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# Asymmetric Epoxidation of Olefins by Manganese(III) Complexes Stabilised on Nanocrystalline Magnesium Oxide

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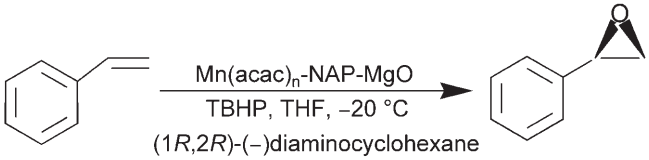
**Abstract:** The asymmetric epoxidation of unfunctionalised olefins to epoxides is realised by using manganese(III) complexes stabilised on nanocrystalline magnesium oxide in the presence of (1*R*,2*R*)-(−)-diaminocyclohexane as a chiral ligand in good yields and up to 91% enantiomeric excess.

**Keywords:** asymmetric epoxidation; heterogeneous catalysis; magnesium oxide; manganese acetylacetonate; nanocrystalline materials

Asymmetric epoxidation (AE) of unfunctionalised olefins is an important organic transformation since the resulting epoxides are important building blocks for the synthesis of biologically active molecules.[1] Although Srinivasan et al.[2a] reported Mn(II)-(salen) complexes for the epoxidation of olefins for the first time, the chiral Mn(III)-(salen) complexes reported by the groups of Jacobsen[2b,c] and Katsuki[3] have emerged as extremely efficient systems for the AE of the unfunctionalised olefins. The high enantiomeric excess (*ee*) values achieved here is ascribed to the directed path of the prochiral olefin to the metal centre, while other possible paths are blocked by the introduction of bulky substituents on salen ligands. Katsuki et al. also reported the asymmetric epoxidation of olefins by using a combination of achiral Mn-salen complex and chiral amine.[3e]

The immobilisation of transition metal complexes on solid supports can provide catalysts that are easier to handle and sometimes exhibit improved activities and enantioselectivities induced by the support.[4] AE has been reported by using chiral Mn-(salen) complex immobilised on mesoporous materials,[5,6] polymer supports,[7a,b] layered double hydroxides,[7c] clays,[7d] and zeolites.[7e,f] Nanocrystalline metal oxides[8a] have been efficiently used as absorbents for gases, for the destruction of hazardous chemicals and as catalysts for organic transformations.[8b–e] Nanomaterials with their three-dimensional structure and defined sizes and shapes are demonstrated to be suitable candidates for proper alignment with prochiral substrates for the unidirectional introduction of the reacting species to induce asymmetric centres as exemplified in asymmetric epoxidation.[9a,b] Similarly, we hypothesise that the catalytic system comprising metal ions exchanged on a support having a defined shape and size is expected to display asymmetric induction upon using a suitable chiral auxiliary. We herein report the asymmetric epoxidation of unfunctionalised olefins to epoxides using manganese acetylacetonate stabilised on nanocrystalline magnesium oxide (aerogel prepared MgO, NAP-MgO) with a defined shape and size in the presence of (1*R*,2*R*)-(−)-diaminocyclohexane (DAC) as a chiral ligand in good yields and up to 91% enantiomeric excess[10] (Scheme 1).

Various magnesium oxide crystals[8b,11,12] [commercial MgO, CM-MgO (SSA: 30 $m^2/g$), conventionally prepared MgO, NA-MgO (SSA: 250 $m^2/g$), aerogel prepared MgO, NAP-MgO (SSA: 590 $m^2/g$)] were initially evaluated in the epoxidation reaction of unfunctionalised olefins separately in order to understand the relationship between the structure and reactivity. They are not active as such for the epoxidation of un-




**Scheme 1.** Asymmetric epoxidation of olefins using Mn-(acac)$_n$-NAP-MgO in the presence of a chiral ligand.


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**Table 1.** Asymmetric epoxidation of styrene using different catalysts at −20 °C.

| Entry | Catalyst | Time [h] | Yield [%] | *ee* [%][e] |
|---|---|---|---|---|
| 1 | NAP-MgO | 24 | 0, 0,[a] 0[b] | 0 |
| 2 | $Mn(acac)_3$ | 24 | 10 | 0 |
| 3 | $Mn(acac)_3$-DAC | 24 | 10 | 0 |
| 4 | Mn $(acac)_n$-NAP-MgO | 24 | 70, 20,[c] 0[d] | 42, 0[c] |
| 5 | $MnO_2$-NAP- MgO | 24 | 0 | 0 |

[a] NA-MgO.
[b] CM-MgO.
[c] $Mn(acac)_n$-NA-MgO.
[d] $Mn(acac)_n$-CM-MgO.
[e] Absolute configuration was found to be (*R*). The *ee* was determined by HPLC using a Diacel Chiralcel OD-H column (flow rate: 1.0 mL min$^{-1}$, 3 % isopropyl alcohol in hexane).

functionalised olefins (Table 1, Entry 1). All the MgO samples were then treated with $Mn(acac)_3$ to afford samples of $Mn(acac)_n$-MgO.

