

Efficient Catalytic Oxidation of Alkanes by Lewis Acid/ $[\text{Os}^{\text{VI}}(\text{N})\text{Cl}_4]^-$ Using Peroxides as Terminal Oxidants. Evidence for a Metal-Based Active Intermediate

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Abstract: The oxidation of alkanes by various peroxides ($^t\text{BuOOH}$, H_2O_2 , $\text{PhCH}_2\text{C}(\text{CH}_3)_2\text{OOH}$) is efficiently catalyzed by $[\text{Os}^{\text{VI}}(\text{N})\text{Cl}_4]^-$ /Lewis acid (FeCl_3 or $\text{Sc}(\text{OTf})_3$) in $\text{CH}_2\text{Cl}_2/\text{CH}_3\text{CO}_2\text{H}$ to give alcohols and ketones. Oxidations occur rapidly at ambient conditions, and excellent yields and turnover numbers of over 7500 and 1000 can be achieved in the oxidation of cyclohexane with $^t\text{BuOOH}$ and H_2O_2 , respectively. In particular, this catalytic system can utilize $\text{PhCH}_2\text{C}(\text{CH}_3)_2\text{OOH}$ (MPPH) efficiently as the terminal oxidant; good yields of cyclohexanol and cyclohexanone (>70%) and MPPOH (>90%) are obtained in the oxidation of cyclohexane. This suggests that the mechanism does not involve alkoxy radicals derived from homolytic cleavage of MPPH but is consistent with heterolytic cleavage of MPPH to produce a metal-based active intermediate. The following evidence also shows that no free alkyl radicals are produced in the catalytic oxidation of alkanes: (1) The product yields and distributions are only slightly affected by the presence of O_2 . (2) Addition of BrCCl_3 does not affect the yields of cyclohexanol and cyclohexanone in the oxidation of cyclohexane. (3) A complete retention of stereochemistry occurs in the hydroxylation of *cis*- and *trans*-1,2-dimethylcyclohexane. The proposed mechanism involves initial O-atom transfer from ROOH to $[\text{Os}^{\text{VI}}(\text{N})\text{Cl}_4]^-$ /Lewis acid to generate $[\text{Os}^{\text{VII}}(\text{N})(\text{O})\text{Cl}_4]^-$ /Lewis acid, which then oxidizes alkanes via H-atom abstraction.

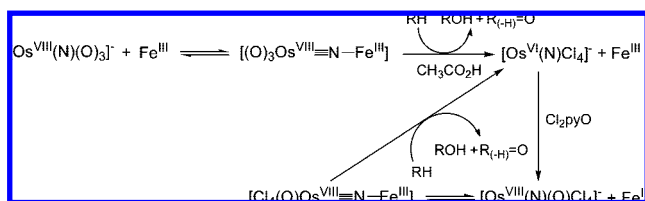
Introduction

The selective oxidation of alkanes under mild conditions continues to be a challenge for chemists.^{1,2} A number of enzymes, such as cytochrome P-450 and methane monooxygenase, are able to make use of highly reactive iron-oxo species to oxidize alkanes,^{3–5} and this has inspired the development of synthetic models that can mimic the reactivity of these enzymes.^{4,6–12} Our approach to design catalytic systems for alkane oxidation is to make use of Lewis acids to activate metal-oxo species that are otherwise stable and rather unre-

active toward alkanes. We have reported that the oxidation of alkanes by anionic oxo species of ruthenium,¹³ iron,¹⁴ chromium,¹⁵ and manganese^{15,16} is greatly enhanced by just a few equivalents of Lewis acids. In particular, we have recently studied the activation of $[\text{Os}(\text{N})(\text{O})_3]^-$ by FeCl_3 in detail.¹⁷ Although $[\text{Os}(\text{N})(\text{O})_3]^-$ is a very stable osmium-oxo species,

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Scheme 1



in the presence of FeCl_3 it is able to oxidize alkanes efficiently at room temperature in $\text{CH}_2\text{Cl}_2/\text{CH}_3\text{COOH}$ to give alcohols and carbonyl products. The active intermediate is proposed to be a bimetallic $[(\text{O})_3\text{Os}^{\text{VIII}}\equiv\text{N}-\text{Fe}^{\text{III}}]$ species. This oxidation can be made catalytic by using 2,6-dichloropyridine *N*-oxide (Cl_2pyO) as the terminal oxidant.¹⁷ However, ^{18}O -labeling studies suggest that the active oxidant in catalytic oxidation is different from that in stoichiometric oxidation, and $[\text{Cl}_4(\text{O})\text{Os}^{\text{VIII}}\equiv\text{N}-\text{Fe}^{\text{III}}]$ is proposed to be the active intermediate (scheme 1). Although yields of >80% are obtained in catalytic oxidation, the rates are rather slow (ca. 4 turnovers/h at 23 °C). Kinetic studies suggest that the rate-limiting step is oxygen-atom transfer from Cl_2pyO to $[\text{Os}(\text{N})\text{Cl}_4]^-$. Herein we report that the $\text{M}^{\text{III}}/[\text{Os}(\text{N})\text{Cl}_4]^-$ ($\text{M}^{\text{III}} = \text{FeCl}_3$ or $\text{Sc}(\text{OTf})_3$) system is a remarkably efficient catalyst for the oxidation of alkanes using peroxides (including $^1\text{BuOOH}$, H_2O_2 , and $\text{PhCH}_2\text{CMe}_2\text{OOH}$) as terminal oxidants, with yields >90% and rates >15 turnovers/min. We also provide evidence that these catalytic reactions do not involve free radicals and that the active intermediate is the same as in oxidation by Cl_2pyO , i.e., $[\text{Cl}_4(\text{O})\text{Os}^{\text{VIII}}\equiv\text{N}-\text{M}^{\text{III}}]$.

Experimental Section

Materials. All chemicals were of reagent grade unless otherwise specified. $[\text{Bu}_4\text{N}][\text{Os}(\text{N})(\text{O})_3]$ and $[\text{Bu}_4\text{N}][\text{Os}(\text{N})\text{Cl}_4]$ were synthesized according to published procedures.^{18,19} The purity of these complexes was determined by CHN analysis and UV/vis spectrophotometry. Anhydrous ferric chloride (98%) and *cis*- and *trans*-1,2-dimethylcyclohexane were purchased from Aldrich and used as received. Other alkanes and solvents were purified according to standard methods.²⁰ Hydrogen peroxide (30%, Merck) and *tert*-butyl hydroperoxide (80%, in *di-tert*-butyl peroxide, Merck) were used as received and standardized by iodometry.^{21,22} 2-Methyl-1-phenyl-2-propyl hydroperoxide (MPPH) was prepared according to a literature method,²³ and its purity was determined to be >99% by NMR. Active MPPH levels were further measured by iodometric titrations, which showed >99% peroxide activity. H_2^{18}O (95 atom % ^{18}O) and $\text{H}_2^{18}\text{O}_2$ (90 atom % ^{18}O) were obtained from Aldrich and Icon Services Inc., respectively. Bromotrichloromethane was purchased from Aldrich and was purified by passing through a short column of neutral alumina prior to use.

