Catalytic Oxidation of Hydrocarbons with O_2 or H_2O_2 Using a Sterically Hindered Ruthenium Complex

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Abstract: The sterically hindered complex *cis*-$[Ru(dmp)_2(S)_2](PF_6)_2$ (S = H_2O; CH_3CN), where dmp is 2,9-dimethyl-1,10-phenanthroline, catalyzes the oxidations of alkenes with dioxygen and of alkanes with hydrogen peroxide under mild pressures (40–50 psig) and temperatures (65–75 °C). The reaction of norbornene, O_2, and a catalytic amount of $[Ru(dmp)_2(CH_3CN)_2](PF_6)_2$ results in 2,3-epoxynorbornane with 94% selectivity. Mechanistic experiments suggest that a free-radical reaction between *cis*-$[Ru(dmp)_2(CH_3CN)_2](PF_6)_2$, norbornene, and O_2 occurs initially to generate a high-valent ruthenium oxo species involved in an oxygen atom-transfer catalytic cycle with O_2. In the presence of H_2O_2 and a catalytic amount of *cis*-$[Ru(dmp)_2(S)_2](PF_6)_2$ (S = H_2O; CH_3CN), unactivated alkanes are hydroxylated. Studies of this reaction indicate a free-radical mechanism in which H atom abstraction is the rate-determining step (k_H/k_D = 4 for cyclohexane).

Introduction

Reductive activation of dioxygen by metal complexes is a long sought goal since dioxygen and its reduced products are inexpensive and plentiful sources of oxidizing equivalents.[1] Metal complexes can be used in a variety of different ways to activate dioxygen to form a metallooxidant which can oxidize hydrocarbons.[1e,f] The metal oxo moiety is a well-known oxidant;[2] however, despite numerous examples of hydrocarbon oxidation catalysis by metal oxo species only a limited number have been found or proposed to catalyze the oxidation of hydrocarbons solely with dioxygen.[3] The goal of our laboratory, therefore, has been to select and evaluate metal complexes with the requisites necessary for both dioxygen activation and oxidation catalysis.[4] Thorough studies of ruthenium metal complexes with polypyridyl ligands by Meyer,[5] Takeuchi,[3c,6] and Che[7] have revealed several features that make these complexes excellent candidates for the catalytic oxidation of organic compounds with dioxygen: (1) they display an extensive range of reversible, accessible oxidation states, i.e., from 2+ to 6+ to completely reduce dioxygen and (2) they form stable ruthenium oxo species, $\{Ru(O)\}^{2+}$ and $\{Ru(O)_2\}^{2+}$, which are good metal oxygen atom-transfer reagents for a myriad of substrates. With few exceptions, stoichiometric oxygen atom-transfer reagents or electrochemical potential have been the only sources of oxidizing equivalents in previous studies with most ruthenium polypyridyl and related catalysts.[8]

We have communicated previously that oxidizing the sterically hindered complex *cis*-$[Ru(dmp)_2(H_2O)_2](PF_6)_2$ (**2**) with Ce^{4+} yielded a product tentatively formulated as *cis*-$[Ru(dmp)_2(O)_2](PF_6)_2$ (**6**),[4a] where dmp is 2,9-dimethyl-1,10-phenanthroline. Following an induction period, this highly oxidized species catalyzed the epoxidation of alkenes selectively at slightly elevated temperatures and O_2 pressures. In a subsequent communication,[4b] we showed that the precursor to

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the active catalyst, *cis*-$[Ru(dmp)_2(S)_2](PF_6)_2$ (S = H_2O (**2**); CH_3CN (**3**)), and hydrogen peroxide can catalytically hydroxylate alkanes. In the course of these studies, spectroscopic measurements established that hydrogen peroxide generated the *cis*-$[Ru(dmp)_2(O)(S)](PF_6)_2$ and *cis*-$[Ru(dmp)_2(O)_2](PF_6)_2$ putative catalysts. In this paper we describe our most recent results and mechanistic hypotheses of alkene epoxidation and alkane hydroxylation reactions by *cis*-$[Ru(dmp)_2(S)_2](PF_6)_2$ with dioxygen and hydrogen peroxide.

Experimental Section

Materials and Methods. Ceric perchlorate was purchased from G. F. Smith. Ethylene glycol and hydrogen peroxide were purchased from Fisher Scientific (ACS grade). All other chemicals were purchased from Aldrich and used as received. Cyclohexane, cyclohexene, and *trans*-β-methylstyrene were purified by washing through a neutral column of alumina. Acetonitrile was distilled over P_2O_5 under dinitrogen and was stored over 4-Å activated molecular sieves. All gases were purchased from Matheson.

Physical Measurements. The NMR spectra were recorded on a Varian VXR300 spectrometer. The UV/vis spectra were obtained using a Perkin-Elmer Lambda 6 spectrophotometer. FAB mass spectral data were obtained by Dr. David Powell (U. F.) in a *m*-nitrobenzyl alcohol matrix. Elemental analyses were performed by U. F. Analytical Services.

