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Vanadyl salen complexes covalently anchored to an imidazolium ion as catalysts for the cyanosilylation of aldehydes in ionic liquids

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Abstract—Two vanadyl salen complexes having peripheral styryl substituents have been reacted with 1-methyl-3-(3-mercaptopropyl)-imidazolium chloride using azoisobutyronitrile as radical initiator. The resulting compounds contain at the same time a vanadyl salen complex and one imidazolium cation. In agreement with the expectations in view of their structure, these compounds were insoluble in conventional organic solvents, but completely miscible in imidazolium ionic liquids. These vanadyl salen complexes bonded to an imidazolium cation are highly active and reusable catalysts for the cyanosilylation of aldehydes. Moderate enantiomeric excesses were obtained using the chiral version of this complex.
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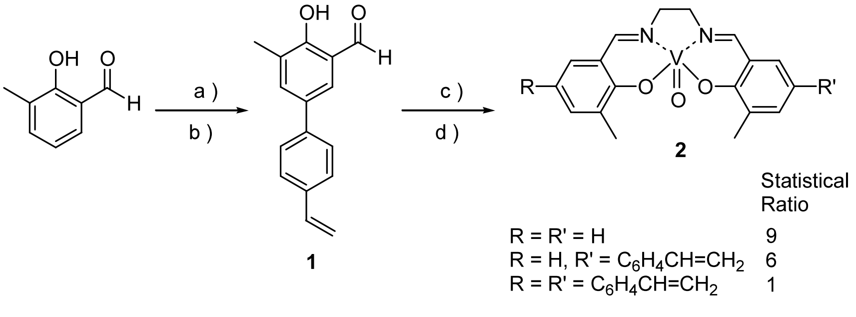
Ionic liquids derived from 1,3-dialkylimidazolium cation have been found to be convenient reaction media for green chemistry, avoiding the use of volatile organic compounds and making possible in some cases the recovery of the catalyst.[1–3] When a catalytic reaction is carried in ionic liquid, the most frequent methodology uses the same catalyst as in conventional organic solvents. Thus, reuse of the catalyst requires that one uses solvents immiscible with ionic liquids, such as hexane or diethyl ether, and that at the same time these solvents do not dissolve the catalyst. For example, in related precedents to this work, chiral metal salen complexes of Cr, Mn and V were dissolved in ionic liquids and they were found to exhibit high activity and enantioselectivity for the epoxidation of alkenes,[4] epoxide ring aperture[5] and carbonyl additions.[6] In these precedents, the metal salen catalysts used in ionic liquids were exactly the same as those employed in conventional organic solvents, such as chloroform. The normal problem encountered in these cases is, however, that during the recovery of the products from the ionic liquid, some catalyst is also extracted thus producing its



Scheme 1. *Reagents and conditions*: (a) Br_2, CH_2Cl_2, 0°C, 1 h; (b) 4-vinylphenylboronic acid, $[Pd(PPh_3)_4]$, 2 M Na_2CO_3, THF, 70°C, 3 h; (c) 3-methylsalicylaldehyde, 1,2-ethanediamine, EtOH, reflux, 1 h; (d) VOacac, MeOH, rt, overnight.

Keywords: ionic liquids; vanadyl salen complex; cyanohydrins; asymmetric catalysis.

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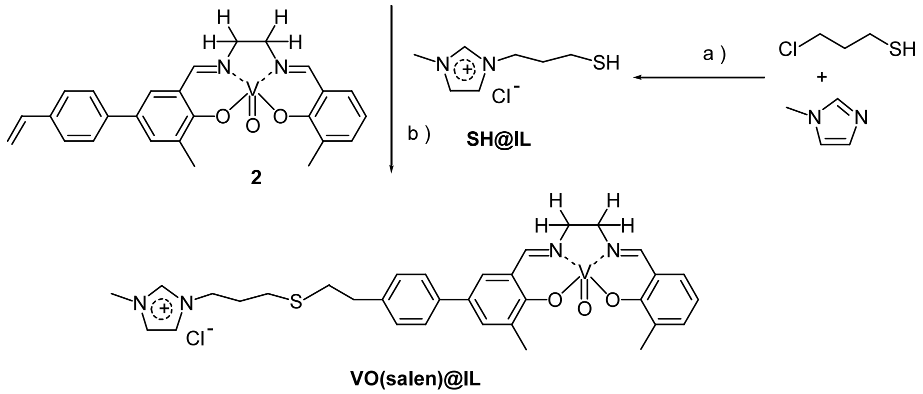


Scheme 2. *Reagents and conditions*: (a) 80°C, 96 h; (b) AIBN, $CHCl_3$ and CH_3CN (degassed), 70°C, 20 h.

gradual depletion from the ionic liquid. Herein we have gone a step forward in the use of ionic liquids as medium for catalytic reactions by modifying adequately the metal salen catalysts to make them more alike to ionic liquids and less soluble in organic solvents.

