These structures are consistent with the shorter C–C bond and slightly longer C–N bond found in $[C(CN)_3]^-$ as compared to CH_3CN or to those in other R_3CCN compounds, e.g., for R = CN, $r(C—C) = 1.484$ Å and $r(C≡N) = 1.161$ Å.[34] They are also consistent with the planarity of the anion.

The calculated frequencies for the cation are given in Table VI and are quite similar to those for the anion. Essentially no change is found in the CN frequencies as compared to the anion. The C–C stretches are slightly higher in the cation than in the anion. The largest differences are found in the out-of-plane modes. The A_2'' mode at 943 cm^{-1} is $\sim$100 cm^{-1} higher in the cation than in the anion. This is consistent with the cation being harder to deform out-of-plane than the anion as is known for the case of simply substituted carbenium ions and carbanions. The E'' out-of-plane bend at 486 cm^{-1} in the cation is $\sim$120 cm^{-1} below that in the anion. Beaumont et al.[12] have studied the vibrational spectrum of the $[SbCl_5][ClC(CN)_3]$ adduct. If $[C(CN)_3]^+$ is present, we can assign the bands shown in Table VII as possibly being due to the cation; however, due to the difficulty in obtaining the experimental spectrum these assignments are only tentative.

The molecular orbitals for the cation differ somewhat from those in the anion. The HOMO is the out-of-plane π orbital of e'' symmetry and the next two orbitals are of a_2' and e' symmetry (in-plane π-type orbitals). The HOMO predicted from the anion would have a_2' symmetry, but this is clearly not the case for the cation. The LUMO for this system is of a_2'' symmetry and is clearly separated from the remaining virtual orbitals. The lowest lying electronic transitions for the cation will be from the top few occupied orbitals to the LUMO. In this case the HOMO → LUMO transition would be allowed.[35]

Comparison of the vibrational frequencies for $[C(CN)_3]^+$ and $[C(CN)_3]^-$ provides further insight into the structures of these compounds. The general conclusion reached from such a comparison is that the frequencies are quite similar. In terms of a valence bond argument this is consistent with the resonance forms for the anion contributing a comparable amount of those for the cation. One can also examine the molecular orbitals and reach a similar conclusion. The HOMO of the anion has essentially no density on C_N. There is no direct overlap between C(1) and N and removal of two electrons to form the cation should not significantly alter the bonding. Thus, little change in the frequencies would be expected.

The Mulliken populations are given in Table VIII for the cation. As in the case of the excess negative charge on the anion, the excess positive charge on the cation is found on the same atoms C(1) and N. Very little change in the charge is found on C_N in going from the anion to the cation. For the cation the CN out-of-plane π bond is polarized $C^{\delta-}–N^{\delta+}$. The CN in-plane bond is not polarized with p_Y populations of 1.01 e^- on C_N and 1.03 e^- on N. The out-of-plane populations on C(1), C_N, and N are similar to those found in the simpler compound[33] $[H_2CCN]^+$ where the populations are 0.25 e^- on C(1), 1.13 e^- on C_N, and 0.60 e^- on N with a DZ+P basis set. Of course three resonance structures of the form $[R_2C{=}C{=}N]^+$ contribute to the compound with R = CN while only one contributes to the compound with R = H. Thus, the electron density on C(1) for R = CN will be larger than that for R = H. Since each resonance structure contributes less electron density on N, the electron density on N will be greater for R = CN than for R = H when only one resonance structure contributes.

Acknowledgment. We thank William M. Reiff and J. H. Zhang (Northeastern University) for obtaining the ^{57}Fe Mössbauer Spectra, B. Chase (duPont) for obtaining infrared and Raman spectra, and E. Mattews and R. E. Richardson (duPont) for obtaining electronic absorption spectra for $[Fe(C_5Me_5)_2]^+\cdot[C(CN)_3]^-$. We also thank R. M. Hilmer (duPont) for developing the digitization and complementary plotting software used in this research.

Registry No. $[Fe(C_5Me_5)_2]^+\cdot[C(CN)_3]^-$, 100021-50-9; $K[C(CN)_3]$, 34171-69-2; $[Fe(C_5Me_5)_2]^+\cdot[BF_4]^-$, 100021-51-0; $[PPN]^+\cdot[C(CN)_3]^-$, 100021-52-1; $[PPN]^+\cdot Cl^-$, 21050-13-5; $[n\text{-}Bu_4N]^+\cdot[C(CN)_3]^-$, 74908-12-6; $[n\text{-}Bu_4N]^+[BF_4]^-$, 429-42-5.

Supplementary Material Available: Complete listings of the anisotropic thermal parameters (Table II) and amplitudes and structure factors (10 pages). Ordering information is given on any current masthead page.

---

(34) Britton, D. *Acta Crystallogr.* **1974**, *B30*, 1818.

(35) An estimate of the ionization potential (IP) for $[C(CN)_3]\cdot$ can be made from the difference in energies between $[C(CN)_3]^-$ and $[C(CN)_3]^+$ and our estimate of the electron affinity of $[C(CN)_3]\cdot$.

Oxygenation of Styrene by Cytochrome P-450 Model Systems: A Mechanistic Study

James P. Collman,* Thomas Kodadek, and John I. Brauman

Contribution from the Department of Chemistry, Stanford University, Stanford, California 94305. *Received July 18, 1985*

Abstract: The manganese and iron porphyrin catalyzed oxygenation of styrene results in the production of phenylacetaldehyde as well as the expected epoxide. It is demonstrated that aldehyde is a primary product and does not result from isomerization of styrene oxide. Isotope labeling studies show that one of the β hydrogen atoms of styrene migrates to the benzylic carbon in the course of aldehyde formation. Experiments using cis and trans deuterated styrenes reveal that there is a stereoelectronic preference for migration of the hydrogen cis to the aromatic ring. Styrene, styrene-d_8, and *cis*-β-deuteriostyrene yield similar ratios of epoxide to aldehyde, indicating that β hydrogen migration occurs after the rate-determining step for formation of phenylacetaldehyde. The mechanism of this rearrangement is discussed. Some new information concerning the mechanism of olefin epoxidation by these catalysts is also presented. These results may have relevance to the mechanism of alkene oxygenation by the cytochrome P-450 monooxygenase enzymes.

