Tetranuclear Manganese-Oxo Complex with a 2.7-Å Mn···Mn Separation and Intramolecular H_2O···(μ-O) Hydrogen-Bonded Contacts: $[Mn_4O_2(TPHPN)_2(H_2O)_2(CF_3SO_3)_2](CF_3SO_3)_3$. Possible Mode for Binding of Water at the Active Site of the Oxygen-Evolving Complex in Photosystem II[1]

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Photosynthetic water oxidation is thought to occur at a polynuclear manganese aggregate within the photosystem II oxygen-evolving complex (PSII OEC).[2] While X-ray absorption studies have established that Mn···Mn contacts of 2.7 and 3.3 Å are present in the OEC,[3] the precise structure of the manganese aggregate has not been established. Furthermore, despite extensive investigation, the detailed mechanism by which water is converted to dioxygen in the PSII OEC remains poorly understood. While the literature abounds with suggestions as to how this process may take place,[2,4] one irrefutable fact is that during the catalytic cycle two oxygen atoms must be brought together in close proximity in order to form an O–O bond. We are currently taking a synthetic analogue approach[5] in order to elucidate this important biological process. Herein, we describe a novel tetranuclear complex, $[Mn_4O_2(TPHPN)_2(H_2O)_2(CF_3SO_3)_2]^{3+}$ (**1**), which meets several important criteria for a synthetic analogue of the OEC manganese center in that it has a 2.7-Å Mn···Mn contact, coordinated H_2O molecules, and quasi-reversible electrochemical properties. Of greatest interest, however, are the intramolecular (μ-O)···(H_2O) interactions which bring two oxygen atoms to within 2.6 Å of one another.

In a previous report,[6] we described a tetranuclear complex, $\{[Mn_2(TPHPN)(O_2CCH_3)(H_2O)]_2O\}^{4+}$, which was isolated from reaction mixtures containing $Mn(OAc)_3$, the septadentate binucleating ligand HTPHPN, and base. If, on the other hand, acetate is excluded from the reaction mixture, the title complex (**1**) may be prepared as follows. Air oxidation of a solution containing 0.724 g (2.00 mmol) of $Mn(ClO_4)_2 \cdot 6H_2O$, 0.458 g (1.00 mmol) of HTPHPN, 0.100 g (1.00 mmol) of Et_3N, and 25 mL of MeCN was allowed to proceed for approximately 2 days. Then the solution was layered with 25 mL of hexanes and allowed to evaporate. The pure,[7] green-black crystalline material that precipitated was washed with CH_3CH_2CN and collected by filtration (yield: 40%). The $CF_3SO_3^-$ salt of **1** was generated in a similar manner.[8] Crystals of **1** $(CF_3SO_3)_3 \cdot 3CHCl_3$ suitable for X-ray diffraction studies[9] were obtained by vapor diffusion of $CHCl_3$ into a CH_3CN solution.

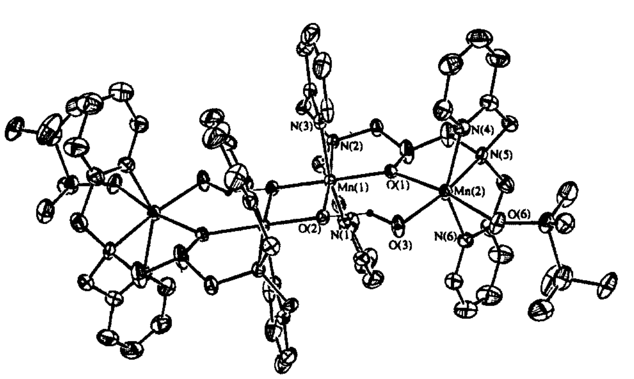
