ChemComm

Practical method to recycle a chiral (salen)Mn epoxidation catalyst by using an ionic liquid

Choong Eui Song* and Eun Joo Roh

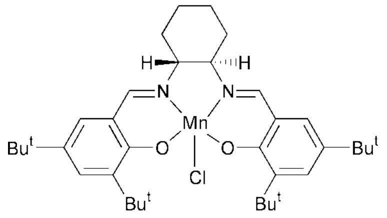
Life Sciences Division, Korea Institute of Science and Technology, PO Box 131, Cheongryang, Seoul, 130-650, Korea. E-mail: s1673@kistmail.kist.re.kr

Received (in Cambridge, UK) 18th February 2000, Accepted 11th April 2000
Published on the Web 28th April 2000

A practical recycling procedure for Jacobsen's chiral (salen)Mn^{III} epoxidation catalyst involving the use of the air- and moisture-stable ionic liquid [bmim][PF$_6$] has been developed.

Development of practical immobilisation methods[1] for chiral homogeneous catalysts is highly desirable, since immobilised chiral catalysts offer several practical advantages over soluble catalysts such as facilitation of catalyst separation from reagents and products, simplification of methods for catalyst recycling, and the possible adaptation of the immobilised catalyst for continuous flow processes. To this end, some homogeneous chiral catalysts have been immobilised either by anchoring the catalyst on a solid support[1a] or by use of a two-phase system.[1b] All of these approaches are interesting but usually require additional modifications of the catalyst. Moreover, such approaches frequently lead to partial loss of activity and/or enantioselectivity.

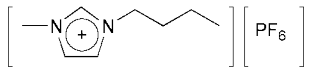
For Jacobsen's chiral (salen)Mn^{III} epoxidation catalyst,[2] [*N*,*N*′-bis(3,5-di-*tert*-butylsalicylidene)-1,2-cyclohexanediamine]manganese(III)] chloride **1**, several attempts to immobilise this catalyst have been made.[3–6] However, no successful immobilisation procedure has, as yet, been reported. Attempts to immobilise Jacobsen's catalyst up to now consisted of covalent attachment of the complex to insoluble solid supports,[3] steric occlusion in nano-sized cages of zeolites,[4] physical entrapment in a polydimethylsiloxane membrane,[5] and use of a fluorous biphasic system (FBS).[6]



(*R*,*R*)-**1**

Recently, a new approach has been adopted for catalyst separation and recycling in a few types of catalytic reaction involving the use of ionic liquids,[7] *i.e.* a salt mixture with a melting point below ambient. Air and moisture-stable room temperature ionic liquids consisting of 1,3-dialkylimidazolium cations and their counter anions, in particular, have attracted growing interest in the last few years.[8] In these solvents, catalysts having polar or ionic character can be immobilised and thus the ionic solutions containing the catalyst can be easily separated from reagents and products. Recent applications include Friedel–Crafts reactions,[8a] Diels–Alder reactions,[8b] alkylations,[8c] olefin dimerisation and oligomerisation,[8d] hydrogenation,[8e] Heck reaction,[8f] hydroformylation[8g] and palladium catalysed allylation reactions.[8h]

Herein, we report a practical recycling procedure of Jacobsen's catalyst (*R*,*R*)-**1** involving the use of the air- and moisture-stable ionic liquid, [bmim][PF$_6$] **2** ([bmim]$^+$ = 1-butyl-3-methylimidazolium cation). The ionic liquid **2** is conveniently prepared,[9] and an excellent solvent for many organic compounds, but is immiscible with saturated hydrocarbon solvents, dialkyl ethers and water. Taking into account the conditions of asymmetric epoxidation (involving the use of aqueous NaOCl) and the unique solvating properties of **2**, it was selected as a solvent for our experiments among many other ionic liquids (*cf.* the BF$_4^-$ or triflate salts which are soluble in water).

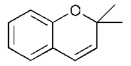
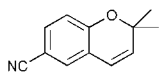
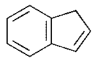
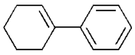


[bmim][PF$_6$] **2**

Asymmetric epoxidations† were carried out in the presence of 4 mol% of (*R*,*R*)-**1** with 2,2-dimethylchromene, 6-cyano-2,2-dimethylchromene, indene, *cis*-β-methylstyrene, and 1-phenylcyclohexene as substrates in [bmim][PF$_6$]–CH$_2$Cl$_2$ (1 : 4, v/v) using NaOCl as the oxidant at 0 °C. Since the ionic liquid **2** solidifies at the reaction temperature (0 °C), the co-solvent system was used. Both the catalyst (*R*,*R*)-**1** and the ionic liquid **2** are soluble in CH$_2$Cl$_2$. The results obtained are shown in Table 1.