The ion exchange capability of NAP-MgO is well established.[13] The exchange capability of $Mn(acac)_3$ on the various MgO supports showed that the maximum amount of $Mn(acac)_n$ is loaded on NAP-MgO, when compared to the other MgO samples, which is attributed to the presence of large surface ionic charges on NAP-MgO. In the process of optimisation of the AE reaction, we explored the various MgO samples (Table 1) using different oxidants (Table 2). Among the MgO samples screened for the AE reaction, the $Mn(acac)_n$-NAP-MgO using TBHP as oxidant was found to be superior over NA-MgO and CM-MgO in terms of both yields and *ee*s. The *ee*s of the AE product, styrene oxide, are 42 %, 0 % and 0 % using the $Mn(acac)_n$-NAP-MgO, $Mn(acac)_n$-NA-MgO and assorted crystals of $Mn(acac)_n$-CM-MgO, respectively (Table 1). The AE reactions catalysed by $Mn(acac)_n$-NAP-MgO conducted in THF using 6-cyanochromene, indene, styrene and 4-methylstyrene gave the chiral epoxides in good yields and *ee*s (Table 3).

The catalyst was recycled for three times. The decrease in yield in the recycling experiments is due to Mn leaching into solution from the support during the reaction as confirmed by AAS (Table 4). The catalyst was recovered by filtration, while the chiral ligand

**Table 2.** Effect of oxidant in the asymmetric epoxidation of styrene[a] at −20 °C.

| Entry | Oxidants | Time [h] | Yield [%][b] | ee [%][c] |
|---|---|---|---|---|
| 1 | TBHP | 24 | 70 | 42 |
| 2 | *m*-CPBA | 15 | 90 | 0 |
| 3 | NaOCl (aqueous) | 24 | 0 | 0 |
| 4 | $H_2O_2$ (aqueous) | 24 | 0 | 0 |

[a] *Reaction conditions:* olefin (1 mmol), dry THF (3 mL), TBHP (1 mL, 3.5 mmol), catalyst (0.100 g), chiral ligand (DAC) (0.025 g).
[b] Yields based on $^1$H NMR.
[c] The *ee* was determined by HPLC using a Diacel Chiralcel OD-H column (flow rate: 1.0 mL min$^{-1}$, 3 % isopropyl alcohol in hexane).

**Table 3.** Asymmetric epoxidation of unfunctionalised alkenes with $Mn(acac)_n$-NAP-MgO at −20 °C.

| Entry | Substrate | Time [h] | Yield [%][a] | ee [%][c] |
|---|---|---|---|---|
| 1 | Styrene | 24 | 70, 55[b] | 42, 41[b] |
| 2 | 4-Methylstyrene | 24 | 78 | 40 |
| 3 | *trans*-Stilbene | 24 | 66 | 24 |
| 4 | 6-Cyanochromene | 18 | 90 | 91 |
| 5 | Indene | 18 | 85 | 84 |

[a] Yields based on $^1$H NMR.
[b] 3$^{rd}$ cycle.
[c] The *ee* values were determined by HPLC using a Diacel Chiralcel OD-H column (flow rate: 1.0 mL min$^{-1}$, 3 % isopropyl alcohol in hexane).

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**Table 4.** Reusability of $Mn(acac)_n$-MgO catalyst in asymmetric epoxidation of styrene at −20 °C.[a]

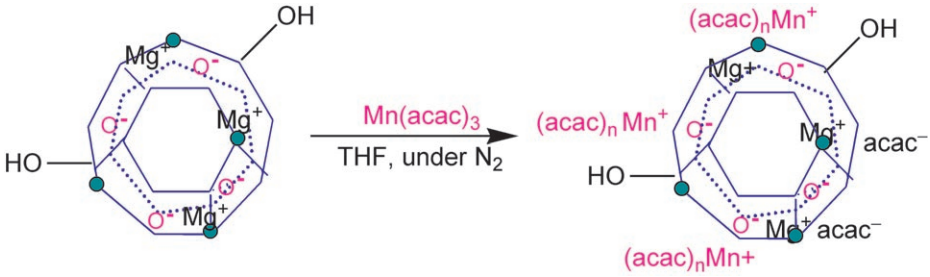
| Entry | Cycle | Mn content in the catalyst [mmol/g][b] | Yield [%][c] | ee [%][d] |
|---|---|---|---|---|
| 1 | 1 | 0.369 | 70 | 42 |
| 2 | 2 | 0.332 | 66 | 42 |
| 3 | 3 | 0.258 | 55 | 41 |

