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# *cis*-Stilbene and (1α,2β,3α)-(2-Ethenyl-3-methoxycyclopropyl)benzene as Mechanistic Probes in the $Mn^{III}$(salen)-Catalyzed Epoxidation: Influence of the Oxygen Source and the Counterion on the Diastereoselectivity of the Competitive Concerted and Radical-Type Oxygen Transfer

Waldemar Adam,[†] Konrad J. Roschmann,*[,†] Chantu R. Saha-Möller,[†] and Dieter Seebach[‡]

*Contribution from the Institute of Organic Chemistry, University of Würzburg, Am Hubland, D-97074 Würzburg, Germany, and Laboratorium für Organische Chemie, Eidgenössische Technische Hochschule, ETH Hönggerberg, HCI H 315, CH-8093 Zürich, Switzerland*

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***Abstract:*** *cis*-Stilbene (**1**) has been epoxidized by a set of diverse oxygen donors [OxD], catalyzed by the $Mn^{III}$(salen)X complexes **3** (X = Cl, $PF_6$), to afford a mixture of *cis*- and *trans*-epoxides **2**. The cis/trans ratios range from 29:71 (extensive isomerization) to 92:8, which depends both on the oxygen source [OxD] and on the counterion X of the catalyst. When (1α,2β,3α)-(2-ethenyl-3-methoxycyclopropyl)-benzene (**4**) is used as substrate, a mechanistic probe which differentiates between radical and cationic intermediates, no cationic ring-opening products are found in this epoxidation reaction; thus, isomerized epoxide product arises from intermediary radicals. The dependence of the diastereoselectivity on the oxygen source is rationalized in terms of a bifurcation step in the catalytic cycle, in which concerted Lewis-acid-activated oxygen transfer competes with stepwise epoxidation by the established $Mn^{V}$(oxo) species. The experimental counterion effect is attributed to the computationally assessed ligand-dependent reaction profiles and stereoselectivities of the singlet, triplet, and quintet spin states available to the manganese species.

## Introduction

Direct oxygen transfer to olefins is a well-established and popular route to prepare epoxides, valuable building blocks in synthetic organic chemistry.[1] In recent years, there has been much effort to conduct this transformation selectively under catalytic conditions.[2] To date, the best known method to epoxidize unfunctionalized olefins enantioselectively is the Jacobsen−Katsuki epoxidation, in which optically active $Mn^{III}$-(salen) complexes are employed as catalysts and PhIO or NaOCl as oxygen sources, with the $Mn^{V}$(oxo) species as the active[3] oxidant.[2−4]

Although the synthetic value of this reaction is undisputed, its mechanism is currently under intensive debate.[3] Substrate isomerization has been of considerable concern, in which *cis*-olefins afford a mixture of *cis*- and *trans*-epoxides (Scheme 1), a process which is particulary prone to occur for phenyl-substituted olefins.[2,3] To account for this loss of stereoselectivity, a radical intermediate has been proposed, which leads to *cis*/*trans*-epoxides through isomerization by simple bond rotation.[3,5] Alternatively, the *trans*-epoxides may be formed from the *cis*-olefins through carbocationic intermediates.[3a] To distinguish between these two options, we selected (1α,2β,3α)-(2-ethenyl-3-methoxycyclopropyl)benzene (**4**) as a mechanistic probe for the Jacobsen−Katsuki epoxidation. A similar cyclopropane derivative (a methyl instead of the vinyl substituent) has already been used by Newcomb and co-workers[6] to elucidate the mechanism of the iron-catalyzed CH oxidation; they found that cationic as well as radical intermediates are involved. Evidently,

* To whom correspondence should be addressed. E-mail: adam@chemie.uni-wuerzburg.de. Fax: (internat.) +49-931/888-4756.
[†] University of Würzburg.
[‡] Eidgenössische Technische Hochschule.

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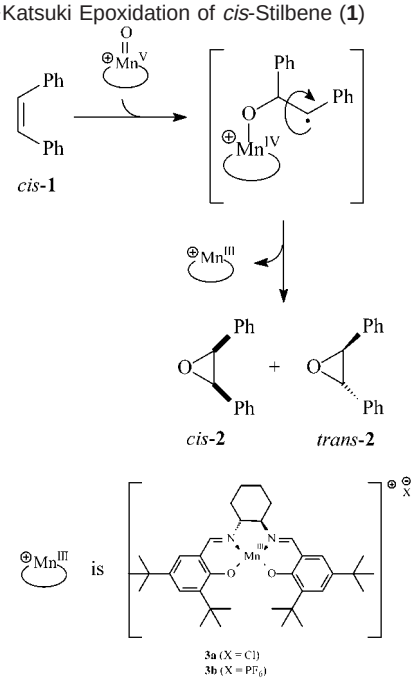
***Scheme 1.*** Possible Mechanism of the Isomerization in the Jacobsen−Katsuki Epoxidation of *cis*-Stilbene (**1**)

