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Mechanism of One Oxygen Atom Transfer from Oxo (Salen)manganese(V) Complex to Olefins

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Abstract: In the Mn-salen catalyzed asymmetric epoxidation of some olefins, non-linear relationship between reaction temperature and enantioselectivity was observed. For example, the epoxidation of 1,3-cycloalkadiene with complex **3a** as a catalyst showed the maximum enantioselectivity at 0 °C. It was also found that the electronic nature of the aromatic substituent in the salen ligand affects enantioselectivity but its effect does not necessarily correspond to the Hammet's σ-values. Based on these new experimental results, we propose a reaction mechanism which proceeds through metallaoxetane intermediate, for one oxygen atom transfer reaction from oxo (salen)manganese(V) complex to olefins.

Introduction of well-designed (salen)manganese(III) catalysts (hereafter, referred to as Mn-salen catalysts) enabled remarkably high level of enantioface selection in the epoxidation of simple olefins.[1,2,3] To explain the stereochemistry observed in Mn-salen catalyzed epoxidation, several hypotheses on the mechanism of asymmetric induction have been proposed.[1] However, the detailed mechanism of one oxygen atom transfer from the intermediary oxo Mn-salen species to olefins is still uncertain. In this paper, we propose a new reaction pathway via metallaoxetane and radical intermediates for the Mn-salen catalyzed oxygen transfer process, based upon non-linear relationship between reaction temperature and enantioselectivity and upon an unusual effect of the substituent of salen ligand on enantioselectivity.

In 1985, Kochi *et al.* first isolated oxo Cr-salen complex (**1**) and its adduct with pyridine *N*-oxide as the axial ligand and determined their structures by X-ray analysis to have roughly square pyramidal and octahedral coordinations in which the chromium atoms are displaced 0.53 and 0.26 Å above the mean salen plane, respectively (Fig. 1). They also showed that these oxo Cr-salen complexes transferred one oxygen atom to olefins to give epoxides.[4] Although oxo Mn-salen complex has not been isolated, it has been postulated as an active species to transfer one oxygen atom by way of a radical intermediate (**2**) in Mn-salen catalyzed epoxidation, also by Kochi *et al.* (Scheme 1).[5] The intermediacy of radical species was also supported from the study on asymmetric epoxidation using optically active Mn-salen catalysts by us[6] and later by Jacobsen *et al.*[7]

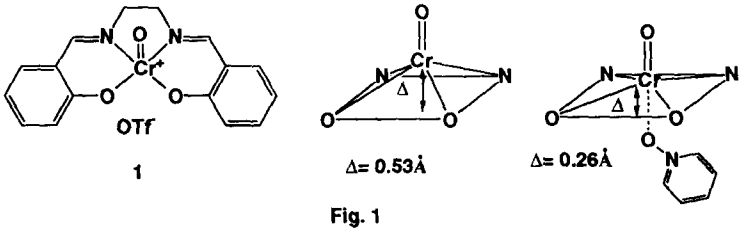
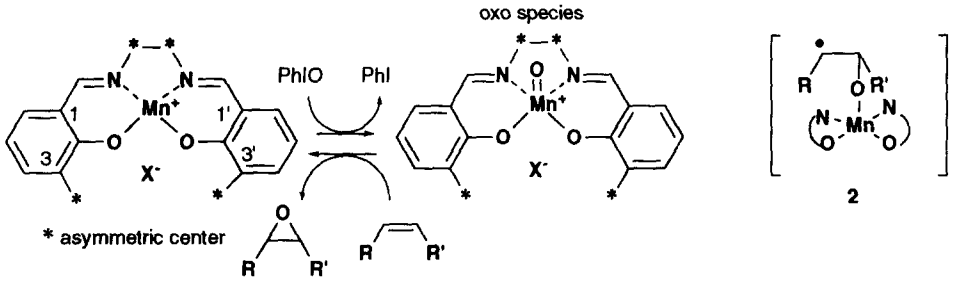


Fig. 1

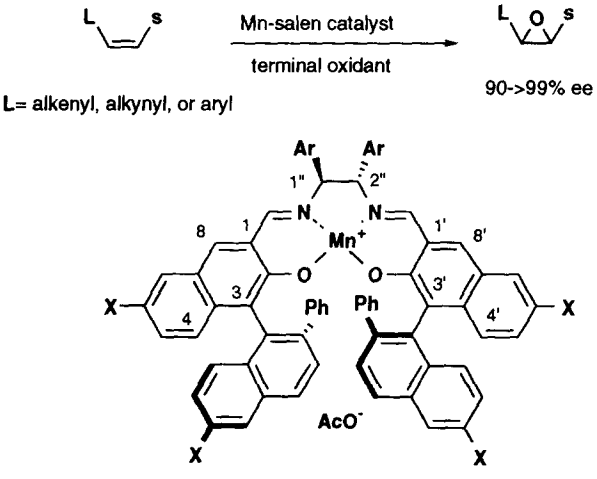
† This paper is dedicated to Professor Emeritus Masaru Yamaguchi on the occasion of his 70th birthday.



Scheme 1

Non-linear relationship between reaction temperature and enantioselectivity

In the course of our study on asymmetric epoxidation by using Mn-salen catalysts bearing chiral elements both at ethylenediamine part and at C3- and C3'-substituents, we have proposed that olefins approach parallel to salen ligand, orienting their sterically bulky and π-electron rich substituent away from C3' substituent on the salen ligand to minimize steric and π-electronic repulsions between the salen ligand and the olefinic substituent.[8] Based on this proposal, we synthesized an efficient Mn-salen catalyst (**3a**) for the asymmetric epoxidation of simple olefins (Scheme 2).[2] Catalyst **3a** shows remarkably high enantioselectivity in the epoxidation of conjugated *cis*-di- and trisubstituted olefins, but the epoxidation of 1,3-cycloalkadienes and dialkylsubstituted olefins shows diminished enantioselectivity probably due to reduced or no π-electronic repulsion between the salen ligand and the substrates.[8b] To improve the enantioselectivity in the epoxidation of this class of substrates, we examined the epoxidation at lower temperature and found that enantioselectivity was in general improved as the reaction temperature was depressed.[9] However, the epoxidation of 1,3-cyclooctadiene showed maximum enantioselectivity of 72.1% ee at 0 °C, when acetonitrile was used as the solvent.