As shown in Table 1, conversion of alkenes to epoxides and enantioselectivity were satisfactory and comparable to those[10] obtained without an ionic liquid. In particular, the epoxidation of 2,2-dimethylchromene and 6-cyano-2,2-dimethylchromene in [bmim][PF$_6$]-CH$_2$Cl$_2$ afforded the corresponding chromene oxides in very high ee (96 and 94%, entries 1 and 2). Moreover, the reaction in the presence of the ionic liquid **2** proceeded faster than without an ionic liquid. For example, the epoxidation of 2,2-dimethylchromene in the presence of **2** was complete in 2 h (entry 1) whereas in a control experiment, the same reaction without **2** required 6 h to achieve a comparable degree of conversion. Furthermore, both the catalyst (*R*,*R*)-**1** and the ionic liquid could be easily recovered after reaction. The recovery procedure was as follows: the organic phase of the reaction

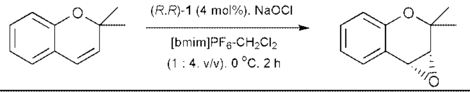
Table 1 Asymmetric epoxidation of alkenes in ionic liquid **2**[a]

Entry	Substrate	*t*/h	Yield[b] (%)	% ee[c]	Confign.[c]
1		2	86	96	(3*R*,4*R*)
2	 NC	4	72	94	(3*R*,4*R*)
3		4	72	84	(1*R*,2*S*)
4	 Ph Me	3	72 (3.7 : 1)[d]	86	(1*R*,2*S*)
5		4	77	84	(*S*,*S*)

[a] See footnote.† [b] Isolated yield. [c] Determined by chiral GC or chiral HPLC: see footnote† and ref. 11. [d] *Cis* : *trans* selectivity.

DOI: 10.1039/b001403f

Table 2 Recovery and reuse of the ionic liquid phase containing (*R*,*R*)-**1**[a]



Run	1	2	3	4	5
Yield (%)[b]	86	73	73	60	53
% ee[c]	96	90	90	89	88

[a] See footnote†. [b] Isolated yield. [c] Determined by chiral HPLC.

mixture was washed with water and concentrated. After extraction of the product with hexane, the brown oily ionic liquid which contains the catalyst, was recovered, which could be reused for further catalytic reactions. The above procedure was repeated five times and results obtained are shown in Table 2. However, the enantioselectivity and the activity of the recovered catalyst decreased slightly upon successive use possibly due to minor degradation of the salen catalyst (*R*,*R*)-**1** under the oxidation conditions.

In summary, we have developed a practical recycling procedure for Jacobsen's chiral (salen)Mn^{III} catalyst **1** by use of ionic liquid **2**. Our results showed that the catalyst (*R*,*R*)-**1** in a reaction medium containing ionic liquid **2** exhibited comparable enantioselectivity (96% ee for 2,2-dimethylchromene) in asymmetric epoxidation of alkenes as those obtained without ionic liquid and, moreover, showed an increase in activity. At the end of reaction the immobilised catalyst in ionic liquid **2** could be easily recycled. In conclusion, the immobilisation method of **1** by using an ionic liquid provides not only simple recycling of catalyst, but also the additional advantage of use of the catalyst without any modification of its structure. A detailed study concerning the optimisation of this process and extension of this methodology to recycle other homogeneous chiral catalysts are currently in progress.

This research was supported by a grant from Korea Institute of Science and Technology.

Notes and references

† *Representative procedure* for asymmetric epoxidation using an ionic liquid: the pH of a solution of commercial household bleach (Clorox®) was buffered to pH = 11.3 with 0.05 M Na_2HPO_4 and 1 M NaOH (a few drops) and then cooled to 0 °C. To 110 mL of this solution was added a precooled solution (0 °C) of 2,2-dimethylchromene (5.0 g, 31.3 mmol) and the catalyst (*R*,*R*)-**1** (0.79 g, 1.25 mmol) in CH_2Cl_2 (30 mL) and [bmim][PF_6] (7.5 mL). The two-phase system was stirred at 0 °C and the progress of reaction was monitored by TLC. After 2 h, the organic phase was separated and washed twice with water. The volatiles were concentrated *in vacuo* and the residue was stirred with hexane. After concentration of the upper hexane phase *in vacuo*, the residue was purified by column chromatography on silica gel (deactivated with 1% NEt_3 solution in ethyl acetate–hexane) with ethyl acetate–hexane (1 : 10) as eluent, to afford 4.74 g (86% yield) of the epoxide with 96% ee. The brown oily ionic liquid phase (the lower phase) containing the catalyst was reused.

Ee values of products were determined by chiral HPLC or chiral GC: for 3,4-epoxy-2,2-dimethylchroman: Daicel Chiralpak AD, propan-2-ol–hexane (5/95), 0.8 mL min^{-1}; 9.30 min (3*R*,4*R*), 10.63 min (3*S*,4*S*). For 3,4-epoxy-6-cyano-2,2-dimethylchroman: Daicel Chiralcel OJ, propan-2-ol–hexane (30/70), 1 mL min^{-1}; 13.95 min (3*R*,4*R*), 26.88 min (3*S*,4*S*). For other epoxides: see ref. 11.