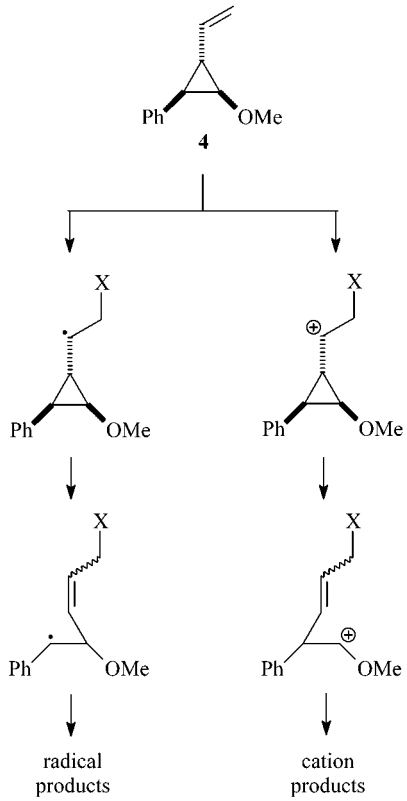



the advantage of the vinylcyclopropane **4** over the simpler probes that have been employed so far in the Jacobsen−Katsuki epoxidation[7] is the fact that it differentiates between cationic and radical intermediates (Scheme 2).

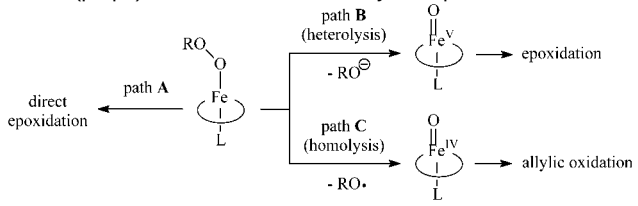
Among the factors that influence the diastereoselectivity in the epoxidation of *cis*-stilbene (**1**), it was recently shown that ligation of the counterion in the Mn(salen)X complex **3** plays an important role.[8] Thus, the *cis*/*trans*-epoxide ratio was ca. 30:70 (extensive isomerization) for *cis*-stilbene, when the complexes **3** were employed with the ligating counterions $Cl^-$, $Br^-$, and $AcO^-$. In contrast, the cis/trans ratio is ca. 75:25 (moderate isomerization) for the complexes **3** with the non-ligating counterions $BF_4^-$, $PF_6^-$, and $SbF_6^-$. This counterion effect was rationalized mechanistically in terms of the *two-state-reactivity* model.[8,9]

That also the oxygen source may affect the selectivity of metal-catalyzed oxidations has recently been demonstrated by Nam and co-workers, who have investigated the mechanism of the epoxidation by iron complexes.[10] When peroxidic oxygen donors (OxD) such as hydrogen peroxide, *tert*-butyl hydroperoxide, and *m*CPBA, were employed with the Fe(porph) complexes, initially an FeOOR(porph) adduct is formed, which oxidizes the substrate by the three different pathways A−C (Scheme 3). First, the FeOOR(porph) adduct may epoxidize olefins directly, which constitutes Lewis-acid activation of the oxygen donor ROOH (path A); alternatively, the O,O bond of

***Scheme 2.*** Vinylcyclopropane **4** as a Mechanistic Probe To Distinguish between Radical and Cation Intermediates




***Scheme 3.*** Three Pathways A−C for the Reaction of the FeOOR(porph) Adduct in the Iron-Catalyzed Epoxidation




the oxygen donor ROOH may be cleaved either heterolytically (path B) to yield an Fe(V)oxo species [actually the Fe(IV)oxo/porphyrin radical cation[11]] or homolytically (path C) to give an Fe(IV)oxo complex. Whereas the Fe(V)oxo species affords high yields of epoxides, the Fe(IV)oxo complex preferably performs allylic oxidation. The ratio between heterolytic and homolytic cleavage depends on the type of oxygen donor ROOH and the axial ligand L. Evidently, this study provides clear-cut evidence for the participation of several metal-activated intermediates as active oxidants.