Syntheses of Compounds. *cis*-Ruthenium(II) Bis(chloride)bis(2,9-dimethyl-1,10-phenanthroline) Monohydrate, $[Ru(dmp)_2Cl_2]\cdot H_2O$ ($1\cdot H_2O$). $[Ru(dmp)_2Cl_2]\cdot H_2O$ was prepared by a modification of the published procedure.[9] In a three-neck 250 mL round-bottom flask equipped with a thermometer and reflux condenser, 1.0 g (3.8 mmol) of $RuCl_3\cdot 3H_2O$, 1.7 g (8 mmol) of neocuproine monohydrate (dmp·H_2O), and 2.5 g (59 mmol) of LiCl were combined with 25 mL of ethylene glycol under dinitrogen. This dark red solution was heated at 150 °C for 6 h, during which time it became dark purple. The yield and purity of **1** decreased significantly if the temperature exceeded 150 °C. The heating source was removed, and 50 mL of acetone was added cautiously in small aliquots (*Caution: flammability hazard*). The solution was allowed to cool to room temperature with stirring, and then 15 mL of distilled H_2O was added. The solution was filtered, and the purple microcrystalline solid was washed three times with 15 mL of distilled H_2O. The product was dried in a vacuum oven at 50 °C overnight to give 1.8 g of $1\cdot H_2O$ (78% yield). Anal. Calcd for $C_{28}H_{26}N_4OCl_2Ru$: C, 55.45; H, 4.29; N, 9.24. Found: C, 55.40; H, 4.30; N, 9.27.

***cis*-Ruthenium(II) Bis(aquo)bis(2,9-dimethyl-1,10-phenanthroline)bis(hexaflourophosphate), $[Ru(dmp)_2(H_2O)_2](PF_6)_2$ (2).** A 1.0-g (1.7 mmol) portion of $1\cdot H_2O$ was dissolved in 150 mL of distilled H_2O over a period of 45 min at 50 °C under dinitrogen. To this solution was added 0.5 mL of 60% aqueous HPF_6 to dissolve any remaining solid. A 4.0-g portion of NH_4PF_6 was added to the solution to induce precipitation of the red-brown product. The solution was cooled to 5 °C on an ice bath to complete precipitation. The precipitate was filtered and washed with 10 mL of cold 0.1 M aqueous HPF_6. Drying of the precipitate at room temperature in a vacuum oven overnight afforded 1.2 g of pure **2** (84% yield). Anal. Calcd for $C_{28}H_{28}N_4O_2P_2F_{12}Ru$: C, 39.85; H, 3.32; N, 6.64. Found: C, 39.52; H, 3.30; N, 6.72.

***cis*-Ruthenium(II) Bis(acetonitrile)bis(2,9-dimethyl-1,10- phenanthroline)bis(hexafluorophosphate), $[Ru(dmp)_2(CH_3CN)_2](PF_6)_2$ (3).** A 0.2-g of $Ru(dmp)_2Cl_2\cdot H_2O$ (0.33 mmol) was added to 20 mL of acetonitrile, and a drop of 1 M aqueous HPF_6 was added resulting in a yellow solution. A 0.17-g (0.67 mmol) portion of $AgPF_6$ dissolved in a minimum amount of acetonitrile was added to the solution in drops. The solution was filtered through a pad of Celite to remove AgCl. To the filtrate was added 15 mL of a saturated aqueous $NaPF_6$ solution with stirring. The yellow-orange solid was filtered, washed with H_2O, and dried under vacuum to give 0.21 g of **3** (72%). This compound can be recrystallized from acetonitrile and diethyl ether. Anal. Calcd for $C_{32}H_{30}N_6P_2F_{12}Ru$: C, 43.19; H, 3.37; N, 9.45. Found: C, 43.20; H, 3.33; N, 9.44. Compound **3** can also be prepared by dissolving and precipitating **2** from acetonitrile as described above.

***In Situ* Generation of *cis*-Ruthenium(IV) (Oxo)(aquo)bis(2,9-dimethyl-1,10-phenanthroline)bis(hexafluorophosphate), $[Ru(O)(dmp)_2(H_2O)](PF_6)_2$ (4), and *cis*-Ruthenium(VI) Bis(oxo)bis(2,9-dimethyl-1,10-phenanthroline)bis(hexafluorophosphate), $[Ru(O)_2(dmp)_2](PF_6)_2$ (5).** In a 100-mL round bottom flask, 0.05 g (0.06 mmol) of **2** was dissolved in 20–25 mL of distilled water. This solution was heated gently to completely dissolve the starting material. To this dark red solution, were added 3 or 7 equiv of H_2O_2 dropwise while the solution was stirred to generate an orange-yellow solution of **4** or **5**, respectively. A variety of other oxidants can also be used in place of H_2O_2: *tert*-butylhydroperoxide, hypochlorite, and ceric ion. In cases when a hydroperoxide is not used, only 2 or 4 equiv (stoichiometric) of oxidant was necessary to form **4** or **5**, respectively. It was possible to obtain a solid product from solutions of **4** or **5** by adding a saturated solution of $NaPF_6$ until a yellow-orange precipitate formed. The precipitate was filtered, washed three times with diethyl ether, and dried overnight under vacuum. Anal. Calcd for $C_{28}H_{26}N_4O_2P_2F_{12}Ru$ (**4**): C, 39.95; H, 3.09; N, 6.66. Found: C, 39.80; H, 2.99; N, 6.52. Upon dissolution, these isolated solids were impure compared to the *in situ* generated solutions of **4** and **5** on the basis of their reported spectroscopic characterization.[4b]

Oxidation Procedure. All pressurized oxidations were carried out in a Parr hydrogenation apparatus described previously.[4c,10] Typically a 40–50 mL volume was used; however, inserting a vial of the reaction mixture into the hydrogenation bottle allowed smaller volume reactions (1–5 mL) to be carried out. Experiments in the absence of oxidant were carried out as a control. The reactions were monitored by one or more of the following techniques: GC, GCMS, GCIR, and ^1H NMR. The products of the oxidation reactions were analyzed and quantified by GC (Varian 3300 gas chromatograph/FID detector/6-ft chromosorb 15% DEGS column) and GCMS (Varian 3400 gas chromatograph interfaced with a Finnegan MAT ITDS 700 mass spectrometer equipped with a 15-m dbl column). GC samples were injected three times to obtain a measure of precision. After the reaction was complete, the spent catalyst was recovered by evaporation. For radical experiments, a 100:1 ratio of radical trap (benzoquinone, BQ) or initiator (azobis(isobutyronitrile), AIBN) to catalyst was used.

