transition of Ce(TPP)$_2^+$ should be at higher energy than that of Ce(OEP)$_2^+$. In fact, the first oxidation potential of Ce(TPP)$_2$ is similar to that of LuTPPOH, and the near IR transition of Ce(TPP)$_2^+$ is at an energy (0.92 eV) which is slightly less than that of Ce(OEP)$_2^{+.31c}$ Both of these results reflect mixing of metal f orbital character into the HOMO as is shown in Figure 7. Such mixing results in a ground-state wave function which contains partial metal f^1/porphyrin dication character. The inclusion of Ce(III) character in the wave function is probably the cause of the significant anisotropy and rapid relaxation observed in the EPR spectrum of Ce(TPP)$_2^+$. The occurrence of significant mixing of the metal f and porphyrin π orbitals is supported by quasirelativistic SCF-Xα scattered-wave calculations on cerocene complexes.[54] These calculations indicate that the f orbitals of the Ce(IV) ion are capable of an unusually large degree of covalent interaction with ligand orbitals. It should be noted that this type of orbital mixing is not expected for f^{14} Lu(III) complexes. The ^{175}Lu hyperfine interactions manifested in the isotropic EPR spectrum of (LuTPPOH)$^+$ are due to spin polarization effects.

The mixing of the metal and porphyrin orbitals is also manifested in the potentials for the first reductions of the two sandwich complexes. For both the OEP and TPP systems, the e$_1$ bonding orbitals (derived from the e$_g$* monomer orbitals) are capable of mixing with the metal f orbitals. The reduction potential observed for Ce(TPP)$_2$ versus Ce(OEP)$_2$ indicates that this mixing is greater in the former complex than in the latter as is schematically represented in Figure 7. This more extensive mixing in the TPP sandwich probably occurs because the metal and porphyrin e$_1$ orbitals of this complex are energetically closer than those of the

OEP sandwich. The relative ease of reduction of LuTPPOH (-1.26 V) versus LuOEPOH (-1.68 V) lends credence to this conclusion.

V. Conclusions

The hole delocalization which is observed for the two oxidized Ce(IV) sandwich porphyrins occurs primarily as a result of the close proximity of the macrocycles. The exact mechanism for delocalization (orbital overlap, strong exciton, etc.) is not immediately obvious and will require detailed theoretical studies. Regardless, hole delocalization in the dimeric systems has interesting implications for higher order aggregates. It might be speculated that if stacked aggregates of the form Ce$_n$(porphyrin)$_{n+1}$(L$^-$)$_{an}$ could be synthesized, these systems would be highly conducting (L$^-$ is a counterion for charge conservation). To date, such high order aggregates have not been prepared; however, the triple-decker Ce(III) sandwich, Ce$_2$(OEP)$_3$, is known.[31a,b,d] This suggests that higher order oligomers may be obtainable. The stacked lanthanide porphyrin systems may offer certain advantages over stacked metallophthalocyanines in that a$_{2u}$-like orbitals are available for oxidation in the former systems but not the latter.[10,13,53] Involvement of these orbitals in hole delocalization facilitates participation of the metal ion and may enhance conductivity. The assessment of conductivity in lanthanide porphyrin polymers must, however, await their synthesis.

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Mechanistic Studies of Alkene Epoxidation Catalyzed by Nickel(II) Cyclam Complexes. ^{18}O Labeling and Substituent Effects

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Abstract: The oxidations of cyclohexene and various aryl-substituted alkenes are catalyzed by the cyclam (1,4,8,11-tetraazacyclotetradecane) complex of Ni(NO$_3$)$_2$ with iodosylbenzene as terminal oxidant. Epoxides are the major products; however, small amounts of ring-opened products, over-oxidation to ketones or aldehydes, and allylic oxidation of cyclohexene are also observed. E olefins are more reactive than the corresponding Z olefins in contrast to the results of iron porphyrin catalysis, and kinetic studies of para-substituted styrenes indicate that the reaction is facilitated by electron-donating substituents. Labeling studies with PhI^{18}O confirm that the epoxide oxygen is derived from PhIO while allylic oxidation and over-oxidation products involve both PhIO and exogenous sources of oxygen. A pericyclic mechanism for the formation of PhCHO is proposed along with the intermediacy of a high-valent nickel–oxo complex as the active oxidant. These results are discussed in light of related transition-metal/PhIO oxidation mechanisms.