Well-characterized examples of biological organometallic complexes are fairly rare, although many metalloenzymes catalyze reactions of organic substrates. It seems possible that some of these catalytic cycles involve as yet undetected metal–carbon bonded species as unstable intermediates. We have speculated that the cytochrome P-450's, an iron–heme based family of mo-

0002-7863/86/1508-2588$01.50/0

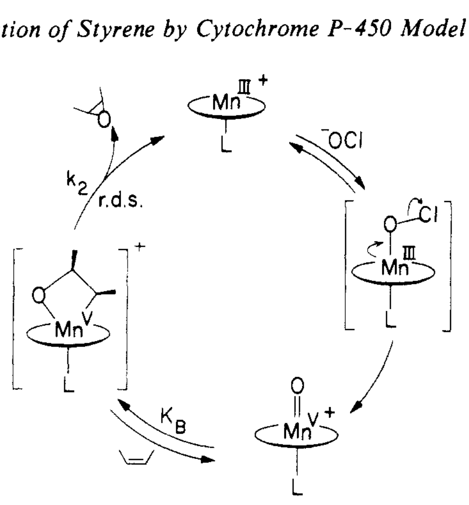


Figure 1. Proposed mechanism for the manganese porphyrin catalyzed epoxidation of olefins by hypochlorite.

nooxygenase enzymes, may be members of this class.[1] The P-450's catalyze the addition of an oxygen atom derived from molecular oxygen to a variety of organic substrates, including alkanes and alkenes. The active oxidant is generally believed to be a high valent iron–oxo complex with the metal formally in the 5+ oxidation state.[2] The resting Fe(III) enzyme can be shunted directly to the active state under anaerobic conditions by treatment with oxygen atom transfer reagents, such as iodosylbenzene.[3]

The desire to understand in detail the molecular mechanisms employed by the P-450 enzymes to carry out these unique oxygenation reactions has resulted in a great deal of work on synthetic porphyrin catalysts.[4–6] Most of these systems generate the high valent oxo species via shunt chemistry, although O_2 activation has recently been reported.[7–9] We have studied one of these shunt systems in detail.[1,10] This is the olefin epoxidation system discovered by Meunier, which employs a manganese porphyrin to catalyze the transfer of an oxygen atom from hypochlorite to an alkene in a phase-transfer reaction.[11] The hypochlorite system is unique in two respects. Nitrogenous axial ligands have a profound effect on the rate of the reaction, catalyst stability, and product stereochemistry.[12,13] Second, the rates of epoxide formation are extremely rapid when compared to most other P-450 model reactions, reaching a dozen catalyst turnovers per s in the best case.

We have reported the results of a kinetic study of this system[10] which revealed that the oxygen atom transfer to the olefin is the rate-determining step of the catalytic cycle. Furthermore, the overall reaction displays substrate saturation kinetics, demanding the intermediacy of an oxo–olefin intermediate in rapid equilibrium with the manganese–oxo species and free substrate (Figure 1). Both the reversible formation of this intermediate and its decomposition to epoxide proceed, in general, with retention of olefin stereochemistry. Radical species are not thought to be involved in either step of the atom transfer reaction since, in addition to the observed stereospecificity, radical stabilizing substituents on the olefin do not greatly affect K_B or k_2 (Figure 1).

We have postulated that the oxo–olefin intermediate is a metallaoxetane formed by a 2 + 2 cycloaddition. Such a species is consistent with all of our data as well as with what is known of the P-450 catalyzed epoxidation of olefins. Unfortunately, we have been unable to characterize this interesting complex spectroscopically, mainly due to its very poor EPR and NMR spectra.[14] Therefore, while structures such as a simple olefin coordination complex do not fit our data as well as the metallacycle, they cannot be rigorously ruled out. The structure of the intermediate is a problem of considerable importance for a number of reasons. Chief among these is the possibility that cytochrome P-450 itself operates by an analogous mechanism. This proposition is supported by our recent discovery that an iron porphyrin based P-450 like olefin epoxidation system also proceeds through an oxo–olefin complex.[15] This iron-catalyzed reaction employs a different porphyrin ((tetrakis(pentafluorophenyl)porphyrinato)iron(III) chloride) (FePFPCl) and a different oxidant (pentafluoroiodosylbenzene (F_5PhIO))[16] (eq 1), yet the oxo–olefin intermediate displays properties astoundingly similar to the manganese analogue.

$$\text{olefin} + F_5PhIO \xrightarrow[CH_2Cl_2]{FePFPCl} \text{epoxide} + F_5PhI \qquad (1)$$

In the hope of shedding further light on this problem, we have undertaken a detailed study of the manganese and iron porphyrin catalyzed oxygenation of styrene and some deuterated derivatives. This olefin is interesting in that phenylacetaldehyde is a primary oxygenation product in addition to styrene oxide, as first shown by Groves and Myers.[17] We describe here experiments directed toward the elucidation of the mechanism of aldehyde formation as well as further information concerning the nature of the oxo–olefin intermediate in both the manganese and iron based systems.

Results

Mechanism of Aldehyde Formation. The (tetraphenylporphyrinato)manganese(III) chloride (MnTPPCl) catalyzed hypochlorite oxygenation of styrene results in the production of a 4.6:1 molar ratio of styrene oxide and phenylacetaldehyde (at 36% conversion) as determined by ^1H NMR. Phenylacetaldehyde was also produced in the FePFPCl-catalyzed reaction between styrene and pentafluoroiodosylbenzene (F_5PhIO). The epoxide to aldehyde ratio in this case was 14.3:1 (45% conversion). In neither case was acetophenone present in the product mixture.

Controls show that styrene oxide is stable to both sets of reaction conditions. Additionally, aldehyde production is constant with

---

[1] (a) We have proposed that this reaction proceeds via a metallaoxetane intermediate. See: Collman, J. P.; Brauman, J. I.; Meunier, B.; Raybuck, S. A.; Kodadek, T. *Proc. Natl. Acad. Sci. U.S.A.* **1984**, *81*, 3245. (b) Other have considered a metallacyclic intermediate in the transfer of an oxygen atom from iron-oxo hemes to olefins but discarded it in favor of a concerted mechanism based on the data available at the time.[1c] Sharpless first proposed the intermediacy of metallaxetanes in the chromyl chloride oxidation of olefins.[1d] (c) Groves, J. T.; Nemo, T. E. *J. Am. Chem. Soc.* **1983**, *105*, 5786. (d) Sharpless, K. B.; Teranishi, A. Y.; Bäckvall, J. E. *J. Am. Chem. Soc.* **1977**, *99*, 3120.

[2] The 5+ oxidation state is meant only to designate that the active oxidant is 2 oxidation equiv above Fe^{III}PorX. No assignment of the electronic configuration of the active species (i.e., Fe(V) porphyrin radical cation) is intended.

[3] White, R. E.; Coon, M. J. *Annu. Rev. Biochem.* **1980**, *49*, 315.

[4] Groves, J. T.; Nemo, T. E.; Myers, R. S. *J. Am. Chem. Soc.* **1979**, *101*, 1032.

[5] Smegal, J. A.; Hill, C. L. *J. Am. Chem. Soc.* **1983**, *105*, 3515.

[6] Groves, J. T.; Kruper, W. J. *J. Am. Chem. Soc.* **1979**, *101*, 7613.

[7] Tabushi, I.; Yazaki, A. *J. Am. Chem. Soc.* **1981**, *103*, 7371.

[8] Khenkin, A. M.; Shteinman, A. A. *J. Chem. Soc., Chem. Commun.* **1984**, 1219.

[9] Fauvet, M. P.; Gaudemer, A. *J. Chem. Soc., Chem. Commun.* **1981**, 874.

[10] Collman, J. P.; Brauman, J. I.; Meunier, B.; Hayashi, T.; Kodakek, T.; Raybuck, S. A. *J. Am. Chem. Soc.* **1985**, *107*, 2000.