1 (*a*) B. Pugin and H.-U. Blaser, *Catalyst Immobilization: Solid Supports*, in *Comprehensive Asymmetric Catalysis III*, ed. E. N. Jacobsen, A. Pfaltz and H. Yamamoto, Springer-Verlag, Berlin–Heidelberg–New York, 1999, p. 1367; (*b*) G. Oehme, *Catalyst Immobilization: Two-Phase Systems*, in *Comprehensive Asymmetric Catalysis III*, ed. E. N. Jacobsen, A. Pfaltz and H. Yamamoto, Springer-Verlag, Berlin–Heidelberg–New York, 1999, p. 1378.

2 E. N. Jacobsen and M. H. Wu, *Epoxidation of Alkenes Other than Allylic Alcohols*, in *Comprehensive Asymmetric Catalysis II*, ed. E. N. Jacobsen, A. Pfaltz and H. Yamamoto, Springer-Verlag, Berlin–Heidelberg–New York, 1999, p. 649.

3 Recent papers: L. Canali, E. Cowan, H. Deleuze, C. L. Gibson and D. C. Sherrington, *Chem. Commun.*, 1998, 2561; M. D. Angelino and P. E. Laibinis, *Macromolecules*, 1998, **31**, 7581; G.-J. Kim and J.-H. Shin, *Tetrahedron Lett.*, 1999, **40**, 6827; D. Pini, A. Mandoli, S. Orlandi and P. Salvadori, *Tetrahedron: Asymmetry*, 1999, **10**, 3883; C. E. Song, E. J. Roh, B. M. Yu, D. Y. Chi, S. C. Kim and K.-J. Lee, *Chem. Commun.*, 2000, 615.

4 M. J. Sabater, A. Corma, A. Domenech, V. Fornes and H. Garcia, *Chem. Commun.*, 1997, 1285; S. B. Ogunwumi and T. Bein, *Chem. Commun.*, 1997, 901.

5 I. F. J. Vankelecom, D. Tas, R. F. Parton, V. Van de Vyver and P. A. Jacobs, *Angew. Chem., Int. Ed. Engl.*, 1996, **35**, 1346; K. B. M. Janssen, I. Laquiere, W. Dehaen, R. F. Parton, I. F. J. Vankelecom and P. A. Jacobs, *Tetrahedron: Asymmetry*, 1997, **8**, 3481.

6 G. Pozzi, F. Cinato, F. Montanari and S. Quici, *Chem. Commun.*, 1998, 877.

7 Review: T. Welton, *Chem. Rev.*, 1999, **99**, 2071.

8 Catalytic reactions: (*a*) A. Stark, B. L. MacLean and R. D. Singer, *J. Chem. Soc., Dalton Trans.*, 1999, 63; (*b*) T. Fischer, A. Sethi, T. Welton and J. Woolf, *Tetrahedron Lett.*, 1999, **40**, 793; (*c*) M. J. Earle, P. B. McCormac and K. R. Seddon, *Chem. Commun.*, 1998, 2245; (*d*) B. Ellis, W. Keim and P. Wasserscheid, *Chem. Commun.*, 1999, 337; (*e*) A. L. Monteiro, F. K. Zinn, R. F. de Souza and J. Dupont, *Tetrahedron: Asymmetry*, 1997, **8**, 177; (*f*) W. A. Herrmann and V. P. W. Bohm, *J. Organomet. Chem.*, 1999, **572**, 141; (*g*) W. Keim, D. Vogt, H. Waffenschmidt and P. Wasserscheid, *J. Catal.*, 1999, **186**, 481; (*h*) W. Chen, L. Xu, C. Chatterton and J. Xiao, *Chem. Commun.*, 1999, 1247.

9 P. A. Z. Suarez, J. E. L. Dullius, S. Einloft, R. F. de Souza and J. Dupont, *Polyhedron*, 1996, **15**, 1217; J. Fuller, R. T. Carlin, H. C. De Long and D. Harworth, *J. Chem. Soc., Chem. Commun.*, 1994, 299.

10 N. H. Lee, A. R. Muci and E. N. Jacobsen, *Tetrahedron Lett.*, 1991, **32**, 5055.

11 Determination of enantiomeric excess: for indene oxide: M. Palucki, G. J. McCormick and E. N. Jacobsen, *Tetrahedron Lett.*, 1995, **36**, 5457; for *cis*-β-methylstyrene oxide: W. Zhang and E. N. Jacobsen, *J. Org. Chem.*, 1991, **56**, 2296; for 1-phenylcyclohexene oxide: B. Brandes and E. N. Jacobsen, *J. Org. Chem.*, 1994, **59**, 4378.