Dalton Transactions

Accepted Manuscript

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ROYAL SOCIETY OF CHEMISTRY

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ROYAL SOCIETY OF CHEMISTRY View Article Online
DOI: 10.1039/C6DT00034G

Journal Name

ARTICLE

Ruthenium complexes bearing an unsymmetrical pincer ligand with a 2-hydroxypyridylmethylene fragment: active catalysts for transfer hydrogenation of ketones

Received 00th January 20xx,
Accepted 00th January 20xx

DOI: 10.1039/x0xx00000x

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Five ruthenium (II) complexes were synthesized, including (HO-C_5H_3N-CH_2-C_5H_3N-C_5H_4N)Ru(PPh_3)Cl_2 (**3**), [(HO-C_5H_3N-CH_2-C_5H_3N-C_5H_4N)Ru(PPh_3)$_2$Cl][PF_6] (**4**) and [(HO-C_5H_3N-CH_2-C_5H_3N-C_5H_4N)Ru(PPh_3)$_2$OH][PF_6] (**5**) bearing an unsymmetrical pincer NNN ligand with a 2-hydroxypyridylmethylene fragment, and [(CH_3O-C_5H_3N-CH_2-C_5H_3N-C_5H_4N)$_2$Ru][$Cl]_2$ (**6**) and [(CH_3O-C_5H_3N-CH_2-C_5H_3N-C_5H_4N)$_2$Ru][$PF_6]_2$ (**7**) containing 2-methoxypyridylmethylene moieties. **4** reacts with H_2O at room temperature to give **5** whose crystal structure reveals the existence of intramolecular hydrogen-bonding between its two -OH groups. **3** exhibits high catalytic activity for transfer hydrogenation of ketones.

Introduction

Metal-ligand cooperative complexes have important applications in bond activation and catalysis.[1] For example, Milstein's pyridine-based PNP-Ru and PNN-Ru complexes exhibit an interesting metal-ligand cooperation based on aromatization-dearomatization processes, and have been exploited for a series of hydrogenation reactions.[1,2]

Transition-metal complexes with 2-hydroxypyridyl (2-HOPy) derivatives are another group of metal-ligand bifunctional catalysts, and have also been applied to many catalytic reactions, such as oxidation of alcohols, hydrogenation of CO_2 and transfer hydrogenation of ketones, and so on.[3-8] In the catalytic cycles, aromatization-dearomatization might also be involved, *via* the tautomerization of 2-HOPy and 2-pyridone.[3-8] Besides these synthetic examples, 2-HOPy is also employed by nature to activate H_2, e.g. [Fe]-hydrogenase. In the active site of [Fe]-hydrogenase, there is a unique bidentate 2-hydroxy-6-acylmethylenepyridyl (2-HO-6-CH_2CO-Py) derivative coordinating with Fe (Fig. 1).[9,10] Although the exact mechanism of [Fe]-hydrogenase is still needed to be explored, the 2-HO-6-CH_2CO-Py ligand must play a critical role.[11,12] Theoretical studies have suggested that the deprotonated 2-hydroxy group acts as the proton acceptor.[12] Recently, the first experimental evidence supported this mechanism, and indicated the 2-hydroxy group was essential for H_2 activation.[13]

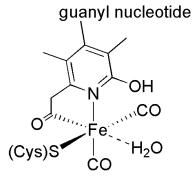

Fig. 1 The active site of [Fe]-hydrogenase.

A number of bidentate structural models of [Fe]-hydrogenase have been synthesized,[9,13-18] but none of them show any catalytic acitvity, except a semisynthetic iron complex[13] and a ruthenium complex.[14] Inspired by [Fe]-hydrogenase, Szymczak *et al.* recently developed a pincer-type ruthenium complex [(dhtp)Ru(PPh_3)$_2$Cl][PF_6) with 6,6'-dihydroxy terpyridine (dhtp) as a ligand, and demonstrated its capability of catalyzing transfer hydrogenation of ketones in 2-propanol.[19] Since a secondary coordination sphere could influence the catalytic activities,[4] in this present work we choose another ligand 6-([2, 2'-bipyridin]-6-ylmethyl) pyridin-2-ol (**2**) for the Ru complexes. Compared to dhtp, **2** is not only structurally closer to the active site of [Fe]-hydrogenase, but also more flexible, which might result in both meridional and facial Ru products, showing some interesting reactivity.[20] We expect the catalytic activity of the ruthenium complexes with the new ligand to be improved significantly. Herein we report the synthesis, reactivity and catalytic transfer hydrogenation activity of several ruthenium complexes supported by **2**.