In view of the experimental facts for the Fe(porph) catalyst, it was of mechanistic relevance to examine also the influence of the oxygen donor on the diastereoselectivity of the $Mn^{III}$-(salen)-catalyzed epoxidation of *cis*-stilbene (**1**). Besides the routinely used iodosyl benzene (PhIO) and bleach ($Na^{\oplus}OCl^{\ominus}$), we decided to employ also iodosyl pentafluorobenzene ($C_6F_5$-IO),[12a] periodate ($TBA^{\oplus}IO_4^{\ominus}$),[12b] ozone, hydrogen persulfate ($TBA^{\oplus}HSO_5^{\ominus}$),[12c] and dimethyldioxirane (DMD)[12d] as oxygen

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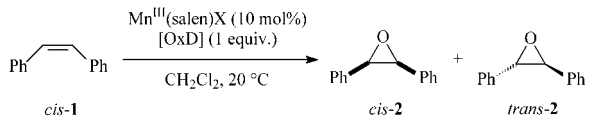
***Table 1.*** Counterion and Oxygen-Donor Effects on the Cis/Trans Ratios of the Epoxides **2** in the $Mn^{III}$-Catalyzed Epoxidation of *cis*-Stilbene (**1**)




| entry | [OxD] | catalyst | convn[a] [%] | epoxides[b] cis/trans |
|---|---|---|---|---|
| 1 | PhIO | **3a** (X = Cl) | 43 | 29:71 |
| 2 | | **3b** (X = $PF_6$) | 64 | 76:24 |
| 3 | $C_6F_5IO$ | **3a** (X = Cl) | 89 | 47:53 |
| 4 | | **3b** (X = $PF_6$) | 95 | 82:18 |
| 5 | $TBA^{\oplus}IO_4^{\ominus}$ | **3a** (X = Cl) | 62 | 38:62 |
| 6 | | **3b** (X = $PF_6$) | 67 | 40:60 |
| 7 | $O_3$[c] | **3a** (X = Cl) | 47 | 56:44 |
| 8 | | **3b** (X = $PF_6$) | 86 | 90:10 |
| 9 | $TBA^{\oplus}HSO_5^{\ominus}$ | **3a** (X = Cl) | 21 | 57:43 |
| 10 | | **3b** (X = $PF_6$) | 20 | 77:23 |
| 11 | $Na^{\oplus}OCl^{\ominus}$ | **3a** (X = Cl) | 14 | 75:25 |
| 12 | | **3b** (X = $PF_6$) | 26 | 69:31 |
| 13 | DMD[d] | **3a** (X = Cl) | 39 | 75:25 |
| 14 | | **3b** (X = $PF_6$) | 31 | 92:8 |

[a] Conversion is relative to *cis*-stilbene (**1**); mass balances were >80%. [b] The cis/trans ratios were determined by $^1H$ NMR analysis directly on the crude product mixture; all cis/trans ratios have been run at least in duplicate and are reproducible within an error of ±5% of the stated values. [c] The reaction was performed at −78 °C and gave benzaldehyde as the main product (ca. 75%) due to ozonolysis. [d] Dimethyldioxirane, used as acetone-free $CH_2Cl_2$ solution (0.185 M), see ref 12d.

sources. As catalysts, the Mn(salen)X complexes **3a** (X = Cl) and **3b** (X = $PF_6$) were used to evaluate − as in the case of PhIO − whether a counterion effect operates on the diastereoselectivity also for these oxygen donors.

## Results

The manganese-catalyzed epoxidation of *cis*-stilbene (**1**) was carried out with 10 mol % of catalyst **3** and 1 equiv of the oxygen donor (OxD). The results are summarized in Table 1. For the set of oxygen donors examined herein, the general trend displayed by catalyst **3a** (X = Cl) is that the cis/trans ratio ranges from mainly *trans*-**2** (entry 1) to mainly *cis*-**2** (entries 11 and 13), whereas with catalyst **3b** (X = $PF_6$), the *cis*-epoxide prevails for all oxygen donors, except $TBA^{\oplus}IO_4^{\ominus}$ (entry 6). Specifically, when iodosyl benzene (PhIO) is used as oxygen donor, the $Mn^{III}$(salen)Cl catalyst **3a** leads mostly to isomerization (cis/trans 29:71, entry 1), whereas the $Mn^{III}$(salen)$PF_6$ catalyst **3b** affords mostly the cis product (cis/trans 76:24, entry 2). Similarly, the related iodosyl pentafluorobenzene ($C_6F_5IO$) also displays a counterion effect on the diastereoselectivity, but less pronounced. Thus, the cis/trans ratio of 47:53 for catalyst **3a** with $C_6F_5IO$ (entry 3) indicates less isomerization than with PhIO (entry 1), while for the catalyst **3b** (X = $PF_6$), the cis/trans ratio is nearly constant for both iodosyl oxygen donors (entries 2 and 4).

