Article

Aerobic, Catalytic Oxidation of Alcohols in Ionic Liquids

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Um sistema catalítico simples e eficiente, baseado em RuCl$_3$ imobilizado em líquidos iônicos, foi desenvolvido para oxidar álcoois a aldeídos e cetonas sob condições brandas. Um novo líquido iônico fluorado, pentadecafluorooctanoato de 1-*n*-butil-3-metilimidazólio, foi sintetizado e demonstrou melhor desempenho que os demais líquidos iônicos empregados. Além disso, este sistema catalítico utiliza oxigênio molecular como agente oxidante, produzindo somente água como subproduto.

An efficient and simple catalytic system based on RuCl$_3$ dissolved in ionic liquids has been developed for the oxidation of alcohols into aldehydes and ketones under mild conditions. A new fluorinated ionic liquid, 1-*n*-butyl-3-methylimidazolium pentadecafluorooctanoate, was synthesized and demonstrated better performance that the other ionic liquids employed. Moreover this catalytic system utilizes molecular oxygen as an oxidizing agent, producing water as the only by-product.

Keywords: biphasic oxidation, ionic liquids, alcohols, molecular oxygen, ruthenium catalysts

Introduction

One of the urgent issues for chemical industries in the twenty-first century is the search for 'clean' or 'green' technologies.[1] Two-phase catalysis represents one of the most important alternatives for the design, development, and implementation of green chemistry.[2] Among the various 'mobile' phases that have been used for the immobilization of transition-metal catalyst precursors, ionic liquids (molten salts) are attracting continuous and increasing interest.[3,4] The advent of the air and water stable, 1-*n*-butyl-3-methylimidazolium tetrafluoroborate (BMI.BF$_4$) and its analog hexafluorophosphate (BMI.PF$_6$),[5] which possesses a wide range of liquid phase, negligible vapour pressure, low viscosity, high thermal and chemical stability as well as a wide electrochemical window (up to 7V),[6] enables reactions to be performed ranging from Diels-Alder type processes to hydroformylations in biphasic conditions.[7-10] In these biphasic systems the products are easily separated from the reaction mixture by simple decantation or distillation and the recovered catalyst solution can be reused several times without any significant changes in its catalytic performance. The greatest advantage of the biphasic catalysis in ionic liquids is that it allows, in many cases, the direct transposition of known homogeneous one-phase reactions to two-phase systems without the synthesis of specially tailored ligands and/or complexes.

The oxidation of alcohols into aldehydes and ketones is a fundamental reaction in organic synthesis, and numerous oxidizing agents are available to influence this key reaction.[11] However, these reagents are usually toxic and their use induces hazardous problems.[12]

From an economical and environmental point of view, the development of catalytic processes using aerobic conditions is of great value.[13] This oxidant is atom efficient[14] and water is its only by-product.

While we were investigating the direct transposition of homogeneous oxidation reactions[15-24] to a biphase conditions,[25-27] we also observed that RuCl$_3$ dissolved in 1-*n*-butyl-3-methylimidazolium tetrafluoroborate (BMI.BF$_4$) in the presence of molecular oxygen can oxidize hydroxyl groups to carbonyl functions. Moreover, we have shown that the ionic liquid medium has a beneficial effect on these ruthenium catalytic systems compared to those performed using organic solvents.

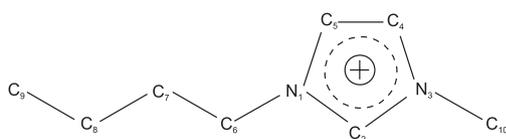* e-mail: jdullius@pucrs.br

Experimental

General

All chemicals acquired from commercial sources were utilized without any further purification. The ionic liquids (BMI.BF$_4$),[28] (BMI.PF$_6$)[28] and (BMI.OOCCF$_3$)[29] were prepared according to literature. The catalytic oxidation was performed in a 100 mL stainless steel autoclave, equipped with a magnetic bar, temperature indicator and a manometer. The catalytic reaction products were analyzed by gas chromatography on an Varian 3400 CX chromatograph with FID detector, equipped with a polydimethylsiloxane column 30 m, 0.25 mm id and film thickness of 0.2 μm, working between 50 and 200 °C with a heating rate of 10 °C min^{-1}.

