Ruthenium(II) complexes bearing (*NNN*) ligand: catalytic evaluation of different solvent-mediated coordination modes

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ABSTRACT

A new (NNN) tridentate ligand was prepared and its ability to coordinate ruthenium(II) was evaluated. The presence of different functional groups on the ligand allowed to obtain bi- or tri- coordinated complexes depending on complexation conditions. The catalytic activity of both bidentate and tridentate complexes was studied in asymmetric transfer hydrogenation of different aryl ketones showing a comparable behavior of the two complexes in terms of efficiency and stereoselectivity.

Keywords: tridentate ligand, asymmetric hydrogen transfer, asymmetric ketones reduction.

1. INTRODUCTION

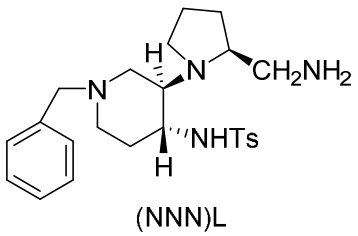
The importance of chirality is widely recognized in fine chemistry, especially in the pharmaceutical, pesticides and food additives industries. The isolation of a chiral compound from a racemic mixture is challenging because it requires the separation of enantiomers. This process is not trivial and in addition half of the product could be lost if not re-convertible or usable as building-block for another synthetic pathway. In this context, the asymmetric catalysis is one of the best methods to introduce one or more stereocenters in bioactive molecules.[1-2] The investigation of new stereocontrolled syntheses by transition metal catalysts modified by incorporating chiral ligands is thus of wide-spreading importance.[3-4]

In the last decades, the monosulfonated diamines have been suggested among other ligands as a very versatile and promising category in homogeneous catalysis.[5-6] Many ruthenium complexes have been reported and found useful in the stereoselective reduction of carbonyls in homogeneous phase.[7] In many examples, ligand structures are

based on a two-carbon-atom chain with two nitrogen substituents in the *anti*-position (1,2 diamine).[8-10] On the other hand, there is a great interest in transition metal complexes with tridentate amine ligands, especially those containing a pyridine due to its unique electronic and steric properties.[8, 11-17] Some of them have good efficiency in the catalytic epoxidation reaction[18-19] and in transfer hydrogenation of aryl ketones.[20]

Starting from this consideration here is reported the synthesis of a new tridentate ligand **1** (Figure 1) and the study of its different coordination modes to a ruthenium metal center.

Recently we studied the introduction of an unnatural β-aminoacidic skeleton in a octapeptide used as ligand in a Cu(II) complex containing the same pyrrolidine-piperidine structure as in the compound reported in Figure 1.[21] In principle the presence of different functional groups on compound **1** could allow to obtain bi- or tri-coordinated complexes depending on solvent and on additive choice thus leading to the possibility to investigate the catalytic performance of the different complexes in asymmetric transfer hydrogenation of aryl ketones.



(NNN)L

Figure 1. (NNN) ligand

2. EXPERIMENTAL

2.1. General: ^{1}H and ^{13}C NMR spectra were recorded in $CDCl_3$ or CD_3OD on Bruker DRX Avance (300 and 75 MHz) equipped with a non-reverse probe. Chemical shifts (in ppm) were referenced to residual solvent proton/carbon peak. Polarimetry analyses were carried out on Perkin Elmer 343 Plus equipped with Na/Hal lamp. MS analyses were performed by using a Thermo Finnigan (MA, USA) LCQ Advantage system MS spectrometer with an electronspray ionization source and an 'Ion Trap' mass analyzer. The MS spectra were obtained by direct infusion of a sample solution in MeOH under ionization, ESI positive. Catalytic reactions were monitored by gas chromatography analysis using a chiral stationary phase column (MEGA DMT β, 25 m, internal diameter 0.25 mm) or by HPLC analysis with Merck-Hitachi L-7100 equipped with Detector UV6000LP and chiral column (OD-H or OJ-H Chiralcel). Commercially reagent grade solvents were dried according to standard procedures and freshly distilled under nitrogen before use.