The tetrabutylammonium periodate ($TBA^{\oplus}IO_4^{\ominus}$) as oxygen donor is exceptional, for which no counterion effect is observed. Not only is the cis/trans ratio the same (ca. 40:60) within experimental error for both catalysts **3a** and **3b** (entries 5 and 6), but $TBA^{\oplus}IO_4^{\ominus}$ is the only oxygen donor for which isomerization to the trans diastereomer dominates also for complex **3b**.

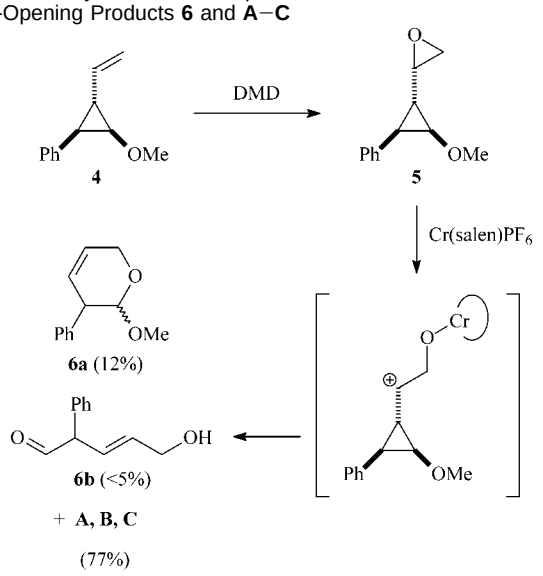
In contrast to the other oxygen sources, the epoxidation with ozone was performed at −78 °C to minimize the ozonolysis of *cis*-stilbene (**1**); yet even at this low temperature, the oxidative cleavage of stilbene to benzaldehyde was the main reaction (ca. 75%). Nevertheless, the cis/trans ratios obtained with ozone demonstrate again a pronounced counterion effect with the catalysts **3a** and **3b**, although the *cis*-epoxide dominates in both cases (entries 7 and 8).

In the case of $TBA^{\oplus}HSO_5^{\ominus}$, more isomerization takes place with catalyst **3a** than with catalyst **3b** (entries 9 and 10). When compared to PhIO, less isomerization is observed with $TBA^{\oplus}HSO_5^{\ominus}$ for catalyst **3a** (entries 1 and 9), whereas for catalyst **3b** the cis/trans ratio stays about the same within experimental error (entries 2 and 10). Significantly, the oxygen donor $Na^{\oplus}OCl^{\ominus}$ affords almost the same cis/trans diastereoselectivity for both catalysts **3a** and **3b** (entries 11 and 12), with the *cis*-epoxide preferred.

The least isomerization is exhibited by dimethyldioxirane (DMD) as oxygen source for both catalysts **3a** and **3b** (entries 13 and 14). Direct epoxidation by DMD rather than metal-catalyzed oxygen transfer by the manganese catalyst **3** is unlikely, since DMD in combination with the Jacobsen Mn(salen*)Cl catalyst epoxidizes 2,2-dimethyl-2*H*-chromenes highly enantioselectively (83−93% *ee*).[13] If the achiral DMD were the oxidant, necessarily racemic epoxide would be formed.

The (1α,2β,3α)-(2-ethenyl-3-methoxycyclopropyl)benzene (**4**) was synthesized according to the literature procedure;[6a] its epoxide **5** was prepared by DMD epoxidation as a 54:46 mixture of diastereomers (Scheme 4). The epoxide **5** is extremely sensitive to acids, and it decomposes on attempted purification by chromatography on deactivated silica gel and even on Florisil. This presented severe difficulties in the workup of the epoxidation mixture that is obtained with the Jacobsen catalyst Mn(salen)Cl (**3a**), which requires removal of the paramagnetic manganese species by silica gel chromatography to enable product analysis by NMR spectroscopy. Fortunately, the epoxide **5** persists exposure to the Mn(salen)Cl complex **3a** (established by a control experiment), and the polymer-bound Mn(salen)

***Scheme 4.*** Synthesis of the Epoxide **5** and the Cationic Ring-Opening Products **6** and **A**−**C**

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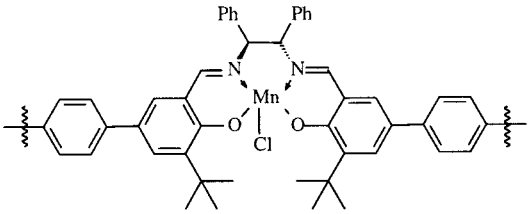
catalyst p-MnCl was employed to circumvent these problems by simple filtration (see Supporting Information).[14]



**p-MnCl**

Furthermore, for the same reasons, the usual HPLC analysis on a silica gel column, to assess the product distribution in the epoxidation mixture, had to be conducted on a reversed-phase column. Although under these HPLC conditions there is also some decomposition of the epoxide **5**, the resulting products did fortunately not elute to interfere with the product analysis.