We are following a strategy widely used in perfluorinated solvents in which to increase the solubility of a certain catalyst, a derivative is prepared containing a perfluorinated pony tail that enormously enhances the fluoricity of the catalyst.[7] Mimicking this methodology, herein we have appended an imidazolium unit to the peripheral position of the salen ligand of vanadyl complexes, the resulting complexes exhibiting a very high activity for the cyanosilylation of aldehydes.

Preparation of the vanadyl salen complexes appended to an imidazolium cation (VOsalen@IL) is depicted in Schemes 1 and 2. In the first place, a statistical mixture of three vanadyl salen complexes (VOsalen) in which one of the components is an unsymmetrical VOsalen having a *para* styryl substituent on the salen ligand was obtained. This synthetic approach has the advantage that unsymmetrical salen ligands are prepared in a single pot without requiring a more time-consuming and stepwise reaction sequence.[8,9] In this mixture, the predominant component can not react with 1-methyl-3-(3-mercaptopropyl)-imidazolium chloride (SH@IL) and will become separated due to its different solubility. On the other hand, the symmetrical minor component having two *para*-styryl units is six times less abundant that the unsymmetrical one and, in addition, this compound can also act as catalyst irrespectively that one or the two styryl groups are derivatized by imidazolium cations. After formation of the vanadyl salen complexes, the last step of our sequence was the covalent attachment of an imidazolium unit (Scheme 2). This was accomplished through a radical chain mechanism initiated by azoisobutyronitrile (AIBN), that produces the addition of the terminal mercapto group to the C=C double bound of the styryl compound. All the reaction intermediates, including VOsalen complexes and VOsalen@IL, were characterized by optical, IR, FAB-MS and NMR spectroscopy. The transmission UV–vis spectra of the VOsalen@IL and the corresponding precursor exhibit the characteristic charge transfer band indicating the presence of the VOsalen complex (Fig. 1).

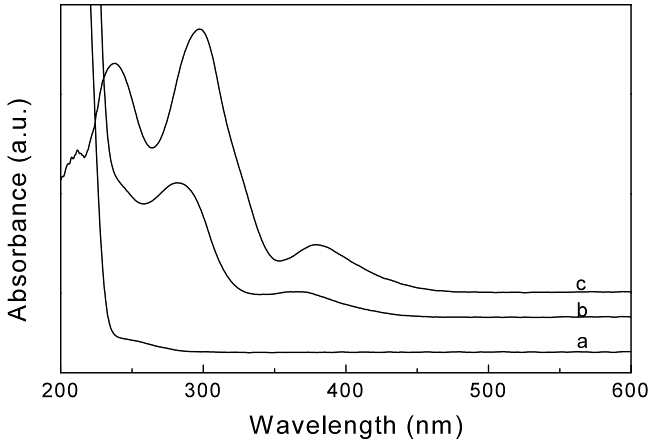


Figure 1. UV-Vis of SH@IL (a), VOsalen@IL (b) and compound **2** (c).

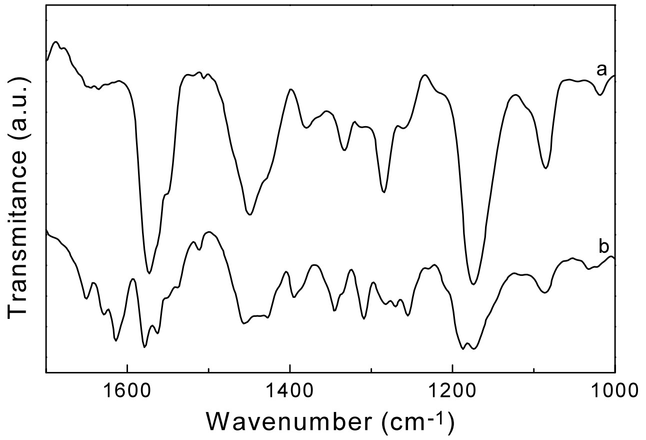
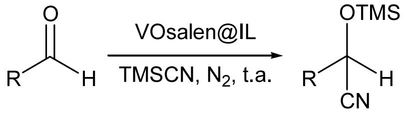


Figure 2. IR of SH@IL (a) and VOsalen@IL (b).

Metal salen complexes exhibits in the IR a phenolate stretching vibration band at 1540 cm^{-1} that was been proposed as characteristic of this type of complexes. Figure 2 shows the IR spectra recorded for SH@IL and for the imidazolium derivative VOsalen@IL. ^1H NMR of VOsalen@IL exhibits at the most characteristic peaks the signal corresponding to the imine proton at 8.4 ppm.

