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Hydrogenation of imines catalysed by ruthenium(II) complexes based on lutidine-derived CNC pincer ligands†

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The preparation of new Ru(II) complexes incorporating *fac*-coordinated lutidine-derived CNC ligands is reported. These derivatives are selectively deprotonated by ^{t}BuOK at one of the methylene arms of the pincer, leading to catalytically active species in the hydrogenation of imines.

Lutidine-derived pincer complexes have become a prominent class of derivatives in organometallic chemistry.[1] In these complexes, pyridine dearomatisation occurs upon deprotonation of the acidic $-CH_2-$ arms, leading to species that are capable of bond activation by a metal–ligand cooperative mechanism. With respect to the flanking donor groups of the pincer, attention has been largely paid to phosphorous derivatives of type PNX (P = phosphine, X = phosphine or a hemilabile N-donor ligand). Of particular importance, group 8 (Ru, Fe) catalysts based on PNX ligands or their deprotonated analogues have provided good levels of activity in the hydrogenation of a variety of polar functionalities, including ketones, esters, amides, ureas, formates, carbamates, and organic carbonates.[2] In addition, replacement of P-donors in PNX–Ru complexes by more electron-donating *N*-heterocyclic carbene (NHC) ligands has recently been reported. Thus, Ru pincer complexes incorporating CNN ligands with a hemilabile amine or pyridine fragment have been described.[3,4] Some of these derivatives are active catalysts in the hydrogenation of non-activated esters, in some cases outperforming their phosphine counterparts.[3] Alternatively, examples of ruthenium complexes of CNC ligands are scarce, and only derivatives of type Ru(CNC)(CO)ClH based on meridionally coordinated CNC ligands with 2,6-diisopropylphenyl and mesityl wingtips have been reported.[4]

In this communication, we present the synthesis and structural characterisation of new Ru complexes **3** containing *fac*-coordinated bis-*N*-heterocyclic carbene CNC ligands. Furthermore, application of these complexes in the hydrogenation of various imines is reported.

Synthesis of new bis-imidazolium salts **1** has been effected by refluxing acetonitrile or THF solutions of the corresponding 2,6-bis(halomethyl)pyridine and 1-substituted 1*H*-imidazole in a 1 : 2 ratio.[5] Initial experiments directed to the synthesis of ruthenium complexes incorporating CNC ligands derived from **1** were performed by the reaction of the imidazolium salt **1a(Br)** with different Ru precursors ($RuHCl(PPh_3)_3$, $RuCl_2(PPh_3)_3$, $RuHCl(CO)(PPh_3)_3$, $RuH_2(CO)(PPh_3)_3$) in the presence of a base. This approach, however, leads to an inseparable mixture of products, and an alternative procedure based on *N*-heterocyclic carbene transfer with Ag–NHC complexes was considered.[6] The reaction of bis-imidazolium salts **1** with 1 equiv. of Ag_2O in CH_2Cl_2 at room temperature results in the clean formation of bimetallic silver complexes **2** (Scheme 1).[5] These derivatives were found to be adequate for CNC ligand transfer to $RuHCl(CO)(PPh_3)_3$. Thus, complexes **3a(Cl)** and **3b(Cl)** were conveniently prepared from the appropriate silver reagent **2** and $RuHCl(CO)(PPh_3)_3$ in THF at 55 °C. Similarly, complexes **3a(BF_4)** and **3c(Br)** were synthesised by the reaction of the corresponding bromide derivatives **2a(Br)** and **2c(Br)** with $RuHCl(CO)(PPh_3)_3$ followed by treatment with $NaBF_4$ and NaBr, respectively. Finally, synthesis of 3,5-xilyl-substituted **3d(Cl)** was more conveniently carried out in CH_2Cl_2 at room temperature.