Results and discussion

Synthesis and characterization of the ligands and their Ru(II) complexes

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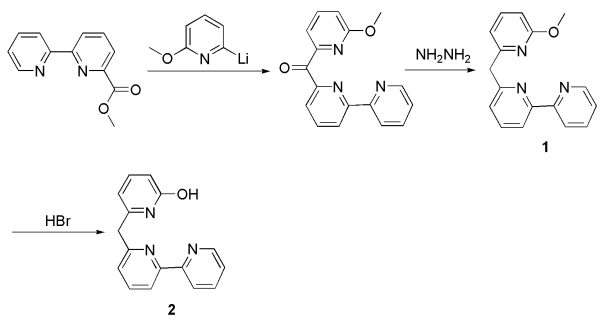
Electronic Supplementary Information (ESI) available: Crystallographic data for complex **5** and NMR spectra of the new compounds. For ESI and crystallographic data in CIF or other electronic format, see DOI: 10.1039/x0xx00000x

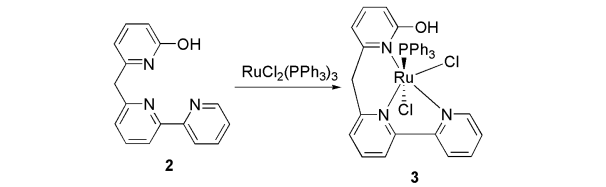


Scheme 1 Synthesis of ligands **1** and **2**.

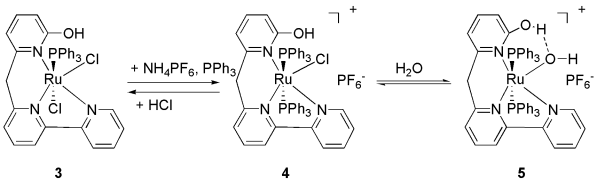
As shown in Scheme 1, **1** was given by the reaction of NH_2NH_2 with (6-methoxypyridin-2-yl)(6-(pyridin-2-yl)pyridin-2-yl)methanone, which was synthesized by the treatment of the known complex methyl [2,2'-bipyridin]-6-carboxylate with one equivalent of the lithium salt of 2-bromo-6-methoxy-pyridine. Hydrolysis of the methoxyl group of **1** with HBr (40% in water) afforded **2**, which is an unsymmetrical pincer NNN ligand with a 2-hydroxypyridylmethylene fragment.

When **2** was treated with $RuCl_2(PPh_3)_3$ in refluxing methanol for 24 hours, a pincer-type complex $(HO\text{-}C_5H_3N\text{-}CH_2\text{-}C_5H_3N\text{-}C_5H_4N)Ru(PPh_3)Cl_2$ (**3**) was formed with 59% yield (Scheme 2). **3** is a red color complex. Its ^1H NMR spectrum shows two doublets at 3.94 and 3.40 ppm for the $-CH_2-$ group, indicating that the two Cl atoms are in *cis* positions. The ^{31}P NMR shows one singlet at 58.1 ppm, which is comparable to that of the NNN-pincer ruthenium complex $L_1Ru(PPh_3)Cl_2$ (L_1 = 2-(1H-pyrazol-3-yl)-6-(3,5-dimethylpyrazol-1-yl)-pyridine) synthesized by Yu's group.[21a]

Complex **3** further reacted with NH_4PF_6 and PPh_3 in methanol, but unexpectedly, a mixture of two ionic complexes $[(HO\text{-}C_5H_3N\text{-}CH_2\text{-}C_5H_3N\text{-}C_5H_4N)Ru(PPh_3)_2Cl][PF_6]$ (**4**) and $[(HO\text{-}C_5H_3N\text{-}CH_2\text{-}C_5H_3N\text{-}C_5H_4N)Ru(PPh_3)_2OH][PF_6]$ (**5**) was constantly produced (Scheme 3). This was because the -Cl in **4** could be easily substituted by the -OH group in the presence of water at room temperature, giving the product **5**, accompanied by the loss of HCl (Scheme 3).[22] A completely pure **4** was not obtained due to the presence of a trace



Scheme 2 Synthesis of **3**.



Scheme 3 Synthesis of **4** and **5**.

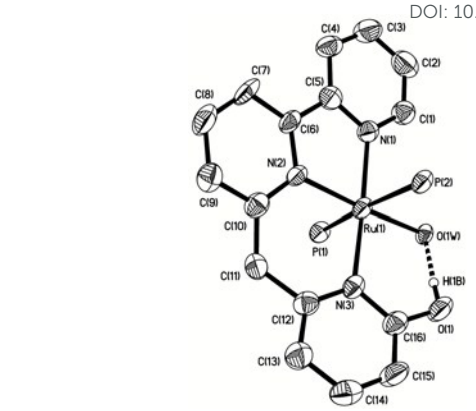
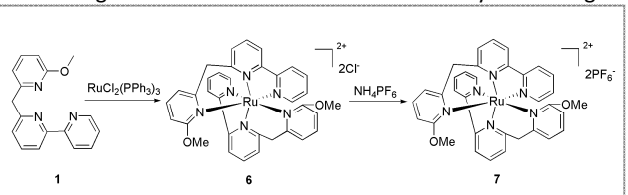