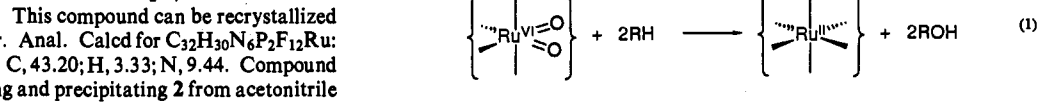
Alkenes. Reactions were performed at 65 °C under 40 psig O_2 initial pressure in acetonitrile. A minimum 100-fold excess of norbornene to catalyst was dissolved in 50 mL of acetonitrile, and 1×10^{-5} mol of catalyst was added. In the case of cyclohexene, 10 mL of cyclohexene was added to 40 mL of acetonitrile. Other reactions were carried out by adding 3 mL of substrate to 47 mL of acetonitrile. No internal GC standard was used other than 2-octanone in the oxidation of cyclohexene.

Alkanes. The reaction mixture comprised 25–35 mL of solvent, 15–25 mL of liquid or 50 psig of gaseous substrate, 1 mL of benzene as an internal GC standard, and 10^{-5} mol of catalyst. H_2O_2 (10^{-2} mol) was used as the oxidant. The temperature of the reaction was maintained at 75 °C. An initial pressure of 50 psig of air was used in the case of liquid substrates. Although oxidations of gaseous substrates were reproduced, the reactions sometimes yielded no or little oxygenated products. We have not been able to identify the conditions that account for this variability.

Safety Precautions. The combination of molecular oxygen with organic compounds and solvents at elevated temperatures and pressures is a potential explosive. **Extreme caution** should be taken during the charging and disassembly of the experimental apparatus, particularly around equipment that generates sparks. The use of a safety shield and allowing the reactants to cool prior to disassembly is highly recommended. Hundreds of reactions have been carried out without incident following these precautions.

Results and Discussion

Our goal was to devise a potent catalytic system based on the *cis*-$\{Ru(O)_2\}^{2+}$ moiety and dioxygen as the sole oxidant. Like RuO_4,[11] the *cis*-$\{Ru(O)_2\}^{2+}$ moiety is a powerful oxidant and has the potential of carrying out a four-electron oxidation in which both oxygen atoms are transferred from the metal oxo species to a hydrocarbon, e.g., eq 1.[4ab,5a,7ab,9,12] A major obstacle in the



(1)

preparation of the *cis*-$\{Ru(O)_2\}^{2+}$ moiety is its propensity to isomerize to the more stable *trans* species, a weaker oxi-

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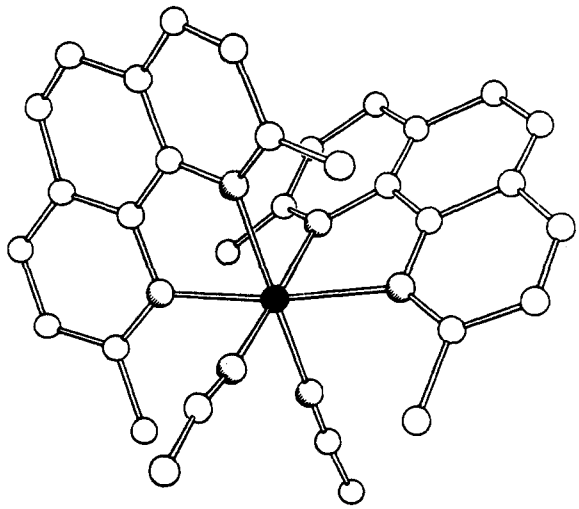
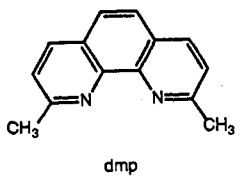
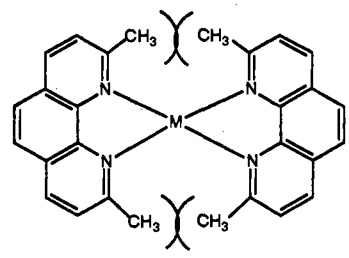


Figure 1. Ball and stick model of $[Ru(dmp)_2(CH_3CN)_2]^{2+}$ (3). Ru (solid), N (shaded), O (open circles).

dant.[5gjo,9,12b,13] This isomerization was overcome by Collin and Sauvage[9] using 2,9-dimethyl-1,10-phenanthroline to prepare *cis*-$[Ru(dmp)_2(S)_2](PF_6)_2$ (S = H_2O (2); CH_3CN (3)). This sterically crowded ligand prevents the formation of *trans*-$[Ru(dmp)_2(S)_2](PF_6)_2$, enforcing the *cis* stereochemistry. Steric





unfavorable steric interactions for dmp in the trans coordination mode

interactions between the methyl groups are also likely to exclude the formation of inactive μ-oxo dinuclear ruthenium species, $\{Ru_2O\}^{n+}$, during catalysis.[14] Che has found that the related sterically hindered ligand, 6,6'-dichloro-2,2'-bipyridine (Cl_2bpy), imparts properties similar to those of the oxidation catalyst *cis*-$[Ru(Cl_2bpy)_2(O)_2]^{2+}$.[7a,b]