[11] Meunier, B.; Guilmet, E.; De Carvallo, M. E.; Poibanc, R. *J. Am. Chem. Soc.* **1984**, *106*, 6668.

[12] Guilmet, E.; Meunier, B. *Nouv. J. Chem.* **1982**, *6*, 511.

[13] Collman, J. P.; Kodadek, T.; Raybuck, S. A.; Meunier, B. *Proc. Natl. Acad. Sci. U.S.A.* **1983**, *80*, 7039.

[14] Solutions of the presumed active catalyst are stable in the presence of olefins at ~78 °C. The NMR spectra of such solutions are *very* broad (consistent with the paramagnetic nature of the complex) and contain many interfering impurities as a result of exposure to the hypochlorite solution. These solutions exhibit no strong EPR signals.

[15] Collman, J. P.; Kodadek, T.; Raybuck, S. A.; Brauman, J. I.; Papazian, L. M. *J. Am. Chem. Soc.* **1985**, *107*, 4343.

[16] (a) For the first report of the use of F_5PhIO in P-450 model reactions see: Traylor, P. S.; Dolphin, D.; Traylor, T. G. *J. Chem. Soc., Chem. Commun.* **1984**, 279. (b) Traylor and co-workers have recently reported a study of a similar iron porphyrin catalyzed reaction[16c] but with alcohol and water included as cosolvents to solubilize F_5PhIO. *Under these conditions*, they found *formation* of the active oxidant (presumably an iron-oxo complex) to be the rate-determining step. This is in contrast to our study[15] (conducted *without* alcohol and water as cosolvent) which is consistent with decomposition of a reversibly formed iron-oxo-olefin complex to epoxide being rate determining. Although the reason for the *apparent* discrepancy between our study and Traylor's is not completely clear, we believe it is possible that the addition of alcohol to the epoxidation reaction accelerates the decomposition of the catalyst–substrate intermediate to the point where it becomes much faster than formation of the oxo complex. (c) Traylor, T. G.; Marsters, J. C., Jr.; Nakano, T.; Dunlap, B. E. *J. Am. Chem. Soc.* **1985**, *107*, 5537.

[17] Groves, J. T.; Myers, T. S. *J. Am. Chem. Soc.* **1983**, *105*, 5791.

Table I. Product Ratios from the Fe- and Mn-Catalyzed Oxygenation of Styrene

catalyst	oxidant	[styrene] (M)	[cyclooctene] (M)	epoxide/ aldehyde[a]
MnTPPCl	LiOCl	0.45	0	4.6
MnTPPCl	LiOCl	0.45	0.038	4.7
MnTPPCl	LiOCl	0.45	0.114	4.5
MnTPPCl	LiOCl	0.45	0.342	4.8
MnTMPCl	LiOCl	0.45	0	>100
FeFPFCl	F_5PhIO	0.87	0	14.3
FePFPCl	F_5PhIO	0.87	0.13	14.1
FePFPCl	F_5PhIO	0.87	0.64	13.8

[a] Error limits: ±0.2 for manganese runs, ±1.0 for iron runs.

time in *both* the iron and manganese catalyzed reactions. Therefore, *phenylacetaldehyde is a primary oxygenation product* and does not arise from epoxide isomerization.[17] However, phenylacetaldehyde is not stable in either the manganese- or iron-catalyzed reactions. Since an accurate measure of the ratio of epoxide to aldehyde products provides a useful mechanistic tool (vide infra), we conducted several control experiments to ascertain the degree of aldehyde decomposition under both sets of conditions. In the manganese system the loss of aldehyde was due to the hypochlorite itself. When present in concentrated (3 M) solutions, phenylacetaldehyde is consumed quantitatively by LiOCl within minutes. Decomposition under catalytic conditions is much less severe since phenylacetaldehyde is present at much lower concentrations. For example, in aliquots withdrawn at 2 and 4 min (approximately 40% and 80% conversion, respectively) after the addition of hypochlorite to a standard styrene reaction (see Experimental Section), the epoxide to aldehyde ratio varied by only 5% (4.4:1 at 2 min, 4.6:1 at 4 min). Therefore, while aldehyde decomposition results in a somewhat less precise measure of the product ratio in the manganese system, comparisons between different reactions of comparable duration are valid.

Methylene chloride solutions of phenylacetaldehyde are stable in the presence of suspended F_5PhIO. However, addition of FePFPCl results in a vigorous, exothermic reaction, and the insoluble oxidant disappears in a matter of seconds. TLC and ^1H NMR reveal the production of phenylacetic acid. GC analysis shows that oxidation of the aldehyde is quantitative with respect to oxidant. Similar, rapid consumption of F_5PhIO also occurs when either nonanal of trimethylacetaldehyde is substituted for the aromatic aldehyde. To the best of our knowledge, oxidation of aldehydes by a cytochrome P-450 model system has not been reported previously. Fortunately, aldehyde oxidation is efficiently suppressed by the addition of olefin. For example, a 1:1 mixture of phenylacetaldehyde and cyclooctene gave an 85% yield (with respect to F_5PhIO) of cyclooctene oxide. Since the ratio of aldehyde to olefin never rises above 1:10 in the catalytic styrene oxygenation, this side reaction will not result in a substantial error.

A 4.7:1.0 styrene oxide/phenylacetaldehyde ratio was observed when varying amounts of cyclooctene were added to the manganese-catalyzed system as a competitive inhibitor. Similar results were obtained for the iron-catalyzed oxygenation of styrene (epoxide/aldehyde = 13.8–14.3 in the presence and absence of cyclooctene. See Table I). Coupled with the insensitivity of the product ratio to olefin conversion, this strongly suggests that phenylacetaldehyde is produced via a similar mechanism to that which produces styrene oxide. The simplest possibility involves a common intermediate. If any nonreversibly formed oxo–olefin intermediates were involved, they would require fortuitously exactly equivalent rate constants for formation and decomposition in order to fit the observed results.[18] This is highly unlikely.

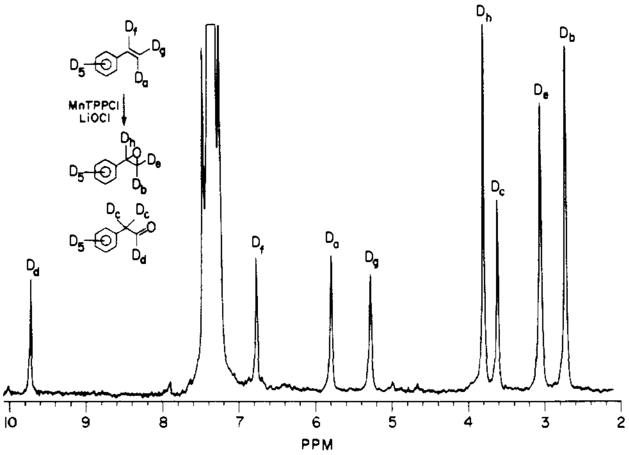


Figure 2. ^2H NMR of the product mixture resulting from the MnTPPCl-catalyzed oxygenation of styrene-d_8 by lithium hypochlorite.