Instrumentation. Gas chromatographic analyses were performed on a HP 6890 GC/FID equipped with either a HP-5MS (30 m \times 0.25 mm i.d.) or a HP-FFAP (25 m \times 0.2 mm i.d.) column. GC/MS measurements were carried out on a HP 6890 gas chromatograph interfaced to a HP 5975 mass-selective detector. Electrospray

ionization mass spectrometry (ESI/MS) was performed on a PE SCIEX API 365 mass spectrometer. ^1H NMR spectra were recorded on a Varian (300 MHz) FT NMR spectrometer. Elemental analyses were done on an Elementar Vario EL analyzer. UV/vis spectra were recorded by using a Hewlett-Packard 8452A diode array spectrophotometer. Infrared spectra were recorded with sample as KBr pellets on a Nicolet Avatar 360 FTIR spectrophotometer.

Catalytic Oxidation of Alkanes. All experiments were carried out under argon, unless otherwise specified. Strict exclusion of oxygen in the oxidation reactions was achieved by four freeze–pump–thaw cycles. In a typical catalytic oxidation reaction, a solution of peroxide (0.10 M) was added to a solution containing $[\text{Bu}_4\text{N}][\text{Os}(\text{N})\text{Cl}_4]$ (1.25×10^{-3} M), FeCl_3 (1.0×10^{-2} M), and alkane (1.2 M) in $\text{CH}_2\text{Cl}_2/\text{CH}_3\text{CO}_2\text{H}$ (5:2, v/v). The resulting red solution was vigorously stirred for 5 min. Chlorobenzene was then added as an internal standard, and the mixture was analyzed by GC/FID and GC/MS.

Kinetic isotope effects for catalytic oxidation of cyclohexane were investigated by using an equimolar mixture of cyclohexane and cyclohexane- d_{12} as substrate. The organic products were quantified and identified by GC and GC/MS. The KIE values were obtained by taking the ratio of the corresponding areas from GC measurements. Kinetic isotope effects were also determined by comparing the rates of single-substrate reactions.

For ^{18}O -labeling experiments, the ^{16}O and ^{18}O compositions of cyclohexanol were determined from the relative abundances of the peaks at $m/z = 100$ (^{16}O) and 102 (^{18}O) in GC/MS (EI).

Analysis of the Iron Species after Reaction. The solution after catalytic oxidation was evaporated to dryness at room temperature. The residue was dissolved in 0.25 M HCl and filtered. Excess potassium thiocyanate was then added, and the resulting intensely red-colored iron(III) thiocyanate solution was analyzed by UV/vis spectrophotometry at 480 nm.²¹ It was found that iron(III) thiocyanate was formed quantitatively, indicating that all the iron species remained in the 3+ oxidation state.

Detection of Peracetic Acid. To investigate whether FeCl_3 or $[\text{Bu}_4\text{N}][\text{Os}(\text{N})\text{Cl}_4]$ could catalyze the formation of peracetic acid from hydrogen peroxide and acetic acid, FeCl_3 (0.01 M) or $[\text{Bu}_4\text{N}][\text{Os}(\text{N})\text{Cl}_4]$ (1.25×10^{-3} M) was added to a solution of H_2O_2 (0.17 M) in $\text{CH}_2\text{Cl}_2/\text{CH}_3\text{CO}_2\text{H}$ (5:2, v/v). After 10 min, the CH_2Cl_2 was removed by rotary evaporation, and 50 μL of the residue was dissolved in D_2O (0.5 mL) and then analyzed by ^{13}C NMR. No peracetic acid was found in the FeCl_3 or the $[\text{Bu}_4\text{N}][\text{Os}(\text{N})\text{Cl}_4]$ solution.

Results and Discussion

Catalytic Oxidation with $^1\text{BuOOH}$. In a typical catalytic oxidation experiment, $^1\text{BuOOH}$ (0.10 M) was added to a solution containing $[\text{Bu}_4\text{N}][\text{Os}(\text{N})\text{Cl}_4]$ (1.25×10^{-3} M), FeCl_3 (1.0×10^{-2} M), and cyclohexane (1.2 M) in $\text{CH}_2\text{Cl}_2/\text{CH}_3\text{CO}_2\text{H}$ (5:2, v/v) at 23 °C under argon. After 5 min, analysis by GC and GC/MS indicated the formation of cyclohexanol (67%), cyclohexanone (21%), and chlorocyclohexane (3%) (Table 1, entry 5), with a total yield of 91% (turnover number, TON = 73). No cyclohexyl *tert*-butyl peroxide was detected. A similar yield and product distribution are observed in cyclohexane oxidation by $[\text{Os}(\text{N})(\text{O})_3]^-/\text{FeCl}_3/\text{Cl}_2\text{pyO}$, but the reaction time is much longer (16 h at 23 °C).¹⁷

This catalytic system requires the presence of both $[\text{Os}(\text{N})\text{Cl}_4]^-$ and FeCl_3 to function efficiently. The background catalytic oxidation by $[\text{Os}(\text{N})\text{Cl}_4]^-$ or FeCl_3 alone was negligible under the same conditions, i.e., 5 min at 23 °C (Table 1, entries 1 and 2), although on a longer time scale, products of cyclohexane oxidation could be observed. If FeCl_3 was used alone, 11% of cyclohexane-derived products could be detected after 24 h. On the other hand, if $[\text{Os}(\text{N})\text{Cl}_4]^-$ was used alone, 48% of products were observed after 8 h.

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Table 1. Catalytic Oxidation of Cyclohexane by [¹⁸Bu₄N][Os(N)Cl₄]/FeCl₃/¹BuOOH under Various Conditions^a

entry	FeCl ₃ (equiv)	CH ₃ CO ₂ H (mL)	CH ₂ Cl ₂ (mL)	product (% yield) ^b			total yield (%)	time
				c-C ₆ H ₁₁ OH	c-C ₆ H ₁₀ O	c-C ₆ H ₁₁ Cl		
1 ^c		2	5	<1	<1	<1	5 min	
				3	2	6	11	
2 ^d	0	2	5	<1	<1	<1	5 min	
				25	20	3	48	
3	2	2	5	56	24	2	82	
4	4	2	5	63	21	3	87	
5	8	2	5	67	21	3	91	
6 ^e	8	2	5	69	21	3	93	
7 ^f	8	2	5	68	19	3	90	
8	16	2	5	68	20	3	91	
9	8	2 ^g	5	18	17	3	38	

^a [¹⁸Bu₄N][Os(N)Cl₄], 1.25 × 10⁻³ M; alkane, 1.2 M; ¹BuOOH, 0.10 M. ^b The yields were based on [¹BuOOH] consumed. % yield of alcohol = (mmol of alcohol/mmol of ¹BuOOH) × 100. % yield of ketone = (mmol of ketone/mmol of ¹BuOOH) × 2 × 100. % yield of RCl = (mmol of RCl/mmol of ¹BuOOH) × 100. ^c FeCl₃, 1.0 × 10⁻² M. The reaction was carried out in the absence of [¹⁸Bu₄N][Os(N)Cl₄]. ^d No FeCl₃ was added. ^e Reaction in air. ^f 0.1 M BrCCl₃ was added. ^g CH₃CN was used instead of CH₃CO₂H.

