Inorg. Chem. **2004**, *43*, 1587–1592

Inorganic Chemistry
Article

Cumene Oxidation by *cis*-[$Ru^{IV}(bpy)_2(py)(O)]^{2+}$, Revisited

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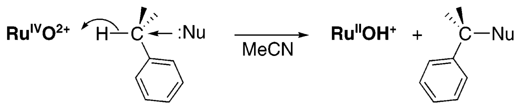
Received November 10, 2003

cis-[$Ru^{IV}(bpy)_2(py)(O)]^{2+}$ oxidizes cumene (2-phenylpropane) in acetonitrile solution primarily to cumyl alcohol (2-phenyl-2-propanol), α-methylstyrene, and acetophenone. Contrary to a prior report, the rate of the reaction is not accelerated by added nucleophiles. There is thus no evidence for the hydride transfer mechanism originally proposed. Instead, the results are consistent with a mechanism of initial hydrogen atom transfer from cumene to the ruthenium oxo group. This is indicated by the correlation of rate with C–H bond strength and by the various products observed. The formation of acetophenone, with one carbon less than cumene, is suggested to occur via a multistep pathway involving decarbonylation of the acyl radical from 2-phenylpropanal. An alternative mechanism involving β-scission of cumyloxyl radical is deemed unlikely because of the difficulty of generating alkoxyl radicals under anaerobic conditions and the lack of rearranged products in the oxidation of triphenylmethane by *cis*-[$Ru^{IV}(bpy)_2(py)(O)]^{2+}$.

Introduction

Oxidations of alkylaromatic compounds by transition metal oxides have been studied for over a century.[1] In addition to standard reagents such as permanganate and osmium tetroxide, there is increasing interest in new metal−oxo complexes because of their potential for catalysis and relative ease of mechanistic study.[2] Oxo−metal units have also been implicated as the reactive species in a number of metalloenzymes.[3] Ruthenium−oxo complexes have received a great deal of attention,[4] and the polypyridyl complexes studied by T. J. Meyer and co-workers have been one of the paradigmatic systems.[5] In 1982, Thompson and Meyer reported studies of aqueous oxidations of carboxylated alkylaromatics by $[(tpy)(bpy)Ru^{IV}O]^{2+}$, and the oxidations of cumene and toluene in acetonitrile by $[(bpy)_2(py)Ru^{IV}O]^{2+}$ {abbreviated here as $\mathbf{Ru^{IV}O^{2+}}$, where $\mathbf{Ru}$ = (bpy)$_2$(py)Ru}.[6] A novel mechanism was proposed for these reactions, involving nucleophile-assisted hydride transfer from a benzylic hydrogen to a ruthenium oxo group (eq 1). This can be viewed



(1)

:Nu = H_2O, Br^-, ^tBuOH

as an S_N2-like mechanism, with hydride as the very unusual leaving group. It is also very unusual to suggest S_N2-like substitution at a tertiary carbon. The key piece of evidence for this mechanism was the observation of third-order kinetics in acetonitrile solution: first order in ruthenium, cumene, and nucleophile.

We have found that a number of metal oxidants react with alkylaromatic compounds by hydrogen atom abstraction.[7] The rates of these processes can be understood in most cases using the thermodynamic affinity of the oxidant for a hydrogen atom—in other words the strength of the O−H or N−H bond it can form. Using these bond strengths, a close connection has been drawn to organic radical chemistry.[7a] For instance, barriers for hydrogen atom abstraction by metal complexes correlate with C−H bond strengths, as has long

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(1) Cf.: (a) Stewart, R. *Oxidation Mechanisms*; Benjamin: New York, 1964. (b) *Organic Syntheses By Oxidation With Metal Compounds*; Mijs, W. J., de Jonge, C. R. H. I., Eds.; Plenum: New York, 1986. (c) Olah, G. A.; Molnár, Á. *Hydrocarbon Chemistry*; Wiley: New York, 1995.

(2) *Biomimetic Oxidations Catalyzed by Transition Metal Complexes*; Meunier, B., Ed.; Imperial College Press: London 2000.

(3) Cf.: *Chem. Rev.* **1996**, *96*, *6*(7), 2237−3042 (Holm, R. H., Solomon, E. I., Eds.).

(4) Che, C.-M.; Yam, V. W. W. *Adv. Transition Met. Coord. Chem.* **1996**, *1*, 209−237.