In order to ascertain the origin of the benzylic hydrogen atoms in the aldehyde product, styrene-d_8 was oxygenated in both the manganese and iron porphyrin catalyzed systems, and the isolated products were analyzed by ^2H NMR. The ^2H spectrum of the product mixture resulting from the hypochlorite reaction is shown in Figure 2. Besides signals due to epoxide and unreacted olefin, resonances were observed at 9.8 ppm and 3.7 ppm representing the aldehydic and benzylic deuterium atoms of phenylacetaldehyde-d_8. The integrated ratio of these signals was 1.0–2.05. The 1:2 ratio demonstrates that phenylacetaldehyde results from a rearrangement which retains all of the label. Interestingly, the ratio of styrene oxide-d_8 to phenylacetaldehyde-d_8 was 4.6:1.0 (at 20% conversion), identical with that found for styrene itself. The ^1H NMR of the product mixture displays no strong signals, confirming that exchange with solvent or water does not occur. In order to demonstrate that the rearrangement is intramolecular, a crossover experiment was done in which styrene and styrene-d_8 were oxygenated in the same flask at equivalent initial concentrations. GC/MS analysis of the resulting products demonstrated that only phenylacetaldehyde-d_8 and unlabeled phenylacetaldehyde were produced.

Exactly analogous results were obtained in the FePFPCl-catalyzed oxygenation of styrene-d_8 by F_5PhIO. Again, the integrated ratios demonstrated that all of the deuterium label had been retained in the aldehyde product. The styrene oxide-d_8/phenylacetaldehyde-d_8 ratio was 19:1. In order to confirm further the lack of exchange with solvent, styrene was oxygenated under the standard reaction conditions but with CD_2Cl_2 as solvent. The ^1H NMR of the resulting product mixture displayed the correct 1:2 ratio of aldehyde signals. There were no strong signals in the ^2H NMR.

The effect of steric congestion in the catalyst active site is remarkable. When styrene was oxygenated under the standard hypochlorite conditions with manganese(III) tetramesitylporphyrin chloride (MnTMPCl) as catalyst, a high yield of styrene oxide was produced, but only a trace (<1%) of phenylacetaldehyde could be detected by ^1H NMR. This point was not investigated in the iron-catalyzed reaction since FeTMPCl is decomposed by excess F_5PhIO. However, Mansuy has shown that the FeTMPCl-catalyzed reaction of styrene and iodosylbenzene yields only styrene oxide, but when FeTPPCl is the catalyst, a mixture of epoxide and phenylacetaldehyde is produced.[19] We have provided evidence that iodosylbenzene and F_5PhIO react with iron porphyrins to produce the *same* active oxidant.[20]

Para substituents on the aromatic ring have only a small effect. The FePFPCl-catalyzed oxygenation of 4-chlorostyrene and 4-methylstyrene yielded 17:1 and 13:1 ratios of epoxide to aldehyde, respectively.

---

(18) This type of analysis is often used in enzymology to determine whether suicide inactivation reactions proceed through the enzyme substrate complex. For a discussion of this method see Abeles, R. H.; Maycock, H. L. *Acc. Chem. Res.* **1976**, *9*, 313.

(19) Mansuy, D.; Leclair, J.; Fontecave, M.; Dansette, P. *Tetrahedron* **1984**, *40*, 2847.

(20) (a) We have carried out a series of FePFPCl catalyzed competitive oxygenation reactions using either F_5PhIO or iodosylbenzene as the oxidant.[20b] In all three cases studied (cyclooctene vs. 2-methyl-2-pentene, cyclooctene vs. *cis*-2-octene, and *cis*-cyclodecene vs. *cis*-β-methylstyrene) the ratio of epoxides was found to be independent of the iodosyl species. This strongly suggests that all of the reactions involve the same active oxidant. (b) Kodadek, T. Ph.D. Thesis, Stanford University, 1985.

Table II. Results of the Fe- and Mn-Catalyzed Oxygenation of Styrene and Some Deuterated Analogues

porphyrin	olefin	epoxide to aldehyde ratio[a]	ratio of benzylic to carbonyl aldehydic signals[b]
FePFPCl	styrene	14.3	2.26
FePFPCl	styrene-d_8	19.5	2.26
FePFPCl	*cis*-β-D-styrene	30.0	1.1
FePFPCl	*trans*-β-D-styrene	15.0	<0.25[c]
MnTPPCl	styrene	4.6	2.10
MnTPPCl	styrene-d_8	4.6	2.35
MnTPPCl	*cis*-β-D-styrene	5.2	3.8
MnTPPCl	*trans*-β-D-styrene	5.0	<0.12[c]

[a] Error limits: ±3.0 for iron runs, ±0.4 for manganese runs. [b] The integrated ratio of the benzylic to carbonyl protons or deuterons of phenylacetaldehyde (or deuterated analogue) from ^{2}H or ^{1}H NMR. [c] A signal due to the benzylic deuterium of the aldehyde product was not observed.

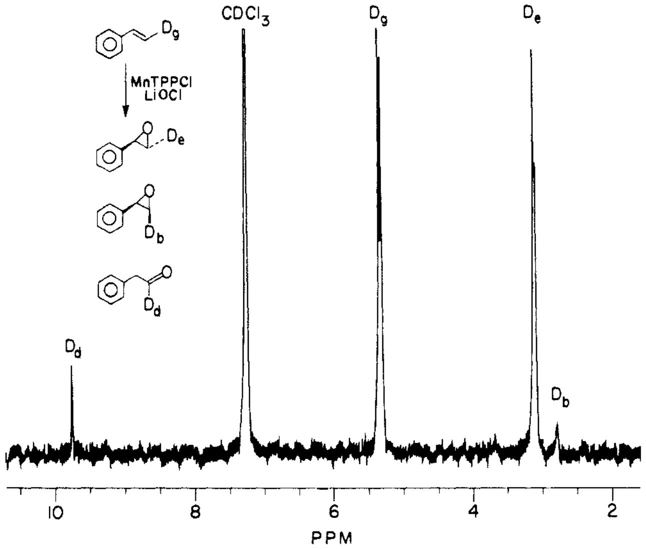


Figure 3. ^{2}H NMR of the product mixture resulting from the MnTPPCl-catalyzed oxygenation of *trans*-β-deuteriostyrene by lithium hypochlorite.

In order to obtain more detailed information concerning the mechanism of phenylacetaldehyde formation, we examined the products resulting from the oxygenation of *cis*- and *trans*-β-deuteriostyrene in both the MnTPPCl and FePFPCl systems (Table II).

The ^{2}H NMR of the products resulting from the MnTPPCl-catalyzed reaction of *trans*-β-deuteriostyrene and LiOCl (at 45% conversion) is shown in Figure 3. The only resonance due to phenylacetaldehyde is the aldehydic signal at 9.8 ppm. No peak for the benzylic deuterons of the aldehyde is observed, even when the reaction is allowed to proceed to 95% conversion. As mentioned previously, the absence of this signal is not due to exchange with solvent. Given the limits of detection of ^{2}H NMR the ratio of carbonyl to benzylic deuteriums of the aldehyde product must be >8:1. The integrated ratio of epoxide to aldehyde is 5.0, very similar to that found for styrene itself.