[a] *Reaction conditions:* olefin (1 mmol), dry THF (3 mL), TBHP (1 mL, 3.5 mmol), catalyst (0.100 g), chiral ligand (DAC) (0.025 g).
[b] Mn content determined by AAS analysis.
[c] Yields based on $^1$H NMR.
[d] The *ee* values were determined by HPLC using a Diacel Chiralcel OD-H column (flow rate: 1.0 mL min$^{-1}$, 3% isopropyl alcohol in hexane).

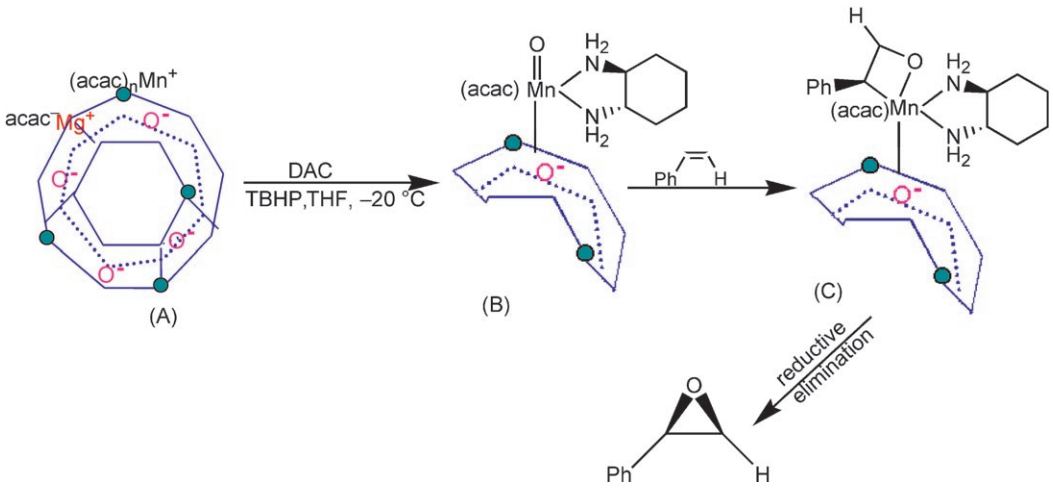
was recovered by column chromatography. When the reaction was conducted with the obtained filtrate, no product formation was observed. This result infers that the Mn leached into solution is inactive in the reaction and that the Mn complex bound to MgO is the only active species in this reaction.

To understand the relation between structure and reactivity in AE, it is essential to know the structure and nature of the reactive sites of NAP-MgO. NAP-MgO has a three-dimensional polyhedral structure, showing the presence of high surface concentrations of edge/corner and various exposed crystal planes (such as 002, 001, 111), which leads to inherently high surface ionic charges per unit area. The presence of corner and edge sites on the surface of NAP-MgO could approach 20%, while on NA-MgO they amount to less than 0.5% and on CM-MgO essentially 0%. For example, an edge or even more a corner O anion is coordinatively unsaturated and seeks Lewis acids to help stabilise and delocalise its positive charge. Conversely, an $Mg^{2+}$ ion on an edge or corner seeks Lewis bases (acac) to stabilise and delocalise its positive charge (Scheme 2).

Therefore, these coordinatively unsaturated $O^-$ and $Mg^{2+}$ ions readily accept incoming Lewis acids and Lewis bases, respectively. Thus, $Mn(acac)_n$-NAP-MgO