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10.1021/ic035298j CCC: $27.50

been known for reactions of main-group radicals (the Bell–Evans–Polanyi correlation).[8] On the basis of this and work from other laboratories, it is becoming increasingly clear that hydrogen atom abstraction is the dominant mechanism for C–H bond oxidation by metal–oxo compounds and coordination complexes.[2,9] (Organometallic oxidations are quite different.[10])

In light of this growing consensus, we were moved to reexamine the oxidations of C–H bonds by $\mathbf{Ru^{IV}O^{2+}}$. A previous study, reporting the reactions of a number of benzylic and allylic organic substrates, concluded that a hydrogen atom transfer mechanism is followed.[11] Described here is our reexamination of the oxidation of cumene and its oxidation products by $\mathbf{Ru^{IV}O^{2+}}$.[12] Meyer and co-workers have independently reexamined this reaction and reached the same conclusion, that the proposed hydride transfer mechanism (eq 1) is not valid.[13]

Experimental Section

General Considerations and Materials. All experiments were performed under an N_2 atmosphere using standard techniques unless otherwise noted. Solvents (including deuterated solvents from Cambridge Isotope Labs) were degassed and dried according to standard procedures.[14] Acetonitrile (low-water, Burdick and Jackson) was dispensed from a steel keg plumbed directly into the drybox. CD_3CN was stirred over CaH_2 for 2 days, vacuum transferred to P_2O_5, and stirred for 4 h. It was then transferred back to CaH_2, stirred for 30 min, and transferred to a sealable flask prior to use. Cumene was purified via standard procedures.[14] Other reagents were purchased from Aldrich and used as received unless otherwise noted.

$Ru(bpy)_2Cl_2$ and $[Ru(bpy)_2(py)Cl](PF_6)$ were synthesized according to literature methods.[15] $[Ru(bpy)_2(py)(OH_2)]^{2+}$ was prepared as the PF_6^- rather than the perchlorate salt by modifying the literature procedure[16] to precipitate the product using saturated aqueous KPF_6. Similarly, $[Ru(bpy)_2(py)O](PF_6)_2$ was prepared by modification of the literature synthesis of $[Ru(bpy)_2(py)^{18}O](ClO_4)_2$.[17] Liquid Br_2 was added in a very small amount to the dissolved $\mathbf{RuOH_2^{2+}}$, and the resulting solution was purged with N_2 for several minutes. The solution was cooled, and 1–2 mL of saturated aqueous KPF_6 was added to precipitate the product. $\mathbf{Ru^{IV}O^{2+}}$, $\mathbf{Ru^{III}OH^{2+}}$, $\mathbf{Ru^{II}(H_2O)^{2+}}$, and $\mathbf{Ru^{II}(MeCN)^{2+}}$ were characterized by NMR and UV–vis spectroscopies.[15,16]

^1H NMR spectra were recorded on Bruker AC-200, AF-300, and DRX-500 spectrometers at ambient temperatures and are reported in ppm relative to TMS. UV–vis spectra were recorded on a Hewlett-Packard 8453 diode array spectrophotometer and are reported as λ_{max} (nm) (ϵ, M^{-1} cm^{-1}). GC/MS spectra were obtained on a Hewlett-Packard 5971 instrument equipped with a nonpolar capillary column and a mass spectral analyzer. GC/FID data were collected on a Hewlett-Packard 5890 series II equipped with an HP DB1 (methyl silicone, 5 m × 0.53 mm × 0.25 μm). ESI-MS spectra were measured by a Bruker Esquire ion trap mass spectrometer with electrospray ionization sources.

Typical Procedure for Organic Oxidations. A solution of cumene (1.7 μL, 12 μmol) and $\mathbf{Ru^{IV}O^{2+}}$ (6 μmol) in 6 mL of acetonitrile turned orange in several hours. Cumyl alcohol, acetophenone, and α-methylstyrene were observed by GC/MS and confirmed by comparison with (and addition of) authentic samples. Products were quantified by GC/FID using response factors. Reactions with α-methylstyrene, cumyl alcohol, 2-phenylpropionaldehyde, and *meso*-2,3-diphenylbutane were carried out under similar conditions. Oxidations were also monitored by ^1H NMR, using $Me_3SiOSiMe_3$ as an internal standard.

^{18}O-Labeling studies were conducted under the same conditions as above, but with 10 mM and 200 mM added $H_2{}^{18}O$. The amount of ^{18}O incorporation was measured by comparing the M^+:$(M + 2)^+$ peak intensity ratios for products formed in the presence of $H_2{}^{18}O$ to those formed in the absence of $H_2{}^{18}O$.

Kinetic Studies. Reaction kinetics were monitored by UV–vis spectroscopy, typically obtaining a spectrum every 30–180 s over several hours. Kinetic measurements were carried out under pseudo-first-order conditions with 0.2 mM $\mathbf{Ru^{IV}O^{2+}}$ and 0.1 to 0.3 M cumene. Solutions were made up in an N_2-filled drybox immediately prior to use in sealable cuvettes with Teflon Kontes valves. Kinetic data were analyzed using the global analysis software package SPECFIT (Spectrum Software Associates, Marlborough, MA). In reactions with added nucleophiles (*tert*-butyl alcohol, water, and LiBr), kinetic data were acquired simultaneously with control reactions containing no added nucleophile.