Fig. 2 Solid-state structure of **5**. The thermal ellipsoids are displayed at a 30% probability. Hydrogen atoms not involved in hydrogen bonds, phenyl rings on PPh_3 ligands and PF_6^- anion have been omitted for clarity. Selected bond distances (Å) and angle (°): Ru(1)-N(1), 2.081(7); Ru(1)-N(2), 2.031(6); Ru(1)-N(3), 2.151(6); Ru(1)-P(1), 2.402(3); Ru(1)-P(2), 2.437(3); Ru(1)-O(1W), 2.135(4); O(1)-O(1W), 2.423(8); C(16)-O(1), 1.341(10); N(2)-Ru(1)-O(1W), 172.4(2); N(1)-Ru(1)-N(3), 171.2(2); P(1)-Ru(1)-P(2), 173.09(7).

of water left in solvents, although they had been dried before use. When the mixture of **4** and **5** was added with excess of water, **4** transformed to **5** completely. Interestingly, **3** could be re-formed when the mixture of **4** and **5** (or pure **5**) was treated with excess of HCl (Scheme 3). Each of the ^1H NMR spectra of **4** and **5** shows one singlet for the $-CH_2-$ group (3.55 and 3.84 ppm, respectively), indicating the *trans* configuration of the PPh_3 groups. The ^{31}P NMR for PPh_3 groups in **4** and **5** are quite similar (22.5 ppm for **4**, and 26.7 ppm for **5**), and are both comparable to that of $[(dhtp)Ru(PPh_3)_2Cl][PF_6]$.[19]

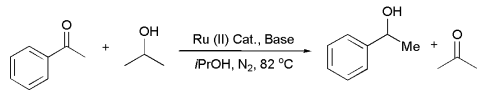
The molecular structure of **5** was further confirmed by X-ray crystallography (Fig. 2). The hydrogen atom of the Ru-O*H* could not be located exactly. The Ru(1)-O(1W) distance (2.135(4) Å) is in the range of Ru-OH bonds.[22b,23] The C(16)-O(1) distance (1.341(10)) is consistent with a C-O single bond, indicating a neutral NNN ligand scaffold. Remarkably, similar to complex $[(dhtp)Ru(PPh_3)_2Cl](PF_6^-)$, the O(1)-O(1W) distance (2.423(8) Å) indicates strong intramolecular hydrogen-bonding interaction between the two hydroxyl groups.[19]

To compare the reactivity and catalytic efficiency of Ru(II) complexes with different secondary coordination spheres, ligand **1** was also treated with $RuCl_2(PPh_3)_3$ in refluxing methanol. Interestingly, the only identified product was $[(CH_3O\text{-}C_5H_3N\text{-}CH_2\text{-}C_5H_3N\text{-}C_5H_4N)_2Ru][Cl]_2$ (**6**), no matter if the ratio of **1** to $RuCl_2(PPh_3)_3$ was 1:1 or 2:1. **6** could also react with NH_4PF_6 to give $[(CH_3O\text{-}C_5H_3N\text{-}CH_2\text{-}C_5H_3N\text{-}C_5H_4N)_2Ru][PF_6]_2$ (**7**) (Scheme 4).[24] **6** and **7**, different from **3**-**5**, have two NNN ligands coordinating with Ru(II). The difference might be because the coordination ability of **1** is higher



Scheme 4 Synthesis of **6** and **7**.

Table 1. Optimization of reaction conditions for the transfer hydrogenation of acetophenone catalyzed by Ru (II) complexes **3** and **5**-**7**.[a]



entry	cat.	base	time(min)	Yield(%)[b]
1	**5**	^{i}PrOK	8	80%
2	**3**	^{i}PrOK	8	95%
3	**6**	^{i}PrOK	8	0%
4	**7**	^{i}PrOK	8	0%
5	**3**	NaOH	15	73%
6	**3**	KOH	15	90%
7	**3**	^{t}BuOK	15	90%
8	**3**	^{i}PrOK	15	98%
9[c]	**3**	^{i}PrOK	15	62%
10[d]	**3**	^{i}PrOK	15	12%
11		^{i}PrOK	15	0%
12	**3**		120	49%

[a] General conditions: ketone, 2.0 mmol (2M in 50ml ^{i}PrOH); ketone/base/cat. = 200/10/1; N_2 (0.1 MPa); 82 °C. [b] GC yield. [c] Ketone/base/cat. = 1000/50/1. [d] Reaction was carried out under an air atmosphere.