The mechanisms by which transition-metal complexes mediate olefin oxidation have intrigued organic, inorganic, and biological chemists alike.[1] In organic synthesis, an understanding of the mechanistic features critical to high stereoselectivity is desired for the design of new oxidation catalysts. In the biological realm,

monooxygenase enzymes, including cytochrome P-450 and various peroxidases, employ iron(III) porphyrins at their active sites in order to effect oxygen atom transfer to olefins and other substrates. Their mechanisms and those of numerous model systems have been the subject of considerable discussion.[2,3] Most of these studies

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Table I. Products of Ni(cyclam)(NO₃)₂-Catalyzed Oxidation of Phenyl-Substituted Alkenes with PhIO as the Terminal Oxidant[a,b]

[a] See text for standard reaction conditions. [b] Reaction time = 5 h. [c] Based on starting alkene. [d] About 1% Z-isomer observed.

have focussed upon chromium, manganese, and iron complexes of tetraarylporphyrins in which hydroperoxides, peracids, hypochlorite, N-oxides or iodosylarenes are substituted for O₂ as terminal oxidant.[4-9] It is generally agreed that a metal oxo species participates as an oxygen atom transfer agent in a shunt or "rebound" mechanism,[10] although the exact structure of the metal oxo intermediate is still a subject of debate.[11]
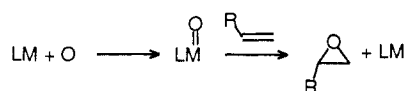

L = ligand, O = oxidant

In light of recent research with nickel-containing redox enzymes and coenzymes,[12] including the macrocyclic nickel complex, Factor F₄₃₀,[13] we became interested in the possibility that synthetic macrocyclic complexes of nickel might also participate in redox processes such as olefin oxidation. Concurrent work in our laboratory and in Kochi's[14] has established that certain ligands, notably cyclam,[15] render Ni²⁺ salts active toward catalysis of olefin epoxidation when iodosylbenzene is used as the terminal oxidant. Prior to this, there were no examples of nickel-catalyzed olefin

epoxidation despite the fact that higher oxidation states of nickel have been described.[16,17]
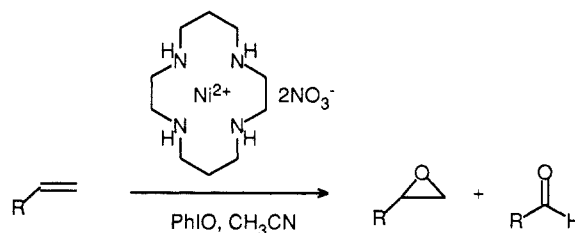
The mechanism of the Ni²⁺ cyclam catalyzed oxidation is presumed to involve two or more discrete steps: (i) reaction of Ni²⁺ cyclam with PhIO to give an oxidized nickel species, A, and (ii) reaction of A with an olefin, possibly via a second intermediate B, to yield oxidation products.
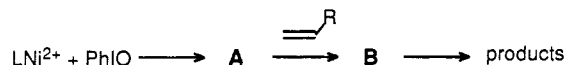
Consequently, the major questions that remain to be answered are the following: (i) What is the structure of A? (ii) Are more than one nickel species involved in oxidation? (iii) What is the nature of the reaction of A with an olefin? Ligand effects, medium effects, and spectroscopic studies have already been reported by Koola and Kochi[14] in order to address questions i and ii. In this paper, we discuss the relative reactivity of various aryl-substituted olefins, ¹⁸O-labeling studies of PhIO, and the effect of added O₂ on the course of the reaction in terms of question iii.

Results

Reaction Conditions. Valentine and co-workers recently reported the catalysis of olefin oxidation by simple salts of manganese, iron, cobalt,[18] and copper[19] using PhIO. In our studies, Ni(cyclam)(NO₃)₂ was used as the catalyst; we verified that the

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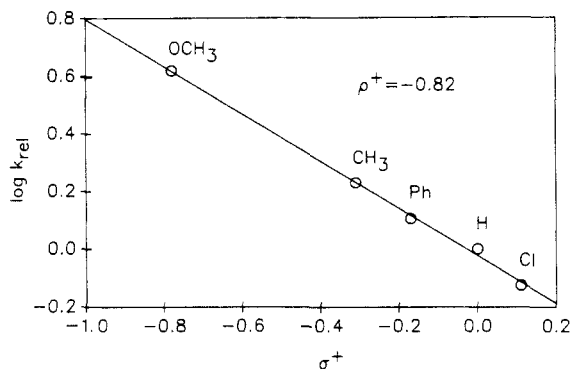
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Table II. Relative Rates for Disappearance of p-X-C_6H_4-CH=CH$_2$ at 20 °C

X	H	Cl	Ph	CH$_3$	OCH$_3$
k_{rel}	1.00	0.75	1.28	1.70	4.16

Figure 1. Hammett plot for relative initial rates of disappearance of p-X-C_6H_5-CH=CH$_2$ at 20 °C.

Table III. Percent Incorporation of ^{18}O from PhIO[a]

		products		
entry	reactant	epoxide	PhCHO	PhCOPh
1	(E)-stilbene[b]	100	45	50
2	(E)-stilbene + O$_2$[c,d]	60	12	10
3	styrene[b]	90	2	

[a] Corrected for isotopic purity of PhIO and natural abundance. [b] Chemical yields of products are listed in Table I. [c] O$_2$ was continuously bubbled through the reaction mixture. [d] Chemical yields of products were respectively 8%, 10%, and 3.8%.