Results and Discussion

Cumene is oxidized by $\mathbf{Ru^{IV}O^{2+}}$ over several hours at ambient temperatures. All the reactions described here were done anaerobically in acetonitrile unless otherwise noted. The ruthenium product is predominantly $\mathbf{Ru^{II}(MeCN)^{2+}}$ by both UV–vis and ^1H NMR spectroscopies (the complexity of the spectra preclude accurate yield measurements). This is the typical product of $\mathbf{Ru^{IV}O^{2+}}$ oxidations due to the solvolysis of intermediate Ru(II) species such as $\mathbf{Ru^{II}(H_2O)^{2+}}$ or $\mathbf{Ru^{II}(HOR)^{2+}}$.[18] The organic products are 2-phenyl-2-propanol (cumyl alcohol), α-methylstyrene, and acetophenone, as well as trace amounts of 2-phenylpropanal and 2-phenylpropenal (eq 2). The products were identified by addition of

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(8) Ingold, K. U. In *Free Radicals*; Kochi, J. K., Ed.; Wiley: New York, 1973; Vol. 1, Chapter 2, p 69 ff. Russell, G. A. In *Free Radicals*; Kochi, J. K., Ed.; Wiley: New York, 1973; Vol. 1, Chapter 7, pp 283–293.

(9) Cf.: (a) Che, C.-M.; Cheng, K.-W.; Chan, M. C. W.; Lau, T.-C.; Mak, C.-K. *J. Org. Chem.* **2000**, *65*, 7996–8000. (b) Qin, K.; Incarvito, C. D.; Rheingold, A. L.; Theopold, K. H. *J. Am. Chem. Soc.* **2002**, *124*, 14008–14009. (c) Goldsmith, C. R.; Jonas, R. T.; Stack, T. D. P. *J. Am. Chem. Soc.* **2002**, *124*, 83–96. (d) Brazeau B. J.; Austin, R. N.; Tarr, C.; Groves, J. T.; Lipscomb, J. D. *J. Am. Chem. Soc.* **2003**, *125*, 11831–11837 and references therein. (e) Mahapatra, S.; Halfen, J. A.; Tolman, W. B. *J. Am. Chem. Soc.* **1996**, *118*, 11575–11586.

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(13) Meyer, T. J.; Huynh, M. H. V. Los Alamos National Laboratory, personal communication, 2002.

(14) Perrin, D. D.; Armarego, W. L. F. *Purification of Laboratory Chemicals*, 3rd ed.; Pergamon Press: New York, 1988.

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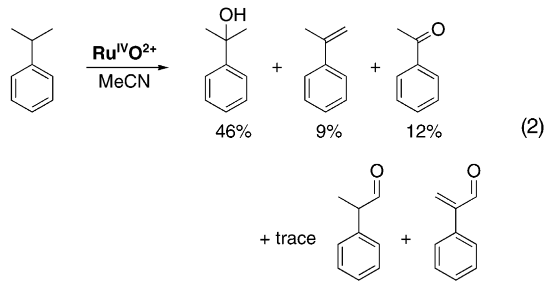
(17) Thompson, M. S.; Meyer, T. J. *J. Am. Chem. Soc.* **1982**, *104*, 4106–4115.

(18) Binstead, R. A.; Stultz, L. K.; Meyer, T. J. *Inorg. Chem.* **1995**, *34*, 546–551.



(2)

authentic samples (except in the case of 2-phenylpropenal) and quantitated by GC/FID.

Kinetics. The kinetics of reaction 2 were followed by UV−vis spectroscopy, typically at 0.2 mM **Ru^{IV}O^{2+}** and ca. 0.1 M cumene (Figure 1). The spectra were globally analyzed using the program SPECFIT and fit to a biexponential model A → B → C. This model roughly corresponds to **Ru^{IV}O^{2+}** → **Ru^{III}OH^{2+}** → **Ru^{II}(MeCN)$^{2+}$** based on the calculated spectra (Figure 2). Most telling is that the model accurately describes the rise and then fall in absorbance around 380 nm. The pseudo-first-order rate constants for the A → B phase are linearly related to the cumene concentration (Figure S1, Supporting Information), indicating that this step obeys simple second-order kinetics with $k_{A\rightarrow B} = (3.4 \pm 0.3) \times 10^{-2}$ M^{-1} s^{-1}. This is close to the value previously reported by Thompson and Meyer of $(2.6 \pm 0.3) \times 10^{-2}$ M^{-1} s^{-1}.[6] The k_{obs}(B→C) values are not simply related to the cumene concentration. This kinetic phase ($t_{1/2}$ ca. 10 m) most likely involves multiple processes including both redox (Ru^{III} → Ru^{II}) and solvolytic steps (**Ru^{II}(L)** → **Ru^{II}(MeCN)$^{2+}$**, L = H_2O, ROH, etc.).

