

Communications to the Editor

Oxidation of Toluene by $[(\text{phen})_2\text{Mn}(\mu\text{-O})_2\text{Mn}(\text{phen})_2]^{4+}$ via Initial Hydride Abstraction

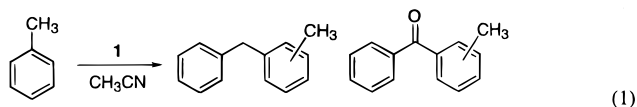
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Metal-mediated oxidations of C–H bonds are of fundamental and technological importance, from enzymatic reactions to industrial processes.¹ The selectivities and rates of these reactions depend critically on the first step in their mechanisms. There are well-documented oxidations that involve initial electron transfer, hydrogen atom transfer, oxidative addition, and electrophilic attack at the C–H bond.² We report here that the manganese(IV) dimer $[\text{L}_2\text{Mn}(\mu\text{-O})_2\text{MnL}_2](\text{ClO}_4)_4$ (**1**, L = 1,10-phenanthroline³) oxidizes toluene and other alkylaromatic compounds by initial hydride abstraction. To our knowledge this is the first example of simple hydride transfer in metal-mediated hydrocarbon oxidation.⁴ In contrast, the $\text{Mn}^{\text{IV}}\text{Mn}^{\text{III}}$ dimer $[\text{L}_2\text{Mn}(\mu\text{-O})_2\text{MnL}_2](\text{PF}_6)_3$ (**2**) has been previously reported to oxidize alkylaromatic compounds with weak C–H bonds (<79 kcal/mol) by initial hydrogen atom abstraction.⁵ Such manganese μ -oxo dimers have long been of interest as models for the manganese cluster active site (the oxygen evolving complex) in photosystem II which oxidizes water to dioxygen.⁶

A solution of **1** (30 mg, 0.023 mmol in 5.0 mL of acetonitrile) reacts with excess toluene (1.0 mL, 9.4 mmol) at 55 °C over a 12 h period, with a change in color from red-brown to yellow-green (eq 1; warning: perchlorate salts are potentially explosive and should be handled with extreme caution). Reactions were done anaerobically with dried solvents.⁷ GC/MS analysis of the



organic products showed methyl substituted diphenylmethanes (0.010 mmol, *o*:*m*:*p* = 42:7:40), as confirmed by independent synthesis.⁸ No bibenzyl was observed, but trace amounts of methyl-benzophenones are formed (0.16 μmol) from further oxidation of the diphenylmethanes. Independent oxidation of diphenylmethane by **1** gives exclusively benzophenone (GC/MS, NMR).⁷ *N*-Benzylacetamide is also observed when the oxidation is performed in undried, HPLC grade acetonitrile. Spectrophotometric titration of the final manganese containing product gave an average oxidation state of 3.52 ± 0.05 .⁹ The oxidation state and UV/vis spectra are consistent with predominant formation of the $[\text{L}_2\text{Mn}(\mu\text{-O})_2\text{MnL}_2]^{3+}$ dimer (**2**). The observed products in the toluene oxidation account for 80% of the oxidizing equivalents of **1** consumed in the reaction. Experiments to determine the fate of the protons provided have not been successful, as a variety of added bases decompose **1**.

The reaction of **1** and toluene, as monitored by UV/vis spectroscopy, proceeds without an induction period and shows an isosbestic point at 668 nm. First-order plots are linear to more than three half-lives, and the rates follow the rate law of eq 2.

$$-\frac{d[\mathbf{1}]}{dt} = k_2[\mathbf{1}][\text{C}_7\text{H}_8] + k_1[\mathbf{1}] \quad (2)$$

The k_1 term in eq 2 is close to the rate of decomposition of **1** in acetonitrile in the absence of toluene and accounts for <10% of the reaction under these conditions.⁷ At 328 K, $k_2 = (4.4 \pm 0.4) \times 10^{-4} \text{ M}^{-1} \text{ s}^{-1}$. Rate constants determined from 308 to 358 K yield $\Delta H^\ddagger = 16.8 \pm 0.6 \text{ kcal mol}^{-1}$ and $\Delta S^\ddagger = -23 \pm 2 \text{ cal K}^{-1} \text{ mol}^{-1}$. Oxidation of an equimolar mixture of $\text{C}_6\text{H}_5\text{CH}_3$ and $\text{C}_6\text{H}_5\text{-CD}_3$ by **1** at 60 °C gives a number of ArCH_2Ph and ArCD_2Ph compounds (as well as d_0 - and d_2 -*N*-benzylacetamide). The product ratios indicate an isotope effect for benzylic activation of 4.3 ± 0.8 .