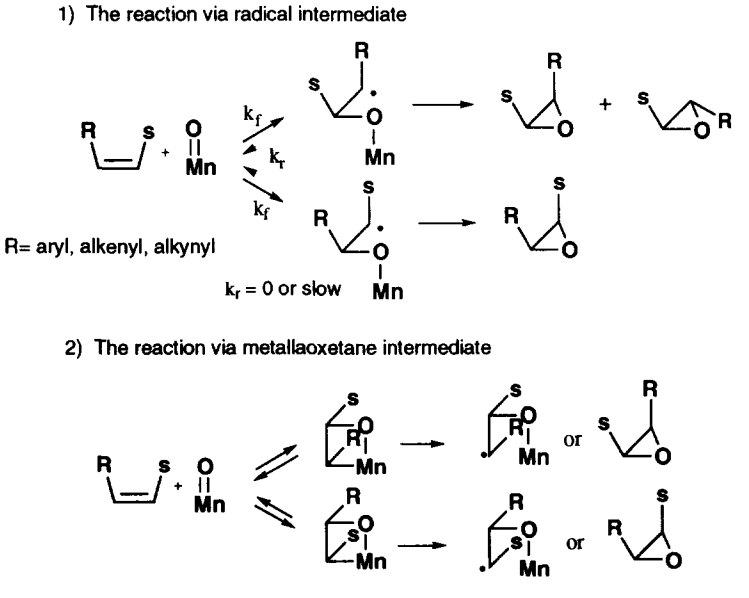


3a: Ar= 3,5-$(CH_3)_2C_6H_3$, X= H
3b: Ar= 3,5-$(CH_3)_2C_6H_3$, X= OMe

Scheme 2

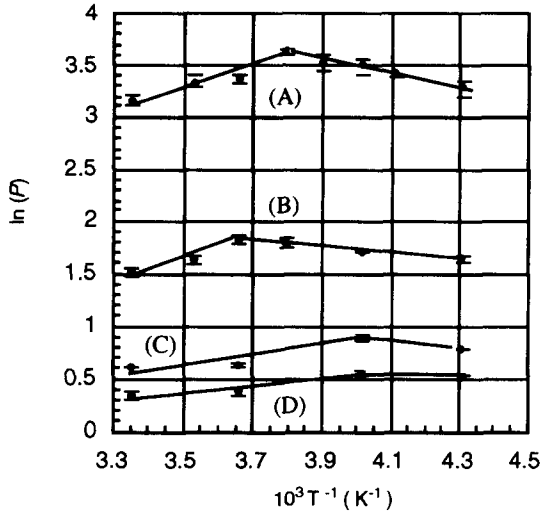
The measurement of the temperature dependence of the enantioselectivity has been demonstrated to be a good probe for investigating the mechanism of the enantioselective reaction by Scharf *et al.*[10] and recently Sharpless *et al.* revealed that the asymmetric dihydroxylation using chirally modified osmium tetroxide as a catalyst proceeds through metallaoxetane intermediate by analyzing the relationship between reaction temperature and enantioselectivity.[11] This study gave a conclusion to a long standing controversy on the mechanism of asymmetric dihydroxylation. These reports and our new findings described above prompted us to further examine about the effect of reaction temperature on enantioselectivity in Mn-salen catalyzed epoxidation.

Fortunately, we could find that epoxidation of some other substrates such as dihydronaphthalene and styrene also showed non-linear relationship between reaction temperature and enantioselectivity. The results obtained are shown in Fig. 2, wherein ln(P) is plotted against 1/T. According to Scharf, the reaction which involves reversible formation of diastereomeric intermediates and irreversible transformation of the intermediates to product or another intermediate has a possibility to show non-linear relationship between reaction temperature and enantioselectivity.[10] At this stage, two possibilities, the reaction via a radical intermediate and the reaction via a metallaoxetane intermediate, occurred to us (Scheme 3).[12] However, the radical intermediate in Mn-salen catalyzed epoxidation is considered to be a long-lived species when R in **2** is aryl, alkenyl, or alkynyl group and actually *cis-trans* isomerization is observed in the epoxidation of this class of substrates since rotation around carbon-carbon single bond is permitted due to a long life of the radical intermediate.[6,7] This strongly suggests that radical formation step is irreversible or its reversed reaction is slow. Therefore, our new data suggests the presence of another intermediate. Assumption of the mediacy of metallaoxetane[11b] meets this criterion. Despite this description, it should be pointed out that we could not exclude the possibility that the reversible isomerization between the conformational isomers of the radical intermediate in the epoxidation of styrene or *p*-niterostyrene, is responsible for non-linear relationship between



Scheme 3

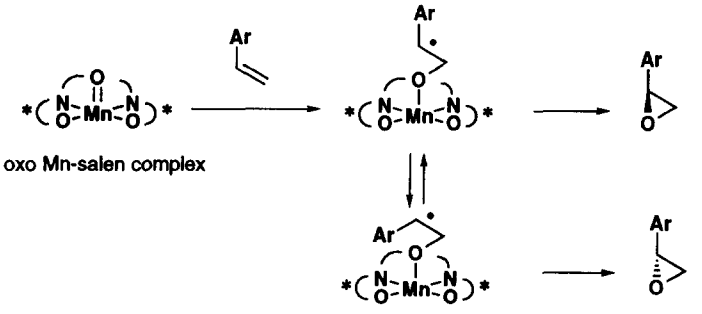
reaction temperature and enantioselectivity (Scheme 4). However, there is no possibility like this in the epoxidation of dihydronaphthelene and cyclooctadiene, wherein isomerization of the radical intermediate is impossible.



$$\ln(P) = -\frac{\Delta\Delta H^{\neq}}{RT} + \frac{\Delta\Delta S^{\neq}}{R}$$

$$P = \frac{l\ (\text{major enantiomer of epoxide})}{l\ (\text{minor enantiomer of epoxide})}$$

Fig. 2. Temperature dependence of enantioselectivity in the epoxidation with **3a** as a catalyst. The reaction was carried out in acetonitrile in the presence of pyridine *N*-oxide. The enantioselectivity of the obtained epoxides was determined by HPLC or GLC analysis using optically active column or by ^{1}H NMR analysis using chiral shift reagent (see experimental section). The lines (A, B, C, and D) stand for dihydronaphthalene, cyclooctadiene, *p*-nitrostyrene, and styrene, respectively. The average ln(*P*) value at each mesurement point is marked with a black dot. The bars above and below the dot mean the obtained highest and lowest values of ln(*P*), respectively.



Scheme 4

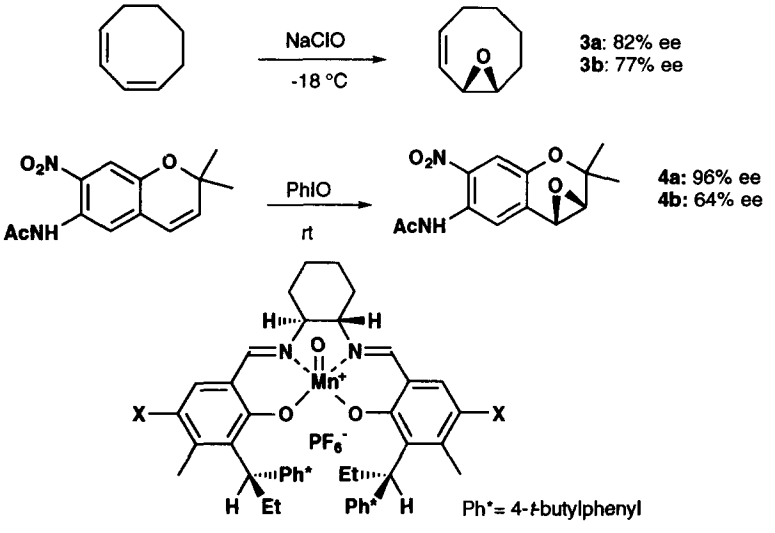
Donor ligand effect on the reaction rate