Table IV. Yields of Cyclohexene Oxidation Products[a] and Percent Incorporation of ^{18}O from PhIO[b]

	epoxide	cyclo-hexanone	cyclo-hexenol	cyclo-hexenone
% yield[c]	30	2	3	5
% label	88	d	12	10

[a] Reaction time = 5 h; see text for standard reaction conditions. [b] Corrected for natural abundance and % enrichment of PhIO. [c] Based on starting olefin. [d] Not determined.

simple salt, Ni(NO$_3$)$_2$, resulted in no epoxidation.[20] Employing similar reaction conditions (0.1 mmol of catalyst, 0.5 mmol of olefin, 2 mmol of PhIO in 5 mL of CH$_3$CN), moderate yields of epoxides were observed after 2–5 h at room temperature. Table I lists the yields of products observed under these conditions with aryl-substituted alkenes as substrates. The 5-h reaction time reflects the point at which most of the iodosylbenzene was reduced to iodobenzene. Much higher yields of epoxides were obtained, however, if additional PhIO was added after a few hours of reaction time.[21]

Oxidation of Aryl Alkenes. Several interesting comparisons emerged from the results of aryl olefin oxidation. (i) The major product of olefin oxidation is the epoxide in each case; minor products include C=C bond cleavage to yield aldehydes, over-oxidation of stilbene to benzil, and rearrangement products such as benzophenone. In addition, the products of epoxide ring opening and concomitant hydride shift, benzyl ketones, are observed. For styrene, a control study showed that the rate of formation of phenylacetaldehyde is greater than that of styrene oxide ring opening under the same reaction conditions.[22] This suggests that phenylacetaldehyde is also a primary oxidation product.[5] (ii) The increased reactivity of (E)-β-methylstyrene compared to styrene (entries 1 and 2 in Table I) is consistent with addition of an electrophilic oxygen to the olefin facilitated by electron donation to the double bond. (iii) The isomerization of Z olefins to E olefins was also observed and would be expected if intermediates are reversibly formed. (iv) The most striking observation is that E olefins (stilbene and β-methylstyrene) were considerably more reactive than Z olefins. This result is opposite the stereospecificity observed for FeTPPCl, which was found to be totally unreactive with (E)-stilbene.[23] Overall, these results bear considerable similarity to those of the simple metal salts.[17,18]

Substituent Effects on Styrene Oxidation. The effect of electronic substituents in the para position of styrene was monitored in order to probe the reaction's sensitivity to positive charge development. Comparison of rates of disappearance of para-substituted styrenes yielded inconsistent results when the olefins were studied individually. This may be attributed to minor changes in the concentration of the active catalyst (due, most likely, to the heterogeneous nature of PhIO reactions) which results in larger changes in the rate of reaction of the olefin. For the same reason, it was difficult to show that the reaction is strictly first order in olefin. Yet, different olefins clearly reacted at different rates, so the step involving reaction of oxidant and olefin must be at least

partially rate determining.[24] Competition studies in which two or more olefins were present in the same reaction mixture produced consistent results. In this way, initial rates for the disappearance of para-substituted styrenes relative to styrene were obtained. The relative rates for various substituents, X, are shown in Table II. A Hammett plot of log k_{rel} vs σ^+ (Figure 1) gave a least-squares line (r^2=0.998) with slope (ρ^+) = –0.82. Correlation with the Hammett parameter σ was poor, ρ = –1.4, r^2 = 0.84.

Effect of Added O$_2$. Benzaldehyde was observed as a product in all reactions of phenyl-substituted alkenes and its yield was dependent upon the reactivity of the alkene and the presence of O$_2$. For carefully degassed samples of reactive olefins (cf. (E)-β-methylstyrene), only trace amounts were formed. For (E)-stilbene, a less reactive olefin, the yield of PhCHO was considerably higher, 8.8%. When the same reaction was run with O$_2$ continuously bubbled through the solution, the amount of PhCHO formed approximately doubled to 17.8%. No oxidation occurred with added O$_2$ in the absence of PhIO.

^{18}O Labeling Studies. In order to trace the source of oxygen atoms in oxidized products studies were carried out with PhI^{18}O. In previous cases,[4a,14,25] researchers have cited exchange of isotopically labeled oxygen between PhIO and H$_2$O in the presence of metal complexes as evidence for metal–oxo species which reversibly hydrate. In CH$_2$Cl$_2$ or CHCl$_3$ solutions, exchange of oxygen between PhIO and H$_2$O may indeed be slow in the absence of metal–oxo species. In our studies in CH$_3$CN, however, a control study showed that PhI^{16}O rapidly exchanged oxygen with H$_2$$^{18}O$ in CH$_3$CN, even in the absence of metal ions.[26] Thus, care was taken to use anhydrous CH$_3$CN for subsequent labeling studies. PhIO of either 70 or 80% ^{18}O isotopic enrichment was used. The amounts of ^{18}O found in oxidation products corrected for natural abundance and for the PhIO enrichment are listed in Table III. For all substrates studied, the epoxide oxygen was derived exclusively from PhIO within experimental error. It is clear, though, that products of over-oxidation (PhCHO, PhCOPh) involve both PhIO and exogenous sources of oxygen atoms. The production of benzaldehyde from (E)-stilbene (entry 1) apparently occurs with half of the oxygen coming from PhIO and about half from a source of ^{16}O. Entries 1 and 2 compare reactions carried out in degassed vs O$_2$-rich media, respectively. Incorporation of ^{18}O from PhIO decreased upon addition of unlabeled O$_2$. This unusual

(20) Trace amounts of benzaldehyde were observed from styrene oxidation.
(21) For example, the yield of trans-β-methylstyrene oxide rose to 80%.
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result requires a mechanism that allows interchange of oxygen atoms between PhIO and O_2 (vide infra). Entries 1 and 3 of Table III compare the isotopic enrichment of oxygen in benzaldehyde produced from (*E*)-stilbene vs styrene. This result supports a mechanism (vide infra) in which a benzylic radical intermediate is trapped by $^{16}O_2$.

