COMMUNICATION

ChemComm
www.rsc.org/chemcomm

# Efficient immobilisation of Rh-MonoPhos on the aluminosilicate AlTUD-1

**Chrétien Simons,[a,b] Ulf Hanefeld,[b] Isabel W. C. E. Arends,[a] Adriaan J. Minnaard,[c] Thomas Maschmeyer*[b]† and Roger A. Sheldon*[a]**

[a] *Laboratory for Biocatalysis and Organic Chemistry, Department of Biotechnology, Delft University of Technology, Julianalaan 136, 2628 BL Delft, The Netherlands. E-mail: R.A.Sheldon@tnw.tudelft.nl; Fax: (+31)-15-2781415*

[b] *Laboratory for Applied Organic Chemistry and Catalysis, Delft University of Technology, Julianalaan 136, 2628 BL Delft, The Netherlands*

[c] *Department of Organic and Molecular Inorganic Chemistry, Stratingh Institute, University of Groningen, Nijenborgh 4, 9747 AG Groningen, The Netherlands*

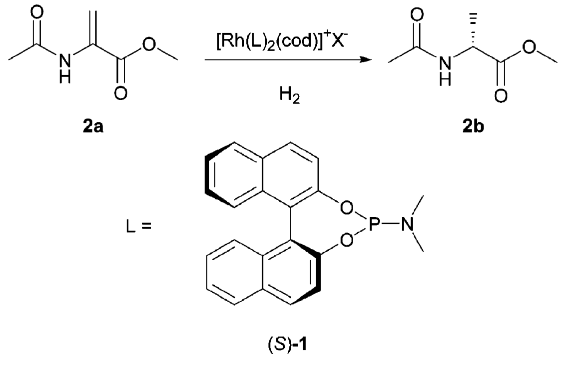
***Received (in Cambridge, UK) 28th July 2004, Accepted 15th September 2004***
***First published as an Advance Article on the web 26th October 2004***

DOI: 10.1039/b411506f

**Rhodium-MonoPhos was successfully immobilised by ionic interactions on aluminosilicate AlTUD-1. The resulting new heterogeneous catalyst can be used in water and showed excellent enantioselectivity and activity in the asymmetric hydrogenation of methyl-2-acetamidoacrylate.**

Recently it was shown that rhodium complexes with chiral monodentate ligands such as phosphoramidites (MonoPhos),[1] phosphites[2] or phosphonites[3] are very powerful tools for reductions[4] and conjugate additions.[5] Contrary to common expectations, these catalysts are highly enantioselective. Since the development of (*R,R*)-DIOP in 1971,[6] it was assumed that a conformationally rigid symmetric bidentate diphosphine is required for effective asymmetric induction.[7] The great advantage of these monodentate ligands compared to bidentate ones is their greater ease of synthesis. However, although more accessible, there are intrinsic difficulties with regard to recycling as the system is homogeneous in nature.

The immobilisation of transition metal catalysts is a well-established approach to improve their recyclability.[8] Although the Rh-MonoPhos catalyst was only reported late in 2000,[1] its first immobilisation was already described by 2003; complexes prepared from *p*-vinylaniline and 3-vinyl-8-quinoline containing ligands (homogeneous and polystyrene incorporated) were investigated.[9] The homogeneous and the heterogeneous pair of Rh-catalysts performed equally well in the reduction of itaconic acid and **2a** (Scheme 1). Although the target of recyclability was met, the ligand modification had a negative influence on the catalyst. Both pairs of Rh-catalysts gave enantioselectivities of only approx. 70%. This is well below the ee's of >95% that are normally achieved with the archetypal MonoPhos **1** as ligand.[1]



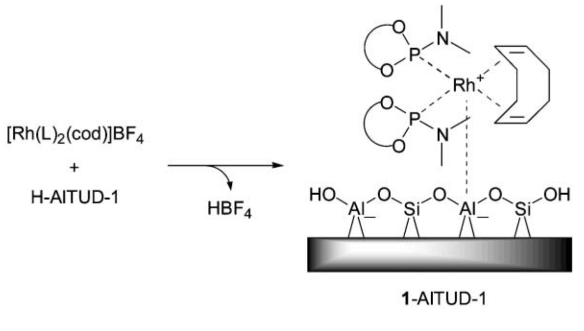
**Scheme 1** Model reaction for the Rh-phosphoramidite catalysed asymmetric hydrogenation.