In our hands, a minor modification of the reported syntheses[9] of 2 and 3 from *cis*-$[Ru(dmp)_2(Cl)_2]$ (1) gave good to excellent yields of these compounds. As we had observed previously with the Ce^{4+} oxidation of 2 to 5, solid products could be obtained from preparations of 4 and 5 with H_2O_2 and other oxygen atom-transfer reagents, but upon dissolution these solids were impure, as determined by UV/vis and NMR spectroscopy.[4b] Therefore, 4 and 5 were generated *in situ* for the studies reported in this paper. In these preparations it was necessary to add >1 equiv of H_2O_2 to 2 or 3 to compensate for the competing metal-catalyzed decomposition of the peroxide.[1a]

Previous work in our laboratory using UV/vis and ^1H NMR spectroscopy has shown that stepwise addition of H_2O_2 to 2 and 3 formed respectively *cis*-$[Ru(dmp)_2(O)(S)](PF_6)_2$ (4) and *cis*-$[Ru(dmp)_2(O)_2](PF_6)_2$ (5) (eq 2).[4a] The ^1H NMR spectra of 2,

$$[Ru^{II}(S)_2(dmp)_2]^{2+} \xrightarrow{H_2O_2} [Ru^{IV}(O)(S)(dmp)_2]^{2+} \xrightarrow{H_2O_2} [Ru^{VI}(O)_2(dmp)_2]^{2+} \quad (2)$$

3, 4, and 5 are consistent with C_2 symmetry being maintained in solution. Figure 1 shows a model of 3 based on X-ray

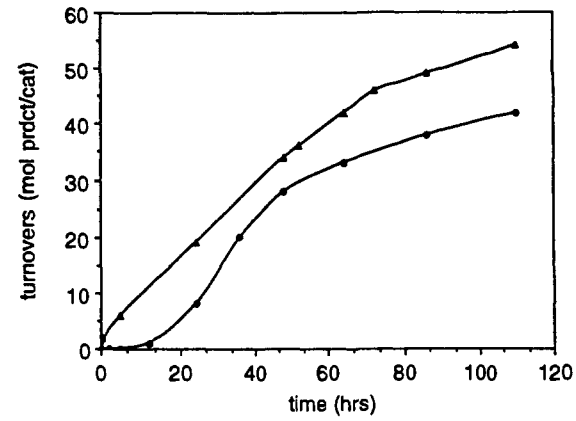


Figure 2. Oxidation of norbornene (0.6 M) in CH_3CN by 2×10^{-4}M (10^{-5} mol) of $[Ru(dmp)_2(CH_3CN)_2](PF_6)_2$ at 65 °C and 40 psig of O_2 (lower) and in the presence of 3×10^{-5} mol of 0.2 M H_2O_2 (upper).

crystallographic studies[14] which shows enforced *cis* stereochemistry similar to other comparable structurally characterized polypyridyl complexes.[15]

Norbornene Epoxidation

The oxidation of norbornene was carried out with 3 at 65 °C and 40 psig (~3 atm) of O_2 pressure in acetonitrile in a 100:1 substrate-to-catalyst ratio. Figure 2 illustrates the number of turnovers (mol product/mol catalyst) of 2,3-epoxynorbornane product formed over a 120-h period. As shown in the lower curve of Figure 2, catalytic activity is preceded by a 12-h induction period during which small amounts of the epoxide, 2-norborneol, and 2-norbornone are observed. Following the induction period, a marked increase in catalytic activity is observed, and epoxide is formed primarily. Overall, the reaction results in a 94% selectivity for 2,3-epoxynorbornane with the balance of the remaining products being 2-norborneol and 2-norbornone. When activity slowed or stopped, 3 could be recovered from the homogeneous yellow reaction mixture, which otherwise appeared unchanged from the start of the reaction. Comparable results could be obtained with 2 since it readily converted to 3 in acetonitrile. Other than the shortening of the induction period from 24 to 12 h, these results are similar to those obtained in our earlier report with $[Ru(dmp)_2(O)_2]^{2+}$ (5) prepared with Ce^{4+}.[4a]

Incubation of O_2 with the catalyst or the substrate alone under experimental conditions prior to the reaction did not alter the induction period. As demonstrated in our previous work,[4a,b] all three components were necessary to observe the induction period and the ensuing catalytic activity. This suggests that the formation of the active catalyst is not the result of either a reaction of the catalyst with O_2, e.g., the oxidative addition of O_2 to Ru^{2+} to form $\{Ru(O_2)\}^{2+}$, or a free-radical autoxidation reaction between O_2 and norbornene. Tests supporting the presence of free radicals in this reaction are summarized in Figure 3. In the presence of a 100-fold excess of the radical trap benzoquinone (BQ), no products are observed for the first 72 h. After this time has elapsed, all the BQ is consumed and the normal product distribution is observed. The addition of radical initiator AIBN (azobis(isobutyronitrile)) shortened the induction period to 4 h and lowered the selectivity for epoxide to 89% but otherwise had little effect on the reaction. AIBN yielded no oxidized products in the absence of catalyst.

