development of new catalysts that operate with high chemoselectivity and productivity is crucial for the improvement of industrial processes. Outstanding catalytic systems for the hydrogenation (HY) of C=O bonds are the Noyori ruthenium catalysts *trans*-$RuCl_2$(PP)-(1,2-diamine)[4] (PP = diphosphine) displaying the N−H function.[5] Conversely, the 2-aminomethylpyridine (ampy) complexes *cis*-$RuCl_2$(PP)(ampy)[6] and the related CNN pincer RuCl(CNN)(PP)[7] (HCNN = 1-(6-arylpyridin-2-yl)-methanamine) are the most active systems for ketone transfer hydrogenation (TH) and HY of bulky substrates and catalyze the dehydrogenation, racemization, and deuteration of alcohols.[8]

N-Heterocyclic carbenes (NHC) have been proven to be efficient alternatives to phosphine ligands for transition metal complexes.[9] On account of the strong metal carbon bond, carbene complexes are expected to give robust catalytic systems. Accordingly, several ruthenium complexes bearing NHC ligands were successfully applied for the TH of carbonyl compounds.[10] Recently, Morris and co-workers described highly active ruthenium HY catalysts displaying chelating NHC−primary amine ligands.[11] Although a few NHC−phosphine ruthenium complexes have been isolated,[12] no example of TH ruthenium catalysts containing a bidentate NHC−phosphine has been reported to date. It is worth noting that when the imidazole-based NHC ligand coordinates through the C4 or C5 atom, instead of C2, an abnormal NHC (aNHC) complex forms. Metal−aNHC compounds are described to exhibit superior catalytic activity compared to their normal analogues, and this can be ascribed to their stronger σ-donating property. Although several metal aNHC−complexes with Ir, Rh, and Pd have been reported,[13] only a few derivatives with Ru have been isolated.[14] The strategy for the preparation of aNHC complexes includes the blocking of the C2 carbon atom, the modification of the bulkiness of N-moieties, and the nature of the anion.

Herein we report the synthesis and characterization of a bifunctional phosphine−abnormal NHC ruthenium complex and its application in TH of ketones. Addition of primary amines has been proven to enhance the catalytic activity of the ruthenium catalyst via formation of a carbene/amine species.

The ruthenium complex **1** was prepared by treatment of $Ru(OAc)_2(PPh_3)_2$[15] with 1.2 equivalents of the phosphine imidazolium bromide P−NHC × HBr[16] and sodium acetate in THF at refluxing conditions (Scheme 1).

The progress of the reaction has been observed by the changing of the color of the precipitate from reddish-brown to yellow, leading to RuBr(OAc)(PPh_3)(P−aNHC) (**1**), which was isolated in 80% yield. Complex **1** is thermally stable in the solid state, and it is air sensitive in solution. The $^{31}P\{^1H\}$ NMR spectrum of **1** in CD_2Cl_2 shows two doublets at δ 62.4 and 53.7 with a $^2J_{PP}$ of 43.1 Hz, indicating that the two phosphorus atoms are in *cis*-position. The ethylene bridge of the phosphine carbene ligand gives rise to a ^1H NMR doublet of doublets at δ 4.33 with J_{HH} = 13.4 Hz and J_{HP} = 29.0 Hz and a pseudoquartet at 4.01 (J_{HH} = J_{HP} = 13.4 Hz) for the NCH_2 moiety, whereas

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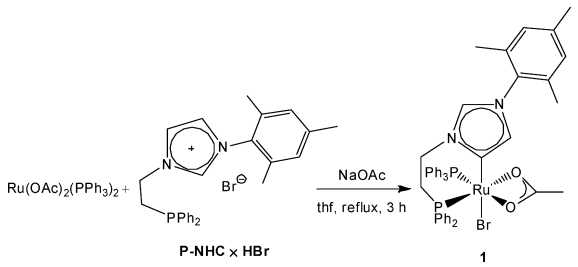
Scheme 1. Synthesis of the Ruthenium Complex 1



the two signals of the PCH_2 unit appear as multiplets at δ 2.33 and 1.57, as inferred from $^1H\{^{31}P\}$ NMR and $^1H-^1H$ COSY experiments. The three methyl signals of the mesityl group appear as three singlets at δ 2.31, 2.13, and 1.86, whereas the signal at δ 1.72 is for the acetate ligand. The imidazolylidene ring shows two doublets at significantly different positions (δ 7.89 and 5.82) with a small $^4J_{HH}$ of 1.9 Hz. In the $^{13}C\{^1H\}$ NMR spectrum, the carbene is relatively upfield shifted (δ 161.2), consistent with an abnormal NHC binding to the ruthenium center.[14]