Oxygenation of *trans*-β-deuteriostyrene in the FePFPCl-catalyzed reaction gives a similar result. Only the carbonyl deuterium resonance of the phenylacetaldehyde product is observed in the ^{2}H NMR spectrum. The integrated ratio of epoxide/aldehyde is approximately 15:1. Since there is less phenylacetaldehyde formed in the iron-catalyzed reaction, we can only say that the ratio of carbonyl to benzylic deterium atoms of the aldehyde product is >4:1.

The oxygenation of *cis*-β-deuteriostyrene in both the manganese- and iron-catalyzed reactions results in the production of both phenylacetaldehyde-*1-d* and phenylacetaldehyde-*2-d* as evidenced by the ^{2}H NMR spectra of the reaction mixtures. In the manganese system (Figure 4), the deuterium signal attributable to

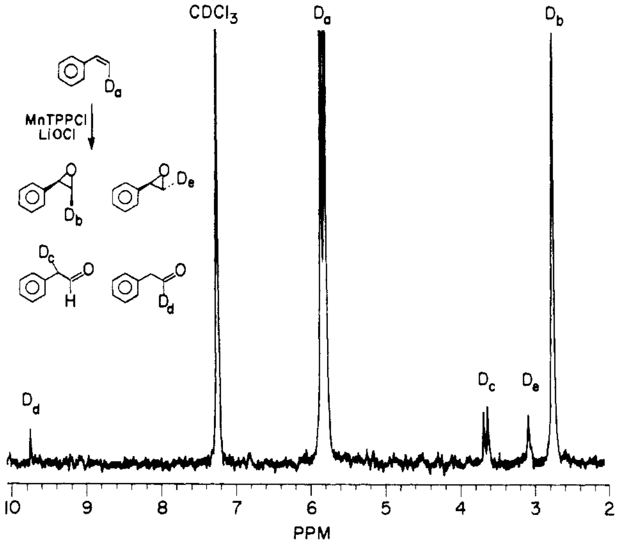


Figure 4. ^{2}H NMR of the product mixture resulting from the MnTPPCl-catalyzed oxygenation of *cis*-β-deuteriostyrene by lithium hypochlorite.

the benzylic position of the aldehyde product (doublet at 3.64 ppm) predominates, the integrated intensity being 3.8 times greater than that of the carbonyl deuterium resonance. In the iron-catalyzed reaction this ratio is about 1:1.

The manganese-catalyzed oxygenation of *cis*-β-deuteriostyrene results in a 5.2:1 ratio of styrene oxide-*d* to phenylacetaldehyde-*d*. The epoxide/aldehyde ratio for the iron-catalyzed reaction is approximately 30:1.

The results of our experiments employing the deuterated substrates are summarized in Table II.

Stereochemistry of Epoxidation. In addition to serving as a useful probe of the mechanism of aldehyde formation, the stereospecifically labeled styrenes provide an excellent opportunity to assess the intrinsic stereochemistry of the epoxidation reaction. As can be seen in Figure 3 and Figure 4, the manganese-catalyzed reaction does yield a minor amount (3–8%) of isomerized epoxide. However, no isomerization of the unreacted olefin is observed. This supports our previous findings[10] that the reversible formation of the manganese–oxo–olefin intermediate rigorously retains olefin stereochemistry, while some isomerization is possible during decomposition of this species to epoxide.[21] The iron-catalyzed reaction is absolutely clean. Neither signals due to isomerized epoxide nor starting material are observed.

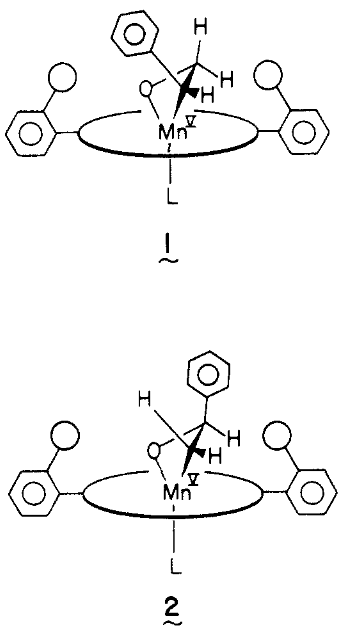
Secondary Isotope Effect. As discussed earlier, we have shown that oxygen atom transfer from the high valent metal–oxo complex to the olefin occurs in at least two distinct steps. Since the overall reaction transforms an olefin, possessing sp^2 carbons, to an epoxide with sp^3 centers, it is possible that a secondary isotope effect might be manifested in either the substrate-binding or epoxide-forming steps.[22] We carefully measured the rates of oxygenation for styrene and perdeuteriostyrene in the hypochlorite system with MnTPPCl as the catalyst. This less hindered porphyrin was chosen since we have previously shown that the corresponding oxo complex is completely saturated with substrate under our standard reaction conditions.[1] Therefore, the observed rate of epoxide formation is simply the rate of decomposition of the oxo–olefin complex (k_2 in Figure 1).

Within experimental error, the rates of oxygenation for styrene and styrene-d_8 were found to be identical (1.54 vs. 1.52 turnovers per s). However, when these same substrates were oxygenated in the same flask at equal initial concentrations, a 1.13:1.00 ratio of styrene oxide-d_8/styrene oxide was produced (by GC/MS). As stated previously (Table II), the epoxide/aldehyde ratios for

---

(21) Isomerization has only been observed in the case of aryl-substituted olefins. All aliphatic olefins we have investigated are epoxidized with complete retention of olefin stereochemistry (see ref 10).

(22) Lowry, T. H.; Richardson, K. S. "Mechanism and Theory in Organic Chemistry"; Harper and Row: New York, 1981.



1

2

Figure 5. The two possible regioisomeric metallaoxetanes which could result from addition of styrene and a manganese–oxo–porphyrin complex. Both metallacycles are shown in their most stable conformations, as suggested by molecular models.

styrene and styrene-d_8 are identical, so aldehyde production is not a complicating factor. This result demonstrates that there is an inverse secondary isotope effect in the reversible formation of the metal–oxo–olefin complex, since the outcome of a competitive reaction between two substrates with identical k_2 values will be determined solely by the differing affinity of the metal–oxo species for each substrate.

Discussion

The above experiments reveal several interesting facts concerning the manganese- and iron-catalyzed oxygenation of styrene. Formation of aldehyde involves migration of a β hydrogen atom to the benzylic carbon. The observation of only a carbonyl deuterium resonance in the aldehyde derived from *trans*-β-deuteriostyrene rules out phenyl migration. Furthermore, there is a stereoelectronic preference for migration of the hydrogen cis to the aromatic ring, since even in the case of *cis*-β-deuteriostyrene the deuterium migrates in preference to the trans hydrogen atom. However, this preference is not absolute. While *trans*-β-deuteriostyrene yields only phenylacetaldehyde-*1-d*, the cis isomer yields a mixture of both regioisomeric aldehydes. The very minor differences in the epoxide/aldehyde ratios observed upon oxygenation of the variously deuterated substrates argues that hydrogen migration occurs subsequent to the transition state for aldehyde formation.