The rate and product yield depend on the relative amount of FeCl₃ used; the optimum amount is 8 mol equiv (entries 3–5, 8). Replacing CH₃CO₂H with CH₃CN resulted in a slower reaction and a much lower yield of 38% (entry 9). When the reaction was run in air, a slightly higher yield of 93% was obtained (entry 6), indicating that O₂ does not play a significant role in the oxidation. BrCCl₃, an efficient scavenger for carbon-centered radicals, had no effect on the catalytic oxidation, and <1% of bromocyclohexane was detected (entry 7). These results suggest that this catalytic system does not produce any freely diffusing cyclohexyl radicals during the oxidation. The KIEs (*k^H/k^D*), determined from competition experiments, are 2.5 ± 0.2, 7.6 ± 0.5, and 2.0 ± 0.2 for cyclohexanol, cyclohexanone, and chlorocyclohexane, respectively; the overall KIE is 3.5 ± 0.4. The overall KIE for cyclohexane oxidation by [Os(N)Cl₄]⁻/FeCl₃/Cl₂pyO is 3.7 ± 0.4.¹⁷

Over 80% of [¹⁸Bu₄N][Os^{VI}(N)Cl₄] could be recovered at the end of the catalytic reaction. The [Os^{VI}(N)Cl₄]⁻ ion was also detected in the reaction mixture by ESI/MS. Spectrophotometric analysis of the iron species after reaction by forming the [Fe(NCS)₆]³⁻ complex indicated that all the iron remains in the 3+ oxidation state. The [Os(N)Cl₄]⁻ catalyst could be replaced with [Os(N)(O)₃]⁻ with almost identical results. If [Os(N)(O)₃]⁻ is used as the catalyst, it would first stoichiometrically oxidize alkane to generate [Os(N)Cl₄]⁻,¹⁷ which then enters the catalytic cycle.

The alcohol/ketone ratio depends on the initial concentration of the alkane; the ratio decreased from 4.2 to 0.2 when [cyclohexane] was varied from 2.31 to 0.12 M. This result suggests that the active intermediate oxidizes both the alkane and the alcohol efficiently. Presumably, the alkane is first hydroxylated to the alcohol, which is then further oxidized to the ketone. Independent experiments show that this catalytic system is highly efficient in oxidizing various alcohols.

In the competitive oxidation of a mixture of cyclopentanol and cyclohexane (in mole ratio of 1:17) by [Os(N)Cl₄]⁻/FeCl₃/¹BuOOH, the products consisted of 12% cyclopentanone, 54% cyclohexanol, 18% cyclohexanone, and 2% chlorocyclohexane. These results are in sharp contrast to stoichiometric oxidation by [Os(N)(O)₃]⁻/FeCl₃, in which products arising from alcohol

oxidation are predominant even though a cyclopentanol/cyclohexane ratio of 1:168 was used (81% cyclopentanone, 6% cyclopentyl acetate, 2% cyclohexanol, and 2% cyclohexanone).¹⁷ This suggests that the active oxidant in catalytic oxidation is different from that in stoichiometric oxidation.

Catalytic oxidations of other alkanes by [Os(N)Cl₄]⁻/FeCl₃/¹BuOOH were also investigated. The total yields were typically around 90% for cycloalkanes and 80% for open-chain alkanes. A TON of 7500 for the oxidation of cyclohexane could be achieved by syringe pump addition of ¹BuOOH. As in catalytic oxidation using 2,6-dichloropyridine *N*-oxide, no products arising from the oxidation of primary C–H bonds were observed. Moreover, oxidation of secondary C–H bonds produced both the corresponding alcohols and ketones, with the alcohols being the predominant product. In the oxidation of adamantane, the yield was almost quantitative, the ratio of tertiary/secondary products is 34 (after statistical correction), and 6% of 1-chloroadamantane is also produced (Table 2, entry 9). Similar results were obtained for oxidation of adamantane by [Os(N)(O)₃]⁻/FeCl₃/Cl₂pyO. This catalytic system is also highly stereospecific; in the oxidation of *cis*- and *trans*-1,2-dimethylcyclohexane, <1% of epimerized products was observed (entries 5 and 6).

Kinetic studies for catalytic oxidation were performed at 23 °C using either c-C₆H₁₂ or c-C₆D₁₂ as single substrate. The plots of % yield of products versus time for c-C₆H₁₂ and c-C₆D₁₂ are shown in Figure 1. The formation of products follows pseudo-first-order kinetics, the pseudo-first-order rate constants (*k_{obs}*) for c-C₆H₁₂ and c-C₆D₁₂ being (5.21 ± 0.15) × 10⁻³ and (1.39 ± 0.1) × 10⁻³ s⁻¹, respectively. The KIE obtained, *k_{obs}*/*k_{obs}*^D = 3.8 ± 0.4, is in good agreement with the value of 3.5 ± 0.4 from competition experiments. These results suggest that in this catalytic system, the rate-determining step is most likely H-atom abstraction from the alkane by the active intermediate. This is in contrast to the [Os(N)Cl₄]⁻/FeCl₃/Cl₂pyO system, where formation of the active intermediate is proposed to be the rate-determining step.¹⁷

Catalytic Oxidation with H₂O₂. Hydrogen peroxide is also an effective reagent for oxidation of alkanes catalyzed by [Os(N)Cl₄]⁻/FeCl₃. In catalytic oxidation of alkanes by [Os(N)Cl₄]⁻/FeCl₃/H₂O₂ in CH₂Cl₂/CH₃CO₂H, good yields were obtained and reactions were completed within minutes at ambient conditions (Table 3). As in the case of ¹BuOOH, the reaction rates and yields (<40%) were much lower if CH₃CO₂H was replaced by CH₃CN. One possible reason is the formation of peracetic acid from hydrogen peroxide and acetic acid. Peracetic acid has been shown to be an efficient terminal oxidant for the epoxidation of alkenes catalyzed by a manganese(II)²⁴ and a μ-oxoiron(III) complex.²⁵ A number of iron(II) complexes have also been found to catalyze the *in situ* formation of peracetic acid from hydrogen peroxide and acetic acid in the course of olefin epoxidation.²⁶ However, we found that neither FeCl₃ nor [¹⁸Bu₄N][Os(N)Cl₄] could catalyze the formation of peracetic acid from hydrogen peroxide and acetic acid, at least within 10 min at room temperature (see Experimental Section).

