Are Mn^{IV} Species Involved in Mn(Salen)-Catalyzed Jacobsen−Katsuki Epoxidations? A Mechanistic Elucidation of Their Formation and Reaction Modes by EPR Spectroscopy, Mass-Spectral Analysis, and Product Studies: Chlorination versus Oxygen Transfer

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Received February 10, 2000

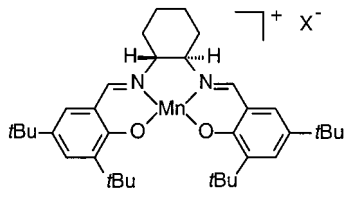
Abstract: EPR and ESI-MS/MS evidence is presented that in the absence of an olefinic substrate the reaction between the Mn^{III}(salen) complexes **A1** (X = Cl) and **A2** (X = PF_6) and PhIO or NaOCl as oxygen sources leads to paramagnetic Mn^{IV}(salen) complexes. Depending on the solvent and the counterion, two distinct Mn^{IV}-(salen) complexes intervene. In CH_2Cl_2, regardless of the counterion, a $ClOMn^{IV}$(salen) complex (**B1**) and a $HOMn^{IV}$(salen) complex (**B1′**) are formed by Cl and H atom abstraction from CH_2Cl_2, and the latter deprotonates to the neutral OMn^{IV}(salen) complex (**B2**). In EtOAc as solvent, only the complex **B2** is obtained from **A1** (X = Cl), presumably by inner-sphere electron transfer from the chloride ion. The Mn^{IV}(salen) complexes display the following reaction modes toward 1,2-dihydronaphthalene (**1**), styrene (**2**), and the radical probe **3** as substrates: Complex **B1** chlorinates the olefins **1**/**2** through an electrophilic pathway to yield the 1,2-dichloro adducts **1a**/**2a** and the chlorohydrins **1b**/**2b** (nucleophilic trapping of the initially formed benzylic cation), while with olefin **3** the ring-opened dichloro product **3a** results. Complex **B2**, however, epoxidizes these olefins through a radical pathway, as evidenced by the formation of isomerized stilbene oxide **4c** (cis/trans ratio 36:64) from *cis*-stilbene (**4**). The relevance of these paramagnetic Mn^{IV}(salen) species in Jacobsen−Katsuki catalytic epoxidations is scrutinized.

Introduction

The first optically active Mn^{III}(salen) complexes have been used independently by Jacobsen[1] and Katsuki[2] as versatile catalysts for the enantioselective epoxidation of unfunctionalized olefins. The active species in these reactions is considered to be an OMn^{V}(salen) complex, as proposed by Kochi in his original work on achiral derivatives.[3] Indeed, Plattner[4] showed by means of an ESI-MS study that the addition of the achiral Mn^{III}(salen) complex to a dispersion of PhIO in CH_3CN afforded the OMn(salen) species, together with various adducts and dimerization products thereof. Recent theoretical work concluded a triplet ground state for the OMn^{V}(salen) complex.[7] In addition to OMn^{V}(salen), Norrby and Akermark proposed also the intervention of an OMn^{IV}(salen) complex to which, in analogy to OMn^{IV}(porph),[5] was ascribed radical-type oxidations to account for the formation of ring-opened products in the Mn^{III}-(salen)-catalyzed epoxidation of a radical probe.[6]

The mechanistic importance of the participation of an OMn^{IV}-(salen) complex in OMn^{V}(salen)-type oxidations, in particular the Jacobsen−Katsuki epoxidation, was pointed out by Linde et al.[7] It was stressed that small amounts of byproduct may be the reason for nonlinear Eyring plots, which in the current mechanistic dispute are taken as evidence for the involvement of a metallaoxetane intermediate,[8] as they generally implicate that a second species intervenes.[9]

We present herein experimental evidence that in the absence of an olefinic substrate, the reaction between Mn^{III}(salen) complexes **A** and an oxygen source (PhIO, NaOCl) leads to



A1 X = Cl
A2 X = PF_6

Mn^{IV}(salen) oxidants. Depending on the solvent (CH_2Cl_2 versus

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(1) Jacobsen, E. N. In *Catalytic Asymmetric Synthesis*; Ojima, I., Ed.; VCH Publishers: New York, 1993; pp 159−202.
(2) Katsuki, T. *J. Mol. Catal. A: Chem.* **1996**, *113*, 87−107.
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10.1021/ja0005082 CCC: $19.00
Published on Web 09/26/2000

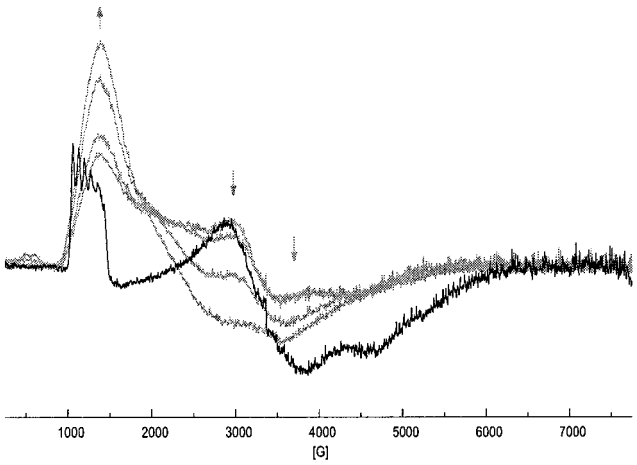

Figure 1. Time profiles for the EPR spectra of the Mn^{IV}(salen) complexes **B** in CH_2Cl_2 at 77 K (frequency 9.43 GHz, power 0.5 mW, time constant 40.96 ms, receiver gain 1.6×10^5, modulation amplitude 10.4 G) generated from the Mn^{III}(salen)Cl complex **A1** + PhIO (5 equiv): from 30 min to 20 h and after 35 h reaction time (lowest spectrum).

EtOAc) and the counterion (Cl^- versus PF_6^-), two different Mn^{IV}(salen) complexes are involved, one chlorinates [ClOMn^{IV}-(salen) as electrophilic chlorinating agent] and the other epoxidizes [OMn^{IV}(salen) as radical-type oxidizing agent] the olefinic substrates **1**−**4**.