To establish the coordination mode of the phosphine–carbene ligand and the arrangement of the ligands at the ruthenium center, a single-crystal X-ray diffraction study was carried out on **1**. Crystals suitable for the solid-state analysis were obtained by slow diffusion of diethyl ether into a CH_2Cl_2 solution of **1**. The complex crystallizes in a distorted octahedral geometry with the two *cis* phosphorus atoms *trans* to the bidentate acetate and the carbene *trans* to the bromide (Figure 1).[17] This structure unambiguously confirms that the bidentate phosphine–NHC ligand adopts the abnormal carbene coordination with a typical carbene Ru–C distance (2.0228(16) Å). The Ru–P length of the chelating phosphine is slightly shorter with respect to that of PPh_3 (2.2294(4) vs. 2.2640(4) Å), whereas the acetate is symmetrically coordinated to the metal center (Ru1–O1 2.2118(11) Å, Ru1–O2 2.2168(11) Å). It is worth noting that the normal coordination mode of the P–NHC ligand has been observed for Pd, Ir, and Ru complexes,[18] whereas the abnormal one has been proven by solid-state studies only for two examples of Ir species.[19] On the basis of NMR studies, abnormal and normal coordination of P–NHC has been reported by Lavigne *et al.*, for six- and five-coordinate Ru(II) and Ru(0) complexes, respectively.[12c] The abnormal NHC coordination observed for the six-coordinate Ru(II) complex **1** can be ascribed to steric factors,[13] which lead to the bulky mesityl group pointing away from the metal center, reducing the strain with the PPh_3 phenyls.

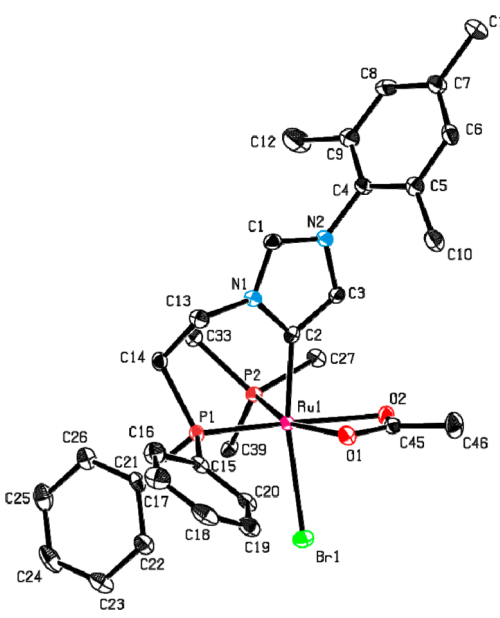
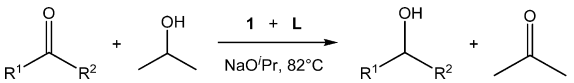


Figure 1. ORTEP representation of complex **1**. Ellipsoids are shown at the 50% probability level. The phenyl rings at P2 as well as the hydrogen atoms are omitted for clarity. Selected bond lengths (Å) and angles (deg): Ru1–Br1 2.6299(2), Ru1–C2 2.0228(16), Ru1–O1 2.2118(11), Ru1–O2 2.2168(11), Ru1–P1 2.2294(4), Ru1–P2 2.2640(4), C2–Ru1–Br1 168.58(4).

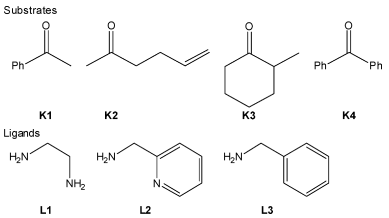
The phosphine–aNHC ruthenium complex **1** is an efficient catalyst for the TH of ketones to alcohols with 2-propanol as hydrogen donor and in the presence of sodium isopropoxide (eq 1).