In air-saturated solutions, the second-order rate constant for the A → B phase is 15 times faster, $k_{O2} = 0.48 \pm 0.02$ M^{-1} s^{-1}. This suggests the intermediacy of cumyl radicals that can be trapped by added O_2. There is no other apparent mechanism by which O_2 could affect the rate, since all the ruthenium complexes are stable to O_2 under these conditions. The aerobic reactions presumably involve a metal-mediated radical chain including cumylperoxyl and cumyloxyl radicals. In this complex process, it is not evident why the consumption of **Ru^{IV}O^{2+}**—what is observed kinetically—is faster in the presence of O_2. Perhaps cumylhydroperoxide formed in the autoxidation is reactive with **Ru^{IV}O^{2+}**.[19] In the related oxidation of xanthene, the disappearance of **Ru^{IV}O^{2+}** is slowed by added O_2,[11] perhaps because the autoxidation radical chain is different for this nontertiary substrate (for instance, it forms less hydroperoxide).

The primary evidence for the proposed nucleophile-assisted hydride transfer pathway was the observation of rate acceleration in the presence of the added nucleophiles water, *tert*-butyl alcohol, and LiBr.[6] We observe no variation in reaction rate upon addition of H_2O or ^{t}BuOH. These experiments were done by dividing a solution of **Ru^{IV}O^{2+}** and cumene into two sealable cuvettes and adding the nucleophile to one, then examining the kinetics concurrently using a thermostated multicell holder. Meyer and co-workers have also reexamined these kinetics, and they too have been unable to reproduce the rate acceleration with nucleophiles.[13] With large amounts of added LiBr (0.6 M concentration), we observe rapid disappearance of **Ru^{IV}O^{2+}** even in the absence of added oxidizable substrate. **Ru^{II}Br^{+}** is the product under these conditions (it can be generated independently from **Ru^{II}(H$_2$O)$^{2+}$** + Br^{-}). In the absence of any effect of added nucleophiles, there is no evidence for the hydride transfer pathway in eq 1.

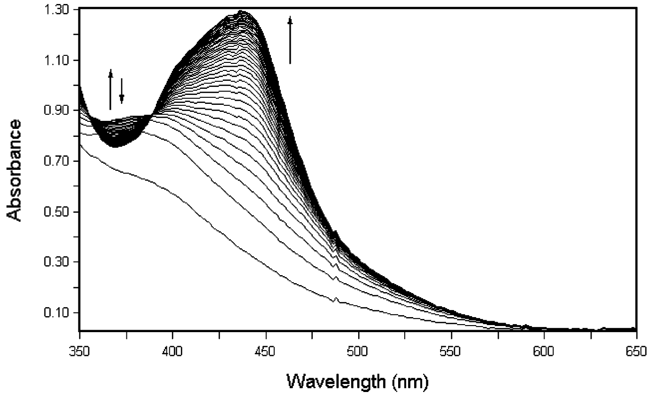


Figure 1. Overlay plot for the reaction of **Ru^{IV}O^{2+}** (0.2 mM) with cumene (80 mM) in MeCN, monitored every 30 s for ~8200 s.