**Scheme 2.** Preparation of the $Mn(acac)_n$-NAP-MgO catalyst.




**Scheme 3.** Proposed mechanism for the $Mn(acac)_n$-NAP-MgO-catalysed asymmetric epoxidation of olefins.

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did indeed display the highest activity compared to NA-MgO and CM-MgO. Conversely, the $MnO_2$-NAP-MgO formed by calcination of $Mn(acac)_n$-NAP-MgO is inactive for this epoxidation reaction. This may be due to a disturbance of the molecular chemistry. In the proposed mechanism for the epoxidation of olefins such as styrene, the Mn(III) on nanomagnesium oxide(A) is complexed with a chiral DAC ligand and subsequently oxidised to form a metal-oxo [Mn(IV)=O] (B) species with the oxidant, *t*-BuOOH (Scheme 3); this is indicated by XPS analysis (see Fig. 10 in the Supporting Information). Mn(IV) is indeed found as an active species in Jacobsen–Katsuki catalytic epoxidations.[14] The complex (B) thus generated transfer oxygen to the interactive olefin in a selected path to give the intermediate (C) which, on reductive elimination, affords the chiral epoxide. The high facial selectivity of the complex is due to its surface chemical properties.[15] The very good result for the enantioselectivities is significant using the simple chiral auxiliary (1*R*,2*R*)-(−)-diaminocyclohexane as a chiral ligand, specially designed for directing a prochiral olefin unidirectionally to metal centre-supported nanocrystalline magnesium oxide, in the place of the widely used chiral salen ligand,[2,3] to facilitate the formation of chiral epoxides.[9a,b] Similarly, the proper alignment of $Mn^{IV}$ complex (B) supported on three-dimensional nanocrystalline magnesium oxide with the unfunctionalised olefin allowed the unidirectional delivery of oxygen to afford the chiral epoxide.[9a]

In conclusion, $Mn(acac)_n$-NAP-MgO has been used as a catalyst for the asymmetric epoxidation of unfunctionalised olefins. The nanomaterials with their three-dimensional structure and defined size and shape as supports for metal complexes have been demonstrated to be suitable candidates for proper alignment with prochiral substrates for the unidirectional introduction of the reacting species to induce an asymmetric centre.

## Experimental Section

### General Remarks

Nanocrystalline MgO samples were obtained from Nano-Scale Materials Inc., Manhattan, Kansas, USA. All chemicals were purchased from Aldrich and used as received. All solvents were purchased as analytical grade and used as received from Merck India Pvt. Ltd. Dry THF was used for all reactions. Commercial column chromatography grade silica gel (100–200 mesh) was used. All reactions were conducted at −20 °C in dry THF under a nitrogen atmosphere. The $^1$H NMR spectra of the samples were recorded on Varian-Unity 400 MHz, and Bruker Avance 300 MHz spectrometers using TMS as an internal standard in $CDCl_3$. IR spectra were recorded on a Perkin–Elmer instrument. All the liquid secondary ion mass spectromertric (LSIMS) experiments were carried out using an Autospec M (Micromass, Manchester, UK) mass spectrometer of EBE geometry, equipped with an OPUS V3.1X data system. Ionisation was effected by a 2.2 mA primary beam of caesium ions accelerated to 25 keV and the ion source was operated at an acceleration voltage of 8 kV. High performance liquid chromatography (HPLC) was performed using an AGILENT-1100 series liquid chromatograph equipped with a single pump and UV detector (fixed at 216 nm) using a CHIRACEL-OD-H capillary column with isopropyl alcohol/hexane as eluting agent. For these studies, all reaction products were taken as column purified. Optical rotations were obtained on an automated JASCO P-1020 Polarimeter, and the values are reported in absolute reactions: $[\alpha]_D^{temperature}$ [concentration $c$ = g/100 mL of solvent].

### Preparation of $Mn(acac)_n$-NAP-MgO

The MgO samples were heated under vacuum at 500 °C before use. $Mn(acac)_n$-NAP-MgO was prepared by treating vacuum-dried NAP MgO (1.0 g) with $Mn(acac)_3$ ( 0.200 g) in THF (8 mL) under a nitrogen atmosphere at room temperature with stirring for 24 h by a method similar to that reported by Klabunde and co-workers.[15] Then the slurry was filtered off, washed with THF and vacuum dried to give $Mn(acac)_n$-NAP-MgO; yield: 1.105 g, with a brownish colour. The IR spectrum shows evidence for the adsorbed $Mn(acac)_n$ moiety. The Mn content in $Mn(acac)_n$-NAP-MgO was found to be 0.369 mmol $g^{-1}$ by atomic absorption spectroscopy (AAS).

### General Procedure for the Epoxidation of Olefins under Heterogeneous Conditions

A mixture of styrene (1 mmol, 0.104 g), TBHP (1 mL, 3.5 mmol), catalyst (0.100 g), chiral ligand (DAC) (0.025 g) in dry THF (3 mL) was stirred at −20 °C for the appropriate time (Entry 1, Table 3) under a nitrogen atmosphere. After completion of the reaction as indicated by TLC, the reaction mixture was centrifuged to separate the catalyst and the catalyst was reused after vacuum drying for another cycle. The reaction mixture was concentrated under reduced pressure to afford the crude product and the resulting product was purified by column chromatography on silica gel with ethyl acetate and *n*-hexane as eluent.

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