(1)

The reaction conditions were optimized in a 0.1 M solution of ketone in 2-propanol with 0.05 mol% loading of **1** in the presence of 2 mol% of NaO^iPr at refluxing conditions. Complex **1** catalyzes the transfer hydrogenation of acetophenone (**K1**) with high rate (TOF = 38 000 h^{-1} at 50% conversion), but requires 2 h for the quantitative conversion of the substrate, indicating that **1** undergoes deactivation after a few minutes (Table 1, entry 1, and Figure 2).

Table 1. Catalytic Transfer Hydrogenation of Ketones Using Complex 1 with the *in situ* Ligands L[a]



entry	ketone	catalyst [mol%]	ligand	conversion[b] % (time)	TOF[c] [h^{-1}]
1	**K1**	0.05		97 (2 h)	38 000
2	**K1**	0.05	**L1**	97 (20 min)	58 000
3	**K1**	0.05	**L2**	85 (1 h)	15 000
4	**K1**	0.05	**L3**	95 (8 min)	34 000
5	**K1**	0.01	**L1**	86 (1 h)	140 000
6	**K2**	0.1	**L3**	95 (8 min)	11 000
7	**K3**	0.1	**L3**	99 (2 min)	39 000
8	**K4**	0.1	**L3**	95 (1 h)	6400

[a]Conditions: reactions were carried out at reflux, 0.1 M ketone in 2-propanol, 2 mol% sodium isopropoxide. [b]The conversion was determined by GC. [c]Turnover frequency is given at 50% conversion.

To increase the catalytic activity of **1**, several nitrogen ligands containing the N–H function have been added to **1** *in situ*. Reaction of complex **1** with ethylenediamine (**L1**) (2 equiv) in refluxing 2-propanol (30 min) gives a more active and productive transfer hydrogenation catalyst. Thus, **K1** is converted quantitatively into 1-phenylethanol in 20 min, leading to a TOF value of 58 000 h^{-1} (0.05 mol% of Ru). Surprisingly, in the presence of 2-aminomethylpyridine (**L2**)

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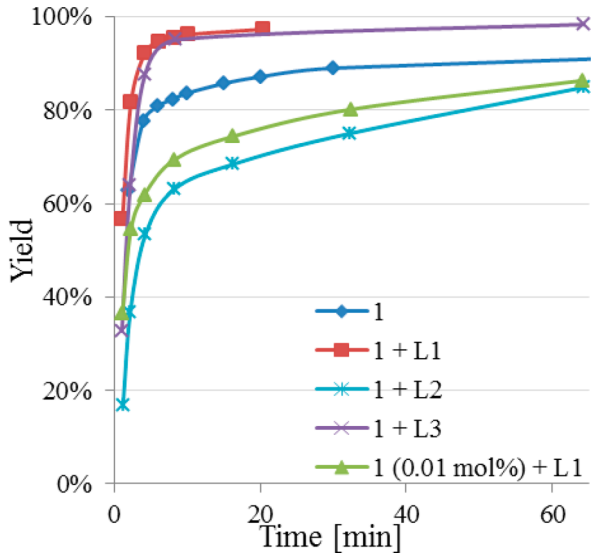


Figure 2. Transfer hydrogenation of acetophenone (**K1**) with **1** (0.05 mol%) in the presence of nitrogen ligands (ethylenediamine, **L1**; 2-aminomethylpyridine, **L2**; and benzylamine, **L3**).

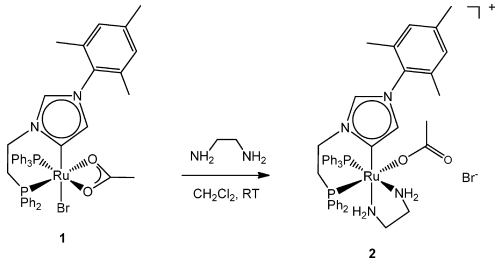
the rate is lower with respect to that of **1**, affording 86% conversion of **K1** in 1 h. Although the *in situ* prepared catalyst with benzylamine (**L3**) provides much of the same rate as **1**, quantitative conversion of the ketone is achieved in 8 min (Table 1, entry 4).