Table 1. Results of the cyanosilylation of aldehydes with TMSCN in the presence of VOsalen@IL[a]



R	Ph[b]	Ph	Ph	Ph	Ph	Ph	Ph	Ph	4-F-Ph	4-OMe-Ph	C_5H_{11}
Reused	–	0	1	2	3	4	5	6	–	–	–
Conv. (%)	94	91	89	92	90	88	91	90	90	89	92

[a] Reactions were run at room temperature under N_2 atmosphere for 3 h: aldehyde (1.64 mmol), TMSCN (1.5 equiv.), VOsalen@IL (64 mg, 0.2 mol%), [bmim]PF_6 (1 g) and nitrobenzene as external standard. Selectivity: >98%. Mass balance: >95%.

[b] Homogeneous catalyst, $CHCl_3$, 0.2% mol, 3 h.

As expected according to its structure, VOsalen@IL was insoluble in hexane and diethyl ether but, completely miscible in 1-butyl-3-methylimidazolium hexafluorophosphate ([bmim]PF_6). The latter ionic liquid containing 2.6% in weight of VOsalen@IL was used as a reaction medium for the addition of trimethylsilyl cyanide (TMSCN) to aldehydes.[10] The results and conditions employed are contained in Table 1. For the sake of comparison, the results of a control experiment in chloroform in which the tetra-*tert*-butyl VOsalen complex was used as catalyst is also included in Table 1. The most remarkable facts concerning Table 1 are the high conversion and selectivity to the cyanohydrin obtained with the hybrid VOsalen@IL complex–ionic liquid as catalyst. After completion of the reaction, the ionic liquid was thoroughly extracted with diethyl ether and the cyanohydrin product recovered with very high mass balances as assessed using nitrobenzene as external standard.

After recovery of the products by extraction and outgassing under reduced pressure to eliminate diethyl ether, the ionic liquid containing VOsalen@IL was reused up to six times without noticeable decrease in activity. Moreover, chemical analysis of vanadium of the reused ionic liquid gives a vanadium content identical to that of the fresh ionic liquid. Reuse and vanadium chemical analysis both agree with the fact that the catalyst remains intact and immobilized in the ionic liquid upon extensive reuses. This contrasts with other vanadyl salen complexes lacking the imidazolium unit, which are extracted in part during the recovery of the products. Visually the extracts were colorless using VOsalen@IL while they are green when tetra-*tert*-butyl VOsalen is used as catalyst in [bmim]PF_6.

We expanded the above methodology to the preparation of a chiral vanadyl salen complex (VOsalen*@IL) derived from (1*R*,2*R*)-(−)-diaminocyclohexane and 3,5-di-*tert*-butylsalicylaldehyde. The resulting chiral complex was tested for the enantioselective addition of TMSCN to benzaldehyde.[9] The conversions and enantiomeric excess (ee) obtained depend on the nature of the counteranion accompanying to the [bmim]$^+$ cation. The results are summarized in Table 2. Although the influence of the counter anion of [bmim]$^+$ in the conversions and enantioselectivities achieved for other chiral metal salen complexes in ionic liquids has been reported,[4–6] it is difficult to correlate the nature of the anion and the ee at this moment. Variations of viscosity, melting point and other physical parameters of IL are important factors that depend on the counter anion, all of them playing a role in catalysis.

Table 2. Results of the asymmetric cyanosilylation of benzaldehyde in the presence of a chiral VOsalen*@IL as catalyst[a]

Solvent	Time (h)	Conversion (%)	e.e. (%)
[bmim]PF_6	3	88	57
[bmim]Cl	24	95	41
[bmim]BF_4	24	16	20

[a] Reaction were run at room temperature under N_2 atmosphere: benzaldehyde (1.64 mmol), TMSCN (1.5 equiv.), VOsalen*@IL (0.2 mol%), [bmim]PF_6 (1 g) and nitrobenzene as external standard.

The ee shown in Table 2 are relatively low compared to the ee previously reported to VOsalen complexes in related [beim]PF_6 ionic liquid (90%).[6] Apparently the covalent linkage between imidazolium and the vanadyl site affects negatively to the ability of the latter to induce asymmetry. One possibility worth to be explored to increase ee would be to disfavor the intramolecular association of the vanadyl group in VOsalen*@IL with the imidazolium or to exchange chloride by a different counter anion.

In conclusion, by modifying a vanadyl salen complex with the covalent attachment of a imidazolium cation we have obtained a catalyst insoluble in conventional organic solvents but totally miscible with imidazolium ionic liquids. The catalyst shows high activity for the cyanosilylation of aldehydes, remains immobilized in ionic liquid phase and can be reused in consecutive runs avoiding the leaching of vanadium. Further improvements are however necessary in order to enhance the asymmetric induction ability of this vanadyl salen imidazolium complex.

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