



**Catalytic properties of N-heterocyclic transition metal carbene
complexes**

Theses

Marianna Fekete

University of Debrecen
Doctoral Council of Science
Chemistry PhD School
Debrecen, 2008

Introduction

For a long time now there have been attempts in homogeneous catalysis to recover metal complex catalysts and reuse them in new processes. Of the different methods the most effective is the use of two immiscible solvents. One of them consists the catalyst and the other the substrate and/or reaction products.

N-heterocyclic carbenes show similar coordination properties as the well known phosphine ligands. Benefits of the NHC carbenes are that they form more stable complexes with metal ions.

Isomerization of allylic alcohols to carbonyl compounds is a good method of producing aldehydes and ketones. The catalytic redox isomerization is especially useful in syntheses which need mild conditions.

Hydrogenation of unsaturated substrates by hydrogen transfer from suitable H-donors (DH_2) is a valuable alternative to the use of dihydrogen. Several excellent reviews describe a wide variety of hydrogen transfer reactions performed with heterogeneous and homogeneous catalysts, of which Ru(II) and Rh(I) complexes stand out with their catalytic activity and selectivity.

The aim of my PhD research was to prepare new Ru(II) and Rh(I) N-heterocyclic carbene complexes which are able to catalyze the redox isomerization of allylic alcohols and transfer hydrogenation.

Applied experimental techniques

I studied the newly synthesized ligands and complexes by NMR and IR spectroscopic techniques, by ESI-TOF mass spectrometry and by elemental analysis.

The NMR measurements (^1H , ^{13}C , and ^{31}P) were made at room temperature on BRUKER DRX 360 and BRUKER DRX 300 (^{19}F -NMR) NMR instruments. The mass spectrometric measurements were carried out on BRUKER micrOTOF-Q ESI-TOF MS instrument. Elemental analyses were made in the Institute of Pharmaceutical Chemistry of the University of Szeged, on a Perkin-Elmer C, H, N, S automatic analyzer. Gas chromatographic analyses were done on a Hewlett-Packard 5890 Series II gas chromatograph.

The isomerization of allylic alcohols was studied in Schlenk tubes in aqueous or in aqueous-organic biphasic systems under inert atmosphere. In the case of complexes which need hydrogen for the initiation of redox isomerization I used 1 bar hydrogen gas. The transfer hydrogenations were carried out similar to the redox isomerizations, in Schlenk tubes, closed systems and under inert atmosphere.

Product distributions and conversions were determined by ^1H -NMR spectroscopy and gas chromatography.

Explanation of the abbreviations in the theses

NHC	N-heterocyclic
<i>p</i>-cymene	<i>p</i> -isopropyl-toluene
[Hbmim]⁺	1-butyl-3-methylimidazol-2-ylidene cation
bmim	1-butyl-3-methylimidazol-2-ylidene
cod	η^4 -cyclo-1,5-octadiene
mpta	1-methyl-3,5-diaza-1-azonia-7-phosphatricyclo[3.3.1.1 ^{3,7}]decane
triflate	trifluoromethyl-sulphonate
pta	1,3,5-triaza-7-phosphatricyclo[3.3.1.1 ^{3,7}]decane
mtpms	sodium 3-diphenylphosphinobenzenesulfonate
mtppts	trisodium 3,3',3''-phosphinetriylbenzenesulfonate
TOF	turnover frequency, (reacted substrate)(catalyst $\times$ time) ⁻¹ , mol/(mol·h)
ESI-TOF	electron spray ionization – time of flight analyzer mass
MS	spectrometry

New scientific results

I. From $[\text{RuCl}_2(\text{bmim})(\eta^6\text{-p-cymene})]$ (**1**) I prepared two new water soluble Ru(II)-NHC carbene complexes and determined their structure: $[\text{RuCl}(\text{bmim})(\eta^6\text{-p-cymene})(\text{mtppms})]$ (**3**) and $[\text{RuCl}(\text{bmim})(\eta^6\text{-p-cymene})(\text{mpta})](\text{CF}_3\text{SO}_3)(\text{PF}_6)$ (**4**)

For the synthesis of both complexes I dissolved $[\text{RuCl}_2(\text{bmim})(\eta^6\text{-}p\text{-cymene})]$ (**1**) in dry methanol and stirred with sodium-salts (NaBF_4 or NaPF_6); from the solution NaCl separated (*Figure 1.*).