The authentic mixture of the cationic ring-opening products **6** was prepared by treatment of the epoxide **5** with catalytic amounts of Cr(salen)$PF_6$ as Lewis acid[15] (see Supporting Information). Whereas 12% of the cyclic acetal **6a** was isolated after column chromatography (Figure S1), no aldehyde **6b** was detected; instead, as outlined in Scheme 4, a mixture of three unknown products **A**, **B**, and **C** (HPLC analysis, Figure S2) was formed in 77% yield (determined gravimetrically).

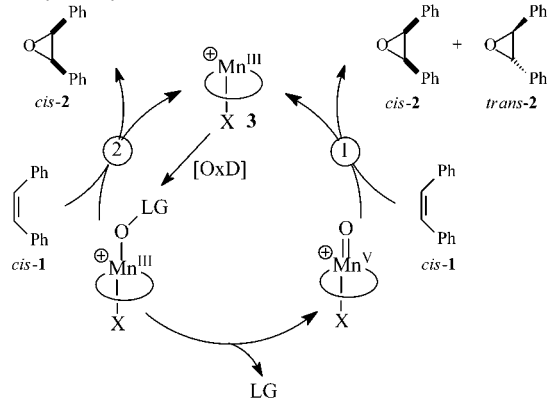
In a test reaction, *cis*-stilbene (**1**) was treated with p-MnCl, 4-phenylpyridine *N*-oxide (PPNO), and iodosyl benzene (PhIO) to yield a 63:37 mixture of the diastereomeric epoxides **2** at a conversion of 67%. When the probe (1α,2$\beta$,3α)-(2-ethenyl-3-methoxycyclopropyl)benzene (**4**) was epoxidized under these conditions, 83% of the olefin was consumed to give 2% of epoxide **5** and 33% of ring-opened products, at a mass balance of 51% (see Figure S3). No cationic ring-opening products **6** or **A**−**C** were detected by RP-HPLC analysis (see Figures S4 and S5). Consequently, the observed ring-opening products derive from radical intermediates, and, hence, the following mechanistic discussion shall be limited to such species.

## Discussion

From the data listed in Table 1, it may be concluded that not only the counterion of the Mn(salen)X complexes **3a**,**b** (X = Cl, $PF_6$), but also the oxygen donor [OxD], has an influence on the cis/trans diastereoselectivity of the Jacobsen−Katsuki epoxidation of *cis*-stilbene (**1**). We shall first address the influence of the oxygen donor on the diastereoselectivity and subsequently the counterion effect. Although we mechanistically interpret the stereochemical trends separately in terms of the oxygen-donor and counterion effects, it should be kept in mind that both factors are intimately intertwined and cause the complexity of the observed diastereoselectivity.

**The Effect of the Oxygen Donor.** It is generally accepted that the first step in the Jacobsen−Katsuki epoxidation is the formation of the $Mn^V$(oxo) species as the actual oxidant.[2−4] After addition of the $Mn^V$(oxo) species to *cis*-stilbene (**1**), the resulting radical intermediate may either collapse immediately

***Scheme 5.*** Catalytic Cycle for the $Mn^{III}$-Catalyzed Epoxidation of *cis*-Stilbene (**1**) by Lewis-Acid Activation (Path 1) versus $Mn^V$(oxo) Species (Path 2)