Complex **1** in the presence of **L1** has been proven to catalyze the reduction of **K1** at 0.01 mol% loading, affording 1-phenylethanol (86% conv. in 1 h) and achieving a TOF of 140 000 h^{-1} (Table 1, entry 5). These results should be compared with those reported for the phosphine/amine complexes $RuCl_2(PP)(NN)$,[4,6] which show high catalytic activity in TH when NN = ampy and poor performances for NN = 1,2-diamine.[2b] Using the system **1**/**L3**, dialkyl, cyclic, and diaryl ketones have been quantitatively reduced with 0.1 mol% of **1**. Thus, hex-5-en-2-one (**K2**), 2-methylcyclohexanone (**K3**) and benzophenone (**K4**) were used as model substrates (Table 1, entries 6–8). The unsaturated ketone **K2** is chemoselectively reduced at the C=O bond without hydrogenation and isomerization of the C=C bond, whereas the diaryl ketone **K4** is reduced to benzhydrol in 1 h (95%). TH of **K3** leads quantitatively to 2-methylcyclohexanol in 2 min (TOF = 39 000 h^{-1}) with a *cis/trans* ratio of 3, whereas after 30 min the two alcohols are in about 1:1 ratio, as a result of a catalytic epimerization process.

To characterize the ruthenium carbene/amine species that forms *in situ*, we studied the reaction of **1** with ethylenediamine (**L1**). The thermally stable complex **2** is promptly obtained as a pale green solid (91% yield) by treatment of **1** with **L1** in CH_2Cl_2 at room temperature (Scheme 2).

The derivative **2** shows two ^{31}P NMR doublets at δ 53.9 and 29.1 with a $^2J_{PP}$ of 32.6 Hz (CD_2Cl_2), lower than that of **1**. In the $^{13}C\{^1H\}$ NMR spectrum the abnormal carbene gives rise to a triplet at δ 155.6 ($^2J_{CP}$ = 13.3 Hz), while the NCH_2CH_2P bridge affords two resonances at δ 46.7 and 21.0 ($^2J_{CP}$ = 30.3 Hz). The diamine ligand leads to a broad singlet at δ 44.1 for the two carbon atoms (free **L1** δ 44.9), which does not significantly change at −60 °C (δ 43.6). A doublet at δ 181.5 ($^3J_{CP}$ = 1.3 Hz) is for the CO acetate, indicating that OAc^- is coordinated to Ru with Br^- as counterion. In the ^1H NMR spectrum the ethylenediamine ligand gives rise to four

Scheme 2. Synthesis of the Ruthenium Carbene/Amine Complex 2



nonequivalent N–H protons at δ 8.66, 4.57, 2.40, and 1.38, as inferred from ^1H–^1H COSY experiments, the low-field resonance being consistent with an intramolecular NH···O=C hydrogen bond interaction.[20] Addition of basic D_2O (KOH) to **2** in CD_2Cl_2 leads to a fast proton exchange of the four NH and the carbene NCHN (δ 8.72) protons, which may play an active role in bifunctional catalysis.[5] Finally, the isolated complex **2** (0.05 mol %) shows the same catalytic activity of the *in situ* generated system **1**/**L1** (Table 1, entry 2), affording quantitative reduction of acetophenone in 20 min with TOF = 55 000 h^{-1}, indicating that **2** is the catalytic precursor.

In conclusion, we have reported the synthesis and characterization of the ruthenium complex $RuBr(OAc)(PPh_3)(P–aNHC)$ (**1**), which displays a phosphine NHC ligand coordinated in an abnormal mode, as proven by an X-ray study. To the best of our knowledge, this is the first solid-state structure of an abnormally coordinated phosphine–NHC Ru complex. Complex **1** shows high catalytic activity in the transfer hydrogenation of ketones, and its rate and productivity increase by addition of ethylenediamine or benzylamine, achieving TOF values up to 140 000 h^{-1}. The carbene/amine complex $[Ru(OAc)(PPh_3)(P–aNHC)(H_2NCH_2CH_2NH_2)]Br$ (**2**) has been isolated and displays the same catalytic activity with respect to the *in situ* generated catalyst. Studies are under way to characterize new Ru carbene/amine complexes and to extend this protocol in asymmetric catalysis.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Details on experimental procedures, ^1H–^1H COSY and $^1H\{^{31}P\}$ NMR spectra of **1** and **2**, details on single-crystal X-ray structure determinations of compound **1**, tables of crystal and data collection parameters, atomic coordinates, bond lengths, and bond angles for **1** in .cif format. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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