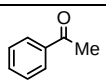
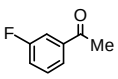
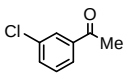
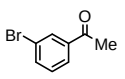
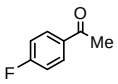
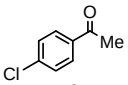
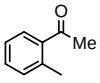
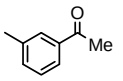
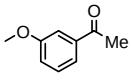
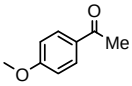
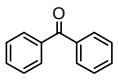
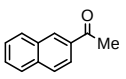
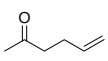
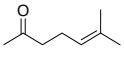
than **2**, which exists as a pyridone form in solution. The results indicate that when -PyOH is changed to -PyOMe group, the coordination mode of transition-metal complexes, as well as their reactivity, might be changed accordingly.[4]

Catalysis

Complexes **3**, **5**-**7** were then tested as the catalysts for the transfer hydrogenation of acetonphenone in refluxing isopropyl alcohol (Table 1). Firstly, ^{i}PrOK was chosen as the base, and the reactions were performed with a molar ratio of 200/10/1 for ketone/base/catalyst under a nitrogen atmosphere. It is shown in Table 1 (entries 1-2) that complex **3** gave 15% higher yield than **5**. Compared to **5**, **3** might be easier to be deprotonated by an external base, to give an intermediate with an open site.[21a] **6** and **7** did not show any reactivity, because they could not react with ^{i}PrOK to give an open site (entries 3-4). Other bases such as NaOH, KOH and ^{t}BuOK were also tested, but ^{i}PrOK gave the best performance, a 98% yield within 15 min (entries 5-8). If the catalyst was reduced to 0.1%, the yield decreased to 62% (entry 9). When the reactions were carried out under air or in absence of a base or catalyst, the yields were negligible or much lower (entries 10-12).

On the basis of the results above, the conditions for entries 2 and 8 in Table 1 were selected as the optimal conditions (except the reaction times), and they were later applied in the reduction experiments of a variety of ketones (Table 2). For all the substrates, the reaction times were optimized, to make sure the yields reached to 90% or above (except entry 13 due to a relative slow reaction speed). The transfer hydrogenation reactions for aryl ketones gave 86−99% yields within 8−150 min, reaching final TOFs up to 1.19×10^3

Table 2. Transfer hydrogenation of ketone catalyzed by complex **2**.[a]

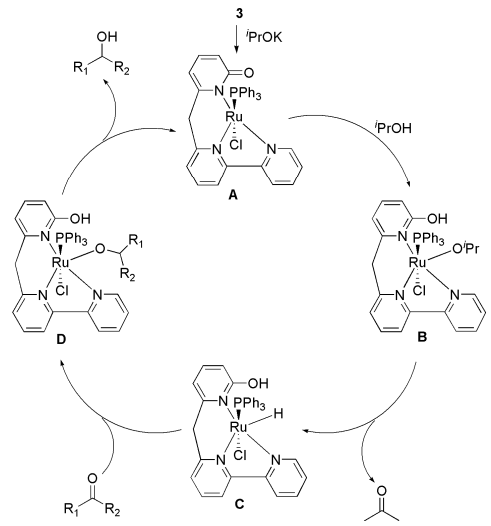
entry	ketone	Time (min)	GC yield (Isolated yield) (%)	final TOF (h^{-1})[b]
1		10	97 (93)	1.16×10^3
2		10	99 (94)	1.19×10^3
3		10	98 (91)	1.18×10^3
4		10	92 (87)	1.10×10^3
5		10	95 (90)	1.14×10^3
6		10	93 (89)	1.12×10^3
7		10	92 (87)	1.10×10^3
8		10	91 (88)	1.09×10^3
9		10	96 (92)	1.15×10^3
10		15	95 (90)	760
11		90	94 (90)	125
12		25	96 (91)	461
13		150	86 (80)	69
14		120	92 (85)	92
15		60	96 (92)	192
16		8	97	1.46×10^3
17		40	99	297
18		120	53[c,d]	n.d.
19		120	88[c]	n.d.

[a] General conditions: ketone, 2.0 mmol (2M in 50 mL of ^{i}PrOH); ketone/base/cat. = 200/10/1; N_2 (0.1 MPa); 82 °C. [b] TOF calculated with GC yield. [c] Yield determined by GC/MS; yield of carbonyl hydrogenation product. Note other products are observed, see text. [d] 1 mol% PPh_3 added.

h^{-1} (Table 2, entries 1-15). Acetophenone was reduced to 1-phenylethanol in approximately quantitative (97%) yield within 10 min (Table 2, entry 1). No obvious reactivity changed was found when electron withdrawing groups such as fluoro, chloro and bromo were introduced into the phenyl group (91%-99%, Table 2, entries 2-9), while adding electron-donating groups decreased the reactivity (86−96% yield, Table 2, entries 10, 11 and 13). Benzophenone and 2-acetonaphthone reacted smoothly to give the desired product in 92−96% yields within 120 min (Table 2, entries 14−15). Aliphatic ketone showed moderate reactivity (Table 2, entry 17), while cyclohexanone exhibited highest reactivity, with a TOF value of 1.46×10^3 h^{-1} (Table 2, entry 16). To the best of our knowledge, the highest reported TOF value in transfer hydrogenation of ketones was 2.5×10^6 h^{-1}, which was reported by Baratta'group.[25a] Stradiotto' group also reported a Ru(II) catalyst showing high catalytic activity (up to 2.2×10^5 h^{-1}).[25b] Besides, Yu *et al.* developed a series of NNN-pincer Ru(II) complexes showing excellent catalytic activity.[21] Our system is still needed to be improved.