The preceding radical evidence and the fact that peroxides oxidize 2 or 3 to 4 and 5 suggest that the induction period involved the metal-catalyzed oxidation of norbornene to the metal alkylperoxide shown in Scheme 1. In the initial step, norbornene, dioxygen, and 3 form a metal peroxo norbornyl radical (shown in brackets). A related intermediate has been proposed by Kochi

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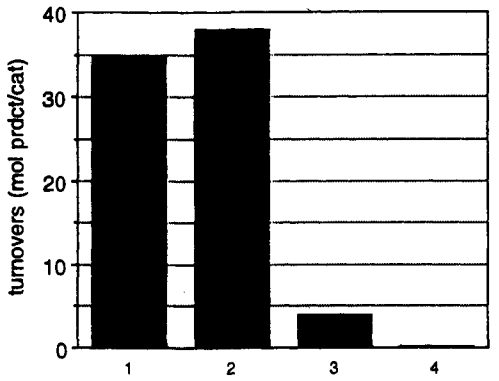
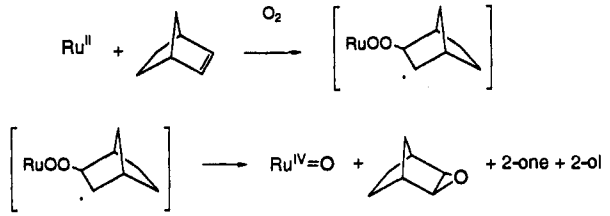
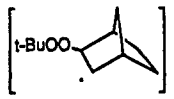


Figure 3. Radical experiments for the oxidation of norbornene. Conditions as in Figure 2: (1) control; (2) with 10^{-2} mol of AIBN (radical initiator); (3) with 10^{-2} mol of BQ (radical trap); (4) with 10^{-2} mol of AIBN in absence of catalyst.

Scheme 1. Proposed Mechanism for Initiation of the Oxidation of Norbornene by $[Ru(dmp)_2(CH_3CN)_2](PF_6)_2$ and O_2



et al.[16] for the cobalt-catalyzed oxidation of norbornene to epoxide by *t*-BuOOH.[11]



How do dioxygen, norbornene, and **3** react to form this complex? If dioxygen binding and activation by **3** is occurring, little is known about potential dioxygen-containing products. Among the reported observed species are a ruthenium superoxo "picnic basket" porphyrin,[17] a μ-peroxo complex, $[\{Ru(EDTA)\}_2(O_2)]$,[18] and a proposed η^2-peroxo complex, $[Ru(O_2)Cl(NO)(PPh_3)_2]$.[19] If dioxygen reacts with **2** to form such species, the unlikely proposal that the adduct forms only in the presence of substrate would have to be made. The thermal formation of norbornyl radical followed by a reaction with **3** seems unlikely since it would be trapped by dioxygen and no products of radical peroxygenation are observed without **3** being present. Stable $[Ru(bpy)_2(diene)]^{2+}$ complexes have been reported by Ludi and Meyer,[20] so it is possible that a transient, less stable monoalkene complex may form between **3** and norbornene. A reaction between a ruthenium norbornene complex and dioxygen to form a ruthenium peroxo norbornyl radical is consistent with the incubation experiments, and though there is no precedence for this chemistry, it is the preferred explanation.

Once the alkyl peroxo intermediate is formed, it decomposes by homolytic cleavage to $\{Ru(IV)O\}^{2+}$, by analogy to iron porphyrin peroxo complexes,[21] forming alcohol and ketone. This explanation accounts for these side products being formed mostly during the induction period. The production of alcohol and ketone primarily during the induction period is consistent with results of catalytic oxidation of hydrocarbons with *t*-BuOOH and $\{Ru(Cl_2bpy)_2(H_2O)_2\}^{2+}$ [7a] and related decomposition reactions of metal alkylperoxides.[22] The formation of these oxygenated products and epoxide has also been observed in the dioxygen-accelerated metathesis polymerization of norbornene with $[RuCl_2(PPh_3)_4]$.[23] The metal-initiated autoxidation of hydrocarbons[16b] shown in eq 3–6 is also possible, where Ru^{3+} is formed from the reaction of **2** and O_2 in the presence of norbornene. Metal-

$$Ru^{III} + RH \rightarrow Ru^{II} + R{\cdot}H^+ \quad (3)$$

$$R{\cdot}H^+ \rightarrow R^{\cdot} + H^+ \quad (4)$$

$$R^{\cdot} + O_2 \rightarrow RO_2^{\cdot} \quad (5)$$

$$RO_2^{\cdot} + RH \rightarrow RO_2H + R^{\cdot} \quad (6)$$

catalyzed decomposition of the peroxide to produce alcohol and ketone would then follow.[1a] The peroxide formed is also capable of oxidizing Ru^{2+} to Ru^{3+} and higher valent species.[4b] We believe this mechanism with Ru^{3+} is less likely because incubation of **2** and O_2 prior to addition of the substrate had no effect on the reaction.

The initiation steps in Scheme 1 account for the induction period and the formation of the proposed $\{Ru(O)\}^{2+}$ catalyst. To evaluate whether *cis*-$[Ru(O)(CH_3CN)(dmp)_2](PF_6)_2$ (**4**) was the active catalyst, an oxidation reaction was carried out with **4** prepared *in situ* from hydrogen peroxide. A 100% selectivity for the epoxide was observed, and the induction period was eliminated as shown in the upper curve of Figure 2. Similar results were obtained by substituting *tert*-butyl hydroperoxide (2.5 equiv) for H_2O_2. Since it was not possible to directly observe the formation of **4** under catalytic conditions, it is conceivable that **5** or other oxidized products may also form. The absence of the induction period coincides with no alcohol and ketone products. These data support the proposed metal alkylperoxide decomposition reaction which occurs only during the induction period. The existence of an induction period in previous work when solid samples of **5** were employed as a catalyst[4a] is in apparent contradiction to this conclusion. We have found, however, that samples of solid **4** and **5** decompose upon dissolution. The reoxidation of the decomposition products may account for the induction.