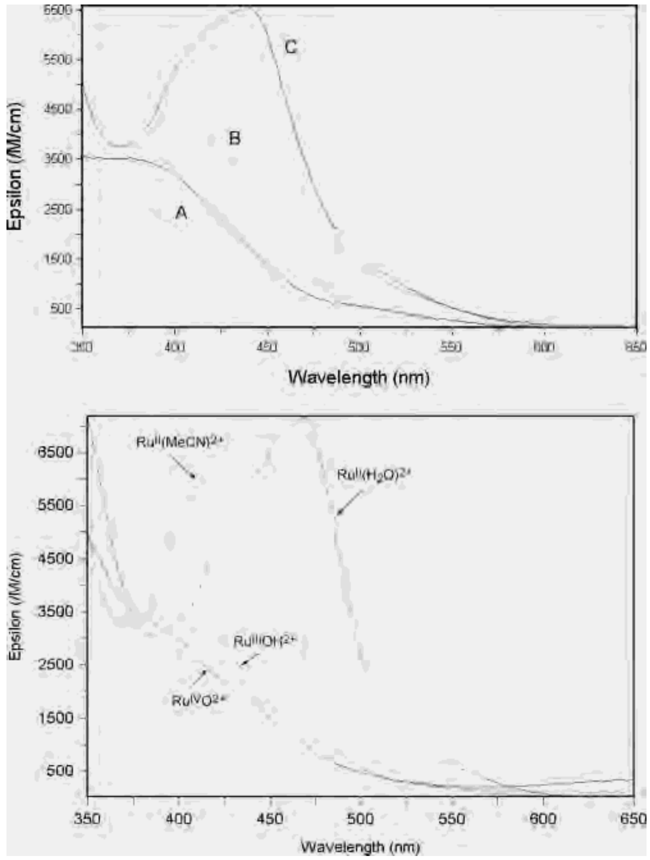


Figure 2. Top: Calculated spectra returned by SPECFIT for A, B, and C of the kinetic model for **Ru^{IV}O^{2+}** (0.2 mM) + cumene (80 mM) in MeCN. Bottom: Spectra of **Ru^{IV}O^{2+}**, **Ru^{III}OH^{2+}**, **Ru^{II}(H$_2$O)$^{2+}$**, and **Ru^{II}(MeCN)$^{2+}$** in MeCN. **Ru^{III}OH^{2+}** is generated in situ from 1:1 **Ru^{IV}O^{2+}** + **Ru^{II}(H$_2$O)$^{2+}$**; a small amount of **Ru^{II}(H$_2$O)$^{2+}$** is present.

Product Yields. The product yields from 2 mM **Ru^{IV}O^{2+}** + 4 mM cumene are 46% cumyl alcohol, 9% α-methylstyrene, and 12% acetophenone. Since acetophenone is an

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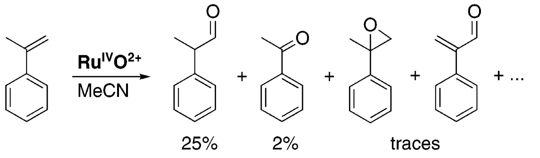
8-electron oxidation of cumene (assuming that the "missing" carbon is lost as CO, vide infra), these products account for all (103%) of the ruthenium oxidative equivalents consumed. At lower Ru concentrations, a lower mass balance is found (50−70%). For instance, 1 mM $\mathbf{Ru^{IV}O^{2+}}$ + 10 mM cumene yields 22% cumyl alcohol, 7% α-methylstyrene, and 10% acetophenone, accounting for 69% of the $\mathbf{Ru^{IV}O^{2+}}$ consumed. Yields were quantitated by GC, which would not reveal carboxylic acids and potentially other products. This may be the origin of the lower mass balance at lower ruthenium concentrations. Attempts to detect carboxylate products by ESI-MS were not successful.

The reaction of 2 mM $\mathbf{Ru^{IV}O^{2+}}$ + 4 mM cumene was also run in the presence of $H_2{}^{18}O$. ($\mathbf{Ru^{IV}O^{2+}}$ does not exchange with $H_2{}^{18}O$ on the time scale of these reactions.[19]) With 200 mM $H_2{}^{18}O$, the cumyl alcohol was 20% ^{18}O-enriched and the acetophenone contained only 2% ^{18}O (by GC/MS). With 10 mM $H_2{}^{18}O$, the values were 9% and <1%, respectively. Formation of $PhCMe_2{}^{18}OH$ is thus not a major pathway; perhaps the higher water concentrations facilitate exchange via solvolysis to cumyl cation.

When reactions are run in the presence of air or under 1 atm of O_2, no α-methylstyrene is observed and more acetophenone is formed.

Reactions of the Oxidation Products. α-Methylstyrene is slowly oxidized by $\mathbf{Ru^{IV}O^{2+}}$ over a period of hours. The largest primary observed product is 2-phenylpropanal, with small amounts of acetophenone, the epoxide, and 2-phenylpropenal (eq 3). Similar products have been reported for the oxidation of for *cis*- and *trans*-stilbene by $\mathbf{Ru^{IV}O^{2+}}$.[20] 2-Phenylpropanal is formed by Lewis-acid-catalyzed ring opening of the epoxide, perhaps before solvolysis from the ruthenium center. 2-Phenylpropanal and 2-phenylpropenal are both observed as trace products in cumene oxidation (eq 2). Carboxylate or carboxylic acid products would not have been observed with our GC and GC/MS analyses.



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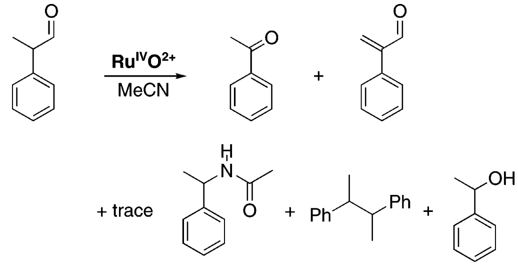
Independent oxidations of 2-phenylpropanal by $\mathbf{Ru^{IV}O^{2+}}$ occur within seconds under typical conditions. The major observed product is acetophenone (∼15% yield assuming this is a four-electron oxidation), with small amounts of 2-phenylpropenal and traces of other products (eq 4). This result explains the formation of acetophenone and 2-phenylpropenal from α-methylstyrene, via overoxidation of the initial 2-phenylpropanal product. Watanabe et al. have reported that the related catalytic oxidations of 2-phenylpropanal by iron(III)−porphyrins and *m*-chloroperbenzoic acid give some decarbonylated products but mostly the carboxylic acid $PhCH(Me)CO_2H$,[21] which would not be detected under our conditions.