To further understand the reaction mechanism, unsaturated aliphatic ketones were also tested. 5-hexen-2-one was converted to a mixture of hydrogenation products with high conversion (93%) over 120 min, and the ratio of 1: 0.6: 0.45 obtained for 5-hexen-2-ol, 2-heptanone and 2-hexanol, respectively, with a 53% yield of 5-hexen-2-ol (Table 2, entry 18). Different from the result of $[(dhtp)Ru(PPh_3)_2Cl](PF_6^-)$, addition of 1 mol% PPh_3 did not significantly change the selectivity, which might be because the dissociation of PPh_3 was not involved in the catalytic cycle.[19] For 6-methyl-5-hepten-2-one, a mixture of 6-methyl-5-hepten-2-ol, 6-methylheptan-2-one and 6-methylheptan-2-ol in a 1: 0.06: 0.02 ratio was obtained (95% conversion) (Table 2, entry 19), which means that the chemoselectivity goes much higher when the steric environment around the olefin is increased.

The low selectivity for 5-hexen-2-one suggests the reactions may follow an inner-sphere hydrogenation pathway.[19,21,26] Combined the mechanisms of $L_1Ru(PPh_3)Cl_2$ and the transition-metal complexes with 2-HOPy derivatives developed by Fujita and Yamaguchi *et al.*,[6,21a] we propose a possible mechanism in Scheme 5. In the presence of ^{i}PrOK, **3** firstly transforms to an intermediate **A** with an open site *via* dearomatization, by extrusion of one molecule of HCl. This intermediate then reacts with ^{i}PrOH to form a Ru(II) alkoxide species **B**. The Ru-H intermediate **C**, regarded as the catalytically active species, is then formed through β-H elimination, by releasing one molecule of acetone. Addition of a ketone to **C** produces another Ru(II) alkoxide intermediate **D**. After the elimination of one molecule of alcohol, **A** is re-formed and the cycle is finished. Attempts to isolate the intermediates were unsuccessful probably due to their unstability. For example, we have tried the reactions of **3** with ^{i}PrOK (1 eq. and 2 eq.) and K_2CO_3 (1 eq. and 10 eq.) in ^{i}PrOH, and **3** with $KN(SiMe_3)_2$ (1 eq.) in THF, however, no identified product was isolated. The reaction of **3** with $NaHBEt_3$ (1 eq.) in THF also did not give any characterized Ru-H product. Since no intermediate has been isolated, the detailed mechanistic analyses are needed in further experiments.



Scheme 5 Proposed mechanism.

Conclusions

In summary, a ruthenium (II) complex **3** bearing a NNN ligand with a 2-hydroxypyridylmethylene fragment was synthesized by the reaction of $RuCl_2(PPh_3)_3$ with **2**. **3** could further react with NH_4PF_6 and PPh_3 to afford **4**. **4** shows a reactivity with H_2O at room temperature in the absence of a base to give **5**, accompanied by the loss of HCl. The crystal structure of **5** shows strong intramolecular hydrogen-bonding interaction between the two hydroxyl groups. Surprisingly, when **1** was treated with $RuCl_2(PPh_3)_3$, the complex **6** with two NNN ligands was formed. The structural difference between **3** and **6** indicates that a small change in the ligands (-PyOH to -PyOMe) might result in a significant change in the coordination mode and reactivity of transition-metal complexes. **3** exhibits higher catalytic activity in transfer hydrogenation of ketones compared against $[(dhtp)Ru(PPh_3)_2Cl](PF_6^-)$ with a symmetrical ligand,[19] but its catalytic efficiency is still needed to be improved compared to other NNN-pincer ruthenium complexes developed by Yu's group.[21] The catalytic pathway might follow an inner-sphere hydrogenation mechanism, and might involve a metal-ligand cooperation, which is based on the aromatization/dearomatization *via* protonation/deprotonation of the 2-hydroxypyridyl group. Detailed mechanistic studies are still ongoing in our lab.

Experimental Section

General Considerations. All manipulations were carried out under an inert nitrogen atmosphere using a Schlenk line. Solvents were distilled from appropriate drying agents under N_2 before use. All reagents were purchased from commercial sources. Liquid compounds were degassed by standard freeze-pump-thaw procedures prior to use. $RuCl_2(PPh_3)_3$[27] and methyl [2,2'-bipyridin]-6-carboxylate[28] were prepared as previously described, respectively. The ^{1}H, ^{31}P and ^{13}C NMR spectra were recorded on a Bruker Avance 400 spectrometer. The ^{1}H NMR chemical shifts were referenced to residual solvent as determined relative to Me_4Si (δ = 0 ppm). The $^{31}P\{^1H\}$ chemical shifts were reported in ppm relative to external 85% H_3PO_4. The $^{13}C\{^1H\}$ chemical shifts were reported in ppm

relative to the carbon resonance of $CDCl_3$ (77.0 ppm). Elemental analyses were performed on a Perkin-Elmer 240C analyzer. High-resolution mass spectrum (HR-MS) was recorded on a Varian 7.0T FTICR-MS by ESI technique. X-ray diffraction studies were carried out in an Xcalibur E X-ray single crystal diffractometer. Data collections were performed using four-circle kappa diffractometers equipped with CCD detectors. Data were reduced and then corrected for absorption.[29] Solution, refinement and geometrical calculations for all crystal structures were performed by SHELXTL-97, and PLATON SQUEEZE was used to remove the undetermined disordered solvent.[30]