Cyclohexene Oxidation. Oxidation of cyclohexene produced products of both allylic oxidation and epoxidation; under the standard reaction conditions described above, the epoxide was the major product while allylic oxidation accounted for only small percentages. The yields of these products and the percentages of ^{18}O transferred from $PhI^{18}O$ are listed in Table IV. Cyclohexenol and cyclohexenone showed very low isotopic incorporation, suggesting that an allylic radical formed from H atom abstraction is trapped by something other than PhIO or PhIO-generated nickel–oxo species. In order to compare aliphatic and aromatic alkene substrates, a competition study using equimolar amounts of cyclohexene and styrene as substrates was carried out. Relative initial rates of disappearance of olefin were determined to be 2.9:1 (cyclohexene:styrene). Neither of these olefins would be expected to display steric hindrance toward epoxidation, so this result indicates that aliphatic olefins may be at least as reactive as aromatic ones.

Reactions Catalyzed by Related Metal Complexes. When the epoxidation reactions were carried out under standard reaction conditions with a complex of (1*R*,4*S*,8*R*,11*S*)-(1,4,8,11-tetramethyl)cyclam, Ni(tmc)(NO$_3$)$_2$, a small amount of cis–trans isomerization (9%) was observed, but no oxidation products were detected. Ni^{2+}(tmc) complexes usually show much higher Ni^{III}/Ni^{II} oxidation potentials, and this may be related to their diminished reactivity. The cyclam complex of Cu(NO$_3$)$_2$ was similarly unreactive, while the Co(cyclam)(NO$_3$)$_2$ showed a minor amount of oxidation after 5 h of reaction time: styrene oxide 4%, benzaldehyde 5%. Optically active cyclam ligands bearing substituents at C-5 have been studied and show essentially the same results as those of the parent Ni^{2+} cyclam.[27] An extensive list of other metal complexes has been studied by Kochi and co-workers.[14]

Discussion

Clearly, nickel cyclam complexes are able to generate very active oxidants upon reaction with iodosylbenzene. The subsequent chemistry of the oxidant or oxidants involves both epoxidation and hydrogen atom abstraction. Although the structure and the number of active oxidants generated in the reaction (intermediate A) are still unknown, three structures may be postulated by analogy to other square-planar and pyramidal metal oxidants.
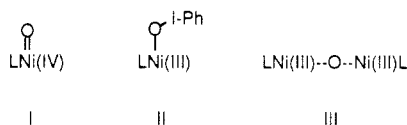
Species I, a nickel(IV)–oxo complex, and species III, a μ-oxo dimer, have already been discussed.[14,28] The structure of species I might be better represented as either LNi^{III}–O$^{\bullet}$ or LNi^{IV}O$^-$ since a doubly bonded metal–oxo is unlikely for nickel.[1b] Species II, a nickel cyclam–iodosylbenzene adduct, is also a potential oxidant[30] and is consistent with some of our results. μ-Oxo dimers of metal porphyrin complexes are generally inactive as olefin oxidants;[31] however, our results do not exclude III as a potential catalyst.