It has already been reported that the addition of donor ligand improves the chemical yield of epoxides[5] and influences on the enantioselectivity[13] in Mn-salen catalyzed epoxidation. However, no

detailed study about the effect of donor ligand on epoxidation rate has been reported. Thus we next investigated the effect of donor ligand and found that the addition of donor ligand did not accelerate the rate. Epoxidation of dihydronaphthalene with **3a**, for example, proceeds at an equal rate in the presence or absence of pyridine *N*-oxide and that of *trans*-stilbene with **4a** was retarded by the addition of the same ligand ($k_{ligand}/k_{no\ ligand}$ = 0.2). The improvement of chemical yield by the addition of donor ligand is probably attributed to the reduction of Lewis acidity of oxo Mn-salen complex[14] which decomposes the resulting epoxide in the absence of donor ligand. The deceleration observed in the epoxidation of *trans*-stilbene is probably due to the increase of steric repulsion between the salen ligand and the downward phenyl substituent on the substrate, because the manganese ion is considered to be pulled back to the salen plane by the addition of donor ligand.[4] These results suggest that donor ligand does not play a crucial role in the determination of the reaction pathway of Mn-salen catalyzed epoxidation.

Substituent effect on enantioselectivity

Jacobsen *et al.* have reported that the electronic nature of C5- and C5'-substituents of Mn-salen complex influences enantioselectivity: the complex with an electron donating group exhibits higher asymmetric induction than that with an electron withdrawing group and this electronic effect of substituents corresponds well to the σ values.[15] However, this is not always true (Scheme 5). We found that complex **3b** having electron donating methoxy group showed a slightly diminished enantioselectivity in the epoxidation of 1,3-cyclooctadiene as compared with complex **3a** (**3a**: 82% ee, **3b**: 77% ee).[9] Complex **4b**[16] also showed lower asymmetric induction in the epoxidation of 6-acetamido-2,2-dimethyl-7-nitrochromene than complex **4a** (**4a**: 96% ee, **4b**: 64% ee).[17] The electronic nature of the substituent affects the reactivity of oxo species and, therefore, influences enantioselectivity in metallaoxetane formation. However, cleavage of metallaoxetane ring is controlled by other factors such as steric effect and the ability of radical stabilization of the olefinic

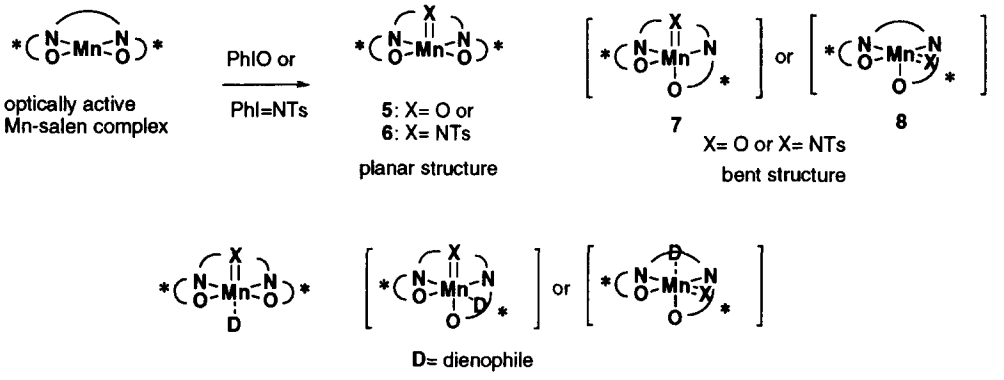


Scheme 5

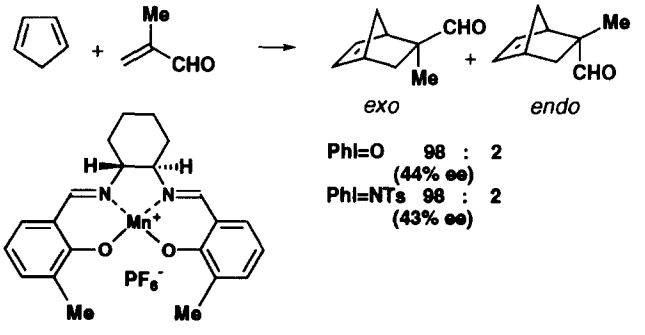
substituent (*vide infra*). Thus, the electronic effect of substituents does not necessarily correspond to the σ-values, if metallaoxetane intermediate is involved in Mn-salen catalyzed epoxidation.

The structure of oxo (salen)manganese(V) species

As described above, the salen ligand in oxo Cr-salen complex has been reported to coordinate chromium ion in square planar geometry. The salen ligand of oxo Cr-salen pyridine *N*-oxide adduct coordinates also in square planar geometry.[4] Although oxo Mn-salen complex has never been isolated, we believe that its salen ligand coordinates manganese ion also in square planar geometry, from the following reason. Treatment of Mn-salen complex by iodosylbenzene or TsN=IPh has been considered to give the corresponding oxo or nitrene complexes (**5** and **6**),[18] respectively (Scheme 6). We found that these species (**5** and **6**) served as Lewis acid catalysts for asymmetric Diels-Alder reaction.[14] If the salen ligand in **5** or **6** coordinates manganese ion in square planar geometry, dienophile must coordinate at the axial site on the face opposite to the ligand **X**, so that the effect of the ligand **X** on enantioselectivity should be small in this case. On the other hand, if the salen ligand takes a bent structure (**7** or **8**), dienophile must coordinate *cis* to the ligand **X** and the ligand **X** should have a strong influence on enantioselectivity. However, Diels-Alder reactions catalyzed by oxo and nitrene Mn-salen complexes were found to show the same level of asymmetric induction as well as the same *exo/endo* ratio, as shown in Scheme 6.[14] This strongly suggests that dienophile coordinates *trans* to the ligand **X** and that the salen ligand coordinates manganese ion in square planar geometry.