Preparation of 1-n-butyl-3-methylimidazolium penta-decafluorooctanoate (BMI.COO(CF$_2$)$_6$CF$_3$)
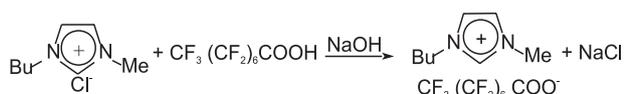
Sodium hydroxide (1.173 mg, 29.32 mmol) dissolved in water (10 mL) was added to the mixture of 1-*n*-butyl-3-methylimidazolium chloride (5.116 mg, 29.32 mmol) and pentadecafluorooctanoic acid (12.139 mg, 29.32 mmol) in water (30 mL), at room temperature. After stirring for 1h, the reaction mixture was dried in a vacuum. After drying the mixture, dichlorometane (100 mL) was added. It was then filtered through a column of celite (*l* = 3 cm) and all volatiles were removed under reduced pressure (15.375 mg, 95%).

IR (film) ν_{max}/cm^{-1}: 3142 and 3052 ν(C-H) aromatic; 2967 and 2878 ν(C-H) aliphatic; 1242, 1203 and 1145 [ν(C-F)]; 1571 and 1467 ν(C=C); 1686 ν(C=O) carboxilic acid.

^{1}H NMR (ppm): δ 9.92, s, 1H, H(2); 7.97, s, 1H, H(4); 7.89, s, 1H, H(5); 4.40, t, 2H, H(6); 4.08, s, 3H, H(10); 1.91 and 1.35, 2m, 4H, H(7) and H(8); 0.94, t, 3H, H(9).

^{13}C NMR (ppm): δ 138.1 C(2); 124.0 C(4); 122.8 C(5); 49.2 C(6); 35.6 C(10); 32.2 C(7); 19.2 C(8); 12.9 C(9); 205.9 C(11).

^{19}F NMR (ppm): δ -81.3 CF$_3$; -116.9 CF$_2$; -122.2, -122.6, -122.8 and –123.3 (CF$_2$)$_4$; -126.7 CF$_2$.

Typical procedure for the oxidation reaction

Initial investigations were performed with RuCl$_3$ since this compound is known as a catalyst for the oxidation of alcohols under homogeneous conditions.[19-24] Note that in these one-phase reactions a second component is usually necessary to create an efficient catalytic system.[15-18] Thus, RuCl$_3$ dissolved in BMI.BF$_4$ promoted efficiently the oxidation of alcohols to the corresponding aldehydes and ketones, under various reaction conditions.

In a typical experiment, RuCl$_3$ (0.1 mmol) was dissolved in the ionic liquid (3 mL). This solution and substrate (10 mmol) were introduced into a 100 mL stainless steel autoclave equipped with magnetic stirring bar. The autoclave was then pressurized with oxygen (7 atm) and heated at 100 °C for 24h. The autoclave was cooled and degassed.

The procuts were isolated by distillation (water was the sole by-product observed) or extracted with organic solvents. The conversion (based on the starting alcohol) and selectivity into carbonyl compound were determined by gas chromatography. The isolated products were characterized by GC-MS, IR, ^{1}H and ^{13}C NMR and by comparison of their retention times (GC) with those ones of the authentic samples.
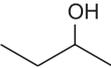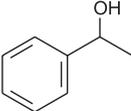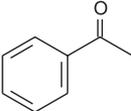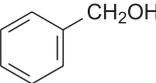
Results and Discussions

Some alcohols were tested, transfering homogeneous reactions, employing RuCl$_3$, in organic solvents to two-phase conditions in ionic liquids.[19]