Results and Discussion

Formation and Characterization of Mn^{IV}(salen) Complexes. We conducted our studies with two different Mn^{III}(salen) complexes **A**, of which **A1** (X = Cl) is the complex usually referred to as "Jacobsen's catalyst" and is commercially available. The complex **A2** (X = PF_6) was necessary, as will become apparent later on, to assess the origin of the chlorinated products.

The method of choice for the detection of the paramagnetic Mn^{IV}(salen) complexes **B** is EPR spectroscopy, especially since Mn^{IV} complexes give well-characterized EPR signals,[10] whereas Mn^{V} and Mn^{III} complexes are EPR-inactive at the usual X-band frequencies.[11] In a typical experiment, a 30 mM solution of Mn^{III}(salen) complex **A1** in CH_2Cl_2 was prepared and 5 equiv of PhIO were added. The EPR spectra of this solution at 70 K, taken after 30, 105, 265, 440, and 755 min and as late as 35 h, showed the characteristic features of a high-spin (d^3 electronic configuration), monomeric Mn^{IV} complex, which changed slightly with time (Figure 1). Two distinct signals were observed, one at *g* ca. 2 and the other at ca. 5, of which the latter showed a six-line hyperfine splitting with a coupling constant of A = 70 G, as expected for a $I = {}^5/_2$ spin system.[10]

The same experiment was conducted with 10 equiv of a 2 M NaOCl solution (pH 11.3) (Figure 2). Again, the relative intensity and shape of the EPR signals at *g* ca. 2 and ca. 5 were the same as for the PhIO oxidant and also changed slightly with time. In this case, however, the addition of 1.1 equiv of *p*-phenylpyridine *N*-oxide (PPNO) was necessary to form a monomeric Mn^{IV}(salen) complex; without PPNO, only a strong signal at *g* ca. 8 was observed, which may be assigned to an even-integer-spin signal of two coupled Mn atoms, e.g. (salen)-MnOMn(salen).

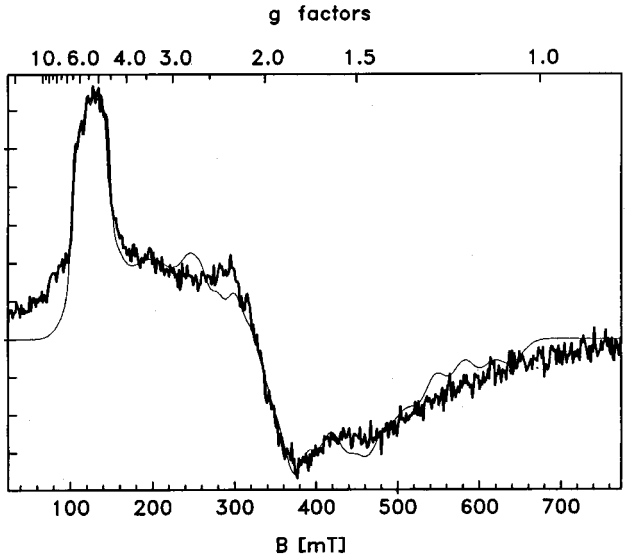

Figure 2. EPR spectrum of Mn^{IV}(salen) complexes **B** in CH_2Cl_2 at 77 K (frequency 9.43 GHz, power 0.5 mW, time constant 40.96 ms, receiver gain 1.6×10^5, modulation amplitude 10.4 G) generated from Mn^{III}(salen)Cl complex **A1** + PPNO (1.1 equiv) + NaOCl solution (2 M, pH 11.3, 10 equiv) after 60 min; experimental (bold spectrum) and computer-simulated (light spectrum) spectra by assuming 80% of Mn^{IV}-(salen) complex with D = 0.950 and E/D = 0.296 and 20% with D = 4.000 and E/D = 0.160. We thank Prof. K. Wieghart (Max-Planck-Institut, Mülheim) for allowing us to measure this EPR spectrum in his laboratory.

Computer simulation[12] of the spectra (Figure 2) revealed two Mn^{IV} species **B** with different D and E zero-field-splitting (zfs) parameters (the first with D = 4.000 and E/D = 0.160, the second with D = 0.950 and E/D = 0.296). Their relative amounts change with time, i.e., after 15 min; the latter makes up 62% of the Mn^{IV} concentration, which increases to 80% after 60 min.

To quantify the amount of Mn^{III}(salen) catalyst **A1** that had been oxidized to the Mn^{IV}(salen) complexes **B**, the areas under the EPR signals were determined relative to a $CuSO_4$-standardized solution. With PhIO as oxidant, about 70% of the Mn^{III}-(salen) complex **A1** was oxidized to the Mn^{IV}(salen) complexes **B** and its EPR signal persisted for at least 35 h (Figure 3). For NaOCl, however, at first as much as 93% of the Mn(salen) catalyst was present as the Mn^{IV}(salen) complex **B**, but within 120 min it decreased to only 33% (Figure 3). Thus, all further experiments were conducted only with PhIO as oxidant.

Treatment of complex **A1** with PhIO in other solvents common for epoxidation, such as CH_2Br_2, EtOAc, CH_3CN, and MeOH, also gave rise to Mn^{IV}(salen) complexes **B** (Figure 4). The same was true for the addition of PhIO to a solution of **A2** (PF_6^- as counterion instead of Cl^-) in CH_2Cl_2. For the complex **A2** in EtOAc, however, no EPR signal could be detected upon addition of PhIO (Figure 5).

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(12) The solution spectra were simulated on the basis of a spin-Hamiltonian description of the electronic ground state: $H_e = D[S_z^2 - S(S+1)/3 + (E/D)(S_x^2 - S_y^2)] + \mu_B \mathbf{B}\bar{g}\mathbf{S}$, where $S = 1$ is the spin of the coupled system and D and E/D are the axial and rhombic zero-field parameters. These simulations were performed with a program that was developed by Dr. Eckhard Bill (Max-Planck-Institut für Strahlenchemie, Mülheim) from the $S = {}^5/_2$ routines of Gaffney and Silverstone (Gaffney, B. J.; Silverstone, H. J. In *Biological Magnetic Resonance*; Berliner, L. J., Reuben, J., Eds.; Plenum Press: New York, London, 1993; Vol. 13); the calculation of the transition fields based on a Newton−Rapshon iterative method was used as described therein.