Reaction of Oxidant with Olefin. Both I and II would be expected to display considerable radical character at the oxygen atom.[32] Results of studies with (*E*)- and (*Z*)-stilbene and (*E*)- and (*Z*)-β-methylstyrene support this view. In both cases, *Z* alkenes were considerably less reactive than their *E* isomers, in contrast to the results of most metal–porphyrin systems. While the nature of the cis selectivity of the porphyrin examples is not fully understood,[11d,33] the trans selectivity observed in nickel-cyclam reactions is consistent with radical character in the approaching oxygen atom.[33] For example, *trans*-stilbene can exist in a planar conformation such that attack of an oxygen radical at an olefinic carbon readily yields a delocalized benzylic radical. Such stabilization of a benzylic radical cannot occur with *cis*-stilbene until after C–C bond rotation since steric hindrance prevents the two phenyl rings from lying coplanar with the double bond. Also, addition of hydroxy radical is known to occur more rapidly with trans olefins than with cis in some cases.[34] Observation of cis–trans isomerization of stilbene and β-methylstyrene suggests that the reaction of A with olefins is reversible. Further evidence for the radical nature of the intermediate A (I or II) is the observation of H atom abstraction from the allylic position of cyclohexene and the presumed decomposition of A by H atom abstraction from the solvent (CH$_3$CN).
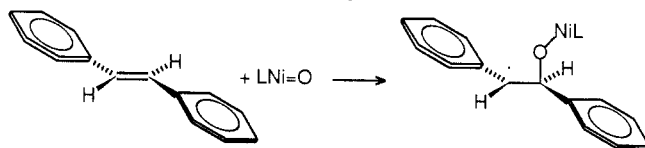
Electron transfer provides an alternative explanation of the greater reactivity of *trans*- compared to *cis*-stilbene and β-methylstyrene. The observation of a ρ^+ value of -0.82 is consistent with other reactions believed to proceed via olefin radical cation intermediates.[35] In such a mechanism, electron transfer from the olefin to any high valent nickel oxo compound (illustrated below for III) might be followed by very rapid collapse to yield a nickel–oxo–olefin intermediate such as VIa. The major piece of evidence against this hypothesis is the observation of greater reactivity of cyclohexene compared to styrene. The ionization potential of styrene is considerably lower than that of cyclohexene (8.43 vs 8.95 eV[36]), and one would consequently anticipate greater reactivity for styrene in an electron-transfer mechanism.[37]
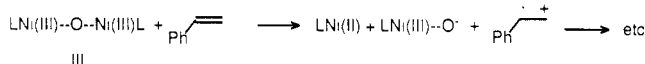
Intermediate B. Although the precise structure of intermediate A is still unknown, many of its characteristics have been gleaned from the nature of its subsequent reaction with olefins. Several structures may be postulated for the next intermediate, B. That B exists is inferred from the incomplete retention of stereochemistry upon epoxidation and the existence of several different oxidation products. A concerted oxygen atom transfer or a symmetrical π complex(IV) leading to direct O transfer are thus ruled out as important pathways. Similarly, the existence of an oxametallacycle,[38] V, as the sole intermediate is inconsistent with the partial loss of stereochemistry observed. Structure VI, on the other hand, is consistent with the stereochemical, substituent effect, and labeling experiments. This intermediate must either be very short-lived in order to give rise to substantial retention of olefin configuration or exhibit weak bonding between the benzylic (R$_2$

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(32) Structure I may be better described as Ni^{III}–O$^{\bullet}$.

(33) Groves, J. T. *J. Chem. Educ.* **1985**, *62*, 928–931.

(34) Morris, E. D.; Niki, H. *J. Phys. Chem.* **1971**, *75*, 3640–3641.

(35) (a) Fox, M. A.; Chen, C. C. *Tetrahedron Lett.* **1983**, *24*, 547–550. (b) Zaklika, A.; Kaskar, B.; Schaap, A. P. *J. Am. Chem. Soc.* **1980**, *102*, 386–388. (c) Schaap, A. P.; Zaklika, K. A.; Kaskar, B.; Fung, L. W. M. *J. Am. Chem. Soc.* **1980**, *102*, 389–391.

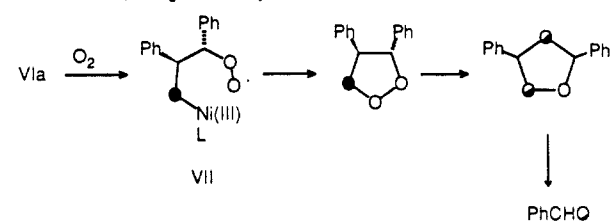(36) See: Miyaura, N.; Kochi, J. K. *J. Am. Chem. Soc.* **1983**, *105*, 2368–2378.

(37) We cannot rule out a more complicated scheme in which aliphatic and aromatic olefins react by different mechanisms.

(38) Collman, J. P.; Brauman, J. I.; Meunier, B.; Raybuck, S. A.; Kodadek, T. *Proc. Natl. Acad. Sci. U.S.A.* **1984**, *81*, 3245–3248.

Mechanism 1, dioxetane formation:
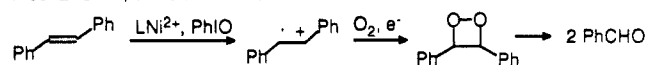
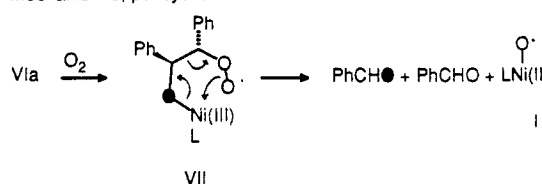Mechanism 2, Criegee ozonolysis:

Mechanism 3, pericyclic:

Figure 2. Possible mechanisms for formation of stilbene: ^{18}O label shown as ●.