The products of toluene oxidation indicate the intermediacy of benzyl cations, which then add to the excess toluene. *N*-Benzylacetamide is formed by addition of PhCH_2^+ to acetonitrile followed by hydrolysis (the Ritter reaction¹⁰). To probe the rate-limiting step, oxidations of substituted toluenes have been examined. *p*-Xylene is oxidized solely to 2,4',5-trimethyldiphenylmethane (GC/MS, ¹³C, and ¹H NMR), as expected for attack of the benzylic cation on the hydrocarbon. Similar products are derived from *m*-xylene. Second-order kinetics are found for both.⁷ The substituted toluenes are much faster than toluene, with relative rates per methyl group at 25 °C of: 34 (*p*-Me): 5 (*m*-Me): 1 (H). *p*-Nitrotoluene is unreactive with **1** under these conditions. Diphenylmethane is oxidized 100 times faster than toluene (per hydrogen). These data indicate a highly electron-deficient transition state, and rule out a pathway involving rate-limiting hydrogen atom abstraction.¹¹ Attempts to extend this

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(4) (a) Hydride transfer has been suggested in other C–H bond oxidations, for instance, in NAD^+/NADH interconversion: Lee, I.-S. H.; Jeoung, E. H.; Kreevoy, M. M. *J. Am. Chem. Soc.* **1997**, *119*, 2722–8 and references therein. (b) Hydride transfer concomitant with nucleophile addition has been proposed: Thompson, M. S.; Meyer, T. J. *J. Am. Chem. Soc.* **1982**, *104*, 5070; Gardner, K. A.; Mayer, J. M. *Science* **1995**, *269*, 1849–1851.

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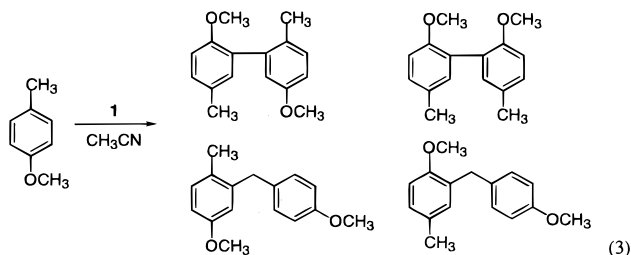
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study to other alkylbenzenes and halobenzenes have so far met with limited success.

The large substituent effects are consistent with either hydride transfer or electron transfer. Based on the primary isotope effect, the latter mechanism would have to be pre-equilibrium electron transfer followed by rate-limiting deprotonation of the toluene radical cation. Electron transfer appears to be a major mechanism for a related reaction, oxidation of *p*-methoxytoluene by **1** because biaryls are the major products, as well as a minor amount of diarylmethanes (eq 3). Preliminary results suggest that this very



rapid reaction is inhibited by addition of the Mn^{IV}Mn^{III} dimer, [L₂Mn(μ-O)₂MnL₂]³⁺ (**2**), the reduced form of **1**.¹² Such inhibition by the reduced form of the oxidant is a hallmark of pre-equilibrium electron transfer.^{2a-e}

Toluene, however, is 0.79 V harder to oxidize than *p*-methoxytoluene ($E = 2.61$ and 1.82 V vs NHE in acetonitrile).^{2a} Cyclic voltammograms of **1** show a reversible couple at 0.95 V vs Cp₂Fe⁺⁰ in acetonitrile (1.48 V vs NHE¹³). Therefore, electron transfer to **1** from *p*-methoxytoluene is only 0.3 V (8 kcal mol⁻¹) uphill, but electron transfer from toluene is much more uphill, by ca. ~ 1.1 V ($\Delta G^\circ = 26$ kcal mol⁻¹, $K_{\text{eq}} = 10^{-19}$). Since back-electron transfer cannot be faster than 10^{10} M⁻¹ s⁻¹, the equilibrium constant means that the forward rate must be slower than 10^{-9} M⁻¹ s⁻¹ at 298 K. Marcus theory can also provide a lower limit for the electron-transfer rate of $< 10^{-10}$ M⁻¹ s⁻¹ using $\Delta G^\circ = 31$ kcal mol⁻¹ and conservatively taking $\lambda > 16$ kcal mol⁻¹.¹⁴ Electron transfer is therefore not kinetically competent to be a pre-equilibrium step in toluene oxidation by **1** with $k = (2.9 \pm 0.3) \times 10^{-5}$ M⁻¹ s⁻¹ at 298 K.¹⁵ In addition, toluene oxidation is not inhibited by addition of **2**. The data are only consistent with a mechanism of initial hydride transfer (Scheme 1). The Mn^{IV}-Mn^{III} product **2** is apparently formed by comproportionation of the initially formed [L₂Mn(μ-O)(μ-OH)MnL₂]³⁺ and **1**; preliminary studies are consistent with this comproportionation forming **2**.¹²

