Intrazeolite assembly of a chiral manganese salen epoxidation catalyst

Steven B. Ogunwumi and Thomas Bein*

Department of Chemistry, Purdue University, West Lafayette, IN 47907, USA

Asymmetric manganese salen epoxidation catalysts are assembled and trapped in a multistep synthesis in the cages of zeolite EMT; these heterogeneous catalysts produce high enantiomeric excess in the epoxidation of aromatic alkenes with NaOCl.

Asymmetric epoxidation of alkenes is of great interest for the synthesis of chiral intermediates in the pharmaceutical and agrochemical fields.[1,2] Zeolite cage structures are attractive hosts for the design of hybrid systems.[3] Such an inclusion strategy is expected to result in easy recovery or continuous use of the catalyst, diffusional selectivity of the reaction, and potentially increased stability *via* site isolation. Very few asymmetric reactions have been performed on zeolites.[4] Here we present an active, asymmetric epoxidation catalyst that was assembled and trapped in the cages of crystalline zeolite EMT. This novel heterogeneous system produces high enantiomeric excess (ee) in the epoxidation of aromatic alkenes with NaOCl (aq).

Chiral manganese salen epoxidation catalysts[5] are particularly active for the epoxidation of *cis*-substituted aryl alkenes. This family of complexes can be assembled in a stepwise manner in the cages of the zeolite EMT. This zeolite is a hexagonal form of the well known faujasite structure.[6,7] The hypercages of EMT are accessible through three 12-ring windows with free dimensions of 0.69 × 0.74 nm and two 0.74 nm circular apertures, while the hypocages have only three windows. EMT was synthesized as previously reported,[7] followed by calcination at 450 °C, washing with water, and dehydration at 300 °C and 10^{-4} Torr before use.

One specific intrazeolite assembly sequence was found to result in active and enantioselective heterogeneous epoxidation catalysts. A mixture of 1.00 g (0.16 mmol) calcined and dehydrated zeolite EMT and 1 equiv. [0.16 mmol (18.4 mg)] of (*R*,*R*)- or (*S*,*S*)-1,2-*trans*-diaminocyclohexane per EMT unit cell were stirred and refluxed in 80 ml of dry thf for 15 h under N_2. The solvent was evaporated, and 2.00 equiv. of the required salicylaldehyde (2-hydroxybenzaldehyde or 3-*tert*-butyl-5-methylsalicylaldehyde) were added and stirred at 80 °C under N_2 for 1 h, followed by refluxing under stirring in thf for 12 h. The zeolite host turns yellow during this process. 1 Equiv. of $Mn(O_2CMe)_2{\cdot}4H_2O$ (39 mg) per unit cell of EMT was added to the slurry, which was exposed to air to oxidize the Mn^{II}. Another 15 h refluxing under air resulted in a brownish slurry, to which was added 1 equiv. of solid LiCl per hypercage, followed by 24 h under reflux in thf, filtration, drying at 80 °C under vacuum, and Soxhlet extraction in CH_2Cl_2 for 24 h to remove excess complex, salen ligand, and reactants from the zeolite exterior and interior. Intrazeolite chloro[*N*,*N*′-bis(3-*tert*-butyl-5-methylsalicylidene)cyclohexanediamine]manganese(iii) (**1**) is denoted **1–**EMT, chloro[*N*,*N*′-bis(salicylidene)-cyclohexanediamine]manganese(iii) (**2**) is denoted **2–**EMT, and chloro[*N*,*N*′-bis(3-*tert*-butyl-5-methylsalicylidene)cyclohexanediamine]manganese(ii) **3** (obtained by reacting intrazeolite salen ligand with Mn^{II} under inert conditions) is denoted **3–**EMT. Complexes **1** and **2** were also synthesized in the homogeneous phase according to ref. 5.

Before assembly of the intrazeolite guest, the micropore volume of degassed EMT is 0.325 ml g^{-1}.[6] The chiral manganese salen complexes have dimensions of *ca.* 1.5 (**1**) and 1.3 nm (**2**; with modifications from crystallographic data of **1**, kindly provided by E. N. Jacobsen), preventing escape of the assembled complex from within the zeolite (crystallographic data for EMT: see ref. 8; Fig. 1). This general approach has been termed 'ship-in-the-bottle synthesis'.[9] No close van der Waals contacts were observed when the complexes were positioned in the hypercages.

The Soxhlet-extracted samples contain 0.50 ± 0.09 Mn per unit cell of EMT in the case of **1**–EMT, and 0.65 ± 0.09 Mn per unit cell in the case of **2**–EMT (XRF data). The free intrazeolite pore volume remaining after encapsulation of the complexes was determined using *T*-plot analysis from N_2 sorption, after evacuating the Soxhlet extracted samples at 120 °C. The original void volume of calcined EMT was reduced to 0.18 ml g^{-1} in both **1**–EMT and **2**–EMT, showing that a significant fraction of the pore volume remains accessible after assembly of the intrazeolite salen complexes in spite of some water remaining in the zeolite after degassing.

