Published in final edited form as:

J Am Chem Soc. 2009 March 4; 131(8): 2762–2763. doi:10.1021/ja8100825.

C—H Bond Cleavage with Reductants:

Re-Investigating the Reactivity of Monomeric Mn^{III/IV}—Oxo Complexes and the Role of Oxo Ligand Basicity

Trenton H. Parsell, Meng-Yin Yang, and A. S. Borovik

Department of Chemistry, University of California-Irvine, 1102 Natural Sciences II, Irvine, California 92697

Abstract

The thermodynamic properties of structurally similar Mn^{III} and Mn^{IV} complexes have been re-investigated to understand their reactivity with substrates having C—H bonds. The complexes have the general formula, [MnH₃buea(O)]ⁿ⁻, where [H₃buea]³⁻ is the tripodal ligand, tris[(*N'*-*tert*-butylureaylato)-*N*-ethylene]aminato. These complexes are unique because of the intramolecular hydrogen-bonding (H-bond) network surrounding the Mn—oxo units. The redox potentials for the Mn^{III/IV}(O) couple was incorrectly assigned in earlier reports: the corrected values is -1.0 V vs Cp₂Fe⁺/Cp₂Fe in DMSO, while the Mn^{IV/V}(O) process is -0.076 under the same conditions. The oxo ligand in the Mn^{III}(O) complexes is basic with a p*K*_a of 28.3; the basicity of the terminal oxo ligand in the Mn^{IV}(O) complex is estimated to be ~15. These values were used to re-evaluate the O—H bond dissociation energy (BDE_{OH}) of the corresponding Mn^{II/III}—OH complexes: BDE_{OH} values of 89 and 77 kcal/mol were determined for [Mn^{III}H₃buea(OH)]⁻ and [Mn^{II}H₃buea(OH)]²⁻, respectively. Both Mn(O) complexes react with 9,10-dihydroanthracene (DHA) to produce anthracene in nearly quantitative yields. This is surprising based on the low redox potential of the complexes, suggesting the basicity of the oxo ligand is a major contributor to the observed reactivity. In contrast to the thermodynamic results, a comparative kinetic investigation found that the Mn^{III}(O) complex reacts nearly 20 times faster than the Mn^{IV}(O) complex. Activation parameters, determined from an Eyring analysis, found that the entropy of activation is significantly different between the two systems (ΔΔ*S*[‡] = -35 eu, where ΔΔ*S*[‡] = Δ*S*[‡](Mn^{IV}(O)) - Δ*S*[‡](Mn^{III}(O))). This unusual kinetic behavior can be explained in the context of the basicity of the oxo ligands that leads to different mechanisms: for [Mn^{III}H₃buea(O)]²⁻ a proton transfer-electron transfer mechanism is proposed, whereas for [Mn^{IV}H₃buea(O)]⁻ a hydrogen-atom transfer pathway is likely.

Metal complexes with terminal oxo ligands have been implicated in a variety of oxidative transformations. For instance, monomeric oxoiron units are proposed to be the competent oxidants in many mono- and dioxygenases.¹ Similarly, numerous synthetic oxometal complexes have been shown to be involved in either C—H bond cleavage or O-atom transfer reactions.² Uncovering the factors that govern these processes is an active area of investigation.³ Redox properties are normally used as a measure of function, but more recently Green has pointed out that basicity of the terminal oxo ligand may contribute to the reactivity of oxometal complexes, especially C—H bond cleavage.⁴ This premise implies that oxometal complexes could function at lower redox potentials, which is advantageous because unwanted oxidation of the surrounding moieties would be avoided, such as those within a protein active site. Goldberg⁵ and Que⁶ have also found that the oxo basicity can affect function in synthetic oxomanganese(V) and oxoiron(IV) complexes. In this report we describe the C—H bond cleavage for two related oxomanganese complexes with unusually low oxidation potentials but

strongly basic oxo ligands. A re-evaluation of their thermodynamic properties and a new kinetic analysis point to a process whereby the basicity of the oxo ligand has a large effect on the observed oxidative chemistry.⁷

We have developed the monomeric oxomanganese complexes,⁸ $[\text{Mn}^{\text{III}}\text{H}_3\text{buea}(\text{O})]^{2-}$ and $[\text{Mn}^{\text{IV}}\text{H}_3\text{buea}(\text{O})]^-$, and their related Mn—OH complexes, $[\text{Mn}^{\text{II}}\text{H}_3\text{buea}(\text{OH})]^{2-}$ and $[\text{Mn}^{\text{III}}\text{H}_3\text{buea}(\text{OH})]^-$ (Figure 1). The Mn(O(H)) complexes are distinct from other synthetic systems because of their intramolecular hydrogen bond (H-bond) networks, a structural feature inspired by the active sites of metalloproteins.⁹ These complexes provided us with the rare opportunity to compare the thermodynamic and kinetic properties of structurally similar oxometal complexes in different oxidation states.¹⁰