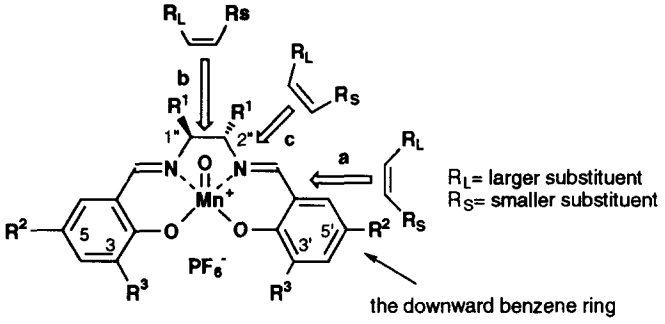
Asymmetric Diels-Alder reaction



Scheme 6

The approaching pathway of the incoming olefin

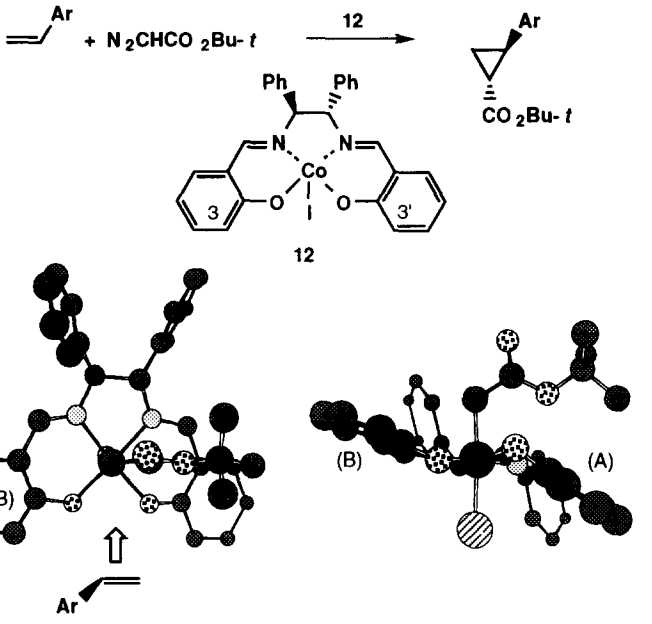
We also considered about the approaching pathway of olefins to oxo Mn-salen species (Fig. 3). So far three pathways (**a**, **b**, and **c**) have been proposed for the olefin's approach to oxo Mn-salen species.[1] Early Mn-salen catalysts (**9**[6] and **10**[19]) were synthesized by assuming that olefins approach along the pathway **a**. Later, another pathway **b** was proposed for the epoxidation with complex **11** as a catalyst,[20] wherein the pathway **a** was considered to be disfavored by the presence of 5 and 5'-*t*-butyl groups, since oxo Mn-salen complex was assumed to have a plane structure.[21] However, the pathway **b** can not give reasonable explanation on the fact that the chirality at C3- and C3'-substituents affects asymmetric induction to a considerable extent. Thus another pathway **c** was proposed to rationalize all the stereochemistry observed in Mn-salen catalyzed epoxidation.[8]



9: R^1= Ph, R^2= H, R^3= (*S*)-phenylpropyl
10: R^1= Ph, R^2= H, R^3= *t*-butyl
11: R^1= -$(CH_2)_4$-, R^2,R^3= *t*-butyl

Fig. 3 The oxo Mn-salen complexes derived from the corresponding Mn-salen complexes (**9**, **10**, and **11**) and the proposed pathway for olefin's access

This proposal **c** is also based on the assumption that Mn-salen complex has a plane structure. However, our recent finding cast a question about the planarity of the structure of oxo Mn-salen complex. Co-salen complex (**12**) which has no C3- and C3'-substituent, serves as a catalyst for asymmetric cyclopropanation. To be surprised, the sense of enantioface selection induced by **12** was opposite to the sense of enantioface selection observed in the epoxidation with Mn-salen catalyst **10** (Scheme 7).[22] This unusual stereochemistry was rationalized by assuming that carbene Co(V)-salen complex has a non-plane structure in which one benzene ring (**A**) was folded downward and another benzene ring (**B**) upward and that the carbenoid ester group orients toward the benzene ring (**A**) blocking the pathway **a**. Accordingly, olefins approach carbene Co(V)-salen complex from its phenolic oxygen side. That carbene Co(V)-salen complex has a folded structure was supported by calculation with TRIPOS-SYBYL on an IRIS Indigo. Although there is no experimental information about the detailed structure of oxo Mn-salen complex, it seems reasonable to assume that the salen ligand coordinates manganese ion in square planar geometry and has a folded form also in the oxo Mn-salen complex. This assumption was also supported by calculation with TRIPOS-SYBYL on an IRIS Indigo (Fig. 4). If oxo Mn-salen complex takes a folded form, we can not exclude the possibility that olefins approach along the pathway **a** any more, because 5'-*t*-butyl group on a downward benzene ring can not block the



The top and side views of carbene Co(V)-salen complex

Scheme 7

pathway (Fig. 3). It should be also mentioned that the orientation of the incoming olefin on either pathway **a** or **c** is considered to be controlled by steric and π-electronic repulsions between the salen ligand and the olefinic substituent. Quite recently, while we were preparing this manuscript, it was reported that the salen ligand in

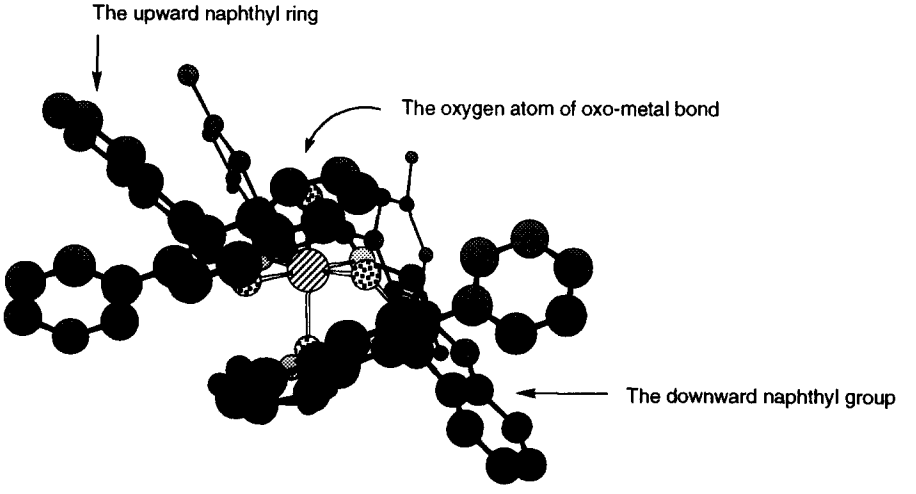


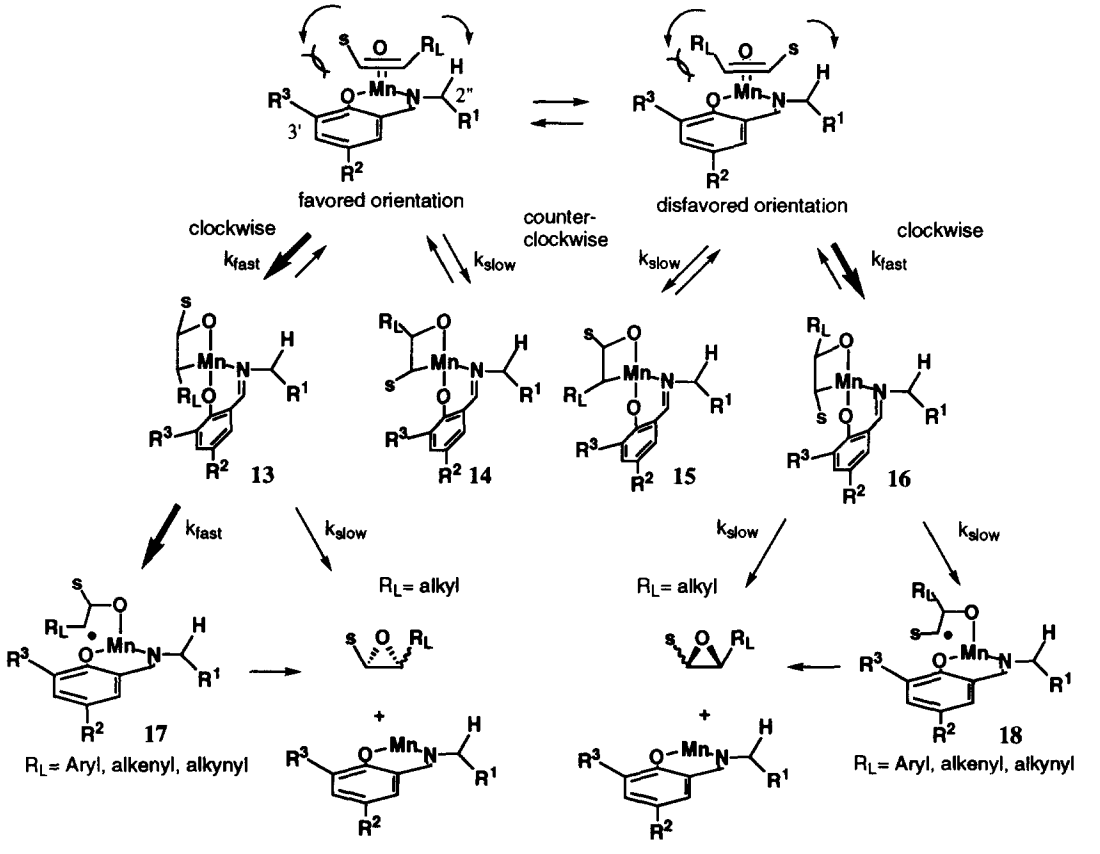
Fig. 4 The side view of oxo (salen)manganese(V)-pyridine *N*-oxide adduct derived from complex **3a**