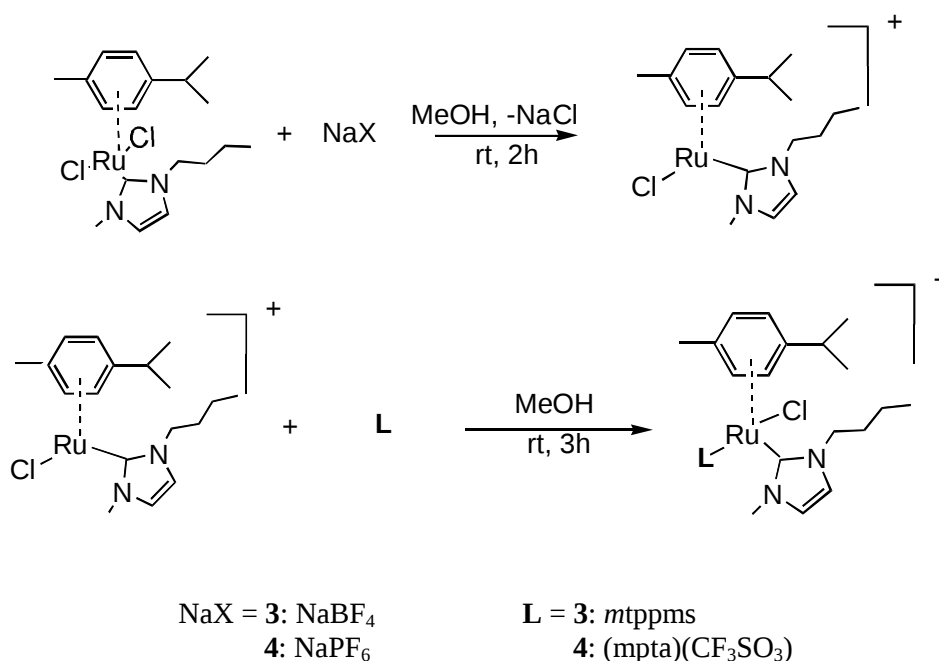


Figure 1.: Synthesis of $[\text{RuClL}(\text{bmim})(\eta^6\text{-}p\text{-cymene})]$

The structure of the new complexes was supported by different spectroscopic methods, mass spectrometry, and elemental analysis.

II. I synthesized $[\text{RhCl}(\text{bmim})(\text{cod})]$ (**7**) by a new method and from it two new Rh(I)-NHC carbene complexes: $[\text{Rh}(\text{bmim})(\text{cod})(\text{mtppts})]\text{Cl}$ (**8**) and $[\text{Rh}(\text{bmim})(\text{cod})(\text{pta})](\text{BF}_4)$ (**9**).

a) The $[\text{RhCl}(\text{bmim})(\text{cod})]$ N-heterocyclic carbene complex was synthesized in a reaction of $[\{\text{Rh}(\text{OH})(\text{cod})\}_2]$ (**6**) and $[\text{Hbmim}]\text{Cl}$ (Fig. 2.). This complex had been prepared before by reacting $[\text{Rh}(\text{MeO})(\text{cod})]_2$ and $[\text{Hbmim}]\text{Cl}$.

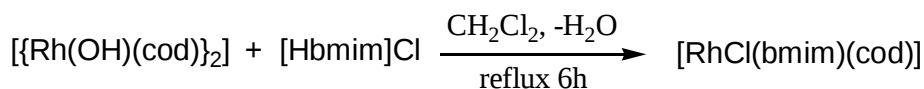


Figure 2.: Synthesis of $[\text{RhCl}(\text{bmim})(\text{cod})]$ (**7**)

b) $[\text{Rh}(\text{bmim})(\text{cod})(\text{mtppts})]\text{Cl}$ was prepared by stirring of **7** with *mtppts* (Figure 3.).