Synthesis of (6-methoxypyridin-2-yl)(6-(pyridin-2-yl)pyridin-2-yl)methanone:

To a solution of n-BuLi (1.44 mL, 1.60 M, 2.30 mmol) in 10 mL dry tetrahydrofuran at -78 ^{o}C was added 2-bromo-6-methoxy-pyridine (0.44 g, 2.30 mmol) in 25 mL tetrahydrofuran. After 30 min of stirring at -78 ^{o}C, methyl [2,2'-bipyridin]-6-carboxylate (0.50 g, 2.30 mmol) was added. The reaction mixture was stirred at -20 ^{o}C for 3 h and left at room temperature overnight. After addition of 15 mL of water the reaction mixture was extracted with dilute HCl. The water phase was neutralized by NaOH in water and extracted with CH_2Cl_2. The crude product was purified by column chromatography on silica gel (petroleum ether/ethyl acetate, v:v = 10:1) to give (6-methoxypyridin-2-yl)(6-(pyridin-2-yl)pyridin-2-yl)methanone (0.61 g, 89%). HR-MS (ESI): Calcd for $C_{17}H_{13}N_3O_2$+H, 292.1086; Found, 292.1083. ^{1}H NMR (400 MHz, $CDCl_3$, ppm): 8.68 (d, *J* = 4 Hz, 1H), 8.63 (d, *J* = 8 Hz, 1H), 8.37 (d, *J* = 8 Hz, 1H), 8.07 (d, *J* = 8 Hz, 1H), 7.99 (t, *J* = 8 Hz, 1H), 7.80-7.73 (m, 3H), 7.31 (t, *J* = 6 Hz, 1H), 6.97 (t, *J* = 4 Hz, 1H), 3.87 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$, ppm): 192.3, 163.2, 155.3, 155.2, 153.8, 151.4, 149.0, 138.6, 137.2, 136.9, 124.8, 124.0, 123.1, 121.2, 118.9, 114.6, 53.4.

Synthesis of 1:

To a solution of (6-methoxypyridin-2-yl)(6-(pyridin-2-yl)pyridin-2-yl)methanone (1.00 g, 3.40 mmol) in 20 mL ethylene glycol was added NaOH (1.50 g) and NH_2NH_2 (20.0 mL, 80% in water). The mixture was heated at 100 ^{o}C for 5 h. Water (20 mL) was added and the solution was neutralized by dilute HCl (1.0 M) and extracted with ethyl acetate. The organic phase was dried over Na_2SO_4 and evaporated under vacuum. The crude product was purified by column chromatography on silica gel (petroleum ether/ethyl acetate, v:v = 4:1) to give **1** (0.77 g, 81%). HR-MS (ESI): Calcd for $C_{17}H_{15}N_3O$+H, 278.1293; Found, 278.1300. ^{1}H NMR (400 MHz, $CDCl_3$, ppm): 8.67 (br s, 1H), 8.45 (d, *J* = 8 Hz, 1H), 8.24 (d, *J* = 8 Hz, 1H), 7.80 (t, *J* = 8 Hz, 1H), 7.73 (t, *J* = 8 Hz, 1H), 7.48 (t, *J* = 8 Hz, 1H), 7.28 (m, 2H), 6.84 (d, *J* = 8 Hz, 1H), 6.58 (d, *J* = 8 Hz, 1H), 4.32 (s, 2H), 3.91 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$, ppm): 163.6, 159.0, 157.1, 156.3, 155.4, 148.9, 138.7, 137.0, 136.6, 123.4, 123.4, 121.1, 118.5, 115.9, 107.9, 53.1, 46.9.

Synthesis of 2:

A solution of **1** (4.30 g, 16.0 mmol) in 20 mL of HBr (40% in water) was heated at reflux for 3 h. After cooling to room temperature, the yellow solution was neutralized by slow addition of a saturated aqueous solution of NaOH (100 mL). The aqueous solution was extracted with CH_2Cl_2 (3 × 100 mL). The combined organic extracts were dried over Na_2SO_4, filtered, and concentrated to afford **2** as a milk white solid (3.00 g, 73%). Mp: 191 ^{o}C. HR-MS (ESI): Calcd for $C_{16}H_{13}N_3O$+H, 264.1137; Found, 264.1140. ^{1}H NMR (400 MHz, $CDCl_3$, ppm): 8.66 (d, *J* = 4 Hz, 1H), 8.44 (d, *J* = 8 Hz, 1H), 8.32 (d, *J* = 8 Hz, 1H), 7.84-7.74 (m, 2H), 7.37-7.27 (m, 3H), 6.43 (d, *J* = 9 Hz, 1H), 6.13 (d, *J* = 7 Hz, 1H), 4.09 (s, 2H). ^{13}C NMR (100 Hz, DMSO, ppm): 163.0, 156.8, 155.0, 154.8, 149.2, 147.0, 140.9, 138.0, 137.1, 124.1, 123.4, 120.4, 118.4, 117.0, 104.6, 40.6.