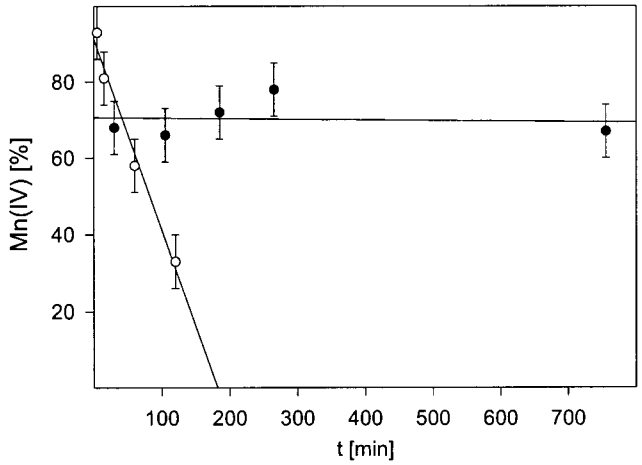


Figure 3. Time dependence of the concentration of Mn^{IV}(salen) complexes **B** (in percent of the total Mn concentration) obtained from the areas of the EPR spectra relative to $CuSO_4$ as external standard: (●) generated from Mn^{III}(salen)Cl complex **A1** + PhIO (5 equiv) and (○) from Mn^{III}(salen)Cl complex **A1** + PPNO (1.1 equiv) + NaOCl solution (2 M, pH 11.3, 10 equiv).

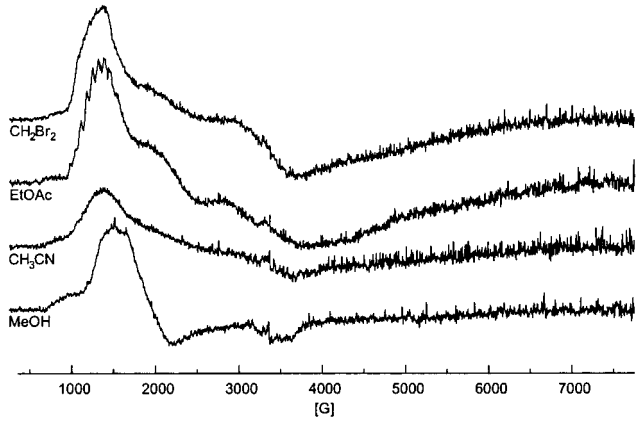


Figure 4. EPR spectra of Mn^{IV}(salen) complexes **B** in different solvents at 77 K (frequency 9.43 GHz, power 2 mW, time constant 40.96 ms, receiver gain 1.6×10^5, modulation amplitude 10.4 G) generated from Mn^{III}(salen) complex **A1** + PPNO (2 equiv) + PhIO (1 equiv).

Further characterization of the Mn^{IV}(salen) complexes **B** was achieved by electrospray-ionization tandem mass spectrometry (ESI-MS/MS), which is the method of choice for the analysis of fragile ionic paramagnetic compounds.[13] Upon addition of a CH_2Cl_2 solution of complex **A1** to a suspension of PhIO in CH_2Cl_2, the molecular ion *m*/*z* 599.3 $[Mn^{III}(salen)]^+$ decreased considerably (to 30% from 100% in the spectrum of the starting material **A1** acquired for comparison); instead, the molecular ions *m*/*z* 616.3 (85%), 634.3 (35%), 650.3 (40%), and 854.3 (100%) dominanted (Figure 6). The assignment of these rests on the product ions, obtained upon low-energy (25 or 35 eV), collision-induced dissociation (CID). CID of molecular ion *m*/*z* 616.3 (complex **B1′**, Scheme 1) yields product ion *m*/*z* 598.3, due to the neutral loss of H_2O (18 amu), and is, thus, identified as the $[HOMn^{IV}(salen)]^+$ ion. The molecular ions *m*/*z* 650.3 and *m*/*z* 652.3 (complex **B1**) show the characteristic Cl isotopic pattern. The product-ion spectrum of *m*/*z* 650.3 displays a fragmentation pattern dominated by the neutral loss of $H^{35}Cl$ (36 amu) and is assigned to the $[ClOMn^{IV}(salen)]^+$ ion. Likewise, precursor ions *m*/*z* 854.3 and *m*/*z* 856.3 represent a Cl isotopic pattern and eliminate 240 or 242 amu (PhI + HCl)

(13) *Electrospray Ionization Mass Spectrometry*; Cole, R. B., Ed.; Wiley: New York, 1997.

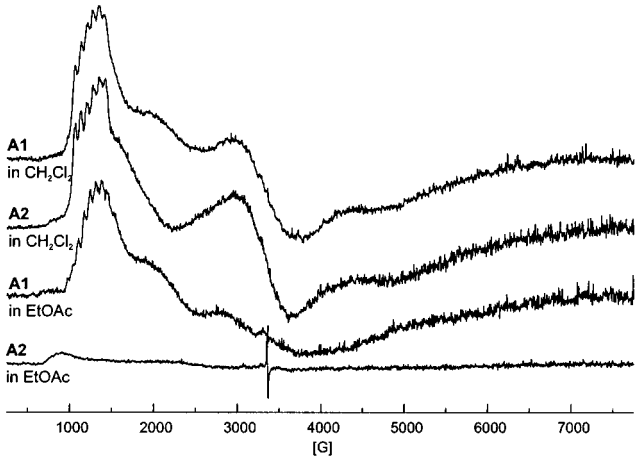


Figure 5. EPR spectra of Mn^{IV}(salen) complexes **B** in CH_2Cl_2 or EtOAc at 77 K (frequency 9.43 GHz, power 2 mW, time constant 40.96 ms, receiver gain 1.6×10^5, modulation amplitude 10.4 G) generated from Mn^{III}(salen) complexes **A1** or **A2** + PPNO (2 equiv) + PhIO (1 equiv).