At first glance, the observation of only phenylacetaldehyde-*1-d* from the oxygenation of *trans*-β-deuteriostyrene, but both possible isomers from the cis labeled compound, seems confusing. In this case it is important to consider the rather modest limit of detection inherent in ^{2}H NMR. In the oxygenation of the trans labeled compound, for example, 5% of phenylacetaldehyde-*2-d* would not have been detected. We believe that our observations are consistent with two competing effects; a stereoelectronic preference for migration of the hydrogen cis to the aromatic ring and a modest primary kinetic isotope effect. In the case of *trans*-β-deuteriostyrene these effects reinforce one another but work in opposition when *cis*-β-deuteriostyrene is employed. For example, a preference for cis hydrogen atom migration of a factor of 9 and a primary isotope effect for migration of 2–3 would yield our observed results. Since hydrogen migration occurs after the molecule is committed to aldehyde formation, the isotope effect would not be manifested in the epoxide/aldehyde ratio.

The production of phenylacetaldehyde from styrene is quite consistent with an oxometallacycle intermediate. Metallacyclobutanes, the all-carbon analogue of a metallaoxetane, have been observed to decompose to chain-extended olefins.[23,24] Production of phenylacetaldehyde from a metallaoxetane intermediate also provides a simple explanation for the absence of aldehyde product in the MnTMPCl-catalyzed reaction. Since phenyl migration is ruled out, phenylacetaldehyde would necessarily result from regioisomer **1** rather than **2** (Figure 5).[25] Examination of molecular models indicates that the aromatic ring of the putative oxometallacycle **1** does not suffer severe interactions with the tetrapyrrolic plane but does approach closely the ortho substituent of one of the meso phenyl rings. When this position is occupied by hydrogen (TPP) or fluorine (PFP), the interaction is not too severe. However, models suggest that introduction of an ortho methyl group (TMP) would greatly destabilize metallacycle **1**, resulting in a drastic decrease in the amount of aldehyde product. Since regioisomer **2** is not so greatly affected, epoxide is still produced. This scheme is in agreement with the results of the competitive reactions with cyclooctene so long as the regioisomers **1** and **2** are in rapid equilibrium.[26]

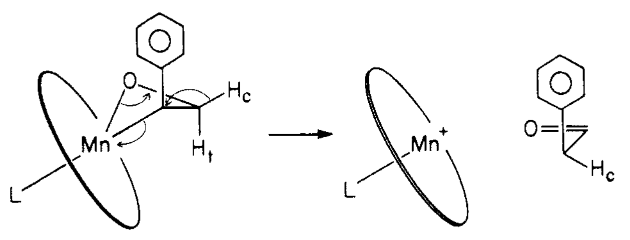


Figure 6. Possible hydrogen migration pathway for the decomposition of metallaoxetane **1** to phenylacetaldehyde and Mn(III) porphyrin. This path may well be stepwise; see text.

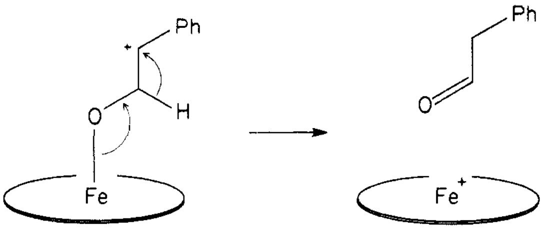


Figure 7. Pinacol rearrangement mechanism proposed by Groves and Myers for iron porphyrin catalyzed production of phenylacetaldehyde from styrene.

The origin of the observed migratory preference of the cis hydrogen atom is less clear. One possible explanation, again invoking an oxametallacyclic intermediate, is that the conformational preference of the four-membered ring results in the cis C–H bond being better aligned for a rearrangement involving migration of H$_c$, formation of the carbon–oxygen double bond, and cleavage of the metal–carbon bond (Figure 6). Clearly, the two β hydrogens in **1** are stereochemically distinct.

Groves and Myers[17] have postulated, partly on the basis of substituent effects, that phenylacetaldehyde is produced via a pinacol-like rearrangement of cationic intermeidate **3** (Figure 7). Although we have previously presented evidence that ionic intermediates are not involved in the *epoxide*-forming reaction[10,15] our kinetic data do not allow us to rule out **3** as a precursor to the *aldehyde*. Indeed, such an intermediate could be imagined to arise from metallacycle **1** via metal–carbon bond cleavage. However, such a mechanism would not be expected to exhibit the small effect of para substituents on the aldehyde/epoxide ratio[27]

---

(23) Casey, C. P. *React. Intermed.* **1981**, *2*, 135.

(24) Schrock, R. R. *Science* (*Washington, D.C.*) **1983**, *219*, 13.

(25) Oxametallacycles **1** and **2** are depicted in the conformations shown since molecular models indicate them to be the most stable.

(26) We have previously shown (see ref 1 and 10) that the oxo–olefin intermediate which leads to epoxide is in rapid equilibrium with the metal–oxo complex and free olefin. This provides a facile route for the rapid interconversion of **1** and **2**.

(27) Groves and Myers, using a different iron porphyrin and PhIO, observed a somewhat larger (though still modest) effect of the para substituent on the aldehyde/epoxide ratio.[17] Additionally, these workers reported considerably larger aldehyde/epoxide ratios than we observe for the FePFPCl-catalyzed reaction.

and the observed preference for migration of the hydrogen cis to the aromatic ring.[28]

On the other hand, a stepwise mechanism involving a transition state with radical character may be a more viable alternative. The weaker carbon–metal bond (due to benzylic resonance) accounts for the lack of aldehyde formation with aliphatic olefins and the lack of ketone formation with the methyl styrenes. It predicts small, if any, aryl substituent effects and accounts for the lack of an isotope effect on the aldehyde/epoxide ratio while allowing an isotope effect discriminating between migrating hydrogens. Thus, the aldehyde/epoxide ratio may reflect a competition between stepwise (aldehyde) and concerted (epoxide) breakdown of the oxometallacycle.

The putative regioisomers **1** and **2** would be expected to exhibit properties which are consistent with our observations, thus supporting the metallaoxetane hypothesis. Regioisomer **1** has a relatively weaker metal–carbon bond whose cleavage would lead to aldehyde by H migration. Regioisomer **2** should be favored by steric hindrance with the porphyrin; its greater metal–carbon bond strength may preclude cleavage, explaining the absence of ketone formation via H migration.