Since ruthenium oxo complexes epoxidize alkenes by nonradical mechanisms,[2a,8] i.e., oxygen atom transfer,[24] this reaction was also carried out in the presence of BQ. The radical trap had no effect on the catalytic reaction, in support of a nonradical mechanism. A comparative experiment in which BQ is added to the standard reaction after the 12-h induction period also had no effect on catalytic activity.

Based on these results, the onset of the catalytic activity corresponds to the formation of the monoxo, **4**. Once formed, **4** can undergo two possible reactions: (1) oxygen atom transfer to norbornene to form the epoxide and a Ru^{2+} species, which then must go through the radical initiation step again, or (2) reaction with dioxygen to form a $\{Ru(O)_2\}^{2+}$ species, presumably **5**. Compound **5** is also capable of reacting with norbornene to form epoxide and **4**, which can react with O_2 again to form **5**. Two equivalents of the monoxo complex could react with dioxygen to form a μ-peroxo ruthenium oxo complex, $\{Ru(O)–O–O–Ru(O)\}^{2+}$, which could then undergo homolytic cleavage to form 2 equiv of the *cis*-dioxo species. Though unprecedented for the

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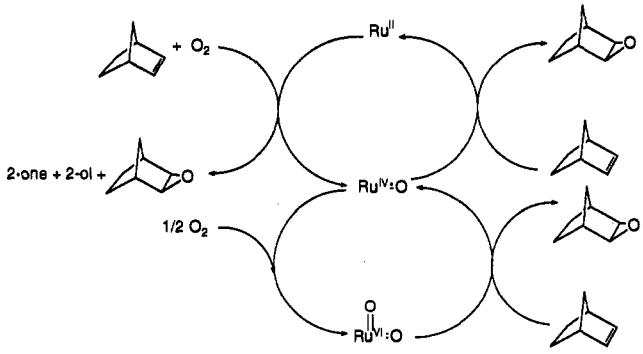
Scheme 2. Proposed Catalytic Cycle for the Oxidation of Norbornene by $[Ru(dmp)_2(CH_3CN)_2](PF_6)_2$ and O_2



$\{Ru(O)\}^{2+}$ species, this mechanism has been invoked for the reaction of dioxygen with polypyridyl and porphyrin Ru^{2+} complexes for aerobic ruthenium oxo epoxidation catalysts.[3b,c,17]

The nonradical character of the active catalyst period implies that the rate of the reaction of **4** with dioxygen must be faster than the rate of epoxidation of norbornene. It is possible that a $\{Ru(O)_2\}^{2+}$ species could transfer an oxygen atom to **3** to form the monoxo complex, but under catalytic conditions the reaction of the *cis*-dioxo species with excess substrate is likely to be faster. An alternative mechanism could involve the disproportionation of **4** into **5** and **3**; however, since we observe that **3** does not readily form **4** with O_2, catalytic activity would be decreased. We favor the mechanistic hypothesis summarized in the two-part reaction shown in Scheme 2: a radical mechanism during the induction period to form the active $\{Ru(O)\}^{2+}$ catalyst, followed by a catalytic oxygen atom-transfer reaction involving dioxygen and two high-valent ruthenium oxo species, $\{Ru(O)\}^{2+}$ and $\{Ru(O)_2\}^{2+}$. We cannot exclude the possibility that rather than **4** and **5**, a lower valent species such as Ru^{3+}, which has been proposed to react with O_2 by Khan,[3g,h] is capable of being or producing the oxidizing species in the catalytic cycle.

With a mechanistic hypothesis formulated, reinvestigation of earlier studies of the oxidation of *trans*-β-methylstyrene[4a] with **3** and dioxygen under the standard oxidation conditions was carried out. After a 12-h induction period, the reaction yielded initially the *trans* epoxide. Benzaldehyde, a C–C bond cleavage product, became the major product as the reaction proceeded. A 6:1 ratio of benzaldehyde to epoxide results after 48 h. Under otherwise standard oxidation conditions, however, benzaldehyde or *trans*-epoxide could be formed exclusively by adding, batchwise, stoichiometric amounts of H_2O_2 to generate **4** or **5** *in situ*. Similarly, 1-hexene was oxidized under standard oxidation conditions to its C–C bond cleavage product 1-pentanal. Under limiting H_2O_2 conditions, only 1,2-epoxyhexane was observed. Competing cleavage and epoxidation reactions were also observed in oxidations with *trans*-$Ru(O)_2(py)_2(O_2CPh)_2$.[12b] These results indicate that *cis*-$Ru(dmp)_2(O)_2^{2+}$ has oxidizing power comparable to that of RuO_4, a powerful reagent for the oxidative cleavage of carbon–carbon double bonds to ketones and carboxylic acids.[1f] Theoretical calculations that distinguish different mechanisms, C–C bond cleavage vs oxygen atom transfer, for *cis*-$\{Ru(O)_2\}^{2+}$ versus $\{Ru(O)\}^{2+}$ and *trans*-$\{Ru(O)_2\}^{2+}$ corroborate these results.[25] Moreover, these experiments demonstrate that one can exercise control over the selectivity of catalytic systems containing **3** by adjusting the amount of oxidant used.