cationic Al-salen$(H_2O)_2$ complex coordinates in aluminum ion in square planar geometry and has a folded structure.[23]

The mechanism of one oxygen atom transfer from oxo Mn-salen complex to olefins

Based on these experimental data and considerations described above, we propose a new mechanism for one oxygen atom transfer from oxo Mn-salen complex to olefins in Mn-salen catalyzed epoxidation (Scheme 8).

Olefins approach oxo-metal bond from its side probably along the pathway **a** with the orientation keeping their bulky and π-electron rich substituent away from C3' substituent to minimize the steric and π-electronic repulsion.[8b] Though coordination of the incoming olefin to metal ion followed by oxygen atom insertion with its rotation may provide four possible metallaoxetane intermediates (**13**, **14**, **15**, and **16**),[11] the intermediate **13** derived from the olefin with favored orientation is considered to be formed the most preferentially, because counter-clockwise rotation leading **14** causes steric repulsion between olefinic substituent and C3'-substituent. The formation of **15** and **16** requires the approach of the olefin with unfavorable orientation and, therefore, should be disfavored. The salen ligand in the resulting metallaoxetane intermediates takes a bent form in



Scheme 8 The oxo Mn-salen complex is viewed from the downward benzene side (see, Fig. 3) and its backhalf is omitted for clarification. Donor ligand attached to Mn-salen and oxo Mn-salen complexes are also omitted for clarification.

which one of the phenolic oxygen atom coordinates at axial site, since the oxygen and carbon atoms of the metallaoxetane coordinate at axial and equatorial coordination site, respectively. However, that the salen ligand takes a bent form is considered to be justifiable, because most of the salen ligands in Cr-, Fe-, and Co-salen complexes having a divalent ligand such as oxalate or acetylacetonate take a bent form.[24] Metallaoxetane intermediates bearing a radical stabilizing group on the carbon proximal to manganese ion rapidly collapses to the radical intermediate, while metallaoxetanes bearing alkyl group at the carbon proximal to manganese ion is slowly transformed into epoxides. This assumption is supported by the fact that epoxidation of *cis*-β-methylstyrene gives a mixture of *cis*- and *trans*-epoxides,[20] while epoxidation of *cis*-1-cyclohexyl-1-propene gives the corresponding *cis*-epoxide exclusively.[8b,9] It has also been reported that radical intermediate is not involved in the epoxidation of alkyl-substituted olefins.[25] Furthermore, epoxidation of alkyl-substituted olefins is much slower as compared with the epoxidation of conjugated olefins.[9] Thus intermediate **13** is readily converted into radical intermediate **17**, when R_L is a radical stabilizing group such as aryl or alkynyl group. On the other hand, the transformation of **16** into **18** is slow. Since the metallaoxetane formation is reversible,[11] the enantioface selection of olefins performed in their approaching process is further enhanced through this selective metallaoxetane cleavage process. Accordingly, olefins conjugated with aryl, alkenyl, or alkynyl group show high enantioselectivity, while olefins bearing only alkyl substituents show moderate enantioselectivity.[1]

In conclusion, we proposed a new reaction mechanism for Mn-salen catalyzed epoxidation, which includes reversible metallaoxetane formation and irreversible metallaoxetane cleavage. This new reaction mechanism gives a reasonable explanation to the stereochemistry observed in Mn-salen catalyzed epoxidation.

Experimental

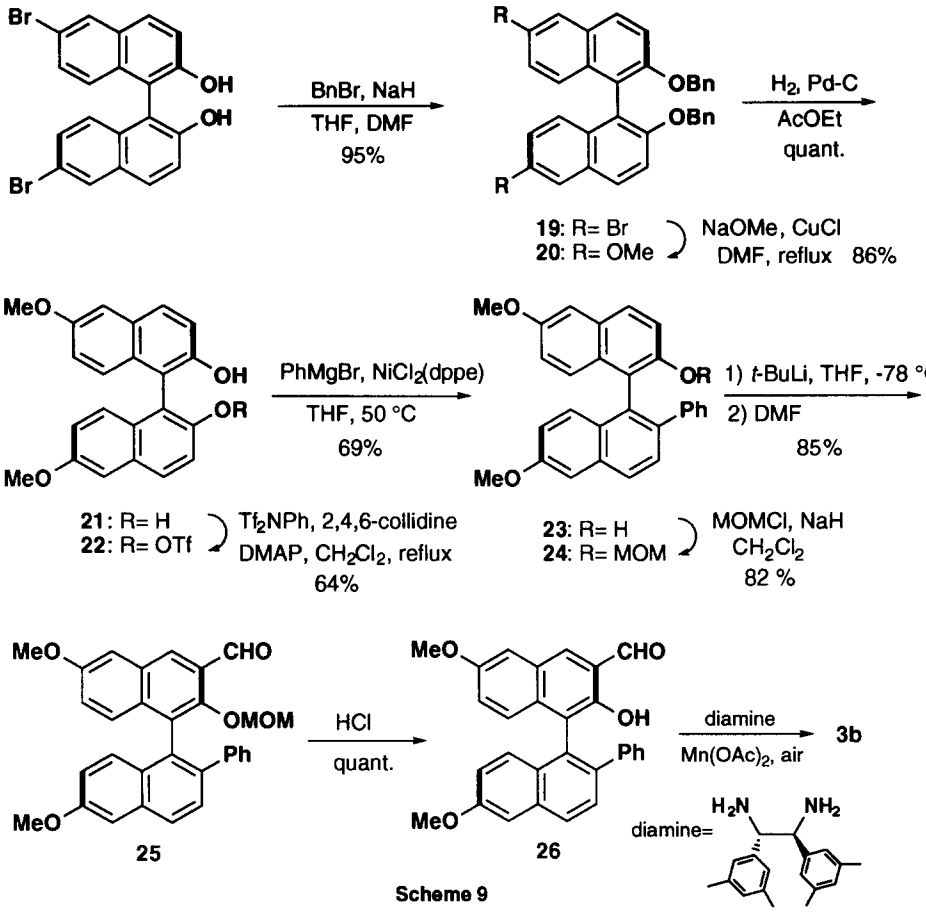
^{1}H NMR spectra were recorded at 400 MHz on a JEOL GX-400, or at 270 MHz on a JEOL EX-270 instrument. All signals were expressed as ppm down field from tetramethylsilane used as an internal standard (δ-value in $CDCl_3$). IR spectra were obtained with a JASCO IR-700 instrument. High resolution mass spectra were recorded on a JEOL JMS-SX/SX 102A instrument. FAB mass spectra were obtained by using *m*-nitrobenzyl alcohol as a matrix. Optical rotation was measured with a JASCO DIP-360 automatic digital polarimeter. Column chromatography was conducted on Silica Gel 60, 70-230 mesh ASTM, available from E. Merck. Preparative thin layer chromatography was performed on 0.5 mm x 20 cm x 20 cm E. Merck silica gel plate (60 F-254). The reaction temperature was controlled with EYELA COOL ECS 50. Solvents were dried and distilled shortly before use. Reactions were carried out under an atmosphere of nitrogen if necessary. The proposed carbene Co(V)- and oxo Mn(V)-salen complex models were optimized using TRIPOS SYBYL program on an IRIS Indigo2.