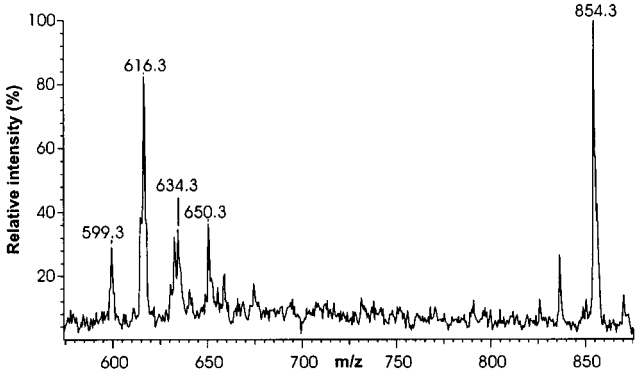


Figure 6. Electrospray mass spectrum of the Mn^{IV}(salen) complexes **B** [obtained directly from the reaction mixture after 5 min of Mn^{III}-(salen) complex **A1** addition to a slurry of PhIO in CH_2Cl_2].

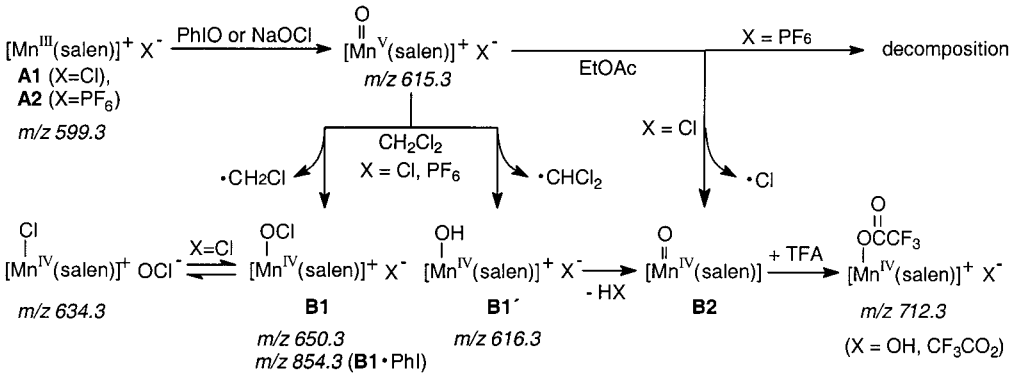
upon collisional activation with 35 eV. These ions are, thus, interpreted as the PhI adduct of complex **B1**. The molecular ions *m*/*z* 634.3 (35%) and *m*/*z* 636.3 were identified as the $[ClMn^{IV}(salen)]^+$ species on the basis of the Cl isotopic pattern and product ions formed by neutral loss of HCl (36 and 38 amu). As additional proof for the assignment of the molecular ions *m*/*z* 650.3 and *m*/*z* 634.3, the neutral loss of $H^{35}Cl$ (36 amu) and $H^{37}Cl$ (38 amu) was monitored. Indeed, the molecular ions *m*/*z* 650.3, 652.3 and *m*/*z* 634.3, 636.3 yielded the productions *m*/*z* 614.3 and *m*/*z* 598.3 with a relative intensity of 3:1, as expected for the Cl isotope distribution, which confirms the assignment of the peaks.

In the case of complex **A2**, except for the molecular ion *m*/*z* 634.3, the same ions were observed as with complex **A1**. In addition, PhIO adducts of these ions were also detected and the initially formed $[OMn^{V}(salen)]^+$ ion (Scheme 1) was evident at *m*/*z* 615.3.

To detect neutral complexes, a few drops of a trifluoroacetic acid (TFA) solution in CH_2Cl_2 were added to the mixture to protonate the neutral complexes. A new molecular ion at *m*/*z* 712.3 appeared, which was assigned to the $[F_3CCOOMn^{IV}$-$(salen)]^+$ cation, formed from the neutral complex **B2**.

A dark green solid precipitated from the CH_2Cl_2 solution of the complexes **B** upon additon of hexane, which on dissolution in CH_2Cl_2 showed the characteristic Mn^{IV} EPR signal observed previously (Figure 1). A chlorine analysis of the solid showed a content of 9.38% Cl for the material derived from complex

Scheme 1



A1 and 6.53% Cl from complex **A2**. Unfortunately, it was not possible to grow adequate crystals of the Mn^{IV}(salen) complexes **B** for X-ray analysis.

To rationalize these EPR and MS results, we suggest the mechanism in Scheme 1 for the formation of the various Mn^{IV} complexes **B**. Reaction of the $[Mn^{III}(salen)]^+X^-$ complexes **A** with PhIO or NaOCl as oxygen sources leads first to the oxo complex $[OMn^{V}(salen)]^+X^-$. In the absence of a substrate, this very reactive triplet species[7] abstracts a Cl or a H atom from the CH_2Cl_2 solvent to afford the complexes $[ClOMn^{IV}(salen)]^+X^-$ (**B1**) or $[HOMn^{IV}(salen)]^+X^-$ (**B1′**). That hydrogen abstraction by the $[OMn^{V}(salen)]^+X^-$ species from organic substrates is possible has been documented for benzylic oxidation catalyzed by Mn^{III}(salen) complexes, which supposedly proceeds through the oxygen-rebound mechanism.[14]

With time, complex **B1′** eliminates HX and forms the neutral complex **B2**. Such a loss of a ligand is expected to be slow for high-spin octahedral complexes. As the Mn^{IV} complexes **B1** and **B1′** bear similar oxygen functionalities, i.e., OCl versus OH, the EPR zero-field-splitting parameters should be similar. Indeed, in the computer simulations of the EPR spectra, these two paramagnetic species appear as one signal with $D = 4.000$ and $E/D = 0.160$. The oxo complex **B2**, however, is distinct and, thus, has different zero-field-splitting parameters ($D = 0.950$ and $E/D = 0.296$ from the computer simulation). The dehydrochlorination of the complex **B1′** (X = Cl) to **B2** is responsible for the changes in the EPR spectrum with time (Figure 1) and, consequently, the relative amounts of the complexes **B1** + **B1′** and **B2** are altered.

Only the **B1** and **B1′** complexes are detected by ESI-MS analysis, because these are cationic. The additionally observed $[ClMn^{IV}(salen)]^+$ ion (*m*/*z* 634.3 in Scheme 1) in the case of complex **A1** is explained by OCl/Cl ligand exchange from complex **B1**. Upon addition of TFA to the solution of the complexes **B1** and **B2**, the neutral complex **B2** is protonated to form **B1′** again; however, the OH^- ligand is quickly replaced by the $CF_3CO_2^-$ anion and the resulting $[F_3CCOOMn^{IV}(salen)]^+$ complex is detected by ESI-MS analysis (*m*/*z* 712.3 in Scheme 1).