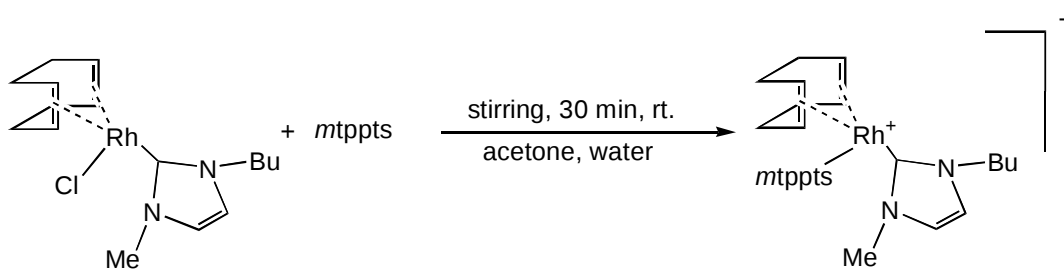


Figure 3.: Synthesis of $[\text{Rh}(\text{bmim})(\text{cod})(\text{mtppts})]$ (**8**)

c) $[\text{Rh}(\text{bmim})(\text{cod})(\text{pta})]^+$ (**9**) was synthesized by two methods. In one of them **6** was refluxed with 1-butyl-3-methylimidazolium tetrafluoroborate ($[\text{Hbmim}](\text{BF}_4)$) and pta (Figure 4.):

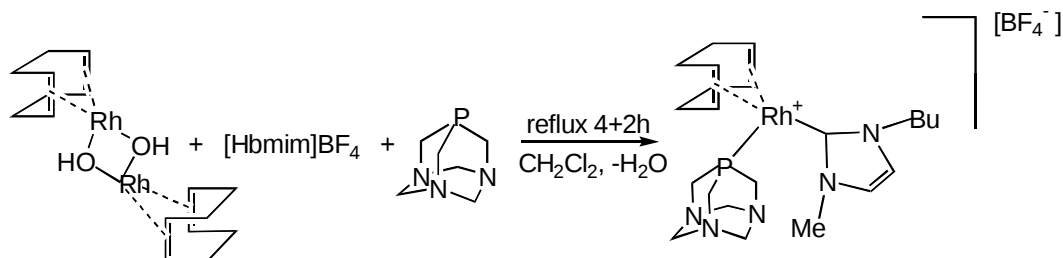


Figure 4.: Synthesis of $[\text{Rh}(\text{bmim})(\text{cod})(\text{pta})]^+$ (**9**) by protonation

In this case [Rh]-OH group was protonated by [Hbmim](BF₄), water was formed, and the carbene atom of the imidazolium salt was coordinated to the rhodium(I) ion and formed Rh(I)-NHC carbene complex.

According to the other method Cl⁻ was removed from **7** and pta was added to the solution of cationic complex (*Figure 5.*).