= Ph) carbon and nickel or oxygen. An explanation of the rearranged products can be found by drawing a resonance structure[39] of intermediate VIa which places positive charge at the R_2-substituted carbon. This structure, VIb, suggests that migration products (phenylacetaldehyde, benzophenone, phenylacetone) are formed by the shift of H_a or R_1 to an adjacent carbocation center.[40] Furthermore, if this resonance structure is a contributor to the transition state involved in attack of a nickel–oxo species to the olefin, a correlation with σ^+ would be expected. The magnitude of ρ^+ would be attenuated by the dual radical/cation nature of the benzylic carbon, and the observed value (-0.82) seems plausible.[41]
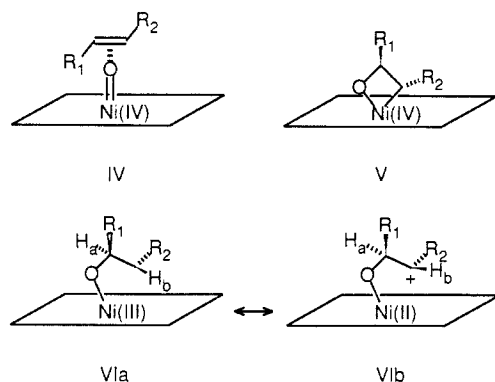
The results of isotopic labeling studies with $PhI^{18}O$ are also informative with respect to the nature of species B. Intermediate VIa should be formed ^{18}O-labeled in the presence of $PhI^{18}O$. Reductive elimination to form the epoxide would incorporate ^{18}O at the same enrichment as PhIO, as is observed in the absence of O_2. Radical VIa would be expected to be very sensitive to O_2, a reaction that would account for partial incorporation of ^{18}O into the more highly oxidized products, benzaldehyde and benzil, generated from (E)-stilbene.

Benzaldehyde Formation. The mechanism of formation of benzaldehyde from phenyl-substituted alkenes was investigated
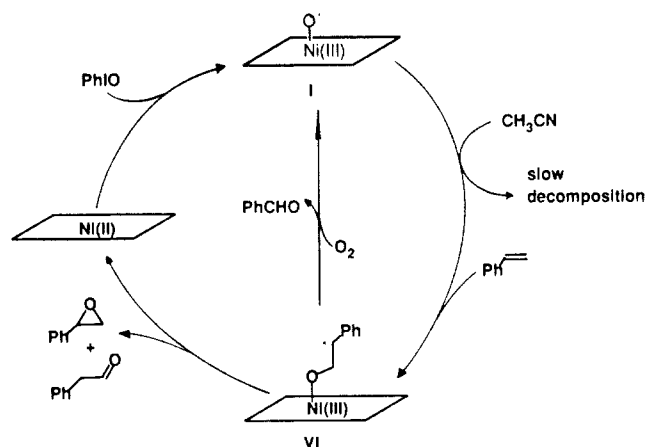

Figure 3. Proposed catalytic cycles for oxidation of olefins in the presence of PhIO and O_2.

by examining the incorporation of ^{18}O into PhCHO with $PhI^{18}O$ and unlabeled O_2 in varying amounts. When O_2 was present in trace amounts, PhCHO formed from styrene contained only 2% labeled oxygen. This is the result anticipated for formation of the more stable radical, VIa (R_1 = H, R_2 = Ph), and attack of unlabeled O_2 at the phenyl-bearing carbon. Under these same conditions, PhCHO formed from (E)-stilbene was nearly 50% labeled. This result allows two of the three possible mechanisms for PhCHO formation to be ruled out (see Figure 2). Mechanism 1 involves trapping of a stilbene radical cation with O_2 to eventually form a dioxetane followed by decomposition to 2PhCHO. Although this mechanism has been postulated in the iron bleomycin catalyzed oxidation of stilbene with PhIO,[42] it can be ruled out here because substantial ^{18}O label is incorporated into PhCHO from PhIO.

Mechanism 2 is essentially the Criegee mechanism of ozonolysis.[43] The ozonide formed from the reaction of (E)-stilbene with $PhI^{18}O$ and $^{16}O_2$ would contain a 1:1 distribution of label between two sites, which, upon either hydrolytic or oxidative workup, would yield benzaldehyde with 25% isotopic enrichment.[44] This result is clearly inconsistent with the observed value of 45%. This mechanism would also predict that the incorporation of labeled oxygen from PhIO would be independent of the amount of O_2; however, a substantial decrease in label of all products was observed when excess O_2 was present. In addition, attempts to observe the known stilbene ozonide[45] by NMR spectroscopy of the crude reaction mixture failed. Mechanism 2 is therefore ruled out.

A third mechanism is consistent with all of the experimental data obtained so far. Mechanism 3 suggests a pericyclic decomposition of the peroxy intermediate VII which would directly yield two molecules of PhCHO and regenerate the nickel–oxo species I. At the limit of low unlabeled O_2 concentration, this mechanism would predict the formation of one molecule each of labeled and unlabeled PhCHO, and complete labeling of the epoxide, although the amount of PhCHO produced would be small compared to epoxide. Increasing the concentration of unlabeled O_2 diverts more of the catalyst through this pathway resulting in the formation of larger amounts of unlabeled nickel oxidant, I, and a concomitant lowering of ^{18}O incorporation into all products. The results listed in Table III are in accord with these predictions, although other

(39) While shift of an electron from the carbon radical to nickel formally constitutes formation of a resonance structure, ligand reorganization might be expected to accompany a change in metal oxidation state.

(40) Traylor, T. G.; Iamamoto, Y.; Nakano, T. *J. Am. Chem. Soc.* **1986**, *108*, 3529–3531.