It has been demonstrated that ionic complexes can successfully be immobilised on ionic carriers. An important advantage of this methodology is that no ligand modifications are necessary. Moreover, the heterogenised catalysts tend to retain their full activity and selectivity.[8,10] In this way, the homogeneous catalyst can be immobilised without the need of a difficult and time-consuming modification, making this approach very versatile. We recently developed as an ionic carrier a Brønsted acidic aluminosilicate, AlTUD-1, with the ideal characteristics for catalyst immobilisation: a three-dimensional mesoporous structure and a high surface area. It was applied successfully in the ionic immobilisation of two well-established Rh hydrogenation catalysts, Rh-DuPHOS and Rh-DIPAMP.[11] Both could readily be re-used and only very little leaching was observed, proving the potential of AlTUD-1.

Based on these results we reasoned that it should be possible to immobilise the ionic Rh-MonoPhos catalyst without modifications of the ligand, while at the same time ensuring recyclability and possibly expanding the range of solvents in which the catalyst can be used.

The enantiopure Rh precursor complex, [Rh(**1**)$_2$(cod)]BF$_4$, was immobilised on AlTUD-1 by a straightforward ion-exchange procedure yielding the supported catalyst (**1**-AlTUD-1, 1wt% Rh; Scheme 2).[11]

This heterogeneous catalyst was tested in the asymmetric hydrogenation of methyl-2-acetamidoacrylate (**2a**). The comparison between the homogeneous ($X^- = BF_4^-$) catalyst and **1**-AlTUD-1 in the same solvent $CH_2Cl_2$ (Table 1, entries homogeneous and −) reveals that the high activity of the catalyst is retained upon immobilisation (TOF of ~2100 h$^{-1}$). The immobilised catalyst also shows good enantioselectivity, although somewhat lower than the homogeneous catalyst. By changing to other solvents, such as 2-propanol (entries 5 and 6) and MTBE



**Scheme 2** Immobilisation of [Rh(L)$_2$(cod)]BF$_4$, wherein L is (*S*)-**1**, on AlTUD-1 according to ref. 11.

---

† Current address: Centre for Molecular Catalysis, School of Chemistry – F11, University of Sydney, NSW 2006, Australia. e-mail: th.maschmeyer@chem.usyd.edu.au

**Table 1** Asymmetric hydrogenation of **2a** using **1**-AlTUD-1 as catalyst[a]

| Entry | Solvent | Time/ min | Conversion (%) | Ee[c] (%) | Rh loss/ mg $L^{-1}$ (%)[d] |
|---|---|---|---|---|---|
| Homogeneous | $CH_2Cl_2$ | 7 | 100 | 97 | — |
| 1 | $CH_2Cl_2$ | 7 | 96 | 83 | 0.76 [2.9] |
| 2 | EtOAc | 7 | 70 | 92 | 1.27 [5.5] |
| 3 | EtOAc | 11 | 100 | 92 | 1.04 [4.5] |
| 4[b] | EtOAc | 1200 | 71 | 94 | 1.08 [35] |
| 5 | 2-PrOH | 7 | 39 | 91 | 2.30 [9.4] |
| 6 | 2-PrOH | 25 | 100 | 97 | 2.06 [8.4] |
| 7 | MTBE | 7 | 11 | 94 | 0.32 [1.3] |
| 8 | MTBE | 30 | 91 | 94 | 0.45 [1.8] |
| 9 | Water | 35 | 75 | 95 | 0.21 [0.6] |
| 10 | Water | 60 | 100 | 95 | 0.11 [0.3] |

[a] 5 bar $H_2$, 50 ml solvent, [**2a**] = 0.05 M, 0.1 g catalyst with 1wt% Rh. [b] 10 bar $H_2$, 50 ml solvent, [**2a**] = 0.2 M, 0.01 g catalyst with 1wt% Rh. [c] Ee's were determined as described in ref. 11. [d] Percentage of total amount of Rh determined by AAS of the filtrate.