Previous work has shown that the oxo ligands in the oxomanganese complexes are basic: a $\text{p}K_a$ of 28.3 was measured in DMSO for $[\text{Mn}^{\text{III}}\text{H}_3\text{buea}(\text{OH})]^-$,¹¹ while a $\text{p}K_a$ of ~ 15 was estimated for $[\text{Mn}^{\text{IV}}\text{H}_3\text{buea}(\text{OH})]$.¹² We had incorrectly assigned the redox potentials for these complexes in early reports. A reinvestigation found that the $\text{Mn}^{\text{III/IV}}(\text{O})$ couple is at -1.0 V and the $\text{Mn}^{\text{IV/V}}(\text{O})$ couple is at -0.076 V.¹³ Moreover, the $\text{Mn}^{\text{II/III}}(\text{O})$ redox couple is not observed under our experimental conditions, indicating that it is less than -2.0 V. Using these results, the O—H bond dissociation energy (BDE_{OH}) for $[\text{Mn}^{\text{III}}\text{H}_3\text{buea}(\text{OH})]^-$ is 89 kcal/mol, lower by 21 kcal/mol relative to the value reported previously; the BDE_{OH} in $[\text{Mn}^{\text{II}}\text{H}_3\text{buea}(\text{OH})]^{2-}$ remains at 77 kcal/mol.

$[\text{Mn}^{\text{III}}\text{H}_3\text{buea}(\text{O})]^{2-}$ and $[\text{Mn}^{\text{IV}}\text{H}_3\text{buea}(\text{O})]^-$ react with a variety of different substrates with X—H bonds of less than 80 kcal/mol. For example, each complex oxidized 9,10 dihydroanthracene (DHA)¹⁴ to anthracene in yields of greater than 95% (Scheme 1).⁸ The oxidation of substrates occurs even though the oxomanganese complexes have redox potentials that are normally associated with species that are reductants.¹⁵ The low values for the relevant $E_{1/2}$ values (see above) suggested that the basicity of the oxo ligand, especially that in $[\text{Mn}^{\text{III}}\text{H}_3\text{buea}(\text{O})]^{2-}$, may have a substantial contribution to the observed reactivity. Moreover, the basicity of the oxo ligands in $[\text{Mn}^{\text{III}}\text{H}_3\text{buea}(\text{O})]^{2-}$ and $[\text{Mn}^{\text{IV}}\text{H}_3\text{buea}(\text{O})]^-$ predict that the complexes should react differently with substrates of different acidities. In fact, reactivity differences have been observed when phenolic compounds are used as substrates. For instance, $[\text{Mn}^{\text{III}}\text{H}_3\text{buea}(\text{O})]^{2-}$ deprotonated 2,4,6-tri-*tert*-phenol,¹⁶ producing the phenolate anion and $[\text{Mn}^{\text{III}}\text{H}_3\text{buea}(\text{OH})]^-$, whereas $[\text{Mn}^{\text{IV}}\text{H}_3\text{buea}(\text{O})]^-$ homolytically cleaved the O—H bond, producing the phenoxyl radical and $[\text{Mn}^{\text{III}}\text{H}_3\text{buea}(\text{OH})]^-$. Similar differences in reactivity were observed when indene and fluorene were used as substrates.^{14,17}

To gain insight into the reactivity of the oxomanganese complexes, a kinetic analysis was conducted for the reaction involving DHA. Kinetic data were obtained by monitoring absorbance features of either $[\text{Mn}^{\text{III}}\text{H}_3\text{buea}(\text{O})]^{2-}$ or $[\text{Mn}^{\text{IV}}\text{H}_3\text{buea}(\text{O})]^-$ during their reaction with excess DHA in DMSO solutions (Figure S1). Under these conditions, all reactions exhibited pseudo-first-order kinetic data for greater than 3 half-lives. The pseudo-first-order rate constant (k_{obs})¹⁸ varied linearly with the concentration of DHA (Figure 2A), indicating a second-order rate law ($\text{rate} = k[\text{Mn}(\text{O})\text{ complex}][\text{DHA}]$). For $[\text{Mn}^{\text{III}}\text{H}_3\text{buea}(\text{O})]^{2-}$ at 20°C the corrected second-order rate constant ($k^{\text{Mn(III)-O}}$)^{12,19} of $0.48(4) \text{ M}^{-1} \text{ cm}^{-1}$ is more than an *order of magnitude larger* than the $k^{\text{Mn(IV)-O}}$ of $0.026(2) \text{ M}^{-1} \text{ s}^{-1}$ found for $[\text{Mn}^{\text{IV}}\text{H}_3\text{buea}(\text{O})]^-$ (Table 1). This result is counter to what would have been predicted based on the BDE_{OH} for the Mn—OH analogs (Scheme 1), in which the BDE_{OH} of $[\text{Mn}^{\text{III}}\text{H}_3\text{buea}(\text{OH})]^-$ is greater than that for $[\text{Mn}^{\text{II}}\text{H}_3\text{buea}(\text{OH})]^{2-}$ by 12 kcal/mol. These data also differ from the results reported by Groves on C—H bond cleavage by oxomanganese(V/IV) porphyrin complexes, in which the Mn(V) systems react faster.¹⁰