2.2. (*S*)-1-[(3*R*,4*R*)-1-benzyl-4-(4-tosylamido)-piperidin-3-yl]pyrrolidine-2-carboxamide 3: Pyridine (0.14 mL, 1.75 mmol), di-*tert*-butyl dicarbonate (0.687 g, 3.15 mmol) and $(NH_4)_2CO_3$ (0.37 g, 3.85 mmol) were added to a solution of ((3R,4R)-1-benzyl-4-((4-methylphenyl)sulfonamido)piperidin-3-yl)-L-proline **2**[22] (0.8 g, 1.7 mmol) in DMF (10 mL) . The reaction mixture was stirred for 24 h at room temperature then the solvent was removed under vacuum. The residue, taken up in CH_2Cl_2 (15 mL), was washed twice with a NaCl saturated solution. The organic layer was dried on Na_2SO_4 and the solvent was removed under vacuum affording compound **3**. Yield 85%, yellow powder. mp 109-112°C (from Et_2O); $[\alpha]_D$ =+ 19,6 (c=0.23, $CHCl_3$), MS (ESI) *m/z* = 457,4$[M+H]^+$; ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.25-1.70 (m, 3H), 1.75-1.84 (m, 2H), 1.95-2.12 (m, 1H), 2.25-2.76 (m, 5H), 2.42 (s, 3H), 2.81-3.05 (m, 1H), 3.12-3.20 (m, 2H), 3.30-3.41(m, 1H), 3.74-3.88 (m,2H), 2.22-7.80 (m, 9H) ppm; ^{13}C NMR (75MHz, $CDCl_3$) δ 20.4 (CH_3), 24.5 (CH_2), 30.9

(CH_2), 31.2 (CH_2), 45.7 (CH_2), 51.1 (CH_2), 51.3 (CH_2), 52.8 (CH), 59.4 (CH), 62.0 (CH_2), 63.6 (CH), 127.1 (CH), 128.5 (CH), 128.7 (CH), 129.8 (CH), 130.2 (CH), 138.5 (C), 143.8 (C), 134.5 (C), 179.8 (C) ppm. Elemental analysis: calcd. for $C_{24}H_{32}N_4O_3S$ C, 63.13; H, 7.06; N, 12.27; found C, 63.00; H, 7.18; N, 12.08.

2.3. *N*-(3*R*,4*R*)-3-[(*S*)-2-(aminomethyl)pyrrolidin-1-yl]-1-benzylpiperidin-4-yl-4-tosylamide 1: Red-Al 60% solution in toluene (2.21 mL, 6.57 mmol) was added to a solution of carboxamide **3** (0.5 g, 1.1 mmol) in toluene (10 mL). The solution was refluxed under N_2 atmosphere for 1,5 h (TLC analysis: CH_2Cl_2/CH_3OH 10:1). The reaction mixture was poured into the ice, the obtained precipitate was filtered off. The precipitate, solubilized in 20 mL of ethyl acetate, was washed with water. The organic phases were acidified with 0.1N HCl until pH 3 and the phase separated. The acid aqueous solution was then pH was raised to 8 with a saturated $NaHCO_3$ solution and extracted with ethyl acetate, dried with Na_2SO_4 and evaporated. The crude was purified by RP-HPLC using a gradient elution of 95–30% solvent A (solvent A: water/acetonitrile/trifluoracetic acid 95 : 5 : 0.1; solvent B: water/acetonitrile/trifluoracetic acid 5 : 95 : 0.1) over 20 min at a flow rate of 20 mL/min^{-1}. The purified compound **1** was freeze-dried and stored at 0 °C. Yield 40%, white solid, mp 35-40°C; $[\alpha]_D$ = -49,6 (c=0.26 , $CHCl_3$); MS (ESI) *m/z* = 443,3$[M+H]^+$; ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.25-2.56 (m, 10H), 2.42 (s, CH_3), 2.61-2.98 (m, 7H), 3.42-3.58 (m, 2H), 7.21-7-82 (m, 9H) ppm; ^{13}C NMR (75MHz, $CDCl_3$) δ 21.9 (CH_3), 23.9 (CH_2), 29.0 (CH_2), 33.2 (CH_2), 45.1 (CH_2), 45.4 (CH_2), 52.2 (CH_2), 52.3 (CH_2), 54.5 (CH), 58.4 (CH), 60.5 (CH), 63.5 (CH_2), 127.5 (CH), 128.3 (CH), 129.3 (CH), 129.7 (CH), 129.9 (CH), 138.3 (C), 138.4 (C), 143.1 (C) ppm. Elemental Analysis: calcd. for $C_{24}H_{34}N_4O_2S$ C, 65.13; H, 7.74; N, 12.66; found C, 65.02; H, 7.92; N, 12.48.