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Oxidation Mechanisms. All of the results above can be accounted for with a mechanism involving initial hydrogen atom transfer from cumene to $\mathbf{Ru^{IV}O^{2+}}$ (Scheme 1). As described elsewhere,[11] rate constants for oxidations of C−H bonds by $\mathbf{Ru^{IV}O^{2+}}$, including cumene and a range of allylic and benzylic substrates, correlate with the strength of the C−H bond being cleaved. This supports an H-atom transfer rate-limiting step. H-atom transfer to $\mathbf{Ru^{IV}O^{2+}}$ forms the ruthenium(III) hydroxide $\mathbf{Ru^{III}OH^{2+}}$,[18] which itself can act as a hydrogen atom abstractor.[11] The H-atom affinities of $\mathbf{Ru^{IV}O^{2+}}$ and $\mathbf{Ru^{III}OH^{2+}}$ are 84 and 82 kcal mol^{-1}, respectively.[11] H-atom abstraction initiates a cascade of reactions, as summarized in Scheme 1. To simplify the scheme, reactions of $\mathbf{Ru^{IV}O^{2+}}$ and $\mathbf{Ru^{III}OH^{2+}}$ are shown together, and coordination and solvolysis are simply indicated by "−(**Ru**)."

The cumyl radical could disproportionate to cumene and α-methylstyrene, but more likely it is trapped by $\mathbf{Ru^{IV}O^{2+}}$ and $\mathbf{Ru^{III}OH^{2+}}$. Metal oxo complexes often react very rapidly with carbon radicals, both by H-atom removal and by addition of the radical to make a C−O bond.[7,11] Addition of cumyl radical to $\mathbf{Ru^{IV}O^{2+}}$ yields the Ru(III) alkoxide $\mathbf{Ru^{III}OCMe_2Ph^{2+}}$, which can be converted to the Ru(II) alcohol complex $\mathbf{Ru^{II}(HOCMe_2Ph)^{2+}}$ on reaction with $\mathbf{Ru^{III}OH^{2+}}$ or $\mathbf{Ru^{II}(H_2O)^{2+}}$.[18] Trapping of cumyl radical by $\mathbf{Ru^{III}OH^{2+}}$ forms the alcohol complex directly. $\mathbf{Ru^{II}(HOCMe_2Ph)^{2+}}$ then solvolyzes to give the observed cumyl alcohol (or perhaps dehydrates to α-methylstyrene). In aerobic reactions, most of the cumyl radicals are trapped by O_2, leading only to oxygenated products without formation of α-methylstyrene.

Hydrogen-atom transfer from cumyl radical to $\mathbf{Ru^{IV}O^{2+}}$ or $\mathbf{Ru^{III}OH^{2+}}$ gives α-methylstyrene (Scheme 1). The alkene undergoes epoxidation and Lewis-acid-mediated ring opening, following eq 3. Oxidation of 2-phenylpropanal occurs by hydrogen abstraction from either the benzylic or aldehydic positions. It is reasonable that these are competitive, as cumene and isobutyraldehyde are equally reactive toward H-atom abstraction by $^tBuOO^\bullet$ (both 10 M^{-1} s^{-1}),[22] and $^tBuOO^\bullet$ and $\mathbf{Ru^{IV}O^{2+}}$ have similar H-atom abstraction reactivity.[11] Benzylic abstraction leads to 2-phenylpropenal by a second hydrogen transfer. Abstraction from the aldehyde gives the acyl radical, which rapidly decarbonylates.[23,24] The resulting 1-phenethyl radical $PhC^\bullet HMe$ is the source of all

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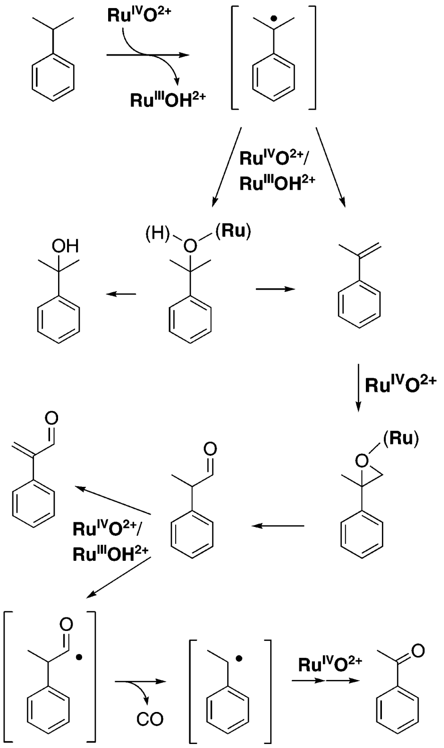
(20) Stultz, L. K.; Binstead, R. A.; Reynolds, M. S.; Meyer, T. J. *J. Am. Chem. Soc.* **1995**, *117*, 2520−2532.