Alkane Hydroxylation

Prior studies have shown that **5**, formed by **2** or **3** in excess hydrogen peroxide, can catalyze the hydroxylation of hydrocarbons.[4b] Mechanistic studies, performed mainly on the substrate methane, revealed several mechanistic features. First, comparable results were obtained with both oxygen atom-transfer reagents and H_2O_2, suggesting that a high-valent ruthenium oxo species rather than a peroxo species was the probable oxidant. Second, radical trapping experiments with BQ inhibited the reaction, indicating a radical mechanism. Further evidence of a radical mechanism was obtained from the observation that halogen scrambling occurred when halogenated hydrocarbons were added to the catalytic reaction. It was concluded, therefore, that the catalytic cycle involved a radical mechanism with a high-valent ruthenium oxo species.[4b]

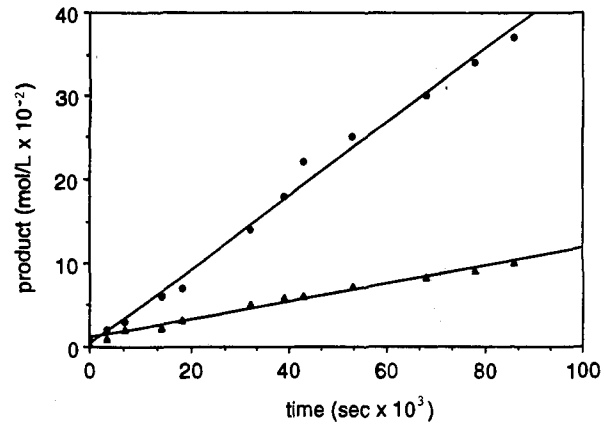


Figure 4. Rate of oxidation of cyclohexane (upper) and perdeuterated cyclohexane (lower) at 75 °C by 2×10^{-4} M (10^{-5} mol) of $[Ru(dmp)_2(CH_3CN)_2](PF_6)_2$ and H_2O_2 (10^{-2} mol).

The regioselectivity of the oxidation of adamantane is a well-accepted mechanistic probe for radical reactions in which the 3° C–H bond is more reactive than the 2° C–H bond.[26] Adamantane in the presence of H_2O_2 and a catalytic amount of **2** formed 1-adamantanol, 2-adamantanol, and 2-adamantanone in a final product distribution of 7:2:1 for 1-ol, 2-ol, and 2-one with a 21% conversion. This corresponds to a normalized 2°/3° ratio of 0.14. Secondary-to-tertiary bond relative reactivities of 1:6.5 are reported for the radical oxidation of adamantane by the related catalyst *cis*-$[Ru(H_2O)_2(Cl_2bpy)_2]^{2+}$ with *t*-BuOOH.[7a] Normalized ratios for 2° to 3° C–H bond oxidation of adamantane for a typical radical reaction range from 0.05–0.15.[26] The overall product ratio of the oxidation of adamantane by **2** and H_2O_2 is consistent with a free-radical mechanism. These results reflect the poorer selectivity of the ruthenium *cis*-dioxo catalysts compared to their *trans* counterparts, which yield 1-adamantanol exclusively.[7c,27] Assuming that C–H bond activation for both *cis*- and *trans*-dioxo catalysts is via hydrogen atom radical abstraction, this difference in selectivity is most likely the result of the stronger oxidizing power of the *cis* configuration.[7d,9] Efforts to modify the dmp ligand are being investigated to optimize the regioselectivity of hydroxylation products.

In order to determine whether this radical reaction involved a rate-determining C–H bond cleavage step, the rates of oxidation of cyclohexane and perdeutrated cyclohexane were compared. A large excess of substrate is used to insure that the rate is zero order in substrate. The rates obtained from Figure 4 are $k_H = 4.4 \times 10^{-6}$ mol L^{-1} s^{-1} and $k_D = 1.1 \times 10^{-6}$ mol L^{-1} s^{-1}, giving a k_H/k_D of 4.0. This isotope effect is similar to that reported by Che[7a] ($k_H/k_D = 3.5$) for the radical-based oxidation of cyclohexane by *cis*-$\{Ru(Cl_2bpy)_2(O)_2\}^{2+}$ and *tert*-butylhydroperoxide. This mechanism is proposed, however, to involve a ruthenium *t*-BuOO· radical species rather than a ruthenium oxo species. The kinetic isotope effect of free-radical oxidation of alkanes often ranges from 1 to 2; however, with metal oxo species this value frequently

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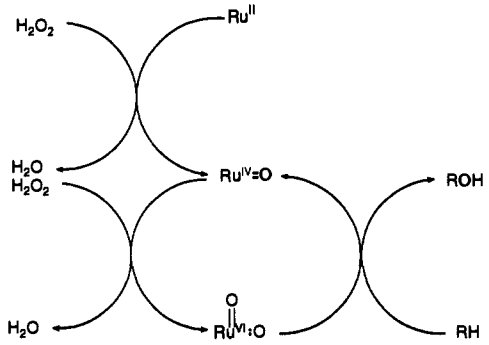
Scheme 3. Proposed Catalytic Cycle for the Oxidation of Alkanes by $[Ru(dmp)_2(S)_2](PF_6)_2$ (S=CH_3CN or H_2O) and H_2O_2



increases to approximately 5 or higher.[28] Isotope effects of cyctochrome P-450 metalloporphyrin model complexes, in which a metal oxo species is the putative oxidant, vary from 4 to 13.[29] Isotope effects for iron enzymes that hydroxylate hydrocarbon substrates, methane, and cytochrome P-450 monooxygenases[30,31] display values ranging from 4 to 14. The widely accepted mechanism of hydroxylation by cytochrome P-450 enzymes and its model complexes is one in which an iron oxo species abstracts a hydrogen atom from a C–H bond.[32] Whether a similar iron oxo species participates in the catalytic cycle of methane monoxygenase, however, is still under contention.[30]