Addition of the nonpolar solvent hexane to the solution of complexes **B1** and **B2** mainly precipitated the ionic complexes **B1** and **B1′**. For the complex **B1** derived from **A1**, which contains also a Cl^- as counterion, i.e., two Cl atoms per complex, a Cl content of 10.33% was calculated. The measured value of 9.38% suggests that about 25% of complex **B1′** is also contained in the material. The complex **B1** derived from **A2** contains only one Cl atom per complex, which corresponds to 4.54% Cl content. The measured value of 6.53% implies that during the reaction the Cl is transferred from the solvent to the complex. Thus, the mechanistic interpretations in Scheme 1 are also consistent with the chlorine analysis of the isolated Mn^{IV} complexes.

In nonhalogenated solvents such as EtOAc, however, there can be no halogen abstraction from the solvent. Since hydroxylation of hydrocarbons through H abstraction is documented for OMn^{V}(salen) species,[14] it should in principle be possible to abstract a H atom from EtOAc and, in fact, more likely than from CH_2Cl_2 (the bond dissociation energies are 397.5 kJ mol^{-1} for EtOAc[15] and 411.7 kJ mol^{-1} for CH_2Cl_2[16]). However, chloride ions must be available to generate the OMn^{IV}(salen) species in EtOAc. Indeed, by starting from **A1** (X = Cl), Mn^{IV} complexes were detected by EPR spectroscopy also in a variety of nonhalogenated solvents (Figure 4), whereas from **A2** (X = PF_6) in EtOAc no paramagnetic signals were seen (Figure 5). These findings are consistent with the following rationale: The initially formed OMn^{V}(salen) complex (from **A1**) suffers inner-sphere electron transfer with the ligated Cl^- counterion to be reduced to the OMn^{IV}(salen) complex **B2**. With the noncoordinating PF_6^- counterion in complex **A2** and no chlorine source (CH_2Cl_2, Cl^-), such a redox process is unlikely and the OMn^{V}(salen) complex is destroyed without formation of a Mn^{IV}(salen) species. The failure to detect paramagnetic intermediates by EPR spectroscopy is taken as evidence for this.

Our in-depth EPR and MS studies reveal that the reaction of Mn^{III}(salen) complexes **A** with an oxygen-atom source in the absence of an olefin leads to paramagnetic Mn^{IV} complexes **B** (Scheme 1) if either a Cl^- serves as counterion or CH_2Cl_2 is employed as solvent. Moreover, the present data provide circumstantial experimental evidence for the very reactive OMn^{V}(salen) complex as the initial reactive species in the Mn^{III}(salen)-catalyzed epoxidation. It is difficult to envisage what highly reactive manganese species other than Mn^{V}(salen) may serve for the formation of the Mn^{IV}(salen) complexes **B**. To assess the role of the herein identified, novel paramagnetic Mn^{IV}(salen) complexes **B** as oxygen-transfer agents, we explored their propensity to epoxidize olefins.

Oxidation of Olefins by the Mn^{IV}(salen) Complexes B. As model substrates, two conjugated olefins were chosen, namely 1,2-dihydronaphthalene (**1**) and styrene (**2**), which have been epoxidized catalytically by Mn^{III}(salen) complexes (Table 1).

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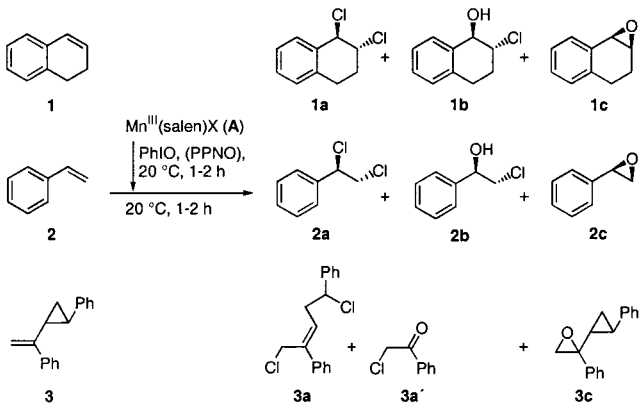
(15) Bordwell, F. G.; Harrelson, J. A., Jr.; Zhang, X. *J. Org. Chem.* **1991**, *56*, 4448−4450.

(16) *CRC Handbook of Chemistry and Physics*, 76th ed.; Lide, D. R., Ed.; CRC Press: Boca Raton, 1995.

Table 1. Oxidation of 1,2-Dihydronaphthalene (**1**), Styrene (**2**), and Olefin **3** by the *in-situ*-Generated Mn^{IV}(salen) Complexes **B1** and **B2**



entry	complex[a]	solvent	m.b.[b] [%]	convn[c] [%]	product distribution[d]		
					1a	**1b**	**1c**
1	**A1**[e]	CH_2Cl_2	73	78	47	22	31[f]
2	**A1**[g]	CH_2Cl_2	> 95	34	60	26	14[f]
3	**A1**	EtOAc	64	20	5		95[f]
4	**A2**	CH_2Cl_2	56	40	68	16	16[f]
5	**A2**	EtOAc	72	0			
					2a	**2b**	**2c**
6	A1	CH_2Cl_2	29	64	62	*h*	38
7	**A1**	EtOAc	27	18			100
8	**A2**	CH_2Cl_2	35	34	86	*h*	14
9	**A2**	EtOAc	19	0			
					3a	**3a′**	**3c**
10	**A1**	CH_2Cl_2		55	53	47	
11	**A1**[g]	CH_2Cl_2	>95	55	63	37	
12	**A1**	EtOAc	>95	12			100
13	**A2**	CH_2Cl_2	93	46	43	57	
14	**A2**	EtOAc	67	0			

[a] The Mn^{III}(salen) complex **A** was first oxidized at 20 °C for 1−2 h and then the resulting Mn^{IV}(salen) complexes **B** were added to the olefin. [b] The mass balances are defined as the sum of all products and unreacted olefin versus initially used olefin, and were determined by ^{1}H NMR spectroscopy (see Supporting Information). [c] Determined from the ^{1}H NMR spectra by assuming that 1 equiv of the Mn^{IV}(salen) complex was consumed per 1 equiv of product. [d] Normalized to 100% conversion; very minor amounts of oxidative decomposition products of the salen ligand were also detected. [e] No PPNO was added. [f] Minor amounts of naphthalene were also formed as byproducts. [g] The isolated Mn^{IV}(salen) complex was used. [h] Product **2b** was formed in such minor amounts that it was only detected by GC-MS and not by ^{1}H NMR analysis.