Synthesis of 3:

Method a: A solution of **2** (0.17 g, 0.63 mmol) and $RuCl_2(PPh_3)_3$ (0.60 g, 0.63 mmol) was refluxed in dried methanol (75 mL) with stirring for 24 h. The mixture was allowed to cool to room temperature and the organic phase was evaporated under vacuum. The crude product was recrystallized with CH_2Cl_2/ether to give **3** as a red powder (0.51 g, 59%). Anal. Calcd for $C_{34}H_{28}Cl_2N_3OPRu$: C, 58.54; H, 4.05; N, 6.02. Found: C, 58.33; H, 4.03; N, 6.08. ^{1}H NMR (400 MHz, CD_3OD, ppm): 8.54 (t, *J* = 8 Hz, 2H), 8.34 (d, *J* = 6 Hz, 1H), 8.00 (m, 2H), 7.74 (t, *J* = 8 Hz, 1H), 7.41-7.33 (m, 4H), 7.04-7.19 (m, 13H), 7.00 (d, *J* = 8 Hz, 1H), 6.85 (d, *J* = 8 Hz, 1H), 3.94 (d, *J* = 14 Hz, 1H), 3.40 (d, *J* = 14 Hz, 1H). ^{31}P NMR (162 MHz, CD_3OD, ppm): 58.1.

Method b: 2 mL of HCl was added to a solution of **5** (0.52 g, 0.50 mmol) in MeOH (50 mL) drop by drop at room temperature, after 24 h, the red precipitate was collected, washed with copious amounts of ether and dried under vacuum to provide **3** as a red powder (0.21 g, 60%).

Reaction of 3 with NH_4PF_6/PPh_3:

A solution of **3** (0.50 g, 0.72 mmol) and PPh_3 (0.40 g, 14.4 mmol) was dissolved in dried methanol (75 mL), and NH_4PF_6 (1.7 g, 10.43 mmol) was added with stirring. After 20 min, the precipitate was collected, washed with copious amounts of diethyl ether and dried under vacuum to provide a mixture of **4** and **5** as an orange-red powder (0.54 g). **4**: ^{1}H NMR (400 MHz, $CDCl_3$, ppm): 11.93 (s, 1H), 8.74 (d, *J* = 5 Hz, 1H), 7.88-6.69 (m, 38H), 6.07 (d, *J* = 8 Hz, 1H), 3.55 (s, 2H). ^{31}P NMR (162 MHz, $CDCl_3$, ppm): 22.5, -141.0. **5**: ^{1}H NMR (400 MHz, $CDCl_3$, ppm): [14.54(s), 14.38(s) (total 1H)], 8.81 (d, *J* = 6 Hz, 1H), 7.60 (m, 2H), 7.43 (d, *J* = 8 Hz, 1H), 7.37 (d, *J* = 8 Hz, 1H), 7.88-6.69 (m, 33H), 6.72 (d, *J* = 7 Hz, 1H), 5.83 (d, *J* = 8 Hz, 1H), 3.84 (s, 2H). ^{31}P NMR (162 MHz, $CDCl_3$, ppm): 26.7, -141.0.

Synthesis of 5:

Method a: A solution of **2** (0.17 g, 0.63 mmol) and $RuCl_2(PPh_3)_3$ (0.60 g, 0.63 mmol) was refluxed in dried methanol (75 mL) with stirring for 24 h. The mixture was allowed to cool to room temperature and diluted with methanol (95% in water, 75 mL) and then was filtered through a pad of Celite (~4 cm tall x 5 cm diam) in the open air. The Celite pad was rinsed with methanol until the eluent became colorless. Solid NH_4PF_6 (1.70 g, 10.43 mmol) was added to the combined filtrates and the solution was placed in a -25 °C freezer overnight, during which time a red precipitate emerged. The precipitate was collected, washed with copious amounts of diethyl ether and dried under vacuum to provide the title compound as a red powder (0.45 g, 68%). A crystal suitable for a single crystal X-ray diffraction experiment was grown by vapor diffusion of diethyl ether into a dichloromethane solution of **5** at room temperature. Anal. Calcd for $C_{52}H_{44}F_6N_3O_2P_3Ru$: C, 59.43; H, 4.22; N, 4.00. Found: C, 59.04; H, 4.13; N, 3.84.

Method b: In a J Young NMR tube, a solution of a mixture of **4** and **5** (5 mg) in $CDCl_3$ (0.5 mL) was added 2 drops of H_2O. The solution was shaken for 30 min and the ^{1}H NMR spectrum showed the mixture was almost completely transformed into **5**.