The ability of **1** to abstract a hydride ion from toluene is reasonable based on its thermodynamic affinity for H⁻. Using a

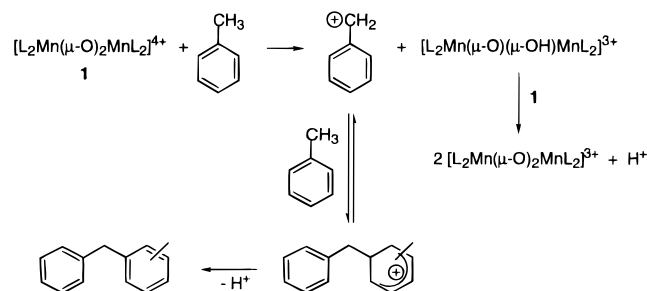
(12) Lockwood, M. A.; Won, T.-J.; Mayer, J. M., unpublished results.

(13) The conversion used here for **1** vs Cp₂Fe⁺⁰ in acetonitrile to **1** vs NHE is $+0.528$ V, following that used by Parker in reference 16: Parker, V. D., personal communication, 1999.

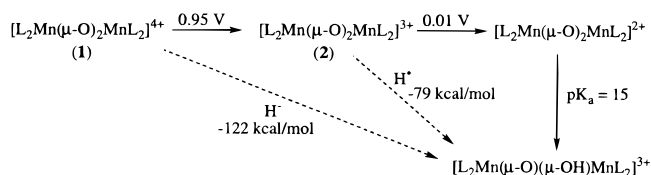
(14) $1/2\lambda(\text{C}_7\text{H}_8/\text{C}_7\text{H}_8^{+\bullet})$ is used as a lower limit for λ , which is equivalent to assuming a λ of zero for the 1/2 couple. Following reference 2a, pp 52 ff. For electron transfer within an encounter complex, Marcus theory gives $< 10^{-10}$ s⁻¹, and an equilibrium constant of 1 M⁻¹ is taken for the encounter complex (following Sutin, N. *Prog. Inorg. Chem.* **1983**, *30*, 441–499).

(15) Similar arguments in favor of hydride transfer can be found in Bunting, J. W. *Bioorg. Chem.* **1991**, *19*, 456–491 and references therein.

Scheme 1. Mechanism of Toluene Oxidation



Scheme 2.^a Thermochemical Analysis of Hydride Transfer



^a Potentials vs Cp₂Fe⁺⁰. Data and equations from references 5, 13, & 16. thermochemical cycle developed by Parker¹⁶ and the known redox potentials and pK_a values,⁵ **1** has a hydride affinity of -122 kcal mol⁻¹ in acetonitrile (Scheme 2). Removal of H⁻ from toluene requires 118 kcal/mol,¹⁶ so hydride transfer from toluene to **1** is ~ 4 kcal mol⁻¹ downhill. The preference for a hydride transfer mechanism appears to be based on its favorable ground-state energetics ($\Delta G^\circ \cong -4$ kcal mol⁻¹) versus a very uphill electron-transfer path ($\Delta G^\circ \cong +26$ kcal mol⁻¹). Hydride abstraction by **1** contrasts with the oxidations by hydrogen atom abstraction observed for **2**.⁵ The mechanistic contrast is illustrated in the oxidation of 9,10-dihydroanthracene: **1** gives predominantly anthraquinone while **2** produces almost exclusively anthracene. The change in mechanism between manganese dimers that only differ by one electron is again a reflection of the ground state thermochemistry (Scheme 2).

In sum, complex **1** oxidizes toluenes via initial hydride abstraction. To our knowledge this is the first example of a metal complex abstracting hydride from a hydrocarbon. The hydride is transferred to a bridging oxide ligand, with concomitant two-electron reduction of the metal centers. This is quite different than hydride transfer to a Lewis acidic metal center to make a metal hydride, which occurs without formal redox change and is not known for abstraction from hydrocarbons.¹⁷ Additional studies are in progress to determine the scope of this reaction.

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Supporting Information Available: Full experimental details, including the preparation and characterization of **1**, kinetics procedures, and product analyses (PDF). This material is available free of charge via the Internet at <http://pubs.acs.org>.

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