Complexes **3** have been fully characterized, and their NMR data reveal very similar features for all complexes of the series. For example, the $^{31}P\{^1H\}$ NMR spectrum of **3a(Cl)** shows a singlet at 42.4 ppm. Furthermore, ^1H and $^{13}C\{^1H\}$ NMR spectra reflect the non-equivalence of the two halves of the CNC ligand. In the ^1H NMR spectrum of **3a(Cl)**, the hydrido ligand gives rise to a doublet at −7.38 ppm (J_{HP} = 30.4 Hz),

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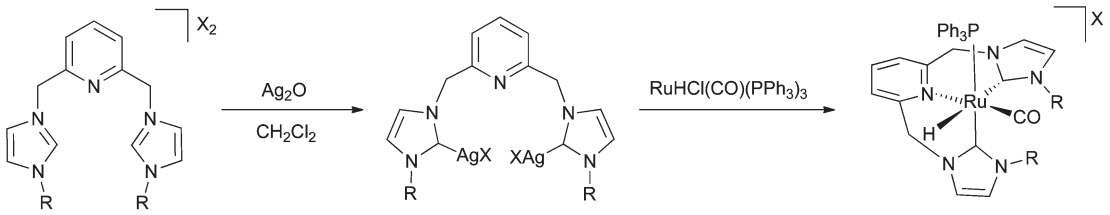
†Electronic supplementary information (ESI) available: Representative experimental procedures, compound characterisation, crystallographic information for **3a(BF_4)**. CCDC 894892. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/c2dt31907a



1a(Cl); R = *i*-Pr, X = Cl
1a(Br); R = *i*-Pr, X = Br
1b(Cl); R = Hexyl, X = Cl
1c(Br); R = Neopentyl, X = Br
1d(Cl); R = 3,5-Xilyl, X = Cl

2a(Cl); R = *i*-Pr, X = Cl
2a(Br); R = *i*-Pr, X = Br
2b(Cl); R = Hexyl, X = Cl
2c(Br); R = Neopentyl, X = Br
2d(Cl); R = 3,5-Xilyl, X = Cl

3a(Cl); R = *i*-Pr, X = Cl
3a(BF$_4$); R = *i*-Pr, X = BF_4 (after treatment with $NaBF_4$)
3b(Cl); R = Hexyl, X = Cl
3c(Br); R = Neopentyl, X = Br (after treatment with NaBr)
3d(Cl); R = 3,5-Xilyl, X = Cl

Scheme 1 Synthesis of silver (**2a–d**) and ruthenium (**3a–d**) complexes of CNC ligands.

while methylene protons of the CNC ligand produce four different doublet signals in the range 4.1–5.7 ppm. The $^{13}C\{^1H\}$ NMR spectrum shows one doublet signal for each C^2 carbon atom of the NHC fragment at 180.4 (J_{CP} = 81 Hz, *trans* to PPh_3) and 187.9 (J_{CP} = 8 Hz, *trans* to H), whereas the carbonyl ligand signal appears at 209 ppm as a doublet (J_{CP} = 15 Hz). These data are consistent with an unprecedented *fac* coordination mode of the CNC ligand, in which one NHC fragment is placed *trans* to the hydrido ligand and the other is *trans* to PPh_3.[7] The CO stretch bands in the IR spectrum of complexes **3** appear in the range 1919–1934 cm^{-1}.

Further confirmation of the structure of coordinated CNC ligands in complexes **3** was obtained from a study by single-crystal X-ray diffraction of **3a(BF$_4$)** (Fig. 1). This complex, in the solid state, consists of a distorted octahedral structure containing the CNC pincer coordinated in a *fac* configuration (C^2(NHC)–Ru–C^2(NHC) = 101.3(8)°), while the CO is placed *trans* to the pyridine nitrogen atom of the pincer system. Complex **3a(BF$_4$)** is chiral by virtue of the stereogenic center present in the Ru atom. Both six-membered ruthenacycles involving the NHC and pyridine donors adopt boat-like conformations defined by dihedral angles C(5)–N(1)–Ru(1)–C(14) and C(1)–N(1)–Ru(1)–C(8) of 25.9(15)° and −47.3(15)°, respectively. In addition, Ru–C^2(NHC) distances (2.117 Å, *trans* to H; 2.084 Å, *trans* to PPh_3) fall in the range of previously reported values,[3] and reflects the expected larger *trans* influence of the hydrido ligand.