(41) (a) Lindsay Smith, J. R.; Sleath, P. R. *J. Chem. Soc., Perkin Trans. 2* **1982**, *1009*–1015. (b) Srinivasan, K.; Michaud, P.; Kochi, J. K. *J. Am. Chem. Soc.* **1986**, *108*, 2309–2320. (c) Howe, G. R.; Hiatt, R. R. *J. Org. Chem.* **1971**, *36*, 2493–2497.

(42) Heimbrook, D. C.; Mulholland, R. L., Jr.; Hecht, S. M. *J. Am. Chem. Soc.* **1986**, *108*, 7839–7840.

(43) Criegee, R. *Angew. Chem., Int. Ed. Engl.* **1975**, *14*, 745–752.

(44) A hydrolytic workup would generate H_2O_2 with 50% of one oxygen labeled and 2 mol of PhCHO with 50% of one of the PhCHO equivalents labeled (25% overall). Under the more likely oxidative conditions, one PhCHO would be generated containing 25% of the original label and one $PhCO_2H$ equivalent would possess one oxygen atom 75% labeled. Only minor traces of $PhCO_2H$ were detected in the product mixture.

(45) (a) Criegee, R.; Korber, H. *Chem. Ber.* **1971**, *104*, 1807–1811. (b) Schaap, A. P.; Siddiqui, S.; Gagnon, S. D.; Lopez, L. *J. Am. Chem. Soc.* **1983**, *105*, 5149–5150.

mechanisms have not been rigorously excluded. This mechanism would also give further support to the existence of a high-valent nickel–oxo species, I, as a likely intermediate in the reaction. Moreover, an interesting consequence of this mechanistic study is the prediction that the nickel cyclam catalyzed oxidation of olefins to aldehydes and ketones should, under ideal conditions, be *catalytic in PhIO and use O_2 stoichiometrically*. Studies along these lines are being pursued.

Conclusions

The results of stereochemical, substituent effect, and isotopic labeling studies allow formulation of a self-consistent mechanism for the nickel cyclam catalysis of olefin oxidation. Figure 3 illustrates such a mechanism. Reaction of nickel cyclam with iodosylbenzene leads to a powerful oxidant. That an excess of PhIO is required for high yields of olefin oxidation has been ascribed to a side reaction with acetonitrile, present in large excess as the solvent. Our studies suggest that the Ni(III) oxo intermediate (I) has considerable oxygen radical character and that it adds to olefins to generate a second alkyl radical intermediate, VI. The primary fate of this intermediate is reductive elimination to give an epoxide, a process that is competitive with C–C bond rotation. In addition, VI is subject to hydrogen or phenyl migrations and to reaction with dioxygen. This latter reaction obviates the need for stoichiometric amounts of PhIO since either the nickel–oxo intermediate is regenerated during the reaction with O_2 or other autocatalytic pathways occur. While the mechanism depicted in Figure 2 is compatible with our results, it is not possible to rigorously exclude other intermediates, such as an oxametallacycle, or to rule out the possibility of parallel pathways operating of which only one is stereoselective.[46] Direct observation of oxidized nickel-containing intermediates would be desirable in the future.

In summary, nickel, in conjunction with certain macrocyclic polyamine ligands, should be included among the transition metals of interest as catalysts for hydrocarbon oxidation. The investigation of new macrocyclic or rigid acyclic ligands may lead to modulation of the reactivity of Ni^{2+}. Furthermore, labeling and substituent effect studies have provided more detailed information on the nature of the reaction of a high-valent nickel–oxo species with alkenes. These studies have led to the suggestion of possible intermediates as well as pathways by which stoichiometric use of expensive and insoluble oxidants may be circumvented. Elaboration of the cyclam macrocycle with additional functional groups and stereocenters[47] may allow efficient catalytic systems to be explored.

Experimental Section

Materials. Cyclam was purchased from Lancaster Synthesis. Iodosylbenzene was prepared from iodobenzene diacetate (Aldrich Chemicals) by a known procedure.[48] $H_2^{18}O$ was obtained from Cambridge Isotope Laboratories. (Z)-β-Methylstyrene was purchased from K&K Laboratories. All other organic compounds were obtained from Aldrich. Impure olefins and olefins containing stabilizers were distilled at reduced pressure immediately before use. With the exception of styrene oxide, epoxides used as GC standards were prepared by oxidation of the corresponding alkene with m-chloroperoxybenzoic acid under standard conditions.[49] Acetonitrile (99%) was purchased from Aldrich and distilled from P_2O_5 before use. All other solvents were ACS reagent grade or HPLC grade from Fisher Scientific and were used without further purification unless otherwise noted. Inorganic reagents were purchased from Fisher with the exception of $Cu(NO_3)_2 \cdot 3H_2O$ which was obtained from J. T. Baker. All reactions were run under dry nitrogen atmosphere at room temperature unless otherwise noted. $Ni(cyclam)(NO_3)_2$ was prepared by mixing equimolar amounts of $Ni(NO_3)_2 \cdot 6H_2O$ and cyclam

in methanol, concentration, and recrystallization from a mixture of tetrahydrofuran and MeOH. $Ni(tmc)(NO_3)_2$ was similarly prepared. Cobalt(II) and copper(II) complexes of cyclam were similarly prepared from $Co(NO_3)_2 \cdot 6H_2O$ and $Cu(NO_3)_2 \cdot 3H_2O$.