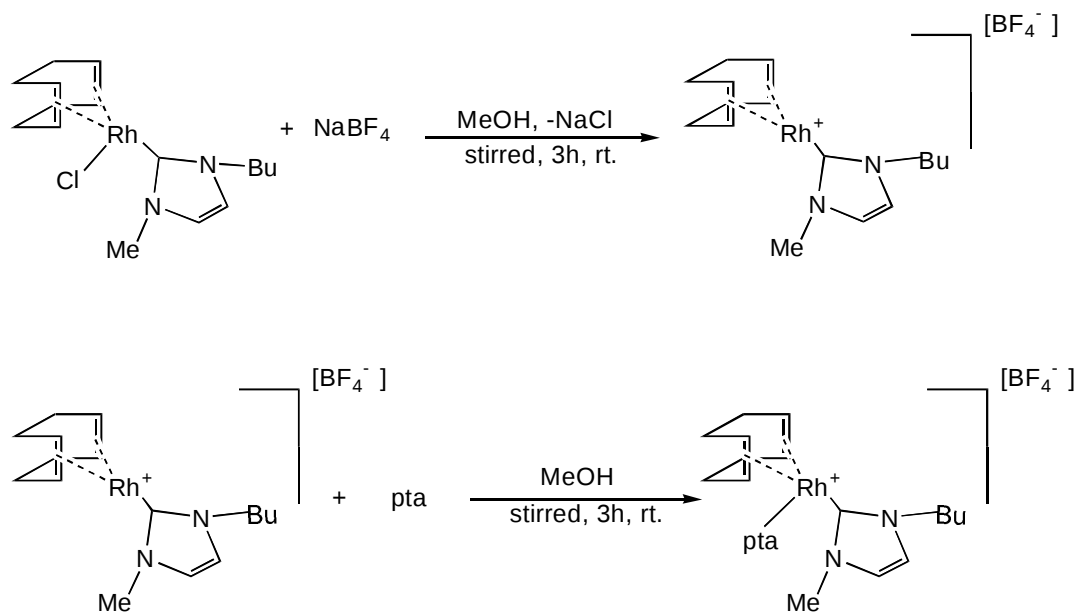


Figure 5.: Synthesis of [Rh(bmim)(cod)(pta)]⁺ (**9**) by chloride removal

The structures of the new complexes were determined by NMR spectroscopic and ESI-TOF MS techniques.

III. Catalytic properties of Ru(II) and Rh(I) NHC-complexes were studied in the redox isomerisation of allylic alcohols.

III. a. **4** catalyzed the redox isomerisation of oct-1-en-3-ol with very good selectivity in the presence of hydrogen gas. The highest selectivities were obtained at pH 7.

The time and pH dependence of the redox isomerization of oct-1-en-3-ol catalyzed by **1** was studied. In a 0.1 M phosphate buffer, at 80 °C, after 90 minutes the maximum of selectivity (86 % octan-3-one and 14 % octan-3-ol) was found between pH = 6.9–7.5 (Figure 6.).

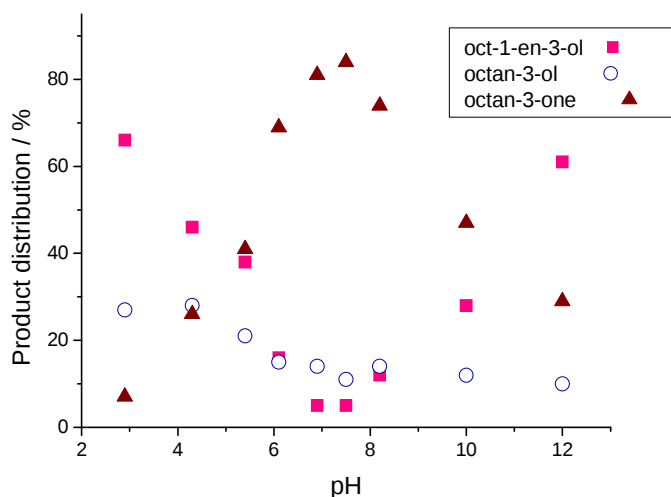


Figure 6.: Hydrogenation/isomerization of oct-1-en-3-ol as a function of pH.
 $1.4 \cdot 10^{-5}$ mol **1**, $1.04 \cdot 10^{-3}$ mol substrate, 3 mL 0.1 M phosphate buffer pH = 6.9, 1 atm H₂, 80 °C

The reaction works well with other allylic alcohols, too (Table 1.). All the investigated allylic alcohols showed the highest reactivity at around pH 7.

Table 1.: Effect of the pH on the isomerization (I) and hydrogenation (H) of allylic alcohols

Substrate	conversion / %							
	pH = 6.1		pH = 6.9		pH = 7.5		pH = 8.2	
	I	H	I	H	I	H	I	H
oct-1-en-3-ol	69	15	86	14	84	16	74	14
hept-1-en-3-ol	58	38	62	38	75	25	61	39
hex-1-en-3-ol	72	11	89	11	90	10	75	9
pent-1-en-3-ol	37	4	58	4	70	4	18	3
but-1-en-3-ol	37	5	37	5	38	5	38	5
2-methylprop-1-en-3-ol	21	2	22	1	24	3	17	2
prop-1-en-3-ol	18	3	33	13	34	16	13	24

$1.4 \cdot 10^{-5}$ mol **1**, $1.04 \cdot 10^{-3}$ mol substrate, 3 mL 0.1 M phosphate buffer, 1 atm H₂, 80 °C, 90 min

III.b. It was found that addition of chloride in the redox isomerization of allylic alcohols increases the total conversion and selectivity of isomerization.