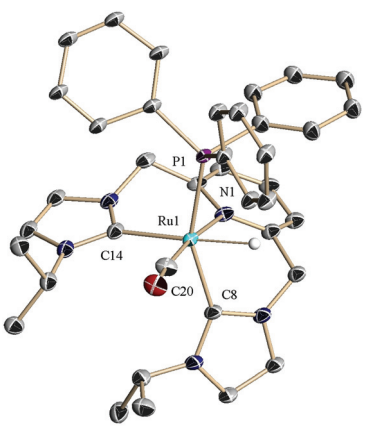
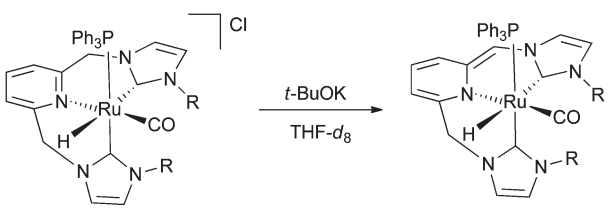


Fig. 1 ORTEP drawing at 30% ellipsoid probability of the cationic component of complex **3a(BF$_4$)**. Hydrogen atoms, except for the hydrido ligand, have been omitted for clarity. Selected bond lengths [Å] and angles [°]: Ru(1)–N(1) 2.233(16); Ru(1)–C(8) 2.084(19); Ru(1)–C(14) 2.117(19); Ru(1)–C(20) 1.79(2); C(8)–Ru(1)–C(14) 101.3(8); N(1)–Ru(1)–C(20) 173.3(8); C(8)–Ru(1)–N(1) 80.8(7); C(14)–Ru(1)–N(1) 87.7(7); C(8)–Ru(1)–C(20) 92.6(9); C(14)–Ru(1)–C(20) 94.9(9); N(1)–Ru(1)–P(1) 92.1(4).

Treatment of complexes **3a(Cl)** and **3d(Cl)** with ^{t}BuOK in THF-d_8 cleanly gives derivatives **4a** and **4d**, respectively (Scheme 2). These compounds are rather unstable and decompose in solution at room temperature in a few hours. In the $^{31}P\{^1H\}$ NMR spectrum, complex **4a** exhibits a singlet at 47.9 ppm. The hydrido ligand gives rise to a doublet at −7.32 ppm (J_{HP} = 23.0 Hz) in the ^{1}H NMR spectrum, while the vinylic proton appears as a singlet at 4.77 ppm. More interestingly, the pyridine proton signals show significant upfield shifts as a consequence of pyridine dearomatisation, appearing in the range 4.6–5.5 ppm. In the $^{13}C\{^1H\}$ NMR spectrum, the carbonyl ligand produces a doublet at 210.6 ppm (J_{CP} = 14 Hz), and the C^2–NHC carbon atoms appear as doublets at 181.2 ppm (J_{CP} = 9 Hz) and 187.4 ppm (J_{CP} = 96 Hz). Similar spectroscopic data have been found for **4d**. These values are in accord with a facially coordinated CNC ligand. In addition, intense cross-peak signals between the vinylic proton and the C^2 of the NHC fragment coordinated *cis* to PPh_3 have been observed in the ^{1}H-^{13}C HMBC experiment, indicative of a selective deprotonation of the methylene arm of the NHC fragment coordinated *trans* to the hydride.