Preparation of new Mn-salen complex 3b

Complex **3b** was prepared from commercially available (a*R*)-6,6'-dibromo-2,2'-dihydroxy-1,1'-binaphthol (Scheme 9).

(a*R*)-2,2'-Dibenzyloxy-6,6'-dibromo-1,1'-binaphthyl (19)

To a solution of sodium hydride (60% dispersion in mineral oil, 84.4 mg, 3.52 mmol) in THF (5.0 ml) was added (a*R*)-6,6'-dibromo-2,2'-dihydroxy-1,1'-binaphthol (937 mg, 2.11 mmol) in THF (17 ml) and *N,N*-



Scheme 9

dimethylformamide (22 ml) at 0 °C. After the mixture was stirred for 1 h at the same temperature, benzyl bromide (0.6 ml, 5.0 mmol) was added and the reaction mixture was stirred overnight. The reaction mixture was quenched with brine, extracted with ethyl acetate, washed with H_2O, dried over $MgSO_4$, and concentrated *in vacuo*. The residue was purified by column chromatography (SiO_2, hexane/ethyl acetate= 30/1 to 8/2) to give **19** (1.26 g, 95%) as colorless crystals. mp. 114 °C. $[\alpha]_D^{26}$ +28.5° (*c* 1.62, $CHCl_3$). ^1H NMR (270 MHz): δ 8.02 (d, *J*= 2.0 Hz, 2H), 7.83, (d, *J*= 8.9 Hz, 2H), 7.42 (d, *J*= 9.2 Hz, 2H), 7.29 (d, *J*= 2.0 Hz, 1H), 7.18-7.10 (m, 7H), 7.09-6.93 (m, 6H), 5.04 (s, 4H). IR (KBr): 3440, 3027, 2873, 2360, 1583, 1493, 1452, 1327, 1267, 1225, 1067, 1028, 910, 877, 800, 735, 696 cm^{-1} Anal. Calc. for $C_{34}H_{24}O_2Br_2$: C, 65.41; H, 3.87. Found: C, 65.37; H, 3.93.

(a*R*)-2,2'-Dibenzyloxy-6,6'-dimethoxy-1,1'-binaphthyl (20)

To a solution of **19** (623 mg, 1.0 mmol) and CuCl (50 mg, 0.51 mmol) in *N,N*-dimethylformamide (10 ml) was added sodium methoxide (540 mg, 1.0 mmol) in methanol (10 ml) and the resulting mixture was refluxed for 10 h. The reaction mixture was quenched with H_2O, extracted with ethyl acetate, dried over $MgSO_4$, and concentrated *in vacuo*. The residue was purified by column chromatography (SiO_2,

hexane/toluene= 1/2 to 0/1) to give **20** (452 mg, 86%) as colorless crystals. mp. 90 °C. $[\alpha]_D^{25}$ +45.3° (*c* 1.05, $CHCl_3$). ^1H NMR (270 MHz): δ 7.79 (d, *J*= 8.9 Hz, 2H), 7.36, (d, *J*= 9.2 Hz, 2H), 7.17-7.06 (m, 10H), 6.99-6.89 (m, 6H), 4.98 (s, 4H), 3.89 (s, 6H). IR (KBr): 3427, 3061, 2833, 1626, 1595, 1504, 1454, 1375, 1348, 1236, 1167, 1126, 1090, 1028, 941, 849, 796, 735, 696, 459 cm^{-1} Anal. Calc. for $C_{36}H_{30}O_4$: C, 82.11; H, 5.74. Found: C, 81.91; H, 5.81.

(a*R*)-2,2'-Dihydroxy-6,6'-dimethoxy-1,1'-binaphthyl (21)

A mixture of **20** (452 mg, 0.86 mmol) and 10% Pd-C (45.2 mg) in ethyl acetate (4.0 ml) was placed under hydrogen and stirred for 24 h. The mixture was filtered through a pad of Celite and concentrated *in vacuo* to give **21** (298 mg, quant.) as colorless crystals. mp. 201 °C. $[\alpha]_D^{26}$ -50.1° (*c* 0.99, $CHCl_3$). ^1H NMR (270 MHz): δ 7.84 (d, *J*= 9.2 Hz, 2H), 7.34, (d, *J*= 8.9 Hz, 2H), 7.20 (d, *J*= 2.6 Hz, 2H), 7.07-6.95 (m, 4H), 4.92 (br s, 2H), 3.90 (s, 6H). IR (KBr): 3424, 2361, 1601, 1560, 1541, 1508, 1369, 1234, 1167, 1123, 1032, 949, 853, 824 cm^{-1} HRFABMS m/z. Calcd. for $C_{22}H_{18}O_4$: 346.1205. Found 346.1211 (M+).

(a*R*)-6,6'-Dimethoxy-2-hydroxy-2'-trifluoromethanesulfonyloxy-1,1'-binaphthyl (22)

To a solution of **21** (80 mg, 0.23 mmol) in CH_2Cl_2 (1.9 ml) was added 2,4,6-collidine (31 μl, 0.23 mmol), 4-(*N*,*N*-dimethylamino)pyridine (cat. amount), and Tf_2NPh (83 mg, 0.23 mmol) and the resulting mixture was refluxed overnight. The mixture was cooled and then concentrated *in vacuo*. The residue was purified by column chromatography (SiO_2, toluene/ethyl acetate= 20/1) to give **22** (70 mg, 64%). Compound **22** was unstable and immediately used for the next reaction. ^1H NMR (270 MHz): δ 7.97 (d, *J*= 8.9 Hz, 1H), 7.84, (d, *J*= 9.2 Hz, 1H), 7.53 (d, *J*= 8.9 Hz, 1H), 7.38-7.25 (m, 3H), 7.19 (d, *J*= 2.3 Hz, 1H), 7.08 (dd, *J*=2.6 and 2.6 Hz, 1H), 6.98-6.89 (m, 2H), 4.84 (br s, 1H), 3.90 (s, 3H), 3.89 (s, 3H). IR (KBr): 3451, 2932, 2837, 2384, 1624, 1603, 1508, 1418, 1377, 1348, 1171, 1140, 1124, 1070, 1032, 945, 851, 746, 617, 592, 505 cm^{-1}. HRFABMS m/z. Calcd. for $C_{23}H_{17}O_6F_3S$: 478.0698. Found 478.0698 (M+).