Synthesis of 6:

A solution of **1** (0.35 g, 1.25 mmol) and $RuCl_2(PPh_3)_3$ (0.60 g, 0.63 mmol) was refluxed in dried methanol (200 mL) with stirring for 24 h. The mixture was allowed to cool to room temperature and the organic phase was evaporated under vacuum. The crude product was recrystallized with CH_2Cl_2/ether to give **6** as an orange powder (0.26 g, 54%). Anal. Calcd for $C_{34}H_{30}Cl_2N_6O_2Ru$: C, 56.20; H, 4.16; N, 11.57. Found: C, 56.25; H, 4.17; N, 11.45. ^{1}H NMR (400 MHz, CD_3OD, ppm): 8.54 (d, *J* = 8 Hz, 2H), 8.31-8.23 (m, 4H), 8.07 (d, *J* = 8 Hz, 2H), 7.85-7.76 (m, 4H), 7.46 (d, *J* = 7 Hz, 2H), 7.08 (t, *J* = 6 Hz, 2H), 6.71 (d, *J* = 7 Hz, 2H), 6.58 (d, *J* = 8 Hz, 2H), 4.81 (d, *J* = 14 Hz, 2H), 4.33(d, *J* = 14 Hz, 2H), 2.92 (s, 6H).

Synthesis of 7:

A solution of **6** (0.8 g, 1.1 mmol) was dissolved in dried methanol (50 mL), and NH_4PF_6 (1.7g, 11 mmol) was added with stirring. After 20 min, the precipitate was collected, washed with copious amounts of diethyl ether and dried under vacuum to provide **7** as an orange-red powder (1.0 g, 77%). HR-MS (ESI): Calcd for [M-PF_6^-], 801.1116; Found, 801.1121. Anal. Calcd for $C_{34}H_{30}F_{12}N_6O_2P_2Ru$: C, 43.18; H, 3.20; N, 8.89. Found: C, 43.39; H, 3.21; N, 8.73. ^{1}H NMR (400 MHz, CD_3COCD_3, ppm): 8.71 (d, *J* = 8 Hz, 2H), 8.45 (d, *J* = 8 Hz, 2H), 8.36 (t, *J* = 8 Hz, 2H), 8.20 (d, *J* = 8 Hz, 2H), 7.91-7.86 (m, 4H), 7.55 (d, *J* = 8 Hz, 2H), 7.22 (m, 2H), 7.02 (d, *J* = 6 Hz, 2H), 6.72 (d, *J* = 8 Hz, 2H), 5.00 (d, *J* = 14 Hz, 2H), 4.52(d, *J* = 14 Hz, 2H), 3.04 (s, 6H).

General procedure for the catalytic transfer hydrogenation of ketones: The catalyst solution was prepared by dissolving complex **3** (69.7 mg, 0.10 mmol) in 2-propanol (10.0 mL) and internal standard solution was prepared by dissolving dodecane (340 mg, 2.0 mmol) in 2-propanol (10.0 mL). Under an N_2 atmosphere, the mixture of a ketone (2.0 mmol), 1.0 mL of the catalyst solution (0.01 mmol), 1.0 mL of the internal standard solution (0.2 mmol), and 2-propanol (10.0 mL) was stirred at 82 °C for 10 min. Then 0.2 mL of a 0.5 M ^{i}PrOK (0.10 mmol) solution in 2-propanol was introduced to initiate the reaction. At the stated time, 0.1 mL of the reaction mixture was sampled and immediately diluted with 0.5 mL of 2-propanol precooled to 0 °C for GC analysis. After the reaction was completed, the reaction mixture was condensed under reduced pressure and subjected to purification by flash silica gel column chromatography to afford the corresponding alcohol product, which was identified by comparison with the authentic sample through NMR and GC analysis.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (Nos. 21302028 and 21201049) and Harbin Science and Technology Bureau (2013RFLXJ002).

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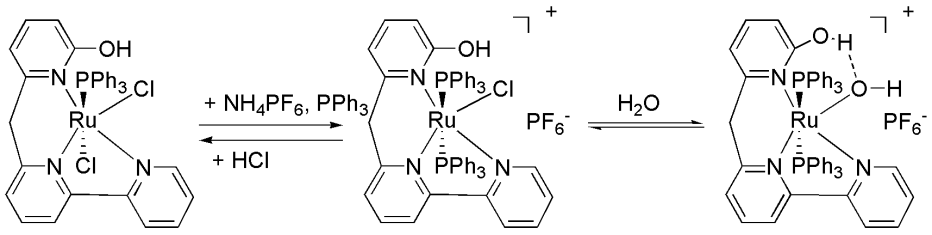

3 **4** **5**

The synthesis, reactivity and catalytic transfer hydrogenation activity of three metal-ligand cooperative ruthenium (II) complexes (**3**-**5**) bearing an unsymmetrical pincer NNN ligand with a 2-hydroxypyridylmethylene fragment were reported.