I studied the effect of NaCl on the reaction rate and product distribution (*Table 2.*). In general, addition of chloride increases the total conversion and favours isomerization over hydrogenation, thus makes the procedure synthetically more valuable.

Table 2.: Effect of NaCl on the reaction rate and product distribution of isomerization (I) and hydrogenation (H)

substrate	conversion / %			
	without NaCl		with NaCl	
	I	H	I	H
oct-1-en-3-ol	86	14	90	10
hept-1-en-3-ol	62	38	89	11
hex-1-en-3-ol	89	11	91	9
pent-1-en-3-ol	58	4	89	11
but-1-en-3-ol	37	5	46	11
2-methylprop-1-en-3-ol	22	1	28	27
Prop-1-en-3-ol	33	13	55	18
			(44) ^a	(19) ^a
			(62) ^b	(12) ^b

$1.4 \cdot 10^{-5}$ mol **1**, $1.04 \cdot 10^{-3}$ mol substrate, 3 mL 0.1 M phosphate buffer or buffer solution + 0.2 M NaCl;
a) 0.15 M NaCl; b) 0.4 M NaCl, 1 atm H₂, 80 °C, 90 min

III.c. Biphasic liquid systems make possible the recovery and recycling of the catalyst separated into one of the phases. Catalyst 1 stayed always in the aqueous phase and it could be reused in the isomerization of 1-octen-3-ol.

The results showed that catalyst **1** could be reused for at least four times without a significant loss of the catalytic activity (Table 3.).

Table 3.: Recycling of **1** in the isomerization of oct-1-en-3-ol to octan-3-one

run	octan-3-one / %
1	93
2	91
3	90
4	89
5	83
6	36

$2 \cdot 10^{-5}$ mol catalyst, $1.04 \cdot 10^{-3}$ mol oct-1-en-3-ol, 4 mL 0,1 M phosphate buffer pH = 6.9, 1 atm H₂, 80 °C, 40 min

III.d. The catalytic properties of the new rhodium(I) complexes were studied – similar to the ruthenium(II) complexes – in the redox isomerization of allylic alcohols.

I found that the total conversion of the isomerization catalyzed with Rh(I)-NHC complexes was less than with Ru(II)-NHC complexes (Table 4.). In the reaction mixture of isomerization/hydrogenation of oct-1-en-3-ol with **8** I could indentify the intermediate oct-2-en-3-ol by the ¹H-NMR spectroscopy (Figure 7.).

Table 4.: The conversion of isomerization (I) and hydrogenation (H) of allylic alcohols catalyzed by different Rh(I)-NHC carbene complexes

substrate	Catalysts					
	7		8		9*	
	I	H	I	H	I	H
oct-1-en-3-ol	17 (8)*	1	42	58	17	-
hept-1-en-3-ol	10	1	0	20	36	-
hex-1-en-3-ol	36 (15)*	19	4	29	70	-
pent-1-en-3-ol	3	1	2	22	84	-
2-methylprop-1-en-3-ol	22	26	32	21	32	-
but-1-en-3-ol	19	62	34	66	98	-
prop-1-en-3-ol	43	33	47	53	83	-

80 °C, 1 h, 3 mL 0.1 M phosphate buffer, pH=7.0, 1 atm H₂ or (*) argon, catalyst = 0.01mmol, substrate=1 mmol; **7**=[RhCl(bmim)(cod)]; **8**=[Rh(bmim)(cod) (mtppts)]Cl; **9** = [Rh(bmim)(cod)(pta)](BF₄).

