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Assembly of Manganese-Oxo Clusters in Solution as Models for the Photosynthetic Oxygen-Evolving Complex

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Introduction

The four-electron oxidation of water to form O_2 in photosynthesis is a light-driven process that occurs in the multi-subunit membrane protein Photosystem II (PSII). The reaction is catalyzed by an inorganic cluster known as the Oxygen Evolving Complex (OEC), which has a composition of $Mn_4O_xCaCl_y$.[1] A preliminary X-ray crystal structure of PSII has recently been determined,[2] but the nature of the ligands bound to the manganese ions and the internal structure of the core were not fully revealed. Insight into the structure of the OEC has been gained primarily through X-ray absorption spectroscopy (XAS) and spin resonance techniques (EPR/ENDOR) (reviewed in [3]). Based on these data, a number of candidate structures for the Mn_4O_x subcore were described, of which the two leading candidates are the Mn_4O_4-funnel and the Mn_4O_4/Mn_4O_2-butterfly subcores (Figure 1).

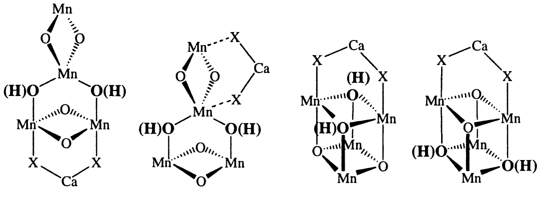
(Funnel) (Cubane)

Figure 1: Proposed structures for the Mn_4Ca cluster of the OEC based on spectroscopic studies (summarized in ref. [3]).

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When we began our collaboration in 1983, few examples of bridged manganese-oxo clusters in oxidation states higher than +2 were known. Our goal, and that of several other investigators,[4-6] has been to study the assembly reactions that form manganese-oxo clusters in solution and to characterize the products and intermediates by spectroscopy, electrochemistry, and by X-ray crystallography. This information helps us to interpret the reactions leading to cluster assembly in vivo during biogenesis[7] as well as the chemistry of the intact holo enzyme.[8]

Pyrazolylborate Complexes

The pyrazolylborate ligand, $HBPz_3^-$, has proven to be valuable as a negatively charged tridentate facially capping ligand in the formation of the neutral binuclear Mn-oxo clusters *I(a-d)*. Compounds *I(a-b)* can be formed directly from the corresponding carboxylic acid. Compounds *I(c-d)* are formed from *I(a-b)* by ligand exchange.[9]

$(HBPz_3)Mn^{III}(\mu\text{-}O)(\mu\text{-}O_2R)_2Mn^{III}(HBPz_3)$ (*I*)

(a) R = CMe (c) R = $CCPh_3$

(b) R = CEt (d) R = PPh_2

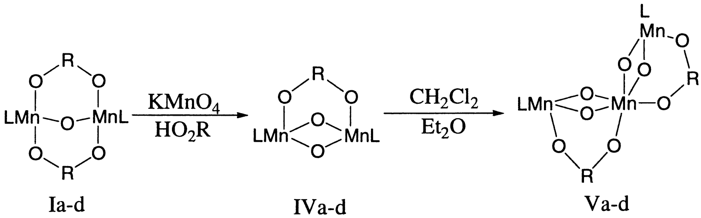
$(HBPz_3)Mn^{II}(\mu\text{-}O_2PPh_2)_3Mn^{III}(HBPz_3)$ (*II*)

$(L^1)Mn(\mu\text{-}O_2CMe)_3Mn(L^1)$ (*III*)

L^1=1,4,7-trimethyl-1,4,7-triazacyclononane

Compound *I(d)*, which contains the slightly larger diphenylphosphinate bridging ligand, undergoes auto-reduction to form the Mn_2(II,III) dimer *II* when dissolved in CH_2Cl_2 and diluted with a 10-fold excess of Et_2O. X-ray crystallography of *II* confirms the tris(μ-O_2PPh_2) bridging structure, with Mn-Mn distance of 4.71 Å. (The Mn-Mn distance in *I(a)* is 3.23 Å.[10]) No tris(μ-O_2CR) complex corresponding to *II* has yet been isolated, although Wieghardt has reported structural data for *III*, which has a Mn-Mn distance of 4.03 Å.[10]