(entries 7 and 8), excellent enantioselectivities (ee up to 97%) are regained. Entry 4 shows that high TON (up to 7100) can be achieved with **1**-AlTUD-1 without compromising the enantiomeric excess. Surprisingly the hydrogenation even proceeds in water, a solvent not commonly used for hydrogenations, with excellent enantioselectivity (95%) and good activity (entries 9 and 10). Normally, asymmetric hydrogenations in water require specially designed water-soluble ligands to proceed and there are only a few examples where the obtained enantioselectivities can match those of the corresponding transformation in organic solvents.[12] By immobilising $[Rh(\mathbf{1})_2(cod)]^+$ on AlTUD-1 the problem of solubility of the Rh complex in water is circumvented, while maintaining the catalyst's activity and outstanding selectivity.

With regard to leaching of the catalyst from the support, water again is an excellent solvent (entries 9 and 10). In water the loss of Rh is less than 1%. MTBE, too, is very suitable in this respect, with a loss of Rh of less than 2%. In 2-propanol, however, leaching is considerable, *i.e.* almost 10%. The heterogeneity of the system has been probed by a filtration test.[13] Using the conditions of entry 3, the catalyst was removed under inert atmosphere by filtration after 4 min, and the reaction was continued using the remaining filtrate. This test revealed that the system is indeed heterogeneous: no activity was found in the filtrate.

$[Rh(\mathbf{1})_2(cod)]^+$ was immobilised on AlTUD-1 in order to obtain a recyclable Rh-MonoPhos catalyst. The results of the recycling experiments are given in Fig. 1. The reaction times chosen are close to the minimum time needed to obtain 100% conversion (see Table 1). From these data, it becomes apparent that the catalyst is recyclable without any appreciable loss of activity and enantioselectivity in almost all solvents. Even in water, the catalyst can be re-used without significant deterioration, proving that the phosphoramidite **1** (MonoPhos) is very stable under aqueous reaction conditions. The increase of activity after run 1, which is observed for $CH_2Cl_2$ and water, can be explained by the slow reduction of the cod ligand; only after its complete removal the catalyst displays its full activity. In several cases the enantioselectivity also increased upon recycling. For $CH_2Cl_2$, MTBE and EtOAc the ee improved from 83 to 88%, 91 to 94% and 92 to 94% respectively. This might also be due to changes of the catalytic species concurrent with the reduction of cod. In 2-propanol, however, the activity decreases significantly upon re-use. The enantioselectivity also decreases, although less dramatically than the activity (from 97 to 92%). The reduced activity can be rationalised by the considerable leaching in this solvent.

In conclusion, we have demonstrated that the Rh complexes with monodentate ligands can be immobilised *via* ionic interaction with the same success as complexes based on bidentate ligands. The activity is hardly affected by the support and the excellent enantioselectivity of these catalysts is maintained, even upon re-use. This, once more, demonstrates the broad scope of immobilisation *via* ionic interactions and of AlTUD-1 as carrier material. The ability to use the heterogeneous catalyst in water, a solvent normally considered as difficult for asymmetric hydrogenations, significantly broadens the scope of the reduction, enabling its application under ecologically sound conditions.

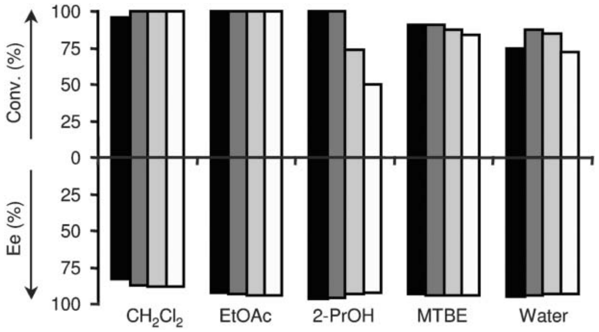


**Fig. 1** Recycling of **1**-AlTUD-1 in the asymmetric hydrogenation of **2a** using conditions *a* and the reaction times in line with those for 100% conversion in Table 1. Different bars represent consecutive runs.