The results in Table 1 show that several different secondary alcohols (entries 1, 2, 3 and 4) have been oxidized to ketones with good conversions in relation to the existent systems. Besides the conversions, a relatively higher selectivity was observed when using the ionic liquid (BMI.BF$_4$). It is interesting to note that under homogeneous conditions the oxidation of cyclohexanol by RuCl$_3$ (1 mol%), dissolved in toluene at 100 °C for 95 h, gives cyclohexanone with only 21% selectivity (at 92% conversion).[19] This demonstrates the beneficial effect of the ionic liquid on the performance of this oxidation system (entry 3, 100% selectivity). Moreover the parameters selectivity and conversion depend of the reaction conditions. For example, in the conditions of 80 ºC, 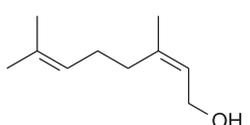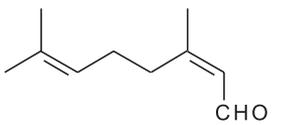1 mol% RuCl$_3$, 1 atm O$_2$ and 5 h was not observed oxidation of 1-phenylethanol into acetopheneone.[19] The change of the reaction conditions, over all the time, leads to 53% conversion and 100% selectivity (Table1, entry 4).

Table 1 shows that the primary activated alcohols present high conversion. According to the entries 5, 6 and

Table 1. Influence of the biphasic system in the oxidation of alcohols [a]

entry	substrate	product	cv.[b](%)	sel.[c](%)	yield [d](%)
1			73	95	61
2			96	97	59
3			82	100	80
4			53	100	47
5			100	2	-
6[e]			76	88	60
7 [e,f]			96	100	70
8			100	0	-
9			100	0	-
10			0	-	-
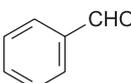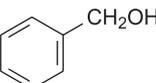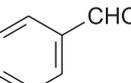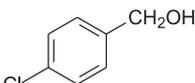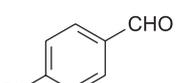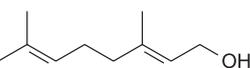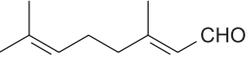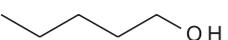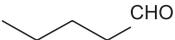
[a]Reaction conditions: 0.3 mmol of RuCl$_3$, 3 mL of BMI.BF$_4$, 10 mmol of substrate, T=100°C, P$_{O2}$ = 2 atm, t = 70 h; [b]cv.= conversion based on starting hydroxyl substrates; [c]sel.= selectivity in the carbonyl product; [d]Yield in separated product; [e]t = 24 h; [f]solvent = 3 mL of BMI.BF$_4$ + 15 mL of tolueno.

7, depending on the reaction conditions, the benzylic alcohols may be transformed into aldehydes or benzoic acids with high selectivity. In the reaction conditions of the entry 6 obtain 76% conversion and 88% selectivity (TOF 1.06 h^{-1}). Theses results are comparable to published by Ishii (80% conversion, 99% selectivity and TOF 0.53 h^{-1}) in homogeneous conditions.[23]

The allylic alcohols did not show selectivity in aldehydes (entries 8 and 9). The oxidation reaction went on until ending in total oxidation. Non-activated primary alcohols such as 1-pentanol failed to react under the reaction conditions investigated (entry 10).

In order to study the influence of reaction parameters on the performance of the system formed by the catalyst RuCl$_3$, dissolved in the ionic liquid BMI.BF$_4$, cyclopentanol was used. The results are shown in the Table 2.

The conversion of cyclopentanol to cyclopentanone increases with increasing oxygen pressure (compare entries 12, 17, 18 and 19), reaction time (entries 2, 20 and 21) and temperature (see entries 2 and 13-16). The selectivity of the ketone formation was very high except when the oxygen pressure was increased to 10 atm (entry 19) whereby cyclopentene was formed and when the temperature was increased to 125 °C (entry 16). In this temperature the

Table 2. Effect of the reaction conditions on the oxidation of cyclopentanol by $RuCl_3$ dissolved in $BMI.BF_4$ (3 mL)

entry	P_{O_2} [a] (atm)	$RuCl_3$ (mol%)	t (h)	T (°C)	cv.[b] (%)	sel.[c] (%)	yield [d] (%)
11	2	0	70	100	0	0	0
12	2	1	70	100	35	100	20
2	2	3	70	100	96	97	59
13	2	3	70	25	17	100	16
14	2	3	70	50	34	100	29
15	2	3	70	75	52	100	52
16	2	3	70	125	58	83	44
17	air	1	70	100	3	100	—
18	7	1	70	100	100	99	94
19	10	1	70	100	100	67	69
20	2	3	24	100	56	100	36
21	2	3	48	100	66	100	52

[a]Initial pressure; [b]cv.= conversion based on starting hydroxyl substrates; [c]sel.= selectivity in the carbonyl product; [d]Isolated yields were from an average of two runs.

selectivity decrease may be associated with the instability of the catalytic system. From Table 2 it can be deduced that the best reaction conditions for the oxidation of cyclopentanol are 1 mol % of Ru, 100°C and 7 atm of oxygen (entry 18).