(21) Watanabe, Y.; Takehira, K.; Shimizu, M.; Hayakawa, T.; Orita, H. *J. Chem. Soc, Chem. Commun.* **1990**, 927−928.

(22) Howard, J. A. *Landolt-Börnstein* Group II, Vol. 18, subvol. D2, *Radical Reaction Rates in Liquids: Peroxyl and Related Radicals*; Fischer, H., Ed.; Springer: Berlin, 1997.

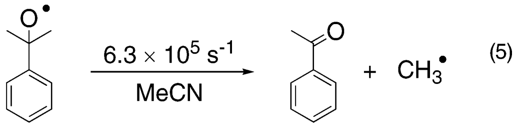
Scheme 1. Mechanism of Product Formation for Cumene Oxidation by $\mathbf{Ru^{IV}O^{2+}}$ [**Ru** = $(bpy)_2(py)Ru$]



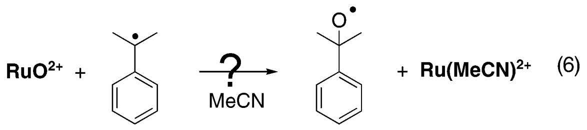
the minor products in eq 4. Addition to $\mathbf{Ru^{IV}O^{2+}}$ or $\mathbf{Ru^{III}OH^{2+}}$ leads to 1-phenethanol, which is readily oxidized to acetophenone. $PhC^{\bullet}HCH_3$ can also dimerize to 2,3-diphenylbutane or be oxidized to the carbocation, leading to the amide product in eq 4 via the Ritter reaction with the acetonitrile solvent.

Formation of Acetophenone from Cumene. There are two possible routes for the formation of acetophenone from cumene, which requires cleavage of a C−C bond. As described above, at least some acetophenone should be formed by the sequence cumene → α-methylstyrene → 2-phenylpropanal → $PhCH(Me)C(O)^{\bullet}$ → $PhC^{\bullet}HMe$ → acetophenone. The C−C bond cleavage results from decarbonylation of the acyl radical. Attempts to observe the predicted CO byproduct were unsuccessful, possibly because of the small amount formed. A similar hydrogen-atom abstraction and decarbonylation route was proposed by Watanabe for the iron−oxo oxidations of 2-phenylpropanal.[21] The report by Stultz, Meyer, and co-workers[20] that $\mathbf{Ru^{IV}O^{2+}}$ oxidations of stilbenes produce some benzophenone can be explained by a similar pathway. Lewis-acid-catalyzed rearrangement of stilbene oxide, with [1,2] phenyl migration, would give diphenylacetaldehyde ($Ph_2CHC(O)H$), which is observed in trace amounts. Hydrogen atom removal, decarbonylation, and oxidation would lead to benzophenone.[25]

The other possible route to acetophenone is via β-scission of the cumyloxyl radical (eq 5).[26] This is a major pathway



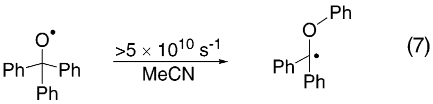
in the *aerobic* oxidation of cumene. Under our anaerobic conditions, however, the only plausible route to cumyloxyl radical is by oxygen atom transfer from $\mathbf{Ru^{IV}O^{2+}}$ (eq 6).



Reaction 6 is reasonable from a thermochemical standpoint. $\mathbf{Ru^{IV}O^{2+}}$ epoxidizes olefins,[20] and $\Delta H°$ for addition of an oxygen atom to an olefin is similar to $\Delta H°$ for $O + PhCH_2^{\bullet} \rightarrow PhCH_2O^{\bullet}$.[27]

As a test of this alkoxyl radical pathway, the oxidations of *meso*-2,3-diphenylbutane and triphenylmethane by $\mathbf{Ru^{IV}O^{2+}}$ have been examined. The tertiary alkoxyl radical from diphenylbutane, $PhC(O^{\bullet})(Me)(CHMePh)$, very rapidly undergoes β-scission to acetophenone and the 1-phenethyl radical[28] (which would be converted to acetophenone as well under the reaction conditions). Reaction of 2 mM *meso*-2,3-diphenylbutane by 1 mM $\mathbf{Ru^{IV}O^{2+}}$ does give some acetophenone, but only 0.08 mM (12% based on $3\mathbf{Ru^{IV}O^{2+}} + MeCHPhCHPhMe \rightarrow 3\mathbf{Ru^{II}(MeCN)^{2+}} + 2PhC(O)Me + H_2O$). Since a variety of pathways could yield a small amount of acetophenone, this result is not very mechanistically informative.