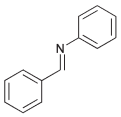
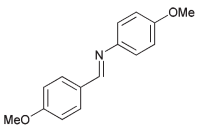
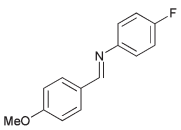
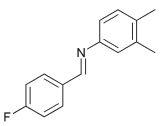
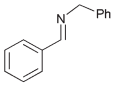
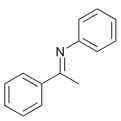
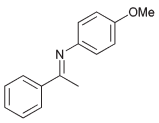
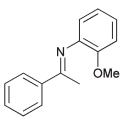
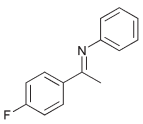
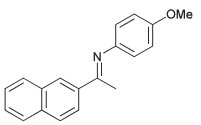
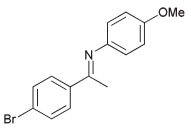
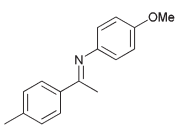
The catalytic behaviour of complexes **3** in the hydrogenation of imines has been examined. In the presence of ^{t}BuOK, complexes **3** catalyse the hydrogenation of *N*-



3a(Cl), 3d(Cl) **4a, 4d**

Scheme 2 Synthesis of **4a** and **4d**.

Table 1 Hydrogenation of imines catalysed by ruthenium complexes **3**[a]

Entry	Imine	Cat.	Conv. (%)	TOF (h^{-1})
1		**3a(Cl)**	60	100.0
2		**3b(Cl)**	100	166.7
3		**3c(Br)**	26	43.3
4		**3d(Cl)**	54	90.0
5		**3b(Cl)**	100	166.7
6			80	133.3
7			54	90.0
8[b]			98	16.3
9			100	166.7
10			100	166.7
11			100	166.7
12			100	166.7
13			100	166.7
14			100	166.7
15			100	166.7

[a] Reaction conditions, unless otherwise noted: 5 atm H_2, 70 °C, 2-methyltetrahydrofuran, S/C/B = 1000/1/10, base: ^{t}BuOK, 6 h. [S] = 1.4 M. Conversion was determined by ^{1}H NMR. TOF values as calculated from conversion. [b] S/C/B = 100/1/10.

benzylideneaniline under 5 bar of H_2 at 70 °C in 2-methyltetrahydrofuran, using an S/C/B ratio of 1000/1/10 (Table 1, entries 1–4). In the series, complex **3b(Cl)** leads to the more active catalyst. Next, we sought to probe the scope of the reaction, and thus various *N*-aryl and *N*-alkyl aldimines were examined. Substrates bearing electron-releasing substituents are also reduced with high activities (entry 5), whereas the presence of strongly electron-withdrawing substituents in both aryl groups significantly reduces the reactivity (entries 6 and 7). Also, an *N*-benzyl aldimine was hydrogenated more slowly than the analogous *N*-phenyl imine (entry 8). Finally, complex **3b(Cl)** also catalyses the hydrogenation of a series of *N*-aryl ketimines with high turnover frequencies, independently of the electronic characteristics of the aryl substituents (entries 9–15).

Conclusions

In summary, new ruthenium complexes **3** incorporating neutral CNC ligands have been prepared and structurally characterised. Contrary to the previously observed *mer* geometry of coordinated CNC ligands, complexes **3** exhibit a *fac* coordination mode for the pincer, which might be relevant for the design of novel chiral catalysts based on structurally similar terdentate ligands. Upon reaction with ^{t}BuOK, selective deprotonation at one of the methylene arms of the CNC ligand occurs, leading to dearomatisation of the pyridine ring. Finally, complexes **3** provide significant levels of catalytic activity in the hydrogenation of a variety of imines. This represents, to the best of our knowledge, the first application of Ru complexes containing dearomatised lutidine-derived pincer ligands in the important hydrogenation of C=N bonds.[8] Investigations directed to obtaining further insight into the mechanism of the imine hydrogenation, as well as the use of complexes **3** in other catalytic processes are being pursued.

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