A TON of at least 1000 for cyclohexane oxidation could be achieved by syringe pump addition of H₂O₂. The TON is probably limited by the presence of water (30% H₂O₂ in water

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Table 2. Catalytic Oxidation of Alkanes by $[^n\text{Bu}_4\text{N}][\text{Os}(\text{N})\text{Cl}_4]/\text{FeCl}_3/{}^t\text{BuOOH}^a$

entry	alkane	product (% yield)	total yield (%)	TON ^b
1	cyclohexane	cyclohexanol (67), cyclohexanone (21), chlorocyclohexane (3), 2-chlorocyclohexanol (tr), cyclohexyl acetate (tr)	91	73
2 ^c	cyclohexane	cyclohexanol (30), cyclohexanone (11), chlorocyclohexane (3), 2-chlorocyclohexanol (tr), 2-chlorocyclohexanone (tr), cyclohexyl acetate (12)	56	7500
3 ^d	cyclohexane	cyclohexanol (68), cyclohexanone (20), chlorocyclohexane (3), 2-chlorocyclohexanol (tr), cyclohexyl acetate (tr)	91	73
4	cyclooctane	cyclooctanol (68), cyclooctanone (22)	90	72
5	<i>cis</i> -1,2-dimethylcyclohexane	<i>cis</i> -1,2-dimethylcyclohexanol (62), <i>trans</i> -1,2-dimethylcyclohexanol (<1), 2,3-dimethylcyclohexanol (4), 3,4-dimethylcyclohexanol (10), 2,3- and 3,4-dimethylcyclohexanone (3)	79	63
6	<i>trans</i> -1,2-dimethylcyclohexane	<i>trans</i> -1,2-dimethylcyclohexanol (26), <i>cis</i> -1,2-dimethylcyclohexanol (<1), 2,3-dimethylcyclohexanol (23), 3,4-dimethylcyclohexanol (24), 2,3- and 3,4-dimethylcyclohexanone (10)	83	66
7	<i>n</i> -hexane	2-hexanol (24), 3-hexanol (25), 2-hexanone (16), 3-hexanone (15), 2-chlorohexane (tr), 3-chlorohexane (tr)	80	64
8	<i>n</i> -heptane	2-heptanol (22), 3-heptanol (23), 4-heptanol (11), 2-heptanone (11), 3-heptanone (11), 4-heptanone (5), 2-chloroheptane (tr), 3-chloroheptane (tr), 4-chloroheptane (tr)	83	66
9 ^e	adamantane	1-adamantanol (85), 1-chloroadamantane (6), 2-adamantanol (7), 2-adamantanone (1)	99	79

^a $[^n\text{Bu}_4\text{N}][\text{Os}(\text{N})\text{Cl}_4]$, 1.25×10^{-3} M; FeCl_3 , 1.0×10^{-2} M; alkane, 1.2 M; ${}^t\text{BuOOH}$, 0.10 M. All reactions were carried out in $\text{CH}_2\text{Cl}_2/\text{CH}_3\text{CO}_2\text{H}$ (5:2, v/v). $T = 23$ °C. Time = 5 min. ^b TON (turnover number) = (mmol of alcohol + mmol of ketone \times 2 + mmol of RCl + mmol of ROAc)/mmol of catalyst. ^c $[^n\text{Bu}_4\text{N}][\text{Os}(\text{N})\text{Cl}_4]$, 1.3×10^{-5} M; FeCl_3 , 1.3×10^{-2} M; cyclohexane, 2.0 M; ${}^t\text{BuOOH}$, 0.174 M. Time = 48 h using syringe pump. ^d $[^n\text{Bu}_4\text{N}][\text{Os}(\text{N})(\text{O})_3]$ was used as the catalyst instead of $[^n\text{Bu}_4\text{N}][\text{Os}(\text{N})\text{Cl}_4]$. ^e $[\text{Adamantane}] = 0.28$ M.

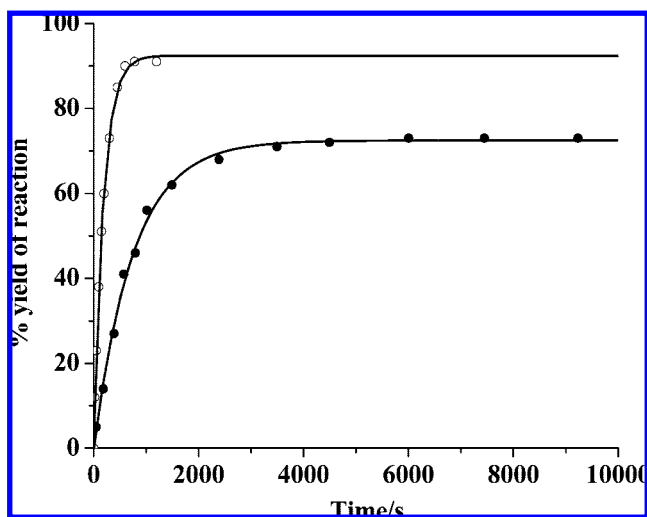


Figure 1. Plot of % yield of reaction versus time for catalytic oxidation of $c\text{-C}_6\text{H}_{12}$ (○) and $c\text{-C}_6\text{D}_{12}$ (●).

was used), which would react with FeCl_3 ; water is also a product of the reduction of H_2O_2 . In the oxidation of adamantane, the ratio of tertiary/secondary products is 28. This catalytic reaction is also highly stereospecific in the oxidation of *cis*- and *trans*-1,2-dimethylcyclohexane.

The KIE ($k^{\text{H}}/k^{\text{D}}$) values determined from competition experiments are 2.7 ± 0.3 , 8.2 ± 0.7 , and 1.9 ± 0.1 for cyclohexanol, cyclohexanone, and chlorocyclohexane, respectively; the overall KIE is 3.5 ± 0.3 , which is in good agreement with the values of 3.5 ± 0.4 and 3.7 ± 0.4 obtained with ${}^t\text{BuOOH}$ and Cl_2pyO , respectively, as the terminal oxidants.

The catalytic oxidation of cyclohexane was carried out in the presence of H_2^{18}O . H_2^{18}O (0.125 M) was first added to a solution containing $[^n\text{Bu}_4\text{N}][\text{Os}(\text{N})\text{Cl}_4]$ (1.25×10^{-3} M), FeCl_3 (1.0×10^{-2} M), and cyclohexane (1.2 M) in $\text{CH}_2\text{Cl}_2/\text{CH}_3\text{CO}_2\text{H}$ at 23 °C, followed by the addition of $\text{H}_2^{16}\text{O}_2$ (1.25×10^{-2} M). The cyclohexanol analyzed by GC/MS after 5 min was found to contain no ^{18}O -labeling. The same result was obtained by

using $[^n\text{Bu}_4\text{N}][\text{Os}(\text{N})(\text{O})_3]$ instead of $[^n\text{Bu}_4\text{N}][\text{Os}(\text{N})\text{Cl}_4]$. This indicates that the active oxidant does not exchange with water under these conditions. These results also strongly suggest that the active intermediate in catalytic oxidation is not $[\text{Os}(\text{N})(\text{O})_3]^-/\text{FeCl}_3$, since in *stoichiometric* oxidation by $[\text{Os}(\text{N})(\text{O})_3]^-/\text{FeCl}_3$ significant incorporation of ^{18}O into the alcohol product (61%) is observed.¹⁷ When $\text{H}_2^{18}\text{O}_2$ was used instead of $\text{H}_2^{16}\text{O}_2$ in the catalytic oxidation reaction, >99% of the oxygen atoms in the cyclohexanol product were ^{18}O -labeled. These results unambiguously demonstrate that O_2 is not involved in the present catalytic oxidation reaction, at least in the production of alcohol product.²⁷ As in the case of oxidation by ${}^t\text{BuOOH}$, the ketone product most likely comes from further oxidation of alcohol. The initial [cyclohexane] affects the relative amount of alcohol and ketone substantially in the present system. Also, this catalytic system oxidizes alcohol to ketone efficiently when alcohol is used as the sole substrate.