The data described here, in conjunction with earlier results, also provide for a better understanding of the epoxidation mechanism. The iron system cleanly transforms either the cis- or trans-labeled olefins to the corresponding epoxide without any detectable loss of stereochemistry. The manganese-catalyzed reaction is not quite so stereospecific, yielding about 5% of the isomerized epoxide. In both systems, there is not isomerization of unreacted olefin. Therefore, formation of the metal–oxo–olefin intermediate, a process which we know to be rapidly reversible, is stereospecific in both cases. Breakdown of this intermediate to epoxide occurs with complete retention of stereochemistry in the iron-catalyzed reaction and a minor amount of isomerization in the manganese system. The stereointegrity of both steps argues against the intermediacy of radical species in the oxygen-atom transfer process but is fully consistent with our postulate of a concerted 2 + 2 cycloaddition followed by reductive elimination. We have previously demonstrated that both the rate of styrene oxygenation and its affinity for the active catalyst are very similar to those of aliphatic olefins. This also argues against radical intermediates, since in the present case they would enjoy benzylic stabilization. Finally, the observation that styrene and its deuterated analogues give very similar epoxide/aldehyde ratios in these reactions seems incompatible with a radical or cationic intermediate which partitions between closure to epoxide and hydrogen migration to yield aldehyde.[17,29] Even if this migration occurred after the rate-determining step, an intramolecular competition between ring closure and β-hydrogen migration would be expected to be influenced greatly by the kinetic primary isotope effect.

The observation of an equilibrium secondary isotope effect in the competitive oxygenation of styrene and styrene-d_8 by MnTPPCl indicates that the olefinic carbons of the oxo–olefin intermediate have considerable sp^3 character. Again, this is the result expected for a metallacyclic intermediate.[30] It appears to be inconsistent, however, with a simple olefin-coordination complex, since one would expect the olefinic carbons to pyramidalize in the rate-determining decomposition to epoxide rather than in the equilibrium-binding reaction.[31]

In terms of the biological relevance of this work, it is intriguing to note that in many cases the cytochrome P-450-catalyzed oxygenation of olefins yields carbonyl compounds as well as epoxide. For example, 1,1-dichloroethylene yields dichloroacetaldehyde.[29] Interestingly, oxygenation of the dideuterio analogue produced aldehyde with deuterium at the α carbon, demonstrating that the P-450-catalyzed reaction also proceeds through β-hydrogen migration, apparently similar to the one discussed in this report (Figure 8).

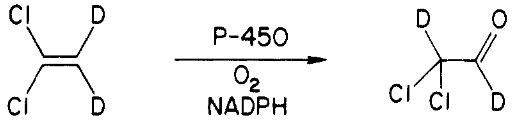


Figure 8. The cytochrome P-450 catalyzed oxygenation of labeled dichloroethylene produces dichloroacetaldehyde as the primary oxygenation product via a deuterium migration mechanism (from Liebler and Guengerich, ref 29).

Conclusion

We have presented evidence concerning the mechanism of styrene oxygenation which is consistent with the intermediacy of a high valent metallaoxetane species. In the absence of spectroscopic information, of course, this remains a conjecture. But given that such an intermediate provides a simple rationalization for many metal–oxo–olefin reactions, both biological and biomimetic, we believe it should be given careful consideration.

Experimental Section

Materials. MnTPPCl, MnTMPCl, and F_5PhIO were synthesized according to literature methods. 4-(Imidazol-1-yl)acetophenone (NAcPhIm) was purchased from Aldrich and twice recrystalized from methylene chloride/hexane. Benzyldimethyltetradecylammonium chloride was purchased from Fluka and used without further purification. Phenylacetylene, cyclooctene, styrene, and styrene-d_8 (Aldrich) were passed through a short alumina column immediately prior to use. Methylene chloride was distilled from CaH_2. THF was distilled and stored over sodium. Solutions of 9-BBN and *n*-butyllithium were purchased from Aldrich. Preparation of the LiOCl solution has been described previously.[10]

Phenylacetylene-*2-d*. A 1.5-M solution of *n*-butyllithium (30 mmol, 20 mL) was added dropwise to 2.5 g of phenylacetylene (24.5 mmol) dissolved in 15 mL of THF at 0 °C under nitrogen. The resulting deep purple solution was stirred for 1 h at 0 °C, after which time it was transferred by syringe to a pressure equalizing dropping funnel and slowly added at 0 °C to 10 mL of D_2O with vigorous stirring. The resulting mixture was stirred for an additional h under nitrogen. Workup consisted of addition of pentane, successive extraction of the organic layer with 5% H_3PO_4, and then water. The organic layer was dried over sodium sulfate. Following evaporation of the solvent, the resulting light yellow oil was chromatographed on neutral alumina (10:1 hexane/ether eluant) to yield 1.3 g (50% yield) of phenylacetylene-*2-d*. The ^2H NMR spectrum displayed a single resonance at 3.13 ppm. The ^1H NMR displayed no signal at this position, indicating >95% deuterium incorporation.

***trans*-β-Deuteriostyrene.** Phenylacetylene (78 mmol, 8 g) in 10 mL of dry THF was added via syringe to 165 mL of a 0.5-M solution of 9-BBN in THF (82.5 mmol) at 0 °C under a nitrogen atmosphere. The mixture was stirred for 1 h at 0 °C and then allowed to stand for 24 h at 4 °C. CH_3COOD (42 mL) was then added at 0 °C, and the resulting solution was stirred at this temperature for 2 h. Sodium hydroxide (3 M) was added, with cooling, until the solution was basic. Pentane was then added, and the organic layer was separated. The aqueous layer was extracted several times with pentane, followed by back extraction of the combined organic layers with brine. After drying over sodium sulfate, 5 mg of hydroquinone was added (to prevent polymerization), and the solvent was evaporated. The resulting oil was chromatographed on neutral alumina (10:1 hexane/ether eluant). Hydroquinone (5 mg) was again added prior to solvent evaporation, which yielded 6 g of material (72% yield). ^2H NMR revealed that only the trans-deuterated compound had been produced, as evidenced by the lone signal (a doublet) at 5.35 ppm. The ^1H NMR spectrum indicated 80% incorporation of the label.

cis-β-Deuteriostyrene was prepared by the same procedure, except employing phenylacetylene-d_2 as starting material and unlabeled acetic acid for hydrolysis of the vinylborane. The ^2H NMR spectrum of this material displayed a single doublet centered at 5.75 ppm. The ^1H NMR spectrum indicated essentially 100% isotopic purity.

FePFPCl was synthesized by condensing pentafluorobenzaldehyde with pyrrole as described by Longo,[32] except that a stream of oxygen was

---

(28) This result might possibly be accommodated by postulating a "memory effect" of the type discussed by Berson; see: Berson, J. A.; Gajewski, J. J.; Donald, D. S. *J. Am. Chem. Soc.* **1969**, *91*, 5550.

(29) Liebler, D. C.; Guengerich, F. P. *Biochemistry* **1983**, *22*, 5482.

(30) Lee, J. B.; Ott, K. C.; Grubbs, R. H. *J. Am. Chem. Soc.* **1982**, *104*, 7491.

(31) Metal-olefin π complexes of considerable "metallacyclopropane" character are fairly common and would be compatible with our secondary isotope effect experiments. However, this type of structure is almost always associated with metal-to-ligand backbonding, which should be negligible for the very high oxidation state species discussed here.