2.4. Synthesis of complex A: In a 10 mL Schlenk tube, the ligand (1.1 eq) was added to a solution of $[RuCl_2(p\text{-cymene})]_2$ (0.5 eq) in 5 mL of 2-propanol under argon atmosphere and stirred for 5 hours at 85°C. After cooling to room temperature, a yellow precipitate has

been formed. The solid was filtered and washed with diethyl ether; finally, the precipitate was dried under *vacuum.* Quantitative yield, reddish solid; MS (ESI) of $C_{34}H_{47}Cl_2N_4O_2RuS$ [M-Cl] (*m/z*): calcd. 713.22, found 713.3 [M], 677.4 [M-Cl]; ^{1}H NMR (CD_3Cl, 300 MHz): δ = 1.18-1.28 (m, 10H), 2.04-2.09 (m, 4H), 2.15 (s, 3H), 2.27 (s, 3H), 2.35-2.37 (m, 3H), 2.38-2.40 (m, 4H), 2.89-2.91(m, 2H), 2.94-3.04(m, 2H), 3.46-3.48 (m, 2H), 4.10-4.12 (m, 1H), 5.32-5.34 (m, 2H), 5.46-5.48 (m, 2H), 7.16-7.37 (m, 7H), 7.70 (d, *J* = 8.1 Hz, 2H) ppm; Elemental Analysis: calcd. for $C_{34}H_{47}Cl_2N_4O_2RuS$ C, 54.54; H, 6.46; N, 7.48; found C, 54.98; H, 6.58; N, 7.51.

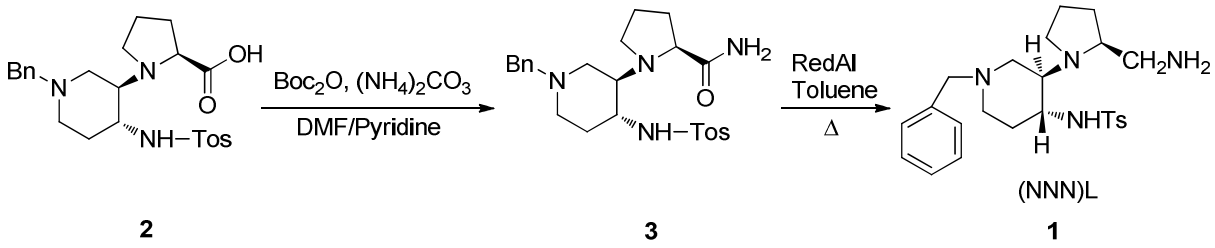
2.5. Synthesis of complex B: In a 10 mL Schlenk tube, the ligand (1.1 eq) and TEA (2 eq) were dissolved in 5 mL of toluene. The dimer $[RuCl_2(p\text{-cymene})]_2$ (0.5 eq) was added and the suspension was stirred for 3 h at room temperature. Then the orange solution was refluxed for 1 h and during this period the solution became yellow-orange. After cooling to room temperature, a yellow precipitate has been formed. The solid was filtered and washed, first with water and then with diethyl ether; finally, the precipitate was dried under *vacuum.* Quantitative yield, brown solid; MS (ESI) of $C_{48}H_{66}Cl_4N_8O_4Ru_2S_2$ (*m/z*): calcd. 1230.15, found 543.4 [(M-C):2]I;^{1}H NMR (CD_3OD, 300 MHz): δ = 0.83-1.2 (m, 1H), 1.21-1.25 (m, 2H), 1.40-1.48 (m, 2H), 1.49-1.53 (m, 2H), 1.68-2.10 (m, 2H), 2.53 (s, 2H), 2.58-2.90 (m, 4H), 3.16-3.23 (m, 4H), 3.53-3.70 (m, 5H), 3.82-4.01 (m, 1H), 7.13-7.37 (m, 5H), 7.76-7.81 (m, 2H), 8.47-8.61 (m, 1H) ppm; Elemental Analysis: calcd. for $C_{48}H_{66}Cl_4N_8O_4Ru_2S_2$ C, 46.98; H, 5.42; N, 9.13; found C, 45.94; H, 5.13; N, 9.04.