A better mechanistic test is the oxidation of triphenylmethane. Following Scheme 1, the only product should be triphenylmethanol. On the other hand, if there is a pathway to the triphenylmethoxyl radical, this is known to undergo a very rapid 1,2-phenyl shift to the α-phenoxydiphenylmethyl radical (eq 7).[29] Trapping of this radical should lead to phenol



and benzophenone. Oxidation of Ph_3CH by $\mathbf{Ru^{IV}O^{2+}}$ gives Ph_3COH in 70% yield, and no benzophenone or phenol are observed by GC or GC/MS. These results indicate that the triphenylmethoxyl radical is not involved, and are therefore evidence against the alkoxyl radical pathway.

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(23) (a) Turro, N. J.; Gould, I. R.; Baretz, B. H. *J. Chem. Phys.* **1983**, *87*, 531−532. (b) Chatgilialoglu, C.; Crich, D.; Komatsu, M.; Ryu, I. *Chem. Rev.* **1999**, *99*, 1991−2070.

(24) Trapping of the acyl radicals by $\mathbf{RuO^{2+}}$ or $\mathbf{RuOH^{2+}}$ would form carboxylate complexes, which would likely solvolyze to acids and would not be observed with the GC analysis used here.

(25) This pathway seems more likely than the mechanism proposed in ref 20 involving an unusual epoxide radical cation.

(26) Avila, D. V.; Brown, C. E.; Ingold, K. U.; Lusztyk, J. *J. Am. Chem. Soc.* **1993**, *115*, 466−470.

(27) $\Delta H°(PhCH_2^{\bullet} + O \rightarrow PhCH_2O^{\bullet}) = 81$ kcal mol^{-1}: Crevier, T. J.; Mayer, J. M. *J. Am. Chem. Soc.* **1997**, *119*, 8485−8491. $\Delta H^{\bullet}$(alkene + O → epoxide) ∼90 kcal mol^{-1}: Atagi, L. M.; Over, D. E.; McAlister, D. R.; Mayer, J. M. *J. Am. Chem. Soc.* **1991**, *113*, 870−879.

(28) Kochi, J. K. Oxygen Radicals. In *Free Radicals*; Kochi, J. K., Ed.; Wiley: New York, 1973; Vol. 2, pp 683−686.

(29) Falvey, D. E.; Khambatta, B. S.; Schuster, G. B. *J. Phys. Chem.* **1990**, *94*, 1056−1059.

The intermediacy of alkoxyl radicals is also problematic once the mechanism of their formation via eq 6 is considered. The addition of a carbon radical $R^\bullet$ to $\mathbf{Ru^{IV}O^{2+}}$ very likely occurs by formation of the C−O bond to make the alkoxide complex $\mathbf{Ru^{III}OR^{2+}}$. This is the typical pathway for oxidations by metal oxo compounds. For instance, phosphine oxidations occur via an intermediate phosphine oxide complex. From $\mathbf{Ru^{III}OR^{2+}}$, the alkoxyl radical would have to be formed by homolysis of the metal−alkoxide bond, a very unlikely process.

Conclusions. The oxidation of cumene by $\mathbf{Ru^{IV}O^{2+}}$ does not occur by nucleophile-assisted hydride transfer, as had been previously proposed.[6] Upon reexamination of the kinetics, we and Meyer et al.[13] have both found that the rate of oxidation is not accelerated by nucleophiles, which was the key evidence for this mechanism. The data indicate that the reaction proceeds by initial hydrogen atom transfer from the weak benzylic C−H bond in cumene to $\mathbf{Ru^{IV}O^{2+}}$ (Scheme 1). All of the various observed products can then be explained by trapping of the cumyl radical by ruthenium complexes and epoxidation of the α-methylstyrene intermediate. Hydrogen atom abstraction appears to be the dominant mechanism for oxidations of hydrocarbon C−H bonds by metal−oxo compounds and by other metal complexes that have a thermodynamic affinity for an electron and a proton (a hydrogen atom).

The surprising formation of acetophenone, with one less carbon than cumene, apparently occurs by decarbonylation of an intermediate acyl radical (Scheme 1). An alternative pathway involving β-scission of the cumyloxyl radical is unlikely on the basis of the difficulty of forming alkoxyl radicals under anaerobic conditions and the lack of rearrangement in the oxidation of triphenylmethane.

Acknowledgment. We are grateful to Drs. T. J. Meyer and M. H. V. Huynh of Los Alamos National Laboratory for sharing their unpublished results. We thank K. U. Ingold for an insightful critique of this paper. We are grateful for financial support from the National Institutes of Health (Grant R01 GM50422) to J.M.M., a UW PRIME Fellowship to J.R.B., and a Japan Society for the Promotion of Science (JSPS) fellowship to T.M.

Supporting Information Available: Plot of pseudo-first order k_{obs} vs [cumene] for the A → B step in the oxidation of cumene by $\mathbf{Ru^{IV}O^{2+}}$. This material is available free of charge via the Internet at http://pubs.acs.org.

IC035298J