to the *cis*-epoxide or undergo C,C-bond rotation and cyclize to the *trans*-epoxide. If the $Mn^V$(oxo) complex were the only oxidant in this epoxidation, irrespective of which oxygen donor is used to generate the reagent, the cis/trans selectivity should be the same. Yet this is not the case (Table 1); besides some qualitative similarities, each oxygen donor displays a distinct *cis*/*trans*-epoxide ratio. Thus, the Jacobsen−Katsuki catalytic cycle must be extended to accommodate this divergence mechanistically (Scheme 5). The fact that the type of oxygen donor affects the diastereoselectivity of the epoxidation requires that besides the $Mn^V$(oxo) species, at least one other oxidant must be involved in this catalytic process. Consequently, we propose the following unprecedented diastereoselectivity-controlling bifurcation step in the catalytic cycle for this epoxidation: After ligation between the $Mn^{III}$ catalyst and the oxygen donor (OxD) to result in the $Mn^{III}$(OLG) adduct, the $Mn^V$(oxo) oxidant is released by splitting off the leaving group LG, and subsequent unselective epoxidation of the substrate (pathway 1) affords a mixture of *cis*- and *trans*-epoxides **2**. Alternatively, the ligated $Mn^{III}$(OLG) adduct functions directly as Lewis-acid-activated epoxidant by concerted oxygen transfer to give the *cis*-epoxide (pathway 2). The latter alternative has already been suggested for the Mn(salen)-[16a] and Fe(porph)-catalyzed[10,17] epoxidation with *m*CPBA as oxygen donor and for the manganese-catalyzed sulfimidation.[16b] The transition structure for the concerted oxygen transfer by the $Mn^{III}$(OxD) adduct with $HSO_5^{\ominus}$ as oxygen donor may be similar to the "butterfly" structure for peracid epoxidations.

An appropriate admixture of the stepwise epoxidation by the established $Mn^V$(oxo) species (path 1 affords a mixture of the *cis*- and *trans*-epoxides[2,3]) and of the concerted epoxidation (path 2 yields only *cis*-epoxide[18]) accounts for the stereochemical data in Table 1.[19]

As shown in the bifurcation step of Scheme 5, the formation of the $Mn^V$(oxo) species depends on the leaving group LG of the oxygen donor; thus, the type of oxygen donor [OxD] is responsible for the observed cis/trans diastereoselectivity. This is most apparent in the cis/trans ratios for catalyst **3a**, which

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vary from dominant trans selectivity for the PhIO oxygen donor (entry 1) to dominant cis selectivity for DMD (entry 13). For this reason, we shall analyze the effect of the oxygen donor for catalyst **3a** and thereby keep the counterion constant, i.e., X = Cl.

Evidently, based on the cis/trans ratios, the oxygen donors fall into two classes: PhIO, $C_6F_5IO$, $TBA^{\oplus}IO_4^{\ominus}$, and $O_3$ afford the $Mn^{V}$(oxo) species as the dominant oxidant with extensive isomerization (pathway 1) through the stepwise radical process (cis/trans ratio 29:71 to 56:44 for catalyst **3a**, entries 1, 3, 5, and 7); for $TBA^{\oplus}HSO_5^{\ominus}$, $Na^{\oplus}OCl^{\ominus}$, and DMD, the concerted process through Lewis-acid catalysis (pathway 2) is also operative, as reflected by the higher cis selectivity with catalyst **3a** (cis/trans ratio 57:43 to 75:25, entries 9, 11, and 13). However, if for the first set of oxygen donors the $Mn^{V}$(oxo) were the principal oxidant, the same diastereoselectivity should be displayed by them since the leaving group of the oxygen donor is no longer involved. This is definitively not the case, because all cis/trans ratios differ (entries 1, 3, 5, and 7).

For both $C_6F_5IO$ and PhIO, the $Mn^{V}$(oxo) species is the main oxidant, but the small differences in the diastereoselectivity for the $Cl^{\ominus}$ as counterion (see entries 1 versus 3) may be explained by the fact that the former is capable of oxidizing the chloride counterion of complex **3a** to the hypochlorite ion but PhIO is not. This has been confirmed by a control experiment with $TEBA^{\oplus}Cl^{\ominus}$ as the chloride source (see Supporting Information). Consequently, the in-situ-generated $OCl^{\ominus}$ competes as oxygen donor with $C_6F_5IO$. Because from the data in Table 1 (entry 11) we suppose that the hypochlorite ion epoxidizes mainly by the concerted Lewis-acid-catalyzed pathway 2, a higher cis selectivity is observed for $C_6F_5IO$, as compared to PhIO (entries 1 and 3). As for the oxygen donor $TBA^{\oplus}IO_4^{\ominus}$, the slightly higher cis selectivity (entry 5) may be caused in the same way, since the reaction of periodate with chloride to form iodate and hypochlorite is feasible (according to their oxidation potentials[20]), whereas for $TBA^{\oplus}HSO_5^{\ominus}$ (entry 9), this possibility was ruled out by a control experiment. Also for DMD (entry 13), the $OCl^{\ominus}$ oxygen donor is generated in situ by oxidation of $Cl^{\ominus}$,[21] as is evident from the 75:25 cis/trans ratio.