Catalytic Oxidation Using $\text{Sc}(\text{OTf})_3$ as the Lewis Acid. Apart from FeCl_3 , $\text{Sc}(\text{OTf})_3$ is also effective in activating $[^n\text{Bu}_4\text{N}][\text{Os}(\text{N})\text{Cl}_4]$ toward catalytic oxidation of cyclohexane by ${}^t\text{BuOOH}$ and H_2O_2 . As in the case of FeCl_3 , good yields were obtained, and reactions were completed within minutes at room temperature (Table 4). Addition of acetic anhydride to the H_2O_2 reaction improved the yield from 82% to 91% (Table 4, entry 5), presumably because it helps to remove water which would coordinate to $\text{Sc}(\text{OTf})_3$. Interestingly, when $[\text{Os}(\text{N})(\text{O})_3]^-$ was used instead of $[\text{Os}(\text{N})\text{Cl}_4]^-$, the yield decreased to 2% (entry 6). This is in contrast to FeCl_3 , where the same result is obtained with $[\text{Os}(\text{N})(\text{O})_3]^-$ or $[\text{Os}(\text{N})\text{Cl}_4]^-$. Presumably this is because the $\text{Sc}(\text{OTf})_3/[\text{Os}(\text{N})(\text{O})_3]^-/\text{H}_2\text{O}_2$ system contains no chloride to convert the osmium complex to $[\text{Os}(\text{N})\text{Cl}_4]^-$. Independent experiments also show that $\text{Sc}(\text{OTf})_3/[\text{Os}(\text{N})(\text{O})_3]^-$ is a much less effective stoichiometric oxidant for cyclohexane than $\text{FeCl}_3/[\text{Os}(\text{N})(\text{O})_3]^-$; only 18% cyclohexanone was obtained after 24 h from $\text{Sc}(\text{OTf})_3/[\text{Os}(\text{N})(\text{O})_3]^-$, whereas 15% cyclo-

(27) Control experiments showed that cyclohexanone exchanges with H_2^{18}O within minutes under typical conditions. This limits studies of ^{18}O labeling for ketones.

Table 3. Catalytic Oxidation of Alkanes by [ⁿBu₄N][Os(N)Cl₄]/FeCl₃/H₂O₂^a

entry	alkane	product (% yield) ^b	total yield (%)	TON
1	cyclohexane	cyclohexanol (60), cyclohexanone (26), chlorocyclohexane (2), 2-chlorocyclohexanol (tr), cyclohexyl acetate (tr)	88	70
2 ^c	cyclohexane	cyclohexanol (61), cyclohexanone (26), chlorocyclohexane (2), 2-chlorocyclohexanol (tr), cyclohexyl acetate (tr)	89	71
3	cyclooctane	cyclooctanol (64), cyclooctanone (18)	82	66
4	<i>cis</i> -1,2-dimethylcyclohexane	<i>cis</i> -1,2-dimethylcyclohexanol (62), <i>trans</i> -1,2-dimethylcyclohexanol (<1), 2,3-dimethylcyclohexanol (4), 3,4-dimethylcyclohexanol (8), 2,3- and 3,4-dimethylcyclohexanone (2)	76	61
5	<i>trans</i> -1,2-dimethylcyclohexane	<i>trans</i> -1,2-dimethylcyclohexanol (23), <i>cis</i> -1,2-dimethylcyclohexanol (<1), 2,3-dimethylcyclohexanol (22), 3,4-dimethylcyclohexanol (20), 2,3- and 3,4-dimethylcyclohexanone (12)	77	62
6	<i>n</i> -hexane	2-hexanol (21), 3-hexanol (21), 2-hexanone (17), 3-hexanone (15), 2-chlorohexane (tr), 3-chlorohexane (tr)	74	59
7	<i>n</i> -heptane	2-heptanol (19), 3-heptanol (20), 4-heptanol (10), 2-heptanone (10), 3-heptanone (10), 4-heptanone (4), 2-chloroheptane (tr), 3-chloroheptane (tr), 4-chloroheptane (tr)	73	58
8 ^d	adamantane	1-adamantanol (77), 1-chloroadamantane (7), 2-adamantanol (6), 2-adamantanone (3)	93	74

^a [ⁿBu₄N][Os(N)Cl₄], 1.25 × 10⁻³ M; FeCl₃, 1.0 × 10⁻² M; alkane, 1.2 M; H₂O₂, 0.10 M. All reactions were carried out in CH₂Cl₂/CH₃CO₂H (5:2, v/v). *T* = 23 °C. Time = 5 min. ^b The yields were based on [H₂O₂] consumed. ^c [ⁿBu₄N][Os(N)(O)₃] was used as the catalyst instead of [ⁿBu₄N][Os(N)Cl₄]. ^d [Adamantane] = 0.28 M.

Table 4. Catalytic Oxidation of Cyclohexane by [ⁿBu₄N][Os(N)Cl₄]/Sc(OTf)₃/ROOH under Various Conditions^a

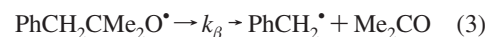
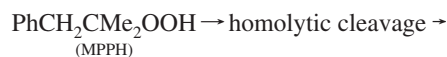
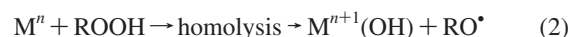
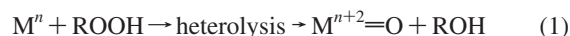
entry	Sc(OTf) ₃	oxidant	product (% yield) ^b			total yield (%)	time
			c-C ₆ H ₁₁ OH	c-C ₆ H ₁₀ O	c-C ₆ H ₁₁ Cl		
1 ^c		^t BuOOH	nd ^d	nd	nd	0	24 h
2	2	^t BuOOH	57	31	2	90	10 min
3	4	^t BuOOH	57	31	2	90	10 min
4	4	H ₂ O ₂	52	28	2	82	10 min
5 ^e	4	H ₂ O ₂	60	29	2	91	10 min
6 ^f	4	H ₂ O ₂	2	tr	nd	2	10 min

^a [ⁿBu₄N][Os(N)Cl₄], 1.25 × 10⁻³ M; alkane, 1.2 M; ROOH, 0.10 M. ^b The yields were based on the system acting as a two-electron oxidant. ^c Sc(OTf)₃, 5.0 × 10⁻³ M. The reaction was carried out in the absence of [ⁿBu₄N][Os(N)Cl₄]. ^d nd = not detected. ^e Acetic anhydride (0.65 M) was added. ^f [ⁿBu₄N][Os(N)(O)₃] was used as the catalyst instead of [ⁿBu₄N][Os(N)Cl₄].

hexanol and 62% cyclohexanone were obtained after 30 s from FeCl₃/[Os(N)(O)₃]⁻.¹⁷ These results demonstrate that the active intermediate in stoichiometric oxidation by Sc(OTf)₃/[Os(N)(O)₃]⁻ is different from that in catalytic oxidation by Sc(OTf)₃/[Os(N)Cl₄]⁻/H₂O₂.