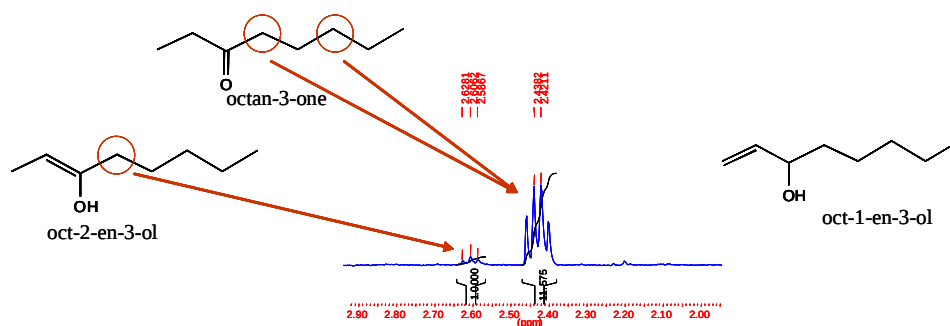


Figure 7.: ¹H-NMR signals of the intermediate oct-2-en-3-ol

IV. The catalytic properties of Ru(II) and Rh(I)-NHC complexes were also studied in hydrogen transfer reactions.

IV.a. The Ru(II)-NHC complexes show good catalytic activity in hydrogen transfer reactions.

The substrates of transfer hydrogenation contained a C=O or C=C bond or both. These carbene complexes proved to be effective catalysts in this reaction, even in the case of sterically more hindered benzophenone (80-90 % conversion). On the other hand, *trans*-stilbene and cyclohexene underwent conversions only in the 3-8 % range.

The catalytic transfer hydrogenation of *trans*-4-phenylbut-3-en-2-one with propan-2-ol by **1** as catalyst is also a very fast reaction. When run with a relatively small [substrate]/[catalyst] ratio ($[S]/[C] \leq 100$), the substrate fully reacted in a few minutes and only the hydrogenation of the intermediate 4-phenylbutan-2-one to 4-phenylbutan-2-ol could be followed. At high substrate loadings ($[S]/[C] \leq 400$) the unsaturated alcohol intermediate was also observed (Fig. 8.) in the first few minutes of the reaction.

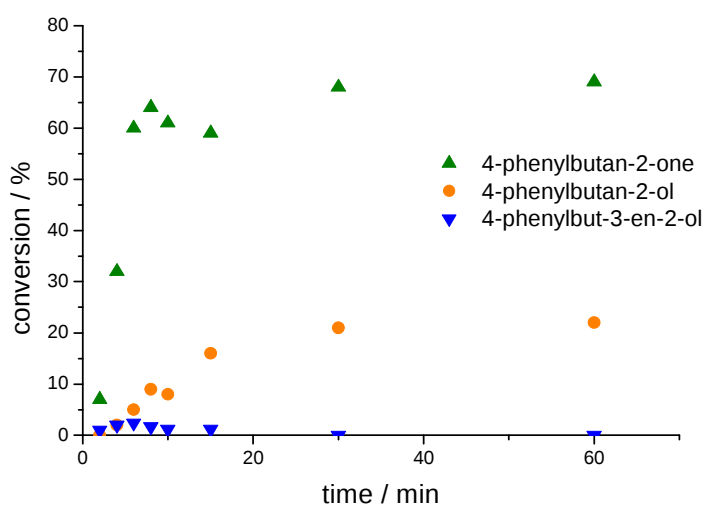


Figure 8.: Transfer hydrogenation of *trans*-4-phenylbut-3-en-2-one by catalyst **1** at high substrate excess.

0.01 mmol **1**, 4 mmol substrate, 2 mmol KOH, 10 mL propan-2-ol, 80°C, under Ar

The catalytic activity of **1** in *aqueous phase* in hydrogen transfer reactions was also studied. *trans*-4-Phenylbut-3-en-2-one was transfer hydrogenated in aqueous sodium formate solution. The reaction proceeded slower than that of the propan-2-ol in the presence of KOH. The total conversion was 14 % while it was 100 % in the organic solvent.