Electronic absorption spectra in Fig. 2 show ligand transitions of the brownish oxidized complex **1** (in solution) at 322 and 438 nm and a weak d–d transition at 500 nm [Fig. 2(*a*)].[10] Upon zeolite encapsulation, the former bands shift to 335 and 422 nm, while the weak d–d transition is still observed at about 500 nm [Fig. 2(*b*)]. Strikingly, the d–d transition at 500 nm characteristic for Mn^{III} in these complexes is absent in the spectrum of **3**–EMT [Fig. 2(*c*)], with bands at 266, 333 and 438 nm. In the IR spectrum (not shown), we observe the imine band at 1638 cm^{-1} and a mode at 1458 cm^{-1} for the salen ligand of **1**, assembled in the zeolite and dehydrated at 110 °C (10^{-5} Torr)

Fig. 1 View of the molecular fit of **1** in EMT (Cerius[2] software)

in situ to minimize interference with the zeolite water band at 1635 cm^{-1}. In solution, the imine C=N stretch vibration of the free ligand at 1631 cm^{-1} shifts to 1610 cm^{-1} upon complexation with Mn^{III}.[10b,11] A striking shift of the imine band to 1583 cm^{-1} occurs upon complexation with Mn^{II} and oxidation to form **1** in the EMT host which shows that a large majority of the ligands is now coordinating the Mn ions.

The encapsulated Mn salen complexes were studied as asymmetric epoxidation catalysts using different substrates (Table 1). In a representative reaction, 1 ml of dichloromethane or acetonitrile, 1 ml NaOCl (5.25%, 0.70 mmol), 0.005 ml Na_2HPO_4 (0.05 m), 0.005 ml *n*-decane (GC standard) and 1 drop of 1 m NaOH were added to a solution containing 0.15 mmol of an alkene such as *cis*-β-methylstyrene, along with 100 mg of **1**–EMT catalyst. The slurry was stirred at 4 °C for 1 h, followed by stirring at room temp. for ⩾23 h. The ratio of Mn to alkene was typically adjusted to 5 mol% (commonly used in homogeneous reactions). No conversion was observed when using an Mn^{II}-exchanged, air-treated zeolite EMT without the chiral salen ligand. The X-ray crystallinity of the zeolite host is retained after assembly of the intrazeolite complexes, and only slightly reduced after completion of the catalytic experiments.

The following observations can be noted (see also Table 1). (*i*) **1**–EMT with the bulky ligand is more active than **2**–EMT (*e.g.* conversion of *cis*-β-methylstyrene with **1**–EMT was 15% (after 24 h), and with **2**–EMT it was only 1%. The catalytic activity increases significantly on addition of axial ligands such as pyridine *N*-oxide, with which conversion of *cis*-β-methylstyrene was 47%. Formally, 100% conversion corresponds to a lower limit of 20 turnovers, but only a small fraction of the intrazeolite salen complexes may be accessed by the substrate during reaction. (*ii*) With PhIO as oxidant, **2**–EMT showed conversion of styrene and was more active than the sterically more encumbered **1**–EMT, suggesting that the access of the bulky terminal oxidant was hindered in the zeolite–**1** assembly (not in Table 1). (*iii*) The highest ee in epoxide, 88% was achieved with *cis*-β-methylstyrene, **1**–EMT plus pyridine *N*-oxide as catalyst, and NaOCl as oxidant, in dichloroethane. (*iv*) *trans*-β-Methylstyrene gives relatively high yields of *trans*-epoxide but the ee is lower. (*v*) Smaller (non-prochiral) alkenes such as 2,3-dimethylbut-2-ene give higher conversions than the more bulky but more reactive aromatic alkenes, suggesting a strong influence of the zeolite pore structure on diffusional access to the active salen complex encapsulated in the zeolite host. Proof for intrazeolite reactions is obtained by reacting cholesterol with the encapsulated **1**–EMT catalyst. While no conversion was observed with the encapsulated catalyst after 18 h, in solution the epoxidation proceeded to 13% conversion during the same time. This behaviour shows that the catalysis of the smaller substrates truly proceeds in the zeolite pores.

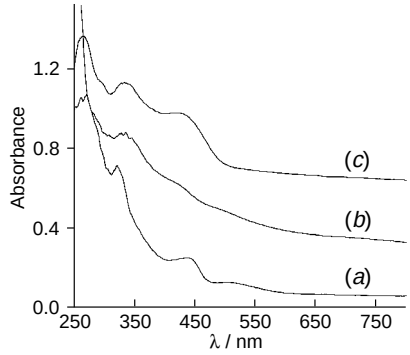

Fig. 2 UV–VIS spectra (in diffuse reflectance mode) of oxidized **1** in solution (*a*), **1**–EMT (*b*) and **3**–EMT containing Mn^{II} complexed by the salen ligand of **1** (*c*)

Table 1 Heterogeneous and homogeneous catalysis reactions of [Mn(salen)Cl] in EMT[a]