When solutions of compounds *I(a)*, *(b)*, and *(d)* and an excess of the bridging ligand are shaken with 0.1 M aqueous $KMnO_4$, the corresponding Mn_2(III, IV) dimers *IV(a-c)* are formed quantitatively. Replacement of a (^-O_2R) ligand with O^{2-} occurs concomitantly with the one-electron oxidation so that overall electrical neutrality is maintained. Compound *I(c)* undergoes oxidation to *IV(c)* very slowly compared to *I(a)*, *(b)*, and *(d)*, even in the presence of excess $KMnO_4$, apparently due to greater shielding of the Mn cluster by the bulky Ph_3C groups.



Scheme 1

Compounds *IV(a)*, *(b)*, and *(d)* are identified primarily by the 16-line EPR spectrum observed at g=2 with a width of 1250 G, which is typical for that of an antiferromagnetically coupled S=1/2 Mn_2(III, IV) dimer. Compounds *IV(a)*, *(b)*, and *(d)* undergo quantitative dismutation to form the Mn_3(3IV) trimers *V(a-d)* and $Mn^{II}(HBPz_3)_2$, following evaporation of solvent from a CH_2Cl_2 solution or dilution 10-fold with ether (Scheme 1). The dismutation of Mn_2(III,IV) dimers is a favorable reaction in acidic media.[10] The driving force for the reaction appears to be the greater stability of the uncharged Mn_3(3IV) and $Mn^{II}(HBPz_3)_2$ and the low solubility of the final product, which precipitates from the reaction solvent.

The X-ray crystal structure of *V(a-b)* reveals a bent Mn_3(IV) trimer with two nearly perpendicular $Mn(\mu\text{-}O)_2Mn$ rings. The Mn-Mn distance is 2.677 Å and the Mn-Mn-Mn angle is 142.0°. Repulsion of the four oxo ligands on the central Mn^{IV} leads to the perpendicular arrangement of the two four-membered $Mn(\mu\text{-}O)_2Mn$ rings and the cis conformation of the RO_2 bridges. An analagous tetranuclear Mn_4(IV) complex with three perpendicular $Mn(\mu\text{-}O)_2Mn$ rings has been reported by Philouze et al.[11]

Resonance Raman spectra of *IV(a)* reveal four Mn-O vibrations at 702, 631, 599, and 507 cm^{-1}, which shift to 673, 605, 579, and 490 cm^{-1}, respectively, upon ^{18}O substitution. A complete vibrational analysis of the $Mn(\mu\text{-}O)_2Mn$ rings of *IV(a)* has been performed.

The 9.5 GHz EPR spectra of *V(a-d)* are identical, with two broad transitions at 1600-2000 G ($g_\perp$=4~3.3, partially resolved ^{55}Mn hyperfine structure) and 2650-3950 G ($g_\parallel$=2, 16 equally spaced ^{55}Mn hyperfine lines), and shoulders at 900 G (g=6.7) and

4000 G (g=1.5). This spectrum is consistent with that of a high-spin (S=3/2) Mn_3(IV) trimer, and differs from that of the Mn_2(III, IV) dimer.

In passing from *I(a-d)* to *IV(a-d)* to *V(a-d)*, the spontaneous replacement of RO_2^- with O^{2-} that occurs successively with each oxidation occurs without increasing the overall charge of the cluster and leads to thermodynamically easier one-electron oxidation potentials. The same mechanism may be operating in the OEC for controlling the redox potential.

Cubanes

The Mn_4O_4 cubane topology was hypothesized several years ago as a potential core type for the OEC,[12,13] but was not realized in any synthetic complex until 1997. We previously synthesized and crystallographically characterized $Mn_4O_4(O_2PPh_2)_6$ (*VI*), which contains a valence-delocalized Mn_4(2III,2IV) core.[14] This cluster can be formed by two different pathways. The first involves the fusion of two $[Mn_2(\mu\text{-}O)_2]^{3+}$ units (from $[Mn_2(\mu\text{-}O)_2(bpy)_4](ClO_4)_3$ in MeCN to form the cubic core with each face of the cube capped by a chelating $Ph_2PO_2^-$ ligand (Figure 2).[14] However, a simpler route involves the spontaneous self-assembly from Mn^{2+}, $Ph_2PO_2^-$, and $KMnO_4$ in DMF (Figure 2). This method produces *VI* in a single step and higher purity than is observed in the fusion pathway.