The somewhat higher cis selectivity for ozone (entry 7) versus PhIO (entry 1) with catalyst **3a** may be explained in terms of a temperature effect since the experiments with $O_3$ were performed at −78 °C, and those with PhIO at ca. 20 °C (a comparative run with PhIO was not possible at −78 °C, because no reaction occurs at this low temperature). At −78 °C, the C,C-bond rotation responsible for cis/trans isomerization is sufficiently slowed[22] such that ring closure becomes the faster process. Therefore, more *cis*-epoxide is observed with $O_3$ as compared to with PhIO (entries 1 and 7).

**Effect of the Counterion.** While for all oxygen donors a counterion effect on the diastereoselectivity is observed, this is not the case for $TBA^{\oplus}IO_4^{\ominus}$ (entries 5 and 6) and $Na^{\oplus}OCl^{\ominus}$ (entries 11 and 12). For these oxygen donors, the cis/trans ratios are about the same (within the experimental error) for both catalysts **3a** and **3b**. This may be rationalized by the fact that a ligating anion ($IO_3^{\ominus}$ and $Cl^{\ominus}$) is released from the oxygen donor ($IO_4^{\ominus}$ and $OCl^{\ominus}$), which then coordinates to the positively charged manganese catalyst. Thus, both catalysts **3a** and **3b** are ligated by the same counterion, causing similar stereoselectivities. The ligating properties of $IO_3^{\ominus}$ and $Cl^{\ominus}$ have been confirmed by means of control experiments (see Supporting Information).

The counterion effect on the cis/trans selectivity in the manganese-catalyzed epoxidation of *cis*-stilbene (**1**) was previously rationalized in terms of the *two-state-reactivity* model.[8] While our results (Table 1) are consistent with this model, recent computations[23] on the mechanism of the oxygen transfer in the Jacobsen−Katsuki epoxidation are informative, which show that the singlet, triplet, and quintet spin states are all accessible in the $Mn^{V}$(oxo) complex. From the qualitative energy profiles (Figure 1), it is evident that for the neutral $Mn^{V}$(oxo) species[23c] with chloride as counterion, the singlet state is lowest in energy (Figure 1a), whereas in the case of the cationic $Mn^{V}$(oxo) species[23a] (Figure 1b), the triplet is the ground state; clearly, the energies of the spin states in the "naked cation" are spaced more closely. For the final $Mn^{III}$(epoxide) adduct, the situation is reversed. For the chloride as counterion, the energies of the spin states fall within a much narrower range than for the hexafluorophosphate; in both cases, the quintet is favored as ground state. According to these calculations, the nature of the counterion X affects drastically the relative energy ordering of the spin states in the $Mn^{V}$(oxo) complex as well as of the final $Mn^{III}$(epoxide) adduct.

Moreover, the computations reveal a mechanistically important feature with respect to the effect of the counterion on the stereoselective behavior of the three spin states. Whereas the singlet state of $Mn^{V}$(oxo)Cl is predicted to epoxidize *cis*-alkenes concertedly (the energy curve displays no minimum) and hence diastereoselectively, the triplet and quintet states involve stepwise oxygen transfer (the energy curves display minima) and should undergo extensive cis/trans isomerization. As for the $Mn^{V}(oxo)^{\oplus}$ complex, the triplet und singlet states should display a similar stereoselectivity as the neutral $Mn^{V}$(oxo)Cl species; that is, the triplet should be unselective (stepwise) and the singlet selective (concerted), but the quintet state should transfer its oxygen atom concertedly in a diastereoselective manner.

The qualitative energy profiles in Figure 1 suggest that for hexafluorophosphate as counterion, the epoxidation is expected to proceed mainly on the quintet surface; the triplet and the singlet channels constitute only minor reaction pathways. Because the $Mn^{V}(oxo)^{\oplus}$ quintet transfers the oxygen atom diastereoselectively, it follows that for the Mn(salen)$PF_6$ catalyst

(19) The participation of a $Mn^{IV}$(oxo) species may also be proposed to explain the observed diastereoselectivity, since it is known to cause isomerization. [(a) Groves, J. T.; Stern, M. K. *J. Am. Chem. Soc.* **1987**, *109*, 3812−3814. (b) Groves, J. T.; Stern, M. K. *J. Am. Chem. Soc.* **1988**, *110*, 8628−8638. (c) Lee, R. W.; Nakagaki, P. C.; Bruice, T. C. *J. Am. Chem. Soc.* **1989**, *111*, 1368−1372. (d) Arasasingham, R. D.; He, G.-X.; Bruice, T. C. *J. Am. Chem. Soc.* **1993**, *115*, 7985−7991. (e) Groves, J. T.; Lee, J.; Marla, S. S. *J. Am. Chem. Soc.* **1997**, *119*, 6269−6273.] On the basis of our experimental data, this mechanistic alternative cannot be the dominant pathway: When *cis*-stilbene (**1**) is treated with the authentic $Mn^{IV}$(oxo) species in EtOAc, that is, under stoichiometric conditions, a 36:64 mixture of the *cis*- and *trans*-epoxides **2** is formed;[7c] however, a control experiment under our catalytic conditions in EtOAc gave even more isomerization (cis/trans 25:75). Moreover, the authentic $Mn^{IV}$ species leads to substantial amounts of chlorinated products in $CH_2Cl_2$, which we do not observe.