(a*R*)-6,6'-Dimethoxy-2-hydroxy-2'-phenyl-1,1'-binaphthyl (23)

To a mixture of **22** (205 mg, 0.43 mmol) and $NiCl_2$(dppe) (227 mg, 0.43 mmol) was slowly added phenylmagnesium bromide in THF (0.5 N, 3.4 ml, 1.7 mmol). The resulting mixture was stirred at 50 °C for 4 h and then quenched with aqueous NH_4Cl. The reaction mixture was extracted with Et_2O, dried over $MgSO_4$, and concentrated *in vacuo*. The residue was purified by column chromatography (SiO_2, toluene/ethyl acetate= 12/1) to give **23** (142 mg, 69%) which was contaminated with a small amount (<5%) of (a*R*)-6,6'-dimethoxy-2-hydroxy-1,1'-binaphthyl. ^1H NMR (270 MHz): δ 7.96 (d, *J*= 8.6 Hz, 1H), 7.65, (d, *J*= 9.2 Hz, 2H), 7.23-6.92 (m, 11H), 6.89 (dd, *J*= 9.2 and 2.6 Hz, 1H), 4.69 (s, 1H), 3.94 (s, 3H), 3.86 (s, 3H). IR (KBr): 3427, 2835, 1624, 1601, 1499, 1474, 1364, 1236, 1207, 1169, 1124, 1032, 951, 907, 854, 824, 781, 758, 732, 702, 646, 598, 467 cm^{-1}. The crude **23** was used for the next reaction without further purification.

(a*R*)-6,6'-Dimethoxy-2-methoxymethoxy-2'-phenyl-1,1'-binaphthyl (24)

To a solution of sodium hydride (60% dispersion in mineral oil, 346 mg, 14.4 mmol) in THF (0.5 ml) was added **23** (529 mg, 1.11 mmol) in THF (5.0 ml) at 0 °C. After the mixture was stirred for 2 h at the same temperature, chloromethyl methyl ether (340 μl, 4.44 mmol)was added and the reaction mixture was stirred 2 h. The reaction mixture was quenched with brine, stirred for 10 min, extracted with ethyl acetate, dried over

$MgSO_4$, and concentrated *in vacuo*. The residue was purified by column chromatography (SiO_2, hexane/toluene= 1/2) to give **24** (474 mg, 82%) which was contaminated with a small amount (<5%) of (a*R*)-6,6'-dimethoxy-2-methoxymethoxy-1,1'-binaphthyl. ^1H NMR (270 MHz): δ 7.89 (d, *J*= 8.6 Hz, 1H), 7.69 (d, *J*= 8.9 Hz, 1H), 7.62 (d, *J*= 8.3 Hz, 1H), 7.38 (d, *J*= 8.9 Hz, 1H), 7.25-6.85 (m, 11H), 4.79 (ABq, *J*=6.9 Hz, 2H), 3.93 (s, 3H), 3.87 (s, 3H), 3.10 (s, 3H). IR (KBr): 3426, 2924, 2833, 1624, 1597, 1499, 1375, 1238, 1198, 1167, 1151, 1034, 1016, 928, 853, 824, 781, 758, 702, 467 cm^{-1}. The crude **24** was used for the next reaction without further purification.

(a*R*)-6,6'-Dimethoxy-3-formyl-2-methoxymethoxy-2'-phenyl-1,1'-binaphthyl (25)

t-Butyllithium (1.0 M in pentane, 560 μl, 0.56 mmol) was added to a solution of **24** (194 mg, 0.43 mmol) in THF (3.0 ml) at -78 °C and the mixture was stirred for 3 h at the same temperature. After *N,N*-dimethylformamide (140 μl, 1.8 mmol) was added, the reaction mixture was allowed to warm to room temperature and stirred for 1 h. The reaction mixture was quenched with aqueous NH_4Cl, extracted with Et_2O, washed successively with aqueous $NaHCO_3$ and brine, dried over $MgSO_4$, and concentrated *in vacuo*. The residue was purified by column chromatography (SiO_2, hexane/toluene= 1/2) to give **25** (174 mg, 85%) which was contaminated with a small amount (<5%) of (a*R*)-6,6'-dimethoxy-3-formyl-2-methoxymethoxy-1,1'-binaphthyl. ^1H NMR (270 MHz): δ 10.32 (s, 1H), 8.29 (s, 1H), 7.93 (d, *J*= 8.6 Hz, 1H), 7.63 (d, *J*= 8.3 Hz, 1H), 7.25-6.95 (m, 11H), 4.49 (ABq, *J*=5.9 Hz, 2H), 3.94 (s, 3H), 3.92 (s, 3H), 2.89 (s, 3H). IR (KBr): 3427, 2924, 1690, 1624, 1591, 1499, 1425, 1371, 1238, 1157, 1113, 1072, 1032, 966, 856, 824, 760, 702, 419 cm^{-1}. The crude **25** was used for the next reaction without further purification.

(a*R*)-6,6'-Dimethoxy-3-formyl-2-hydroxy-2'-phenyl-1,1'-binaphthyl (26)

To a solution of **25** (197 mg, 0.36 mmol) in THF (3.0 ml) was added 2-propanol saturated with HCl (1.0 ml) and the reaction mixture was stirred for 1 h, and concentrated *in vacuo*. The residue was purified by column chromatography (SiO_2, hexane/ethyl acetate= 7/3) to give **26** (183 mg, quant.) which contained a small amount of (a*R*)-6,6'-dimethoxy-3-formyl-2-hydroxy-1,1'-binaphthyl. The crude **26** was recrystallized from ethanol to give a pure material as yellow crystals. The optical purity of this compound was determined to be >99% ee by HPLC (DAICEL CHIRALPAK AD, hexane/2-propanol=9/1). mp. 184°C. $[\alpha]_D^{26}$ -38.3° (*c* 0.38, $CHCl_3$). ^1H NMR (270 MHz): δ 10.26 (s, 1H), 10.07 (s, 1H), 8.03 (s, 1H), 7.92 (d, *J*= 8.6 Hz, 1H), 7.60 (d, *J*= 8.3 Hz, 1H), 7.20-7.16 (m, 2H), 7.13-7.10 (m, 2H), 7.03-6.94 (m, 7H), 3.93 (s, 3H), 3.87 (s, 3H). IR (KBr): 3566, 3427, 2380, 2349, 1734, 1655, 1560, 1508, 1458, 1375, 1340, 1224, 1121, 1032, 824, 733, 702, 419 cm^{-1}. Anal. Calcd. for $C_{29}H_{21}O_4$: C, 80.17; H, 5.10. Found: C, 79.98; H, 5.16.