Instrumentation. Proton NMR spectra were recorded on either an 80-MHz Varian CFT-20 or a 300-MHz General Electric QE-300 spectrometer. IR spectra were recorded on a Perkin-Elmer 1430 spectrometer. Electronic spectra were obtained on either a Perkin-Elmer Lambda 4B or 5. Gas chromatography was performed with either a Hewlett Packard 5830A interfaced with an HP 18850A GC terminal or an HP 5890A GC interfaced with an HP 3393A integrator. Inert internal standards were used. Mass spectral data were obtained on an HP 5980A dodecapole mass spectrometer equipped with an HP 5710A GC. Elemental analyses were performed by Desert Analytics.

Alkene Oxidations. In a typical procedure, 0.1 mmol of metal catalyst, 0.5 mmol of alkene, and an appropriate amount of an inert internal standard (usually bromobenzene) were dissolved in 5 mL of CH_3CN. The solution was degassed with 3 or more freeze–pump–thaw cycles. PhIO (2.0 mmol) was added all at once. Aliquots (0.2–0.4 mL) were removed at timed intervals and passed through a 0.3 × 1 cm column of alumina which was followed by a CH_3CN rinse (0.2–0.6 mL). The eluate was analyzed on either a $^1/_8$ in. × 6 ft 3% OV-17 column or a 0.53 mm × 10 m 5% phenylmethylsilicone capillary column. In order to separate styrene oxide from phenylacetaldehyde an additional analysis was performed with a $^1/_8$ in. × 6 ft 10% Carbowax 20M column.

To study the effect of added O_2, the procedure above was followed except that solutions were not degassed and a steady stream of O_2 was bubbled continuously through the reaction mixture. The reactions of para-substituted styrenes were carried out in a constant temperature bath thermostated to 20 °C.

Competitive substituent effect studies were performed in N_2-purged dry acetonitrile with the standard amounts listed above. In these studies, the total olefin concentration was held constant (0.5 mmol/5 mL) but the mixture was composed of equal molar amounts of styrene and one or more other olefins. The disappearance of olefin was monitored by GC as described above. Initial rate constants were obtained from the data obtained within 1 h reaction time or less. Competitive studies of cyclohexene and styrene were performed in the same manner.

Reactions with $PhI^{18}O$. $PhI^{18}O$ was prepared from $PhI^{16}O$ by the method of Schardt and Hill[25c] with 97% ^{18}O-enriched H_2O. **Caution:** *During one preparation of $PhI(OCH_3)_2$, the recrystallized product decomposed violently at room temperature. This and all other oxidized iodobenzenes should be handled with care.* The amount of ^{18}O incorporation in PhIO was assayed by its reaction with dimethyl sulfide at 60 °C (20 min) followed by GC–MS analysis of the M + 2 ion (m/e 80) of the dimethyl sulfoxide formed. The degree of enrichment for these studies was between 70% and 85%, varying somewhat with each batch. Inconsistent results were obtained if triphenylphosphine was used as the assay. Reactions with $PhI^{18}O$ were carried out as described above. Products were subjected to GC–MS analysis, and isotopic enrichments were calculated from molecular ions or M - 1 peaks in the case of alcohols. Entries in Table III represent values averaged from, typically, three independent experiments.

In order to study exchange of oxygen between PhIO and H_2O, a sample of unlabeled PhIO (40 mg, 0.18 mmol) was added to 1.5 mL of CH_3CN containing a 10-fold excess of $H_2^{18}O$ (50 μL, 2.5 mmol, 97% enriched). After 30 min at 30 °C, CH_3SCH_3 (0.4 mmol) was added, and the solution was heated to 60 °C for 1 h followed by GC–MS analysis. The DMSO formed showed the following peaks in the mass spectrum: m/e 65 (parent peak), 100% relative abundance; m/e 78 (molecular ion, $DMS^{16}O$), 6.0%; m/e 80 (M + 2, $DMS^{18}O$), 74.9%. In other words, the ^{18}O contents of PhIO and H_2O were completely equilibrated. In order to confirm that DMSO does not exchange its oxygen with H_2O, 0.56 mmol of DMSO (natural abundance M + 2 ion = 5% relative to M) was treated with 1.11 mmol of $H_2^{18}O$ (97% enriched) in 0.15 mL of CH_3CN at 60° for 1 h. Re-examination by GC–MS showed a 6% abundance of the DMSO M + 2 ion, or, essentially no exchange between DMSO and H_2O.

(46) See, for example: Groves, J. T.; Stern, M. K. *J. Am. Chem. Soc.* **1987**, *109*, 3812–3814.

(47) Wagler, T. R.; Burrows, C. J. *J. Chem. Soc., Chem. Commun.* **1987**, 277–278.

(48) Saltzman, H.; Sharefkin, J. G. *Organic Synthesis*; Wiley: New York, 1973; Collect. Vol. V, pp 658–659.

(49) Swern, D. *Org. React.* **1953**, *7*, 378–433.