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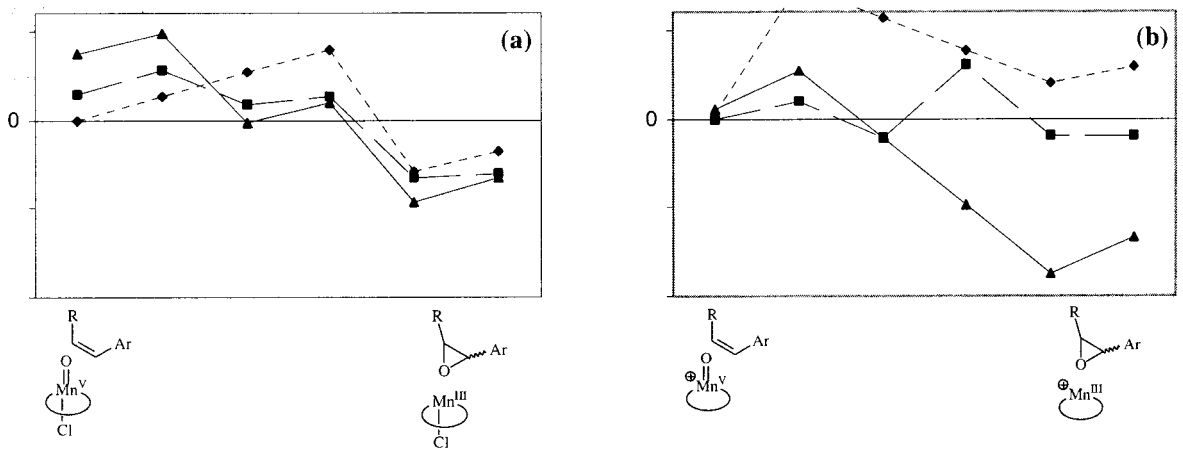


***Figure 1.*** Qualitative energy profiles of the singlet (s, ◆), triplet (t, ■), and quintet (q, ▲) trajectories for chloride (a) and hexafluorophosphate (b) as counterions (ref 23).

**3b** the *cis*-epoxide **2** is formed preferentially. When the chloride ion is the counterion, all three spin states of $Mn^{V}$(oxo)Cl participate in the oxygen-transfer process. Thus, since only the singlet state reacts diastereoselectively through a concerted epoxidation and the triplet and quintet states give rise to isomerization through the stepwise pathway, for catalyst **3a** (X = Cl) more *trans*-epoxide **2** is expected as compared to catalyst **3b** (X = $PF_6$), as experimentally observed (Table 1). Indeed, for the latter catalyst, the highest cis/trans ratio (92:8) is given by DMD (entry 14), which follows almost exclusively the stereoselective quintet pathway.

## Conclusion

We have demonstrated that the oxygen donor (OxD) and the counterion X of the Mn(salen)X catalysts **3a** and **3b** have a definite influence on the diastereoselectivity of the $Mn^{III}$-catalyzed epoxidation of *cis*-stilbene (**1**). By application of the mechanistic probe (1α,2*β*,3α)-(2-ethenyl-3-methoxycyclopropyl)-benzene (**4**), which enabled us to distinguish between radical and carbocationic intermediates through selective opening of the cyclopropane ring, the participation of cationic species in the Jacobsen−Katsuki epoxidation could be ruled out. Consequently, the formation of stereochemically isomerized epoxide product is attributed to radical pathways. To account for the complex behavior of the diverse oxygen donors, the generally accepted catalytic cycle had to be extended to incorporate a bifurcation step (Scheme 5). For the latter product branching, the unselective epoxidation by way of the stepwise radical process with the $Mn^{V}$(oxo) complex (path 1) competes with the concerted Lewis-acid-activated selective epoxidation by the $Mn^{III}$(OxD) adduct (path 2). The counterion effect on the stereoselectivity may be explained in terms of ligand-dependent reaction profiles for the three available spin states (singlet, triplet, and quintet) of the $Mn^{V}$(oxo)X species.

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**Supporting Information Available:** Experimental details and spectral data (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

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