A proposed mechanism consistent with experimental data and analogous to the "rebound" radical mechanism[32] proposed to occur for the monooxygenase cytochrome P-450 and its model complexes is illustrated in Scheme 3. Initially, hydrogen atom abstraction from hydrocarbon by **5** occurs to form a ruthenium hydroxo alkyl radical cage as shown in eq 7.

$$Ru^{VI}(O)_2 + HR \rightarrow [Ru(O)\text{–}OH \ \cdot R] \rightarrow Ru^{IV}(O) + ROH \quad (7)$$

Radical recombination of the hydroxide ligand and the alkyl radical and solvation of the ruthenium complex forms alcohol and the monoxo complex. The *cis*-dioxo oxidant can then be regenerated from the monoxo complex in the presence of excess H_2O_2. Though proton-, hydride-, and proton-coupled electron-transfer mechanisms are all plausible for hydrocarbon oxidation by the *cis*-dioxo complex, the hydrogen atom abstraction and transfer reaction in eq 7 has been proposed as a mechanism for several other ruthenium oxo oxidants.[7b,12b,27,33,34] *cis*-$Ru(dmp)_2(O)_2^{2+}$ is a viable hydrogen atom radical-abstracting agent; it exhibits a high oxidation potential (1.42, irreversible)[9] and possesses an electrophilic oxide atom.

Theoretical calculations support hydrogen atom abstraction as one possible reaction pathway for alkane hydroxylation by metal oxo complexes.[35] Like alkane functionalization by cytochrome P-450, enzymatic methane hydroxylation by iron methane monooxygenase may involve hydrogen atom abstraction by an iron oxo moiety in a mechanism analogous to the one shown in eq 7.[30,36] Though we believe that the ruthenium oxo species is the most likely oxidant involved in eq 7, in the presence of hydrogen peroxide a metal peroxyl radical species, $\{RuO_2\cdot\}$, is also capable of forming and subsequently abstracting a hydrogen atom.[37] Based upon our results, we also cannot exclude the participation of hydrocarbon peroxide and peroxyl radicals formed by a free-radical chain reaction.[1a]

Loss of activity, often accompanied by a small amount of precipitate and a red solution, is observed after 24 h or longer. The precipitate was an intractable ruthenium-containing solid resulting from ligand oxidation and/or decomposition of the catalyst. The red solution contained compound **2** by UV/vis spectroscopy and dissociated dmp by ^1H NMR and mass spectroscopy. These results are consistent with the ligand loss and reduction to Ru^{3+} of *cis*-$[Ru(bpy)_2(O)_2]^{2+}$ in aqueous solution reported by Meyer.[5g] No ligand-derived partially oxidized products, i.e., 2,9-dicarboxy-1,10-phenanthroline, were observed. Some dissociated ligand may have been converted to CO_2, observed by GCMS, and H_2O. It is noteworthy that attempts to oxidize coordinated dmp in $[Zn(dmp)Cl_2]$ with Cl_2 or other oxidants failed.[38] Control experiments in the absence of substrate showed that compound **5**, formed initially from **2** and excess H_2O_2 in H_2O, re-formed **2** quantitatively. This reaction is most likely due to the metal-catalyzed decomposition of H_2O_2 by **5** or, less likely, the oxidation of water by **5**. In cases in which no catalytic activity occurred, **2** was formed quantitatively.

In our earlier studies with **2**,[4b] we reported that the oxidation of methane yields methanol and formaldehyde in a 4:1 ratio with a 1.5% conversion in acetonitrile and a 1.9% conversion in water. Although oxidation of homologous gaseous hydrocarbons, including methane, were reproduced many times, the reactions sometimes yield no or little oxygenated products. Catalyst reproducibility, activation, and inactivation is currently under investigation, but, to date, we have not been able to identify the conditions that account for this variability. Until recently,[39] no homogeneous catalysts hydroxylated methane or its low molecular weight homologues under mild conditions. Appreciable conversions have yet to be realized with **2** or these other catalysts.

Conclusions

Using a polypyridyl nitrogen donor that stabilizes the *cis*-$\{Ru(O)_2\}^{2+}$ moiety, we have found that this species is a versatile oxidant which can catalyze the epoxidation and cleavage of alkenes with dioxygen and hydroxylate alkanes with hydrogen peroxide. Two different mechanisms have been proposed to explain the catalytic activity of **3** involving ruthenium oxo complexes and *cis*-dioxo complexes. Like cytochrome P-450 and its iron oxo poryphyrin counterparts,[31a] these complexes are oxidants that can be used to epoxidize olefins via oxygen atom-transfer reactions and hydroxylate alkanes via radical reactions. These mechanisms are working hypotheses that we are using to guide future studies.

Acknowledgment. This work was supported by the U.S. Army ERDEC, ARO, and the Amoco University Methane Project.

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