With complexes **A1** and **A2**, mainly dichlorination of the olefin **1** (entries 1, 2, and 4) was observed in CH_2Cl_2, to afford *trans*-1,2-dichloro-3,4-dihydronaphthalene (**1a**). The oxyfunctionalized products *trans*-1-hydroxy-2-chloro-3,4-dihydronaphthalene (**1b**) and 1,2-epoxy-3,4-dihydronaphthalene (**1c**) were formed in lower amounts. These products were obtained not only with the in situ-generated Mn^{IV} complexes **B** but also with the isolated complex that was redissolved in fresh CH_2Cl_2 (entry 2). In EtOAc, however, complex **A1** led in low conversion almost exclusively to the epoxide **1c** (entry 3), while complex **A2** in EtOAc was unreactive toward olefin **1**. The results with styrene (**2**) as substrate (entries 6−9) parallel those obtained with 1,2-dihydronaphthalene (**1**), except that only traces of the styrene chlorohydrin (**2b**) were detected. This lack of reactivity is in agreement with the fact that under these conditions no EPR signal was detected (Figure 5) and, thus, no Mn^{IV}(salen) species was generated to conduct oxidation.

To gain mechanistic insight into these oxidations, the olefin **3** was chosen as radical probe.[6,17] The Mn^{IV}(salen) complexes generated from **A1** and **A2** in CH_2Cl_2 gave with substrate **3** the chlorinated, ring-opened products **3a** and **3a′** (entries 10 and 13); in fact, no epoxide (**3c**) could be detected. Again, also addition of the isolated complex to a CH_2Cl_2 solution of olefin **3** resulted in the same products (entry 11). In contrast, the Mn^{IV}-(salen) complex formed from **A1** in EtOAc oxidized the olefin **3** in low conversion cleanly to the epoxide **3c** with no ring-opening products (entry 12). Complex **A2** in EtOAc was again unreactive toward the olefin (entry 14).

In regard to the enantioselectivity of the chlorination and epoxidation reactions, the enantiomeric excess (ee) was determined by multidimensional gas chromatography (MDGC) and HPLC on chiral phases. Thus, the reaction between the Mn^{IV}-(salen) complexes **B** formed from **A1** and PhIO in CH_2Cl_2 with olefin **1** (entry 1) afforded the products **1a** (5% ee), **1b** (23% ee), and **1c** (25% ee) in much lower enantioselectivity compared to the catalytic mode of operation (53% ee for **1c** in the control reaction described below).

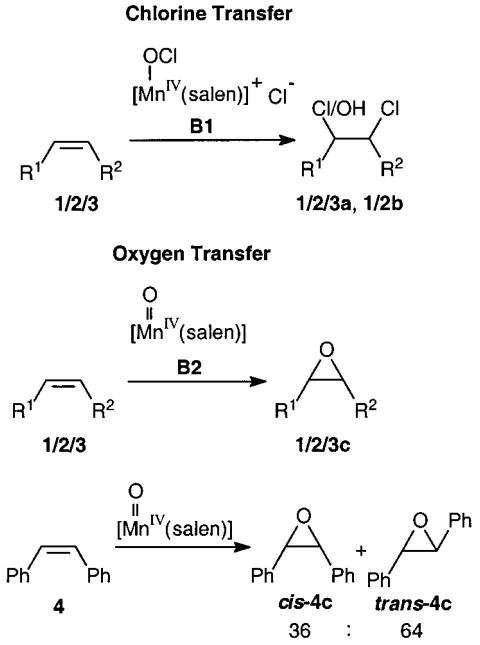
To ascertain whether the identified products persist under the reaction conditions and, thus, are not transformed into each other, several control reactions were conducted. Thus, the independently synthesized epoxides **1c** and **3c** were submitted to a CH_2Cl_2 solution of the in situ-formed Mn^{IV} complexes **B** (from complex **A1**). They were, however, reisolated unchanged after a reaction time of 2 h. The same was true for chlorohydrin **1b**, which was not transformed into the epoxide **1c**. The formation of product **3a′**, however, was shown to originate from the oxidative cleavage of the dichloroproduct **3a**, since submission of the latter to a CH_2Cl_2 solution of the Mn^{IV} complexes **B** gave within 1 h the cleavage product **3a′** in 6% yield.

To assess the relevance of the herein described Mn^{IV}(salen) complexes **B** in the catalytic epoxidation reactions with Mn^{III}-(salen) complexes, the oxidation of the olefins **1**, **2**, and **3** was conducted under the usual catalytic conditions (1 equiv of the olefin, 5−7 mol % of the catalyst **A1**, 0.3 equiv of PPNO, and 1.5−2.0 equiv of the oxygen source PhIO in CH_2Cl_2 at 20 °C) and the products submitted to ^{1}H NMR and GC-MS analyses. Only the usual epoxides **1c** and **2c** were observed; in the case of 1,2-dihydronaphthalene (**1**), also 30% naphthalene was found. More significantly, the chlorinated products **1a** and **2a** were not detected. With olefin **3**, the catalytic oxidation with Mn^{III}-(salen)/PhIO gave mainly epoxide **3c**; however, several ring-opened products were also found as byproducts, in particular the dichloro product **3a**. Thus, these findings corroborate the preliminary results reported by Åkermark and Norrby[6] with Mn^{III}(salen)/PhIO.

These oxidation results may be rationalized in terms of the different reactivity of the two Mn^{IV} complexes **B1** and **B2** (Scheme 2). The Mn^{IV}(salen) complex **B1** chlorinates the olefins in a stepwise pathway, as evidenced by the chlorine-containing ring-opening product **3a**. In this context, it is important to emphasize that the chlorinated products were also observed when the isolated Mn^{IV}(salen) complexes **B** were added to a CH_2Cl_2 solution of the olefin **1** or **3**. Thereby it has been unequivocally demonstrated that the Mn^{IV}(salen) complex **B1** is the chlorinating agent and not a reactive Cl species (Cl_2, HOCl), which might have been formed from CH_2Cl_2 during the generation of the Mn^{IV}(salen) complexes **B**. Further evidence for this fact is the enantiomeric excess of the reaction products (23% for **1b** and 5% for **1a**) as these engage the chiral salen ligand in the oxygen-transfer step.