Due to the selectivity improvement of the reactions made in $BMI.BF_4$, it has been decided to test this reaction with other ionic liquids (see Table 3).

The new ionic liquid 1-*n*-butyl-3-methylimidazolium pentadecafluorooctanoate ($BMI.COO(CF_2)_6CF_3$) was synthesized to check whether the amount of oxygen dissolved in fluorinated ionic liquids increases as it happens with the fluorinated hydrocarbons,[30] and enables a higher conversion.

Table 3. Influence of the ionic liquid about the oxidation reaction of cyclopentanol by $RuCl_3$[a]

entry	Ionic Liquid	cv.[b] (%)	sel.[c] (%)	Yield[d] (%)	TOF (h^-1)
22	BMI. BF_4	15	100	15	0.63
23	BMI. PF_6	0	-	-	-
24	$BMI.OOCCF_3$	37	100	37	1.54
25	$BMI.OOC(CF_2)_6CF_3$	35	100	35	1.46
26	BMI. BF_4 + sieve [e]	61	100	60	2.54

[a]Reaction conditions: 0.1 mmol of $RuCl_3$, 3 mL of ionic liquid, 10 mmol de substrate, T=100 °C, P_{O_2}= 7 atm, t = 24 h; [b]cv.= conversion based on starting hydroxyl substrates; [c]sel.= selectivity in the carbonyl product; [d]Yield in separated product; [e]Molecular powder sieve=100mg.

In Table 3 it can be noticed a significant improvement with the fluorinated liquids (entries 22, 24 and 25). Theses results indicate better performance of the fluorinated liquids (TOF 1.54 h^-1, $BMI.OOCCF_3$, and 1.46 h^-1, $BMI.OOC(CF_2)_6CF_3$) when compared to the other ionic liquids employed (TOF 0.63 h^-1, BMI. BF_4) in the reaction conditions investigated.

Notwithstanding, it is important to note that the $BMI.BF_4$ and the fluorinated ionic liquid does not decompose apparently during the reaction according to the ^{1}H and ^{13}C NMR analysis of the recovered ionic liquid. However, attempts to perform these oxidation reactions using 1-*n*-butyl-3-methyl imidazolium hexafluorophosphate ($BMI.PF_6$) ionic liquid resulted in extended decomposition of the latter (entry 23).

The ionic catalytic solution can be reused maintaining the selectivity in ketone, however, a continuous drop in the conversion had been observed.

Trying to understand the reason of the deactivation molecular powder sieve was added to reaction with $BMI.BF_4$ (entry 26), because this ionic liquid was chosen with standard in the study of reaction conditions. To Schwartz,[31] water may decrease the activity of the Ru-catalytic systems, and to Markó,[32] the use of molecular powder sieves increases the activity of the reactions.

From this experiment (entry 26), the use of molecular powder sieves in the proposed system, increases significantly the conversion (TOF 2.54 h^-1), however a continuous drop in the conversion was observed (from 61% on the first run to 15% on the fourth run). The nature of this catalyst deactivation is not yet clear and it is under investigation.

Conclusions

In summary, the advantages of this oxidation system are numerous: (*i*) transition-metal catalyzed oxidation reactions can be performed in room temperature ionic liquids; (*ii*) $RuCl_3$ is completely soluble in the ionic liquids tested, giving a homogeneous oxidation solution; (*iii*) the ionic liquids medium has a beneficial effect on the $RuCl_3$ catalyst performance when the selectivity; (*iv*) molecular

oxygen with an oxidizing agent produces water as the only by-product, that is removed by molecular powder sieves; (*v*) this system can be reused; (*vi*) most rates of oxidation in these systems are at least comparable to previously published data; (*vii*) the new fluorinated ionic liquid has better performance that the others ionic liquids employees.

Acknowledgments

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