C. S. gratefully acknowledges the National Research School Combination Catalysis (NRSC-Catalysis) for financial support. U. H. thanks the Royal Netherlands Academy of Arts and Sciences (KNAW) for a fellowship. D. van Rij is gratefully acknowledged for the INAA analysis, and J. Padmos for AAS analysis.

## Notes and references

1 M. van den Berg, A. J. Minnaard, E. P. Schudde, J. van Esch, A. H. M. de Vries, J. G. de Vries and B. L. Feringa, *J. Am. Chem. Soc.*, 2000, **122**, 11539–11540.

2 M. T. Reetz and G. Mehler, *Angew. Chem., Int. Ed.*, 2000, **39**, 3889–3890.

3 C. Claver, E. Fernandez, A. Gillon, K. Heslop, D. J. Hyett, A. Martorell, A. G. Orpen and P. G. Pringle, *Chem. Commun.*, 2000, 961–962.

4 M. van den Berg, A. J. Minnaard, R. M. Haak, M. Leeman, E. P. Schudde, A. Meetsma, B. L. Feringa, A. H. M. de Vries, C. E. P. Maljaars, C. E. Willans, D. Hyett, J. A. F. Boogers, H. J. W. Henderickx and J. G. de Vries, *Adv. Synth. Catal.*, 2003, **345**, 308–323.

5 A. Duursma, L. Lefort, J. A. F. Boogers, A. H. M. de Vries, J. G. de Vries, A. J. Minnaard and B. L. Feringa, *Org. Biomol. Chem.*, 2004, **2**, 1682–1684.

6 (*a*) T.-P. Dang and H. B. Kagan, *J. Chem. Soc., Chem. Commun.*, 1971, 481; (*b*) H. B. Kagan and T.-P. Dang, *J. Am. Chem. Soc.*, 1972, **94**, 6429.

7 (*a*) T. Ohkuma, M. Kitamura and R. Noyori, in *Catalytic Asymmetric Synthesis*, ed. I. Ojima, Wiley, New York, 2nd edn., 2000; (*b*) M. J. Burk and F. Bienewald, in *Transition Metals for Organic Synthesis*, ed. M. Beller and C. Bolm, Wiley-VCH, Weinheim, 1998, **vol. 2**.

8 P. McMorn and G. J. Hutchings, *Chem. Soc. Rev.*, 2004, **33**, 108–122.

9 S. Doherty, E. G. Robins, I. Pal, C. R. Newman, C. Hardacre, D. Rooney and D. A. Mooney, *Tetrahedron: Asymmetry*, 2003, **14**, 1517–1527.

10 (*a*) R. Augustine, S. Tanielyan, S. Anderson and H. Yang, *Chem. Commun.*, 1999, 1257–1258; (*b*) H. H. Wagner, H. Hausmann and W. F. Hölderich, *J. Catal.*, 2001, **203**, 150–156; (*c*) F. M. de Rege, D. K. Morita, K. C. Ott, W. Tumas and R. D. Broene, *Chem. Commun.*, 2000, 1797–1798.

11 C. Simons, U. Hanefeld, I. W. C. E. Arends, R. A. Sheldon and T. Maschmeyer, *Chem.–Eur. J.*, 2004, in press.

12 (*a*) U. M. Lindstrom, *Chem. Rev.*, 2002, **102**, 2751–2772; (*b*) R. Selke, in *Asymmetric Catalysis on Industrial Scale: Challenges, Approaches and Solutions*, ed. H. U. Blaser and E. Schmidt, Wiley-VCH, Weinheim, 2004, ch. 2.

13 H. E. B. Lempers and R. A. Sheldon, *J. Catal.*, 1998, **175**, 62–69.