(32) Longo, F. R.; Finarelli, M. G.; Kim, J. B. *J. Heterocycl. Chem.* **1969**, *6*, 927.

continuously bubbled through the refluxing solution. This procedure eliminates the formation of chlorin contaminants. The solvent was then removed on a rotary evaporator, and the remaining thick purple oil was combined with 20 g of basic alumina. The porphyrin impregnated solid was placed in a Sohxlet extractor and extracted with methanol until the condensate was almost clear. This removes tarry impurities, but leaves the porphyrin bound to the silica since it is insoluble in methanol. Methylene chloride was then substituted for methanol, and the relatively pure porphyrin was washed off the support. After evaporation of the solvent, the porphyrin was chromatographed on neutral alumina (1:1 toluene/hexane eluant) and metallated by the literature procedure.[32]

Instrumentation. All proton NMR spectra were obtained on a Nicolet NMC 300 MHz spectrometer. Chemical shifts are reported relative to Me_4Si. ^2H NMR spectra were recorded on the same instrument operating at 46 MHz, employing the lock channel for signal observation. Chemical shifts are reported relative to $CDCl_3$ internal standard (7.25 ppm). Gas chromatographic analyses were performed on a Hewlett-Packard model 5880A gas chromatograph fitted with 12 ft × $^1/_8$ in. column of Chromasorb P.

Methods. The reaction conditions employed for the manganese porphyrin catalyzed epoxidation of olefins by lithium hypochlorite have been described previously.[10] The same reaction conditions were used for all experiments reported in this paper unless otherwise stated. All runs which were analyzed by NMR involved a modified workup. Once the oxygenation reaction had reached the desired conversion, stirring was stopped, and the organic layer removed by pipette. The solvent was evaporated, and approximately 5 mL of pentane added. This resulted in the precipitation of the porphyrin, the quaternary ammonium salt, and the axial ligand. The resulting mixture was filtered through a short plug of sand to remove insoluble material. The pentane was evaporated, yielding a mixture of the olefin(s) and oxygenated products. These were dissolved in the appropriate solvent and analyzed by NMR. This procedure avoids any fortuitous separation of products prior to analysis.

Iron-Porphyrin Catalyzed Reactions. F_5PhIO (0.24 mmol) was suspended in 500 μL of methylene chloride containing 0.5–1.0 mmol of substrate. Then 3.34×10^{-4} mmol of FePFPCl in 100 μL of methylene chloride was added. The reaction was allowed to proceed until all of the oxidant had disappeared. The solvent was then removed by rotary evaporation, and the product mixture dissolved in the appropriate solvent for NMR analysis.

Acknowledgment. We thank Dr. Scott A. Raybuck and Philip Hampton for assistance in the synthesis of FePFPCl. We also thank Dr. Lisa McElwee-White and Jeffrey Fitzgerald for helpful discussions. Financial support from the National Institutes of Health (Grant NIH GM17880-13,14) and the National Science Foundation (Grant NSF CHE83-18512) is gratefully acknowledged. The NMC-300 NMR spectrometer was purchased with funds from the National Science Foundation (Grant NSF CHE81-09064 to Stanford University).

Note Added in Proof. We have shown previously that both the manganese and iron porphyrin catalyzed reactions proceed through reversibly formed oxo–olefin intermediates.[10,15] This is assumed in the mechanistic arguments presented in this paper. Traylor and co-workers, however, have reported a kinetic study of an iron porphyrin catalyzed oxygenation reaction similar to the one discussed here and could find no evidence for an oxo-olefin intermediate.[16c] The major difference between our reaction conditions and those employed by Traylor's group is their addition of alcohol and water as co-solvents to solubilize pentafluoroiodosylbenzene. The *apparent* discrepancy between our results and Traylor's has been clarified recently in an elegant spectroscopic study by Groves and co-workers: Groves, J. T.; Watanabe, Y. *J. Am. Chem. Soc.* **1986**, *108*, 507–508. Their results are consistent with our kinetic study, as they are able to observe directly a high valent oxo–olefin complex which decomposes slowly to Fe^{III} porphyrin and epoxide. This species was formed by the addition of an olefin to an iron-oxo compound at −78 °C in methylene chloride. However, when alcohol was added to the preformed oxo–olefin complex, the intermediate immediately decayed to Fe^{III} and epoxide. How alcohols act to accelerate the decomposition of the high valent intermediate is an open question, but these experiments appear to provide a reconciliation between Traylor's kinetic studies and our own (see ref 16b).

Registry No. MnTPPCl, 32195-55-4; FeFPCl, 36965-71-6; PhCH=CH_2, 100-42-5; D_2, 7782-39-0.

A Photoelectron and Extended-Hückel Study of the Double-Metal-Layered Zirconium Monochloride, the Related Zirconium and Scandium Chloride Carbides M_2Cl_2C, and Their Relationship to Carbon-Centered Clusters

Robin P. Ziebarth, Shiou-Jyh Hwu, and John D. Corbett*

Contribution from the Department of Chemistry, Iowa State University, Ames, Iowa 50011.
Received August 12, 1985

Abstract: The bonding in the double-metal-layered ZrCl (AbcA), the hypothetical reordered ZrCl (AbaB), and the product of insertion of carbon into the latter to give M_2Cl_2C (Ab(c)aB), M = Zr, Sc, have been examined by photoelectron spectroscopy (UPS, XPS) and by extended-Hückel band calculations. The compounds characteristically exhibit well-resolved chlorine 3p and carbon 2p (when present) valence bands and a zirconium conduction band, with the substantial metal–nonmetal covalency in the first two bands. A significant amount of M–M bonding is contained within the carbon-binding states. The calculated density-of-states curves are in good agreement with UPS data for all three compounds in both energy and band shape, with the zirconium phases being metallic by both criteria. Bonding correlations between the known $Zr_6Cl_{12}C$-type clusters and the Zr_2Cl_2C condensation product of these are examined. The energies of the chlorine, carbon, and metal MO's (bands) in the two limits show a close correspondence in both experiment and theory. The orbital description of the relatively localized bonding of carbon within the Zr_6C cluster unit is also preserved on condensation. On the other hand, substantial delocalization leads to marked dispersion of the Zr–Zr bonding HOMO and LUMO cluster orbitals within the conduction band. Theoretical predictions of unknown derivatives of the title phases are also considered.

The zirconium monohalides ZrCl and ZrBr and the derivatives these form with a variety of nonmetals provide some novel and apparently unique bonding features that are relevant to the behavior of both metals and octahedral metal cluster compounds. The ZrX structures[1-3] consist of tightly bound infinite slabs containing four cubic-close-packed (ccp) layers sequenced X–Zr–Zr–X. A section of one slab is approximated by I although

---

(1) Adolphson, D. G.; Corbett, J. D. *Inorg. Chem.* **1976**, *15*, 1820.
(2) Troyanov, S. J. *Vestn. Mosk. Univ., Ser. 2: Khim.* **1973**, *28*, 369.

0002-7863/86/1508-2594$01.50/0