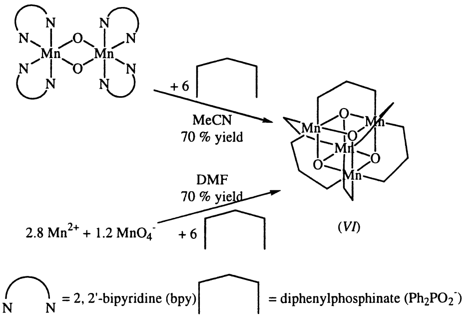


Figure 2: Two pathways to the synthesis of *VI*.

Protonation of *VI* with strong acids such as HOTf, $(Me_3Si)OTf$, or $HClO_4$ results in quantitative oxidation of the cluster to form $[Mn_4O_4(O_2PPh_2)_6]X$ (X=OTf (*VII*) or ClO_4 (*VIII*)), containing a Mn_4(III, 3IV) cubane core. Approximately two equivalents of acid are required for the quantitative conversion of *VI* to either *VII* or *VIII*, depending on the counterion of the acid. The reaction is dependent on the presence of O_2. The crystal structure and mechanism of formation of *VII* were determined previously,[15] and *VII* contains a trigonally-distorted Mn_4O_4 cubane core with one metrically distinct Mn^{III} ion.

The reduction of the cubanes *VI* and *VIII* by the hydrogen atom donor phenothiazine (pzH) has been investigated as a means to produce reduced manganese cluster derivatives. Phenothiazine is a useful reducing agent since its oxidized species have unique spectroscopic signatures that simplify their identification. Four equivalents of pzH are required to react completely with *VI*, resulting in four successive hydrogen atom transfers (overall 4 e^-/4 H^+ transferred) producing four neutral $pz^\bullet$ radicals. The Mn cluster is reduced to form $Mn_4O_2(O_2PPh_2)_6$ (*IX*, Mn_4(2II,2III)), in which two of the core oxo ligands are released as H_2O.[16] This cluster was characterized by mass spectrometry and spectroscopically, and appears be a pinned-butterfly containing an Mn_2O_2 base with two wingtip Mn ions bridged by a single $Ph_2PO_2^-$ ligand.[16]

The analogous reaction of pzH with the oxidized cubane *VIII* also consumes four equivalents of pzH. However, the first reaction involves the transfer of hydride (2 e^-/1 H^+) to form the pz^+ cation and $Mn_4O_3(OH)(O_2PPh_2)_6$ (*X*). Preliminary kinetic experiments using rapid-mixing UV-Vis spectrophotometry have not found any intermediates in this reaction; only pz^+ is observed in the time scale of the experiment (no $pzH^{+\bullet}$ or $pz^\bullet$), so that the hydride transfer appears to be concerted. Three subsequent hydrogen atom transfers then occur in succession to form *IX*. Overall, the reaction process results in the transfer of 5 e^- and 4 H^+.

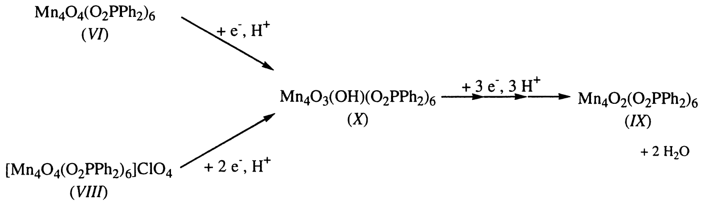


Figure 3: Summary of the reaction of pzH with VI and VIII.

The reactions of one equivalent of pzH with *VI* and *VIII* both produce *X* as the sole product. However, the reaction of pzH with *VIII* produces the pz^+ cation, which precipitates from solution as $pz(ClO_4)$, whereas the reaction of pzH with *VI* produces the neutral $pz^\bullet$ radical. Thus, *X* can be isolated from the reactions of pzH with *VIII*. Further characterization is in progress.

Acknowledgements

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