The kinetic isotope effects (KIEs) for the complexes were measured at 20°C using *d*₄-DHA (Table 1, Figure S3); the values obtained are indicative of primary KIEs with the value for [Mn^{IV}H₃buea(O)]⁻ being nearly twice that of [Mn^{III}H₃buea(O)]²⁻. The temperature-dependency of the rate constants were determined to probe the surprising relative rates of C—H bond cleavage by [Mn^{III}H₃buea(O)]²⁻ and [Mn^{IV}H₃buea(O)]⁻. The complexes produced linear plots of *k*_{obs} vs [DHA] for each temperature studied (Figure 2A, Table S1). Activation parameters were calculated from an Eyring analysis (Figure 2B, Table 1): the $\Delta H^\ddagger$ for the Mn(O) complexes follow the trend predicted by the BDE_{OH} values. However, there is a large difference in the entropy of activation for the two complexes [$\Delta\Delta S^\ddagger = -35$ eu, where $\Delta\Delta S^\ddagger = \Delta S^\ddagger(\text{Mn}^{\text{IV}}(\text{O})) - \Delta S^\ddagger(\text{Mn}^{\text{III}}(\text{O}))$], which has a major effect on the relative rate constants for C—H bond cleavage.

We suggest that the observed difference in rate constants is related to the basicity of the oxo ligands, which causes the complexes to have different mechanisms. There is a large difference between the *pK_a* values of the C—H bonds in DHA and [Mn^{IV}H₃buea(OH)]⁻ ($\Delta pK_a \sim 15$), resulting in [Mn^{IV}H₃buea(O)]⁻ reacting via H-atom transfer, in which substrate and the oxoMn(IV) complex come together in the transition state. For [Mn^{III}H₃buea(O)]²⁻, the oxo ligand is significantly more basic and a two-step mechanism could occur, whereby proton transfer occurs prior to electron transfer (PT-ET, Scheme 2).^{3b,7,20} The similar *pK_a* values for DHA and [Mn^{III}H₃buea(OH)]⁻ ($\Delta pK_a < 2$), and the measured KIE suggest rate-limiting PT.²¹ Moreover, a PT-ET path is consistent with a more positive $\Delta S^\ddagger$ value because an increase in charge delocalization is expected to lead to less organized solvent molecules.²²

In summary, our results support the idea that the basicity of terminal oxo ligands in metal complexes has important effects on reactivity. This effect contributes to oxometal complexes with low redox potentials being able to oxidize substrates via C—H bond cleavage. The observation of a greater rate constant for the oxomanganese complex with the lower thermodynamic driving force for C—H bond cleavage can arise because of a mechanistic change between Mn(O) complexes. This finding offers the intriguing possibility that the basicity of the oxo ligands can significantly affect the kinetics of a reaction, a concept that may influence enzymatic activity and be used to develop new synthetic reagents.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

ACKNOWLEDGMENT is made to the NIH (GM 050781) for financial support and Professor Alan Heyduk for helpful advice. We also thank the reviewers for valuable comments.

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Figure 1.
The $Mn^{III/IV}(O)$ and $Mn^{II/III}(OH)$ complexes investigated.

Figure 2. Kinetic data for $[\text{Mn}^{\text{III}}\text{H}_3\text{buea}(\text{O})]^{2-}$ (black) and $[\text{Mn}^{\text{IV}}\text{H}_3\text{buea}(\text{O})]^-$ (blue) at various temperatures (A) and Eyring plot (B). Temperature key (°C): 20(●); 30(■); 40(◆); 50(▲).

Scheme 1.

Reactions of DHA with the $Mn^{III/IV}$ (O) complexes in DMSO.

Scheme 2.

Proposed mechanism for the reaction of $[\text{Mn}^{\text{III}}\text{H}_3\text{buea}(\text{O})]^{2-}$ with DHA.

Table 1Kinetic Properties of the Mn^{III/IV}(O) Complexes

	[Mn ^{III} H ₃ buea(O)] ²⁻	[Mn ^{IV} H ₃ buea(O)] ⁻
$\Delta H^\ddagger_a$	14(2)	5(1)
$\Delta S^\ddagger_b$	-14(6)	-49(4)
$\Delta G^\ddagger_{a,c}$	18(3)	19(2)
$k^{Mn(O)c,d}$	0.48(4)	0.026(2)
$k^{Mn(O)}_{H^+}/k^{Mn(O)}_D^c$	2.6	6.8

^a kcal/mol^b eu^c 20°C^d M⁻¹s⁻¹