(17) Donnelly, J. A.; Hoey, J. G.; O'Brien, S.; O'Grady, J. *J. Chem. Soc., Perkin Trans. 1* **1973**, 2030−2033.

Scheme 2



As far as the mechanism of the chlorination by complex **B1** is concerned, it is important to realize that the radical probe **3** does not differentiate between a radical and an electrophile addition to the double bond.[18] Indeed, electrophilic addition would lead to a cyclopropylcarbinyl cation, whose nonclassical behavior is well established.[19] Recent solvolysis experiments of 3-arylcyclobutyl tosylates and ab initio computations have shown that with a cation-stabilizing group such as phenyl on the cyclopropyl ring, solvolysis only affords homoallylic products.[20] Thus, the formation of the ring-opened product **3a** may in principle be envisioned through a radical as well as a cation pathway. The radical option seems, however, to be unlikely, because the abstraction of a Cl atom from the Mn^{IV}-(salen) complex **B1** would regenerate the very reactive OMn^{V}-(salen) complex. By contrast, in the cation alternative, the positively polarized Cl atom in complex **B1** is electrophilically added to the double bond to afford a benzylic cation, which is nucleophilically trapped by chloride ions or water[21] to afford the dichloro products and the chlorohydrins (Scheme 3). In the case of olefin **3**, the ring-opened dichloro product is obtained due to the rearrangement of the benzylic cation before nucleophilic trapping.

This reaction sequence bears a remarkable resemblance to that proposed for the chlorination catalyzed by chloroperoxidase (CPO),[22] which has been supported by recent studies on Fe(porph) chemical model systems (Scheme 4).[23] Besides the chlorination of activated C−H bonds (e.g., in dimedon or aromatic compounds), CPO also catalyzes the halohydration of glycals.[24] Although the enzyme itself has been a topic of considerable interest during the past decades, model systems are still scarce.[23,25] In addition to the Fe(porph) complexes mentioned above, there is the example of a polymer-supported Mn(porph) complex that catalyzes the chlorination of dimedon by H_2O_2 and Cl^-.[25] Consequently, we have observed for the first time that Mn^{III}(salen) complexes also display CPO-type activity, besides their usual role as effective catalysts in asymmetric epoxidation.

In contrast to **B1**, complex **B2** does epoxidize the olefins **1**−**3**. When CH_2Cl_2 is used as solvent, both complexes **B1** and **B2** are formed (cf. Scheme 1) and, thus, chlorination as well as epoxidation were observed (Table 1, entries 1, 2, 4 and 6, 8). However, in EtOAc as solvent, from **A1** the **B2** Mn^{IV}complex is formed (Scheme 1) and accordingly only epoxide is found (Table 1, entries 3, 7, and 12); moreover, from **A2** in EtOAc no oxidation was detected (Table 1, entries 5, 9, and 14).

As for the mechanism of the epoxidation by complex **B2**, the exclusive formation of the epoxide **3c** (no ring-opened products) suggests a nonradical/noncation oxygen transfer; however, the phenyl substitution at the carbinyl-radical site renders this radical clock rather slow ($k = 3.6 \times 10^8$ s^{-1}).[26] A more appropriate radical probe is the cis/trans isomerization of *cis*-stilbene, for which the rate constant for rotation around the C−C single bond is ca. 10^{11} s^{-1}.[27] Therefore, *cis*-stilbene was treated with a solution of the complex **B2** formed from **A1** and PhIO in EtOAc to afford the stilbene oxide as the only product in a 36:64 cis/trans ratio at 14% conversion (Scheme 2). This fact confirms that a stepwise radical mechanism is operating in the oxygen-transfer process of the Mn^{IV}(salen) complex **B2**, which is consistent with the findings by Groves and Bruice[5] for the epoxidation with analogous OMn^{IV}(porph) complexes. We conclude that the Mn^{IV}(salen) complexes described herein react with olefins either by stepwise electrophilic chlorination (complex **B1**) or by stepwise radical epoxidation (complex **B2**).

Are the herein described Mn^{IV}(salen) complexes **B** of any relevance in the usual Jacobsen−Katsuki catalytic epoxidation reaction with Mn^{III}(salen) complexes? Under the conditions typical for such Mn^{III}(salen)-catalyzed epoxidations (olefin, oxygen source, catalyst, and additive all together present from the start), none of the chlorinated products were detected for the olefins **1** and **2** as substrates. Therefore, under theses conditions, no significant amount of the $ClOMn^{IV}$(salen)

(18) Newcomb, M.; Le Tadic-Biadatti, M.-H.; Chestney, D. L.; Roberts, E. S.; Hollenberg, P. F. *J. Am. Chem. Soc.* **1995**, *117*, 12085−12091.

(19) Wiberg, K. B.; Hess, B. A., Jr.; Ashe, A. J., III In *Carbonium Ions*; Olah, G. A., Schleyer, P. v. R., Eds.; Wiley-Interscience: New York, 1972; Vol. III, pp 1295−1345.

(20) Wiberg, K. B.; Shobe, D.; Nelson, G. L. *J. Am. Chem. Soc.* **1993**, *115*, 10645−10652.

(21) Both nucleophiles should be present in the solution in low concentrations. In the case of **A1** as starting material, it is also possible that the counterion is the source of the chloride ion.

(22) Libby, R. D.; Shedd, A. L.; Phipps, A.; Beachy, T. M.; Gerstberger, S. M. *J. Biol. Chem.* **1992**, *267*, 1769−1775.

(23) (a) Wagenknecht, H.-A.; Claude, C.; Woggon, W.-D. *Helv. Chim. Acta* **1998**, *81*, 1506−1520. (b) Wagenknecht, H.-A.; Woggon, W.-D. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 390−392.

(24) Liu, K. K.-C.; Wong, C.-H. *J. Org. Chem.* **1992**, *57*, 3748−3750.