Catalytic Oxidation with PhCH₂C(CH₃)₂OOH (MPPH). MPPH has been used as a mechanistic probe to distinguish between free radical and metal-based (radical-free) hydrocarbon oxidations.^{23,28} The interaction of a metal center with ROOH may involve heterolysis or homolysis (eqs 1 and 2). Both RO[•] and metal–oxo intermediates are capable of abstracting a H-atom from alkanes to form alkyl radicals, which may then be converted to alcohol and/or ketone. When MPPH is the oxidant, the *tert*-alkoxyl radical (PhCH₂C(CH₃)₂O[•]) generated from homolytic cleavage of the O–O bond will undergo an extremely rapid β-scission process (eq 3); thus, H-atom abstraction from an alkane by PhCH₂C(CH₃)₂O[•] cannot occur. This means that if homolytic cleavage of MPPH to generate alkoxyl radical is involved in the catalytic oxidation of cyclohexane by M^{III}/[Os(N)Cl₄]⁻/MPPH (M^{III} = FeCl₃ or Sc(OTf)₃), no cyclo-

hexane-derived products will be formed. On the other hand, if a metal–oxo species is produced from [Os(N)Cl₄]⁻ and MPPH by a heterolytic process, oxygenated products derived from cyclohexane (c-C₆H₁₁OH and c-C₆H₁₀O) will be observed.



The results of cyclohexane oxidation by MPPH are summarized in Table 5. When only FeCl₃ was used as the catalyst, no products were observed for at least 1 h at 23 °C.²⁹ When FeCl₃/[Os(N)Cl₄]⁻ was used, oxidation of cyclohexane occurred within 5 min. When MPPH was added all at once into the reaction mixture, the yield was 53% after 5 min (Table 5, entry 4). The products cyclohexanol, cyclohexanone, and MPPOH are derived from heterolytic cleavage of MPPH. On the other hand, products derived from homolytic cleavage of MPPH were also observed, including benzyl alcohol (1%), benzaldehyde (1%), and benzyl chloride (11%). With syringe pump addition of MPPH (entries 5 and 6), the products from heterolytic cleavage increased to 76%, while products from homolytic cleavage were reduced to <4%. In the absence of FeCl₃, [Os(N)Cl₄]⁻ can also catalyze cyclohexane oxidation using MPPH. The product yields were similar, but the reaction was much slower (14 h). Efficient catalytic oxidation of cyclohexane can also be effected with Sc(OTf)₃/[Os(N)Cl₄]⁻/MPPH (entry 7), with 64% cyclohexane-derived products within 40 min at room temperature. However, in this case, no products arising from homolytic cleavage of MPPH were detected.³⁰

(28) (a) MacFaul, P. A.; Ingold, K. U.; Wayner, D. D. M.; Que, L., Jr. *J. Am. Chem. Soc.* **1997**, *119*, 10594–10598. (b) Ingold, K. U.; MacFaul, P. A. In *Biomimetic Oxidations Catalyzed by Transition Metal Complexes*; Meunier, B., Ed.; Imperial College Press: London, 2000; pp 45–89.

(29) Excess PPh₃ was added before injection into GC to quench any MPPH left. When MPPH alone was injected into GC/FID, a mixture of organic products were detected, including benzyl alcohol, benzaldehyde, benzyl chloride, benzyl acetate, and MPPOH. On the other hand, when excess PPh₃ was added to MPPH before injection, only PPh₃, PPh₃O, and MPPOH were detected by GC/FID.

Table 5. Cyclohexane Oxidation by MPPH under Various Conditions^a

entry	catalyst	syringe pumped	products (% yield)		time
			heterolytic cleavage	homolytic cleavage	
1	FeCl ₃	no	nd ^b	nd	1 h
2	[Os(N)Cl ₄] ⁻	no	cyclohexanol (61), cyclohexanone (3), chlorocyclohexane (3), MPPOH (91)	benzyl alcohol (5), benzaldehyde (3), benzyl chloride (nd)	14 h
3	[Os(N)Cl ₄] ⁻	yes; flow rate = 100 μL/h	cyclohexanol (57), cyclohexanone (2), chlorocyclohexane (3), MPPOH (95)	benzyl alcohol (3), benzaldehyde (2), benzyl chloride (nd)	14 h
4	[Os(N)Cl ₄] ⁻ /FeCl ₃	no	cyclohexanol (49), cyclohexanone (2), chlorocyclohexane (2), MPPOH (83)	benzyl alcohol (1), benzaldehyde (1), benzyl chloride (11)	5 min
5	[Os(N)Cl ₄] ⁻ /FeCl ₃	yes; flow rate = 200 μL/min	cyclohexanol (63), cyclohexanone (2), chlorocyclohexane (3), MPPOH (93)	benzyl alcohol (1), benzaldehyde (1), benzyl chloride (3)	5 min
6	[Os(N)Cl ₄] ⁻ /FeCl ₃	yes; flow rate = 25 μL/min	cyclohexanol (69), cyclohexanone (4), chlorocyclohexane (3), MPPOH (97)	benzyl alcohol (2), benzaldehyde (<1), benzyl chloride (<1)	40 min
7	[Os(N)Cl ₄] ⁻ /Sc(OTf) ₃	yes; flow rate = 25 μL/min	cyclohexanol (61), cyclohexanone (2), chlorocyclohexane (1), MPPOH (90)	benzyl alcohol (nd), benzaldehyde (nd), benzyl chloride (nd)	40 min

^a [¹⁸Bu₄N][Os(N)Cl₄], 1.25 × 10⁻³ M; FeCl₃ or Sc(OTf)₃, 1.25 × 10⁻³ M; cyclohexane, 1.2 M; MPPH, 1.25 × 10⁻² M. All reactions were carried out in CH₂Cl₂/CH₃CO₂H (5:2, v/v) at 23 °C. For entry 1, PPh₃ (3.75 × 10⁻² M) was added before injection into GC/FID. For entries 2–7, the same results were obtained with or without addition of PPh₃ prior to analysis by GC/FID. ^b nd = not detected.