(Salen)manganese(III) complex (3b)

To a solution of (*S,S*)-1,2-diazido-1,2-bis(3,5-dimethylphenyl)ethane[2a] (17.5 mg, 55 μmol) in THF (0.4 ml) was added LAH (4.2 mg, 0.11 mmol) at 0 °C. The mixture was stirred for 30 min at room temperature and quenched with aqueous KF (15.9 N, 21 μl, 0.33 mmol). The suspension was filtered through a pad of Celite and extracted with ethyl acetate. The organic layer was dried over Na_2SO_4 and concentrated *in vacuo*. To the concentrate including (*S,S*)-1,2-diamino-1,2-bis(3,5-dimethylphenyl)ethane were added $Mn(OAc)_2 \cdot 4H_2O$ (13.3 mg, 54 μmol) and EtOH (0.8 ml) and the mixture was stirred for 1 h at room temperature. To this solution was added **26** (47.8 mg, 0.11 mmol). The mixture was stirred in air for 4 h at 50 °C, then allowed to cool to room

temperature, and concentrated to dryness. The residue was recrystallized from CH_2Cl_2-hexane. The combined first and second crops of **3b** weighed 35.8 mg (54%). IR (KBr): 3443, 1653, 1624, 1597, 1585, 1497, 1391, 1373, 1333, 1273, 1219, 1167, 1126, 1032, 943, 851, 822, 735, 702 cm^{-1}.

General procedure for asymmetric epoxidation using complex 3a as a catalyst

1,2-Dihydronaphthalene: complex **3a** (2.7 mg, 2.5 μmol) was added to a solution of 1,2-dihydronaphthalene (13.0 mg, 0.1 mmol) and pyridine *N*-oxide (2.4 mg, 25 μmol) in acetonitrile (1.25 ml) and the mixture was set at the appropriate temperature. Iodosylbenzene (22.0 mg, 0.1 mmol) was added at the same temperature and the whole mixture was stirred for 45 min, and quickly filtered through a pad of Celite and silica gel. The filtrate was concentrated and the residue was purified by column chromatography (SiO_2, pentane/ether= 1/0 to 49/1) to give the corresponding epoxide. The enantiomeric excess of the epoxide was determined by GC (SUPELCO β-DEX 120 fused silica capillary column, 30 m x 0.25 mm ID, 0.25 μm film, col. temp.: 120 °C). The same reaction was repeated five times. The average enantiomeric excesses of the epoxides obtained at 25, 10, 0, -10, -17, -24, -30, and -41 °C were 91.8, 93.1, 93.3, 94.9, 94.3, 94.1, 93.7, 92.8% ee, respectively. All the enantiomeric excesses obtained at the same temperatures were within plus or minus 0.7% ee from the average value.

1,3-Cyclooctadiene: The reaction was carried out for 1 h in a similar manner to that of 1,2-dihydronaphthalene. The reaction mixture was submitted to column chromatography (SiO_2, pentane/ether=1/0 to 19/1) to give the corresponding epoxide. The enantiomeric excess of the epoxide was determined by ^1H NMR (400 MHz) analysis [$Eu(hfc)_3$ in $CDCl_3$]. The same reaction was repeated four times. The average enantiomeric excesses of the epoxides obtained at 25, 10, 0, -10, -24, and -41 °C were 64.1, 67.4, 72.1, 71.5, 69.7, 67.9% ee, respectively. All the enantiomeric excesses obtained at the same temperatures were within plus or minus 1.2% ee from the average value.

Styrene: The reaction was carried out for 1.5 h in a similar manner to that of 1,2-dihydronaphthalene. The reaction mixture was submitted to column chromatography (SiO_2, pentane/ether=1/0 to 49/1) to give the corresponding epoxide. The enantiomeric excess of the epoxide was determined by HPLC (DAICEL CHIRALPAK AD, hexane/2-propanol=1000/1). The same reaction was repeated three times. The average enantiomeric excesses of the epoxides obtained at 25, 0, -24, and -41 °C were determined to be 17.2, 18.9, 26.0, 25.1% ee, respectively. All the enantiomeric excesses obtained at the same temperatures were within plus or minus 1.9% ee from the average value.

p-Nitrostyrene: The reaction was carried out for 2 h in a similar manner to that of 1,2-dihydronaphthalene. The reaction mixture was submitted to column chromatography (SiO_2, pentane/ether=1/0 to 9/1 to 8/2) to give the corresponding epoxide. The enantiomeric excess of the epoxide was determined by HPLC (DAICEL CHIRALPAK AD, hexane/2-propanol=9/1). The same reaction was repeated three times. The average enantiomeric excesses of the epoxides obtained at 25, 0, -24, and -41 °C were determined to be 29.1, 30.0, 41.7, 37.8% ee, respectively. All the enantiomeric excesses obtained at the same temperatures were within plus or minus 1.7% ee from the average value.

Epoxidation of 1,3-cyclooctadiene using catalyst 3a or 3b as a catalyst

Compound **3a** (2.7 mg, 2.5 μmol) was added to a solution of 1,3-cyclooctadiene (10.8 mg, 0.1 mmol) and 4-phenylpyridine *N*-oxide (4.3 mg, 25 μmol) in dichloromethane (0.8 ml) and the mixture was cooled to -18 °C. NaOCl in phosphate buffer saturated with NaCl (0.45 M, pH= 11.3, 1.1 ml) was added at the same

temperature and the two phase solution was stirred for 1.5 h, and extracted with dichloromethane at the same temperature. The combined organic phase was dried over Na_2SO_4, and concentrated. The residue was purified by column chromatography (SiO_2, pentane/ether=1/0 to 19/1) to give the corresponding epoxide (6.7 mg, 54%). The optical purity of this sample was determined to be 82% ee by ^1H NMR (400 MHz) analysis [$Eu(hfc)_3$ in $CDCl_3$].

The epoxidation of 1,3-cyclooctadiene with **3b** as a catalyst was also carried out in the same manner as described for the epoxidation with **3a**. The optical purity of the product was determined to be 77% ee.

Epoxidation of 6-acetamido-2,2-dimethyl-7-nitrochromene using catalyst 4a or 4b as a catalyst

Iodosylbenzene (16.9 mg, 77 μmol) was added to a solution of 6-acetamido-2,2-dimethyl-7-nitrochromene (20.1 mg, 77 μmol) and **4a** (1.7 mg, 1.9 μmol) in CH_3CN (1.4 ml) under nitrogen atmosphere. After stirring for 24 h at rt, the mixture was carefully concentrated in *vacuo*. The residue was chromatographed on silica gel (SiO_2, hexane/ethyl acetate= 4/1 to 1/1) to give 6-acetamido-3,4-epoxy-2,2-dimethyl-7-nitrochromane as yellow crystallines (16.7 mg, 65%). The optical purity of this sample was determined to be 96% ee by HPLC (DAICEL CHIRALCEL OJ, hexane/2-propanol= 1/1).

The epoxidation of 6-acetamido-2,2-dimethyl-7-nitrochromene with **4b** as a catalyst was also carried out in the same manner as described for the epoxidation with **4a**. The optical purity of the product was determined to be 64% ee.

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