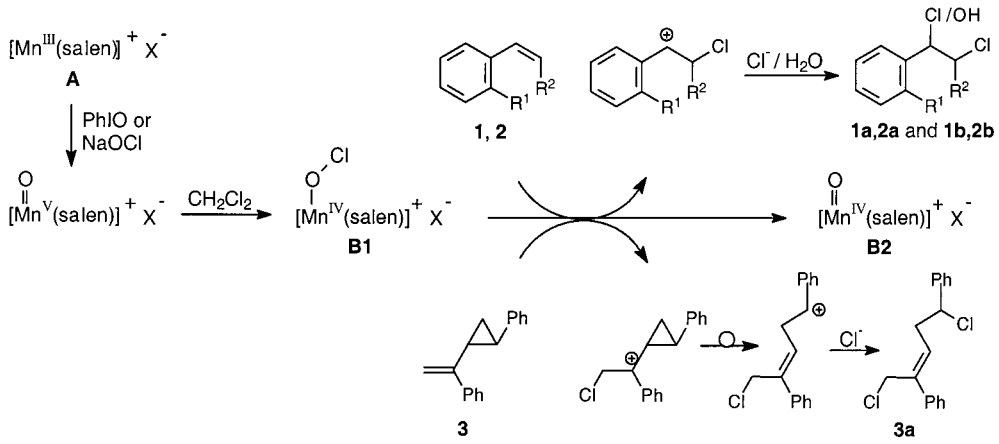
(25) Labat, G.; Meunier, B. *J. Chem. Soc., Chem. Commun.* **1990**, 1414−1416.

(26) The rate constant for the opening of the secondary benzyl radical in *trans*-1-benzyl-2-phenylcyclopropane has been estimated to have this value (Hollis, R.; Hughes, L.; Bowry, V. W.; Ingold, K. U. *J. Org. Chem.* **1992**, *57*, 4284−4287). Since such secondary and tertiary radicals usually ring-open at similar rates (Newcomb, M.; Tanaka, N.; Bouvier, A.; Tronche, C.; Horner, J. H.; Musa, O. M.; Martinez, F. N. *J. Am. Chem. Soc.* **1996**, *118*, 8505−8506), this value was assumed for the radical clock **3**.

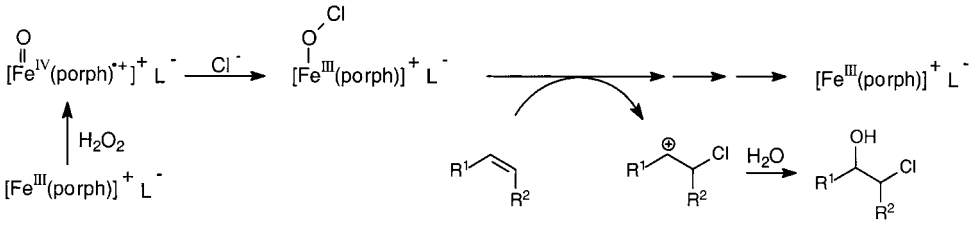
(27) For the ethyl radical, a rotation barrier of $E_a = 0.06$ kcal/mol has been determined experimentally (Sears, T. J.; Johnson, P. M.; Jin, P.; Oatis, S. *J. Chem. Phys.* **1996**, *104*, 781−792). For a value of $A = 8.7 \times 10^{12}$ s^{-1} (determined by the torsional motion of 290 cm^{-1} in ethane, cf.: Horn, B. A.; Herek, J. L.; Zewail, A. H. *J. Am. Chem. Soc.* **1996**, *118*, 8755−8756), the Arrhenius equation gives a rate constant for rotation of 7.9×10^{12} s^{-1} about the C−C bond. In the benzyl radical derived from the epoxidation of stilbene (cf. structure),

the steric hindrance should be larger in view of the two phenyl groups and the bulky OMn(salen) moiety. A conservative estimate of 1−3 kcal/mol is proposed for the rotation barrier, which results in rate constants of rotation between 1.6×10^{12} and 5.5×10^{10} s^{-1}. We are grateful to Prof. M. Newcomb (Wayne State University, Detroit) for advice on this issue.

Scheme 3



Scheme 4



complex (**B1**) is formed. With olefin **3**, however, the chlorinated products detected with **B1** confirm the preliminary studies by Norrby and Åkermark,[6] in which the observed ring-opened products have been proposed to originate from oxidations by Mn^{IV}(salen) complexes. Nevertheless, even if only trace amounts of Mn^{IV}(salen) complexes **B** were formed and they would not effectively compete to reveal detectable quantities of byproducts, the nonlinearities in Eyring plots, as suggested by Akermark[7] et al. and observed by Katzuki[8] et al., may derive therefrom.

Conclusion

Clearly, and mechanistically and preparatively important, the present results demonstrate that in the Mn^{III}(salen)-catalyzed epoxidation, the order of mixing of the components is important: In the absence of an olefinic substrate, the initially formed OMn^{V}(salen) complex transforms into the Mn^{IV}(salen) complexes **B**, i.e., the hypochlorite-ligated **B1** in CH_2Cl_2 and the oxo one **B2** in EtOAc. **B1** is responsible for electrophilic chlorination (chloroperoxidase-type activity), while **B2** performs radical-type epoxidation. Be this as it may, fortunately, under the usual Jacobsen−Katsuki epoxidation conditions (all components together from the very start), the Mn^{IV}(salen) complexes **B** play a minor, if at all noticeable, role. Nevertheless, these complexes, which for the first time were fully characterized by means of EPR and MS analyses as well as product studies, have been postulated in the literature to be responsible for radical-type oxidation products.

Acknowledgment. The Deutsche Forschungsgemeinschaft (SFB 347 “Selektive Reaktionen Metall-aktivierter Moleküle”) and the Fonds der Chemischen Industrie are thanked for generous financial support, Drs. E. Bill and H. Hummel (Max-Planck-Institut für Strahlenchemie, Mülheim) for help with the interpretation of the EPR spectra and their simulation, and Dr. M. Bröring (Institut für Anorganische Chemie, Würzburg) for fruitful discussions. We are grateful to Prof. P. Schreier (Institut für Pharmazie und Lebensmittelchemie, Würzburg) for making his facilities available to us to carry out the ESI-MS measurements. This work is dedicated to Prof. Dr. R. Neidlein (Heidelberg) on the occasion of his 70th birthday.

Supporting Information Available: General experimental procedures and the characterization of the products (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

JA0005082