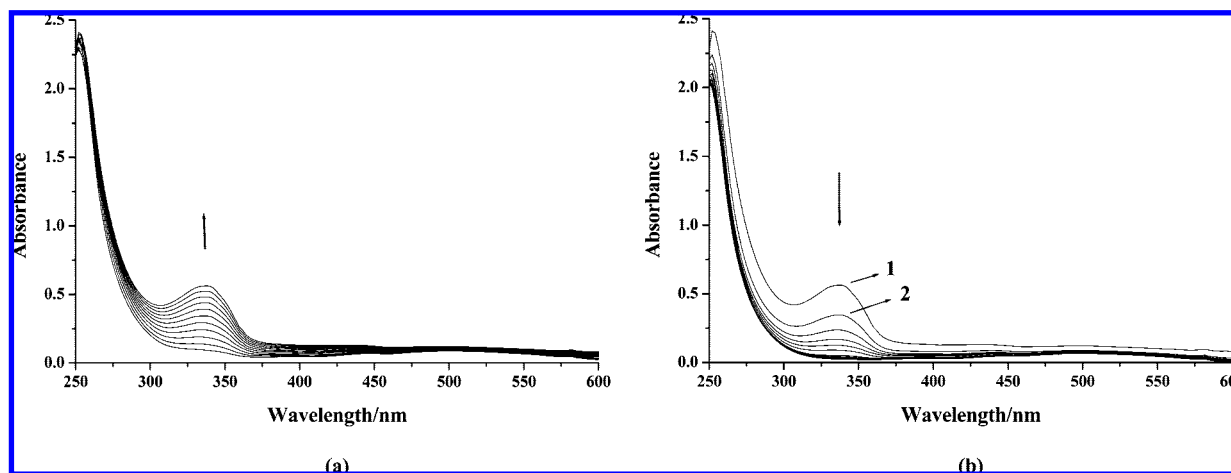


Figure 2. (a) Spectral change at 2-s intervals upon adding ¹BuOOH (2 × 10⁻² M) to Sc(OTf)₃ (2 × 10⁻³ M) and [¹⁸Bu₄N][Os(N)Cl₄] (1 × 10⁻³ M) in CH₂Cl₂/CH₃CO₂H (5:2, v/v) at 23 °C. (b) Spectral change after the addition of cyclohexane (0.926 M) to the solution in (a) that has reacted for 20 s. 1, spectrum before addition of cyclohexane; 2, spectrum obtained ca. 5 s after addition of cyclohexane. Subsequent spectra were obtained at 30-s intervals.

Detection of Active Intermediate. Since FeCl₃ absorbs strongly in the UV/vis region, Sc(OTf)₃ was used as the Lewis acid to investigate the active intermediate in the catalytic oxidation of cyclohexane by ¹BuOOH using UV/vis spectrophotometry. No spectral change in the UV/vis region was observed when Sc(OTf)₃ (2 × 10⁻³ M) was mixed with a pink solution of [¹⁸Bu₄N][Os(N)Cl₄] (1 × 10⁻³ M) in CH₂Cl₂/CH₃CO₂H (5:2, v/v) at 23 °C. However, upon addition of ¹BuOOH (2 × 10⁻² M), the solution rapidly changed to pale green, and the UV/vis spectrum showed the growth of a peak at 334 nm (Figure 2). After ca. 20 s, cyclohexane (0.926 M) was added, and the pale green solution rapidly changed back to pink. Analysis by GC and GC/MS after 5 min indicated the formation of 65% of cyclohexane-derived products (54% cyclohexanol, 8% cyclohexanone, and 3% chlorocyclohexane). The final spectrum was

identical to that of the initial [¹⁸Bu₄N][Os(N)Cl₄]/Sc(OTf)₃ solution. No spectral change and no oxidation products were found if the reaction was run in the absence of [Os(N)Cl₄]⁻. On the other hand, similar spectral changes were observed if the reaction was run in the absence of Sc(OTf)₃, but both the formation and decay of the intermediate were slower by >100 times (Supporting Information). These results show that the reaction of [Os(N)Cl₄]⁻ with ¹BuOOH produces an intermediate that oxidizes cyclohexane, and both steps are activated by Sc(OTf)₃.

The UV–vis spectrum of this active intermediate is different from that of [Os(N)(O)₃]⁻ in the presence or absence of Sc(OTf)₃ (Supporting Information). Attempts to detect the active intermediate (in the presence or absence of Lewis acid) at various temperatures by ESI-MS were unsuccessful; the only osmium-containing species found was [Os(N)Cl₄]⁻. Attempts to isolate the active intermediate by precipitating with various solvents again produced only [¹⁸Bu₄N][Os(N)Cl₄].

Mechanism. Several pieces of evidence suggest that the oxidation of alkanes by [Os(N)Cl₄]⁻/M^{III}/ROOH (M^{III} = FeCl₃, Sc(OTf)₃) occurs via a metal-based active intermediate that is derived from heterolytic cleavage of ROOH. In catalytic oxidation of cyclohexane using MPPH, the good yields of cyclohexanol and cyclohexanone (>70%) and MPPOH (>90%)

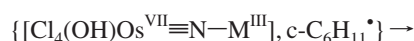
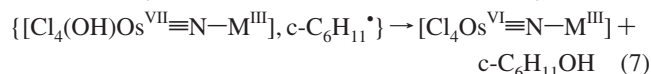
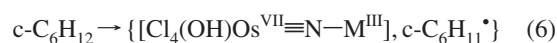
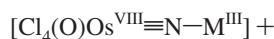
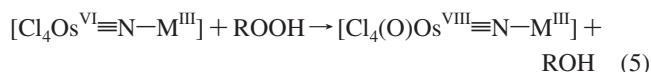
(30) There were, however, around 2% each of C₆H₅CH₂C(CH₃)=CH₂, C₆H₅CH=C(CH₃)₂, HOC₆H₄CH₂C(CH₃)=CH₂, and HOC₆H₄CH=C(CH₃)₂. Independent experiments show that Sc(OTf)₃ (1.25 × 10⁻³ M) catalyzes the dehydration of MPPOH (1.25 × 10⁻² M) in CH₂Cl₂/CH₃CO₂H (5:2, v/v) to give 3% of C₆H₅CH₂C(CH₃)=CH₂ and 4% of C₆H₅CH=C(CH₃)₂ after 40 min at 23 °C. The presence of HOC₆H₄CH₂C(CH₃)=CH₂ and HOC₆H₄CH=C(CH₃)₂ in the cyclohexane oxidation by MPPH probably comes from the oxidation of C₆H₅CH₂C(CH₃)=CH₂ and C₆H₅CH=C(CH₃)₂, respectively. Independent experiments also show that this catalytic system attacks aromatic rings faster than aliphatic C–H bonds.

clearly indicate that these products are derived from heterolytic cleavage of MPPH. The observed small amounts of benzyl-containing products are probably not derived from homolytic cleavage of a small amount of MPPH but are more likely due to H-atom abstraction from MPPH by the metal-based active intermediate. This would produce $\text{PhCH}_2\text{C}(\text{CH}_3)_2\text{OO}^\bullet$, which could then undergo a bimolecular reaction to produce $\text{PhCH}_2\text{C}(\text{CH}_3)_2\text{O}^\bullet$ and O_2 . Under syringe pump conditions, the concentration of the active intermediate would remain low, and hence the amount of benzyl-containing products would decrease. This is one of the very few catalytic systems that can utilize MPPH efficiently in hydrocarbon oxidation, and the process is genuinely two-electron, without involving alkoxy radicals. Efficient oxidation of hydrocarbons by MPPH has been reported only for a titanium(IV)^{31,32} and a binuclear iron(II) catalyst.³³