The effect of the change of the amount of KOH on hydrogen transfer reaction was investigated. The results revealed that the reaction also proceeds – albeit with a low yield – in the absence of base (27 %). The addition of small amount of base (KOH/Ru = 6), however, significantly increases the amount of product.

In summary, new water soluble (Ru(II) and Rh(I)) N-heterocyclic carbene complexes were prepared that show remarkable catalytic activities in the redox isomerization of allylic alcohols in water and in biphasic systems as well as in hydrogen transfer reactions. 1 is reusable in biphasic systems where the complex is in the aqueous phase and the substrate resides in the organic phase. Ru(II)-NHC carbene complexes are good catalysts mainly for the reduction of C=O bond in hydrogen transfer processes while Rh(I)-NHC carbenes favour the reductions of C=C bonds.

List of publications:

1. Marianna Fekete, Ferenc Joó: Redox isomerization of allylic alcohols in aqueous-organic biphasic systems catalyzed by water-soluble Ru(II)-N-heterocyclic carbene complexes, *Catalysis Communication*, **2006**, 7, 783-786;
2. Marianna Fekete, Ferenc Joó: Transfer hydrogenation of carbonyl compounds and alkenes catalyzed by ruthenium(II)-N-heterocyclic carbene complexes, *Collections of Czechoslovak Chemical Communications*, **2007**, 72 (8), 1037-1045;
3. Tatiana Campos-Malpartida, Marianna Fekete, Ferenc Joó, Ágnes Kathó, Antonio Romerosa, Mustapha Saoud, Wojciech Wojtków Redox isomerization of allylic-alcohols catalysed by water-soluble ruthenium complexes in aqueous systems, *Journal of Organometallic Chemistry*, article in press, doi:10.1016/j.jorganchem.2007.11.011.

Posters (P) and oral (O) presentation at conferences:

1. P. Csabai, M. Fekete, F. Joó: Synthesis and catalytic properties of new water-soluble Ru(II)-N-heterocyclic carbene complexes, *14th International Symposium on Homogeneous Catalysis – ISHC*, Munich, Germany, 5th -9th July, 2004, (P).
2. P. Csabai, M. Fekete, F. Joó: Synthesis and catalytic properties of new water-soluble Ru(II)-N-heterocyclic carbene complexes, *Green Solvents For Synthesis*, Bruchsal, Germany, 3rd – 5th October, 2004, (P).
3. P. Csabai, M. Fekete, G. Papp, H. Horváth, Á. Kathó, F. Joó: Synthesis and catalytic properties of new water-soluble organometallic Ru(II) complexes, *COST D30 Workshop*, Tarragona, Spain, 19th – 20th November, 2004, (O).
4. M. Fekete: Study of Ru(II)-carbene complex catalysts in aqueous solutions, *First Year Aquachem Meeting*, Lisbon, Portugal, 7th – 8th February, 2005, (O).
5. M. Fekete: Redox isomerization of allylic alcohols, *COST D30 Working Group Meeting*, Debrecen, Hungary, 7th – 9th October, 2005, (O).
6. M. Fekete, F. Joó: Új Ru(II)- és Rh(I)-kARBÉN komplexek előÁllítása és katalitikus alkalmazása allil-alkoholok redox izomerizÁciójÁban és hidrogénÁtviteli reakciókban, *41. Komplexkémia Kollokvium*, Mátrafüred, Magyarország, 2006. május 31- június 2., (O).
7. M. Fekete, F. Joó: Aldehydek és ketonok hidrogénezése hidrogén Átvittel ruténium(II)- és ródium(I)-N-heterociklusos kARBÉN komplexek katalizÁtorokkal, *42. Komplexkémia Kollokvium*, Mátrafüred, Magyarország, 2007. május 23-25., (O).
8. M. Fekete, H. Horváth, F. Joó: Synthesis and catalytic properties of new rhodium(I) and iridium(I) NHC complexes of the type $[M(X)(bmim)(cod)]$ (M=Rh, Ir), *Advances in Organic Chemistry*, Smolenice, Slovakia, 16th – 20th September, 2007, (P).