2.6. General procedure for asymmetric transfer hydrogenation (ATH): In a Schlenk tube sealed under argon, ketone (1 mmol) was added to the Ru-complex (**A** or **B**) (5×10^{-3} mmol) followed by 1.5 mL of solvent and hydrogen donor (10 mmol). The solution was stirred for 24 h at 40°C. The conversion and enantioselectivity were evaluated by chiral GC or HPLC analysis.[23-25]

GC analysis condition for **4a**: iso 120°C, rt_R=11 min., rt_S=12 min.

HPLC condition for **4b**: column: OD-H Chiralcel, hexane: ethanol = 95:5, flow = 0.8 mL/min, λ = 216 nm: rt_R = 12.6 min, rt_S = 15.8 min; for **4c**: OD-H Chiralcel, hexane: ethanol = 98:2, flow = 0.8 mL/min, λ = 220 nm: rt_S = 16.1 min, rt_R = 17.2 min; for **4d**: OD-H Chiralcel, hexane: ethanol = 95:5, flow = 1.0 mL/min, λ = 220 nm: rt_R 11.9, rt_S =12.7 min; for **4e**: OD-H Chiralcel, hexane: 2-propanol = 95:5, flow = 1.0 mL/min, λ = 230 nm: rt_R =6.5, rt_S =7.5 min; for **4f**: OD-H Chiralcel, hexane: ethanol = 95:5, flow = 0.8 mL/min, λ = 216 nm: rt_R = 13.9 min, rt_S = 14.6 min; for **4g**: OJ-H Chiralcel, eluent: hexane: 2-propanol = 90:10, flow = 1.0 mL/min, λ = 216 nm: rt_S = 23.4 min, rt_R = 29.7 min.

3. RESULTS and DISCUSSION

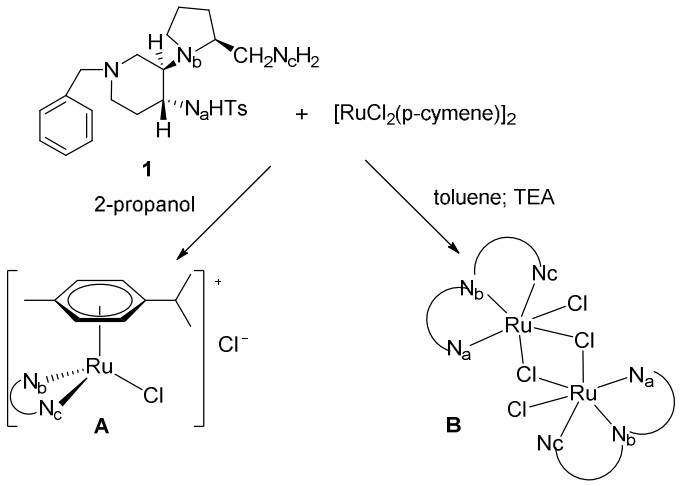


Scheme 1. Synthesis of (NNN) ligand **1**

Compound **1** was synthesized starting from known acid **2** that was obtained in good yields through a multicomponent reaction as recently described elsewhere.[22] Compound **2** was at first transformed in carboxamide **3** (85%) by reaction with di-*tert*-butyl-dicarbonate (1.8 eq), ammonium carbonate (2.2 eq) and pyridine (1 eq) in DMF. The intermediate **3** was turned into the final tridentate ligand **1** (40%) by reduction with bis(2-methoxyethoxy) aluminum hydride (6.5:1 molar ratio) in toluene solution at reflux temperature (Scheme 1).

The Ru(II) complexes bearing the tridentate ligand were synthesized using two different methodologies: in the first case the use of 2-propanol, a protic and polar solvent in

absence of a base, at reflux for 5 h allowed to obtain a bidentate coordination involving the two over three more nucleophilic amino functions leaving the one bearing the sulfonic moiety aside. In the second method, the synthesis of the complex was realized in toluene for 3 h in presence of 2 equivalents of TEA employing in this case an aprotic apolar solvent in presence of a base with the aim of involving in coordination all the three amino functions (Scheme 2). Either the use of 2-propanol in presence of TEA or only toluene led the formation of complex which involved heterogeneously the three N atoms.



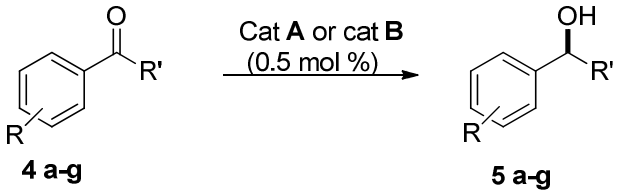
Scheme 2. Synthetic pathways of Ru(II) complexes.

As confirmed by ^{1}H-NMR and ESI spectroscopy investigations two different complexes **A** and **B** were formed bearing a bidentate or tridentate ligand.[26-28] In the ^{1}H-NMR spectra of complex **A** the presence of the *p*-cymene ring as evinced by the two multiplet signals at 5.32-5.34 and 5.46-5.48 ppm for the aromatic protons, confirmed a bidentate coordination mode. When the reaction takes place in the absence of a base, we can exclude the involvement of the tosylamine N_a in the coordination of the metal center. It is likely, thus, that the possible coordination mode preferentially involves the N_b and N_c of methylamino-proline moiety. In this way, a more stable five-membered ring at the metal center is obtained.

On the contrary, in the presence of TEA and toluene, the tridentate complex **B** is obtained as evinced by the absence of the peaks belonging to *p*-cymene group in the ^{1}H-NMR spectrum. Satisfactory elemental analyses and ESI-MS data corresponding to the proposed structures were obtained for both complexes.

Considering the distinctive features of the complexes here proposed, we then evaluated their capability to be used as precatalysts in asymmetric transfer hydrogenation of different aryl ketones (Table 1).[29]

Table 1: ATH of different substituted aryl ketones.



4 a-g → **5 a-g**

a: R= H; R'= CH_3
b: R= 3-OCH_3; R'= CH_3
c: R= 4-CF_3; R'= CH_3
d: R= 4-OCH_3; R'= CH_3
e: R= 2,5-CH_3; R'= CH_3
f: R=H; R'= CH_2COOEt
g: R= H; R'= CH_2CN

Entry[a]	Substrate	H donor	Reaction solvent	Catalyst	Conversion[b]	e.e.
1	**4a**	HCOOH	H_2O	**A**	63%	17%
2		HCOOH/TEA	H_2O		-	-
3		HCOONa	H_2O		85%	81%
4		HCOOH	H_2O	**B**	-	-
5		HCOONa	H_2O		63%	44%
6		HCOONa	H_2O/MeOH 1:1		65%	70%
7		HCOONa	2-propanol		54%	82%
8	**4b**	HCOOH	H_2O	**A**	30%	33%
9		HCOONa	H_2O		45%	58%
10		HCOONa	H_2O/MeOH 1:1		22%	5%
11		HCOONa	2-propanol		30%	15%
12		HCOOH	H_2O	**B**	-	-

13		HCOONa	H_2O		35%	54%
14	**4c**	HCOOH	H_2O	**A**	65%	-
15		HCOONa	H_2O		55%	9%
16		HCOONa	2-propanol		48%	33%
17		HCOONa	H_2O	**B**	20%	2%
18		HCOONa	H_2O/MeOH 1:1		35%	-
19		HCOONa	2-propanol		23%	22%
20	**4d**	HCOONa	H_2O	**A**	20%	-
21	**4e**	HCOONa	H_2O	**A**	32%	31%
22	**4f**	HCOONa	H_2O	**A**	67%	96%
23	**4g**	HCOOH	H_2O	**A**	90%	12%
24		HCOONa	H_2O		>99%	28%

[a]Reactions were carried out at 40°C using 1 mmol of substrate with 0.5 mol % of ruthenium complex in 2 mL of solvent with 10 equivalents of HCOOH, HCOONa or HCOOH/TEA azeotropic mixture as hydrogen donors. [b] Conversion and e.e. were determined by GC and by HPLC after 24 h.

The catalysts performance was evaluated using different reaction conditions (solvent, temperature) and different hydrogen donors (HCOOH, HCOONa, azeotropic mixture 5:2=TEA:HCOOH).

Water was found as the best solvent for carrying out the reaction. Indeed, when 2-propanol or the mixture H_2O/MeOH were employed the reaction conversion significantly decreased (Table 1, entries 6, 7, 10, 11, 16, 18 and 19). Only in the case of complex **B,** it is worth noting that the enantiomeric excess in the reduction of acetophenone resulted increased under these conditions (entries 6 and 7 vs 5). The temperature variation (20°C, 40°C or 60°C) did not show any significant effect on enantioselectivity (data not shown). Regarding the hydrogen donors, HCOONa resulted the more effective in terms of enantioselectivity, in a ratio 10:1 with the substrate. On the contrary, using HCOOH, the

reaction didn't proceed with complex **B** (entries 4 and 12) while in the case of complex **A**, a racemic mixture or endowed with a low e.e. of the product was obtained (entries 1 vs 3, 8 vs 9, 14 vs 15 and 23 vs 24).

The comparison of different catalytic systems revealed that TOF (turnover frequency) for the *p*-cymene-containing complex A is 7 h^{-1} similarly to 5 h^{-1} for dimer complex B (calculated for ATH of acetophenone in water and in the presence of HCOONa as hydrogen donor, Table 1 entry 3 *vs* entry 5). The corresponding alcohol was achieved in good yield by both catalytic systems but with modest enantioselectivity in the case of dimer B.[12, 30]

The cooperation of the metal hydride and the amine nitrogen hydrogen functions in the ATH of ketones and imines with 2-propanol or triethylammonium formate as the hydrogen source, was a key discovery by Noyori group and this represented an outstanding example of outer-sphere mechanism.[31-34] This last one remains the generally accepted mechanism for hydrogen-transfer step in the case of complex A, in which only two nitrogen atoms resulted coordinated to metal center.[23, 35-36]

In the case of complex B, in which there are three functional groups coordinated, the formation of dimer afforded two 16-electron ruthenium precatalysts that might rearrange in the formation of the active hydride species.

In spite of the loss of *p*-cymene moiety, the mechanism of ATH probably involved, also in this case, a classical catalytic cycle.[37-40]

Taking into consideration the differences in both structural coordination mode, our complexes resulted less active and straightly less stereoselective in comparison with other similar catalytic systems reported in literature.[16, 35, 41-42] In those systems better results might depend on the presence of an additive in formation of bimetallic 6-membered

transition state or in alternative on the presence of an additional phosphine ligand known for reducing the acidity of metal center that favors the hydride transfer. Furthermore, the results obtained with our complexes, indicated that the steric hindrance around the Ru center in the transition state, deriving both from the ligand and the substrate, could affect the reactivity and the enantioselectivity of the reactions.[27, 37]

In summary, the best result in terms of reaction rate and enantioselectivity was obtained with complex **A** in the reduction of the activated ketone substrate **4f**, ethyl 3-oxo-3-phenylpropanoate (entry 22).

4. CONCLUSION

In conclusion, we developed a new (NNN) compound able to be used as ligand in ruthenium(II) complexes. Depending on complexation conditions, it was possible to obtain a bi- or a tri-dentate coordinated complex. The catalytic activity in asymmetric transfer hydrogenation shown by the tridentate complex **B** could be compared to arene-Ru(II) complexes (bidentate complex **A**) only in terms of reactivity whereas stereoselection is influenced by the reaction conditions and the substituents on aromatic ketones.

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Table 1: ATH of different substituted aryl ketones

Insert figure

Entry	Substrate	H donor	Reaction solvent	Catalyst	Conversion	e.e.
1	**4a**	HCOOH	H_2O	**A**	63%	17%
2		HCOOH/TEA	H_2O		-	-
3		HCOONa	H_2O		85%	81%
4		HCOOH	H_2O	**B**	-	-
5		HCOONa	H_2O		63%	44%
6		HCOONa	H_2O/MeOH 1:1		65%	70%
7		HCOONa	2-propanol		54%	82%
8	**4b**	HCOOH	H_2O	**A**	30%	33%
9		HCOONa	H_2O		45%	58%
10		HCOONa	H_2O/MeOH 1:1		22%	5%
11		HCOONa	2-propanol		30%	15%
12		HCOOH	H_2O	**B**	-	-
13		HCOONa	H_2O		35%	54%
14	**4c**	HCOOH	H_2O	**A**	65%	-
15		HCOONa	H_2O		55%	9%
16		HCOONa	2-propanol		48%	33%
17		HCOONa	H_2O	**B**	20%	2%
18		HCOONa	H_2O/MeOH 1:1		35%	-
19		HCOONa	2-propanol		23%	22%
20	**4d**	HCOONa	H_2O	**A**	20%	-
21	**4e**	HCOONa	H_2O	**A**	32%	31%
22	**4f**	HCOONa	H_2O	**A**	67%	96%
23	**4g**	HCOOH	H_2O	**A**	90%	12%
24		HCOONa	H_2O		>99%	28%

[a]Reactions were carried out at 40°C using 1 mmol of substrate with 0.5 mol % of ruthenium complex in 2 mL of solvent with 10 equivalents of HCOOH, HCOONa or HCOOH/TEA azeotropic mixture as hydrogen donors. [b] Conversion and e.e. were determined by GC and by HPLC after 24 h.[9]

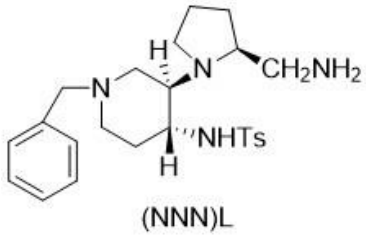


Figure 1

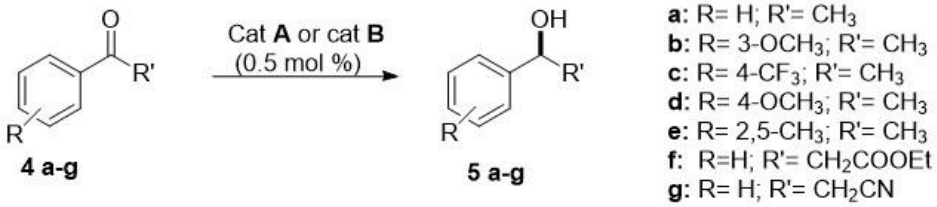
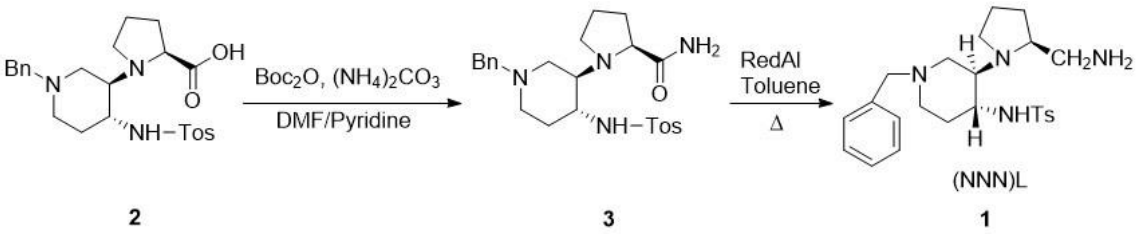
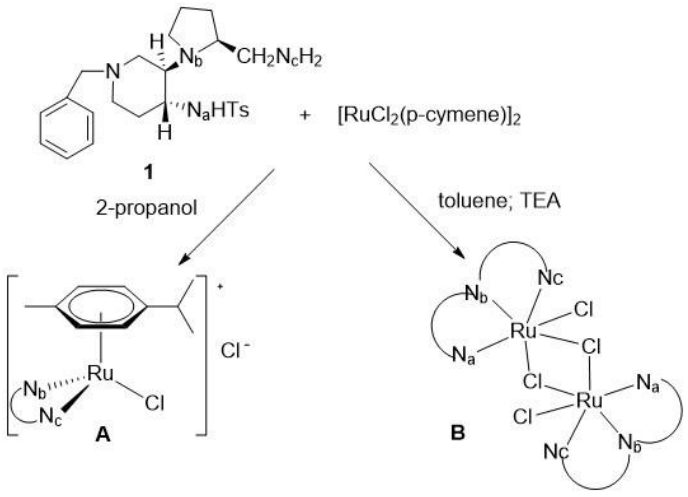


Figure in the Table 1



Scheme 1



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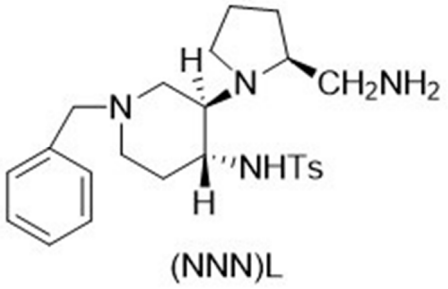

(NNN)L

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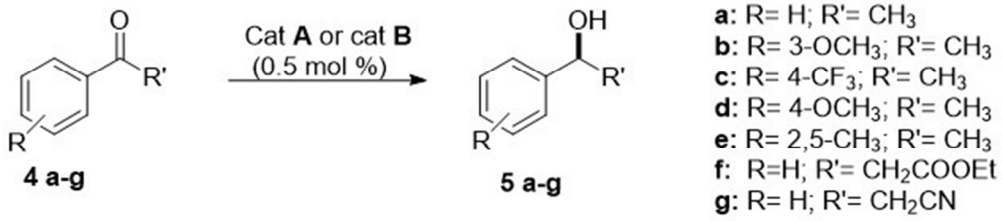

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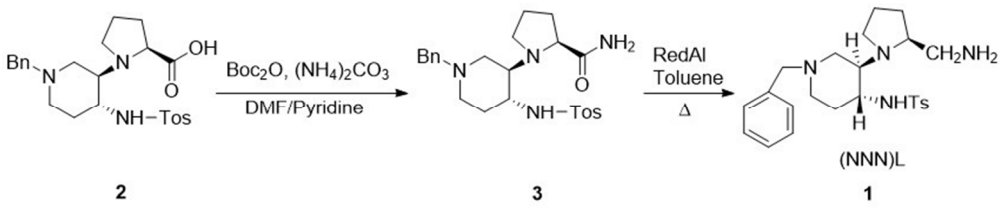

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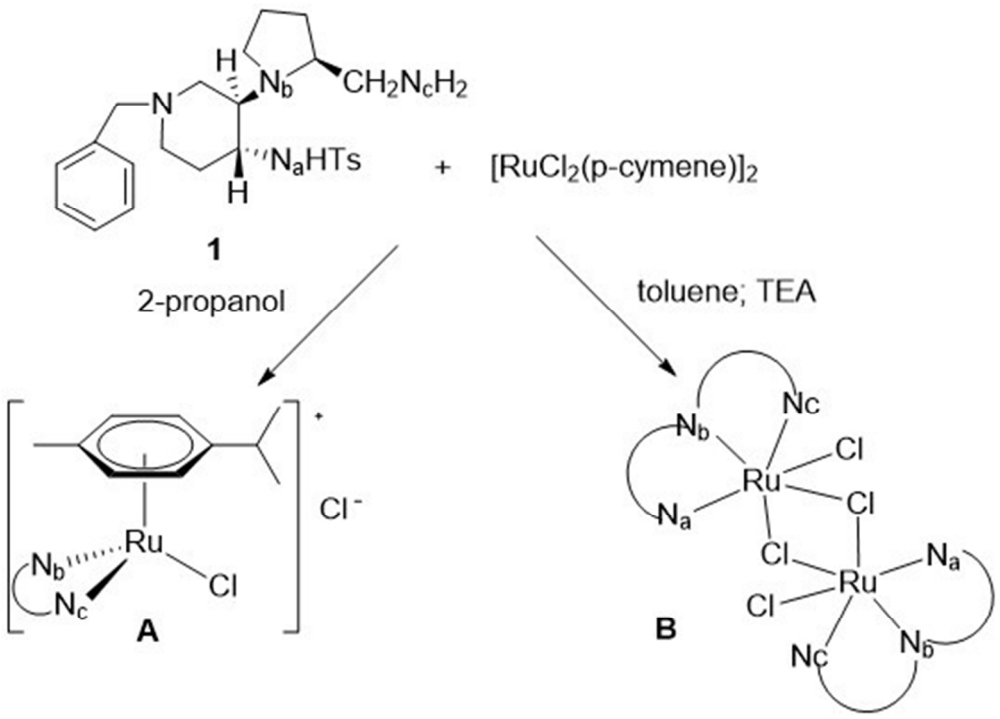

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