Further evidence supporting a mechanism that does not involve alkoxy and free alkyl radicals is described as follows. (1) The product yields and distributions are only slightly affected by the presence of O_2 . (2) Addition of BrCCl_3 does not affect the yields of cyclohexanol and cyclohexanone in the oxidation of cyclohexane, and only a trace amount of bromocyclohexane is produced. (3) In the oxidation of cyclohexane using $^t\text{BuOOH}$, no mixed peroxides such as $c\text{-C}_6\text{H}_{11}\text{OOCMe}_3$ are detected. (4) The overall KIE for cyclohexane (around 4) and the ratio of tertiary/secondary products for adamantane (around 30) are in good agreement with the values obtained with the $[\text{Os}(\text{N})(\text{O})_3]^- / \text{FeCl}_3/\text{Cl}_2\text{pyO}$ system, in which the active oxidant is proposed to be $[\text{Cl}_4(\text{O})\text{Os}^{\text{VIII}}\equiv\text{N}-\text{Fe}^{\text{III}}]$.¹⁷ Cl_2pyO is usually regarded as an oxygen-atom transfer reagent. (5) A complete retention of stereochemistry is observed in the hydroxylation of *cis*- and *trans*-1,2-dimethylcyclohexane. Oxidation via a carbon-centered free radical would give a mixture of epimeric alcohols.^{28b} (6) The ketone/alcohol ratio depends on the initial alkane concentration. Oxidation involving alkoxy radicals would result in the formation of roughly equal yields of ketone and alcohol.^{28b}

The similarities in product distributions, KIE, and stereoselectivity in catalytic oxidation by the various peroxides suggest a common active intermediate. Although in catalytic oxidation using FeCl_3 as the Lewis acid, $[\text{Os}(\text{N})\text{Cl}_4]^-$ can be replaced by $[\text{Os}(\text{N})(\text{O})_3]^-$ to give the same yields and rates, $\text{Fe}^{\text{III}}/[\text{Os}(\text{N})(\text{O})_3]^-$ is not the active intermediate. If $[\text{Os}(\text{N})(\text{O})_3]^-$ is used, it will be activated by FeCl_3 to oxidize alkane to generate $[\text{Os}(\text{N})\text{Cl}_4]^-$, which then enters the catalytic cycle. The oxo ligands in $[\text{Os}(\text{N})(\text{O})_3]^-$ exchange rapidly with H_2O in the presence of FeCl_3 .¹⁷ However, in catalytic oxidation by $\text{FeCl}_3/[\text{Os}(\text{N})\text{Cl}_4]^-$ using H_2O_2 in the presence of H_2^{18}O , there is no incorporation of ^{18}O in cyclohexanol, indicating that the active intermediate does not exchange with water under these conditions. Moreover, the activating effects of $\text{Sc}(\text{OTf})_3$ are much less than that of FeCl_3 when $[\text{Os}(\text{N})(\text{O})_3]^-$ is used in stoichiometric or catalytic oxidation, but $\text{Sc}(\text{OTf})_3$ is as efficient as FeCl_3 in activating $[\text{Os}(\text{N})\text{Cl}_4]^-$. This again indicates that $\text{Sc}^{\text{III}}/[\text{Os}(\text{N})(\text{O})_3]^-$ is not the active intermediate in catalytic oxidation by $\text{Sc}^{\text{III}}/[\text{Os}(\text{N})\text{Cl}_4]^-$. The UV-vis spectrum of the active intermediate generated from addition of $^t\text{BuOOH}$ to $[\text{Os}(\text{N})\text{Cl}_4]^- / \text{Sc}(\text{OTf})_3$ is also different from that of $[\text{Os}(\text{N})(\text{O})_3]^- / \text{Sc}(\text{OTf})_3$.

Based on all the evidence, a proposed mechanism for alkane oxidation by $[\text{Os}(\text{N})\text{Cl}_4]^- / \text{M}^{\text{III}}/\text{ROOH}$ is shown in eqs 4–8 (the charge of the binuclear species is not specified). In the first step, $[\text{Os}^{\text{VI}}(\text{N})\text{Cl}_4]^-$ combines with the Lewis acid M^{III} (FeCl_3 or $\text{Sc}(\text{OTf})_3$), presumably through the nitrido ligand, to form an adduct $[\text{Cl}_4\text{Os}^{\text{VI}}\equiv\text{N}-\text{M}^{\text{III}}]$. O-atom transfer from ROOH to $[\text{Cl}_4\text{Os}^{\text{VI}}\equiv\text{N}-\text{M}^{\text{III}}]$ then occurs to generate $[\text{Cl}_4(\text{O})\text{Os}^{\text{VIII}}\equiv\text{N}-\text{M}^{\text{III}}]$, which is the active intermediate in the catalytic reaction. $[\text{Cl}_4(\text{O})\text{Os}^{\text{VIII}}\equiv\text{N}-\text{M}^{\text{III}}]$ oxidizes alkanes by H-atom abstraction from a C–H bond, followed by OH rebound in the solvent cage to generate ROH. The ROH is then further oxidized by the active intermediate to generate the ketone. The minor product chlorocyclohexane could be formed via Cl-atom abstraction from $[\text{Cl}_4(\text{OH})\text{Os}^{\text{VIII}}\equiv\text{N}-\text{M}^{\text{III}}]$ by R^\bullet in the solvent cage (eq. 8). Electron-withdrawing by the electrophilic Fe^{III} or Sc^{III} center in $[\text{Cl}_4(\text{O})\text{Os}^{\text{VIII}}\equiv\text{N}-\text{M}^{\text{III}}]$ would enhance the oxidizing power of the $\text{Os}(\text{VIII})$ -oxo species. In the absence of Lewis acid, both the rate and the yield become much lower. Spectrophotometric studies indicate that both the formation of the active intermediate and its subsequent oxidation of alkanes become much slower in the absence of Lewis acid. This suggests that the Lewis acid also enhances the O-atom transfer from ROOH to $[\text{Os}(\text{N})\text{Cl}_4]^-$. Presumably, the Lewis acid forms an adduct with $[\text{Os}(\text{N})\text{Cl}_4]^-$, and it facilitates heterolytic cleavage of coordinated ROOH in $[\text{Cl}_4(\text{ROOH})\text{Os}^{\text{VI}}\equiv\text{N}-\text{M}^{\text{III}}]$.



Concluding Remarks. The oxidation of alkanes by peroxides is efficiently catalyzed by a simple catalytic system consisting of $[\text{Os}(\text{N})\text{Cl}_4]^-$ and a Lewis acid. Oxidation occurs rapidly at ambient conditions, and yields of >90% and thousands of turnovers can be readily achieved. In particular, this catalytic system can utilize MPPH efficiently as the terminal oxidant. These reactions do not involve alkoxy and free alkyl radicals. The active intermediate is proposed to be an osmium(VIII)-oxo intermediate which is activated by the Lewis acid. The use of a Lewis acid in combination with a relatively stable metal-oxo species as oxidation catalyst has a number of advantages over the use of a single, highly oxidizing species. Reactivity and selectivity can be readily tuned by changing the steric and electronic properties of the Lewis acid. Enantioselective oxidation could be achieved simply by using a chiral Lewis acid. A stable metal-oxo species with a relatively low redox potential could also be more rapidly generated by the terminal oxidant.

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Supporting Information Available: Catalytic oxidation data and UV-vis spectra. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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