Substrate	Substrate conv.(%)	Epoxide selectivity (%)	ee (%)	Confign.
Heterogeneous				
$Me_2C{=}CMe_2$[b]	40	75	NC[c]	NC
$PhC(H){=}CH_2$	15	87	34	*S*-(−)
(*E*)-PhC(H)=CH(Me)	29	62	20	1*S*,2*S*-(−)
(*Z*)-PhC(H)=CH(Me)[d]	15	67	80	1*S*,2*R*-(−)
(*Z*)-PhC(H)=CH(Me)[e]	47	58	88	1*S*,2*R*-(−)
Cholesterol	None	—	—	—
Homogeneous				
$PhC(H){=}CH_2$	55	95	35	*S*-(−)
(*Z*)-PhC(H)=CH(Me)	85	97	80	1*S*,2*R*-(−)
Cholesterol[f]	13	85	—	—

[a] Salen = (*S*,*S*)-*N*,*N*′-bis(3-*tert*-butyl-5-methylsalicylidene)-cyclohexanediamine. (Other products and distribution not given.) *Reagents and conditions:* 5 mol % catalyst, reaction maintained at 0 °C for 1 h then room temp. for 24 h; solvent, CH_2Cl_2; oxidant, NaOCl; Astec chiraldex B-TA column (decane: GC standard). [b] Reactivity of a non-prochiral alkene. [c] Not chiral. [d] Initial experiments addressing the recyclability of the catalyst after Soxhlet extraction with acetonitrile showed significantly lower ee; the origin of this reduced enantioselectivity is currently being studied. [e] Catalyst with pyridine *N*-oxide (5 mol%); solvent dichloroethane. [f] Isolated yield determined by ^1H NMR using CH_2Br_2 as internal standard (after 18 h).

The authors gratefully acknowledge funding from the U.S. Department of Energy for this work. We thank Professor Merritt B. Andrus for assistance with chromatographic separations.

References

1 R. A. Sheldon and J. K. Kochi, *Metal-Catalysed Oxidation of Organic Compounds*, Academic Press, New York, 1981; J. Gorzynski Smith, *Synthesis*, 1984, 629.

2 Li. Deng and E. N. Jacobsen *J. Org. Chem*., 1992, **57**, 4320; D. M. Hodgson, P. J. Parsons and P. A. Stones, *J. Chem. Soc., Chem. Commun*., 1988, 217.

3 D. E. De Vos, J. L. Meinershagen and T. Bein, *Angew. Chem., Int. Ed. Engl.*, 1996, **35**, 2211; P. P. Knops Gerrits, D. E. De Vos, F. Thibault-Starzyk and P. A. Jacobs, *Nature*, 1994, **369**, 543.

4 (*a*) S. Feast, D. Bethell , P. C. B. Page, F. King, C. H. Rochester, M. R. H. Siddiqui, D. J. Willock and G. J. Hutchings, *J. Chem. Soc., Chem. Commun*., 1995, 2409; (*b*) A. Corma, M. Iglesias, C. del Pino and F. Sanchez, *J. Chem. Soc., Chem. Commun*., 1991, 1253; (*c*) A. Carmona, A. Corma, M. Iglesias, A. San Jose and F. Sanchez, *J. Organomet. Chem.*, 1995, **492**, 11; (*d*) A. Corma, M. Iglesias, V. M. Martin and F. Sanchez, *Tetrahedron Asymmetry*, 1992, **3**, 845; (*e*) U. Böhmer, K. Morgenschweis and W. Reschetilowski, *Catal. Today*, 1995, **24**, 195; (*f*) A. Corma, A. Fuerte, M. Iglesias and F. Sanchez, *J. Mol. Catal. A*, 1996, **107**, 225.

5 W. Zhang, J. L. Loebach, S. R. Wilson and E. N. Jacobsen, *J. Am. Chem. Soc*., 1990, **112**, 2801; T. Katsuki, *Coord. Chem. Rev*., 1995, **140**, 189 and references therein.

6 E. J. P. Feijen, K. De Vadder, M. H. Bosschaerts, J. L. Lievens, J. A. Martens, P. J. Grobet and P. A. Jacobs, *J. Am. Chem. Soc.*, 1994, **116**, 2950.

7 S. L. Burkett and M. E. Davis, *Microporous Mater*., 1993, **1**, 265.

8 J. L. Lievens, J. P. Verduijn, A.-J. Bons and W. J. Mortier, *Zeolites*, 1992, **12**, 698.

9 N. Herron, *Inorg. Chem.*, 1986, **25**, 4714.

10 (*a*) M. T. Rispens, A. Meetsma and B. L. Feringa, *Recl. Trav. Chim. Pays-Bas*, 1994, **113**, 413; (*b*) J. Skarzewski, A. Gupta and A. Vogt, *J. Mol. Catal. A.*, 1995, **103**, L63.

11 J. R. Dilworth, C. A. McAuliffe and B. J. Sayle, *J. Chem. Soc., Dalton Trans*., 1977, 849.

Received in Bloomington, IN, USA, 20th November 1996; Com. 6/07879F

Typeset and printed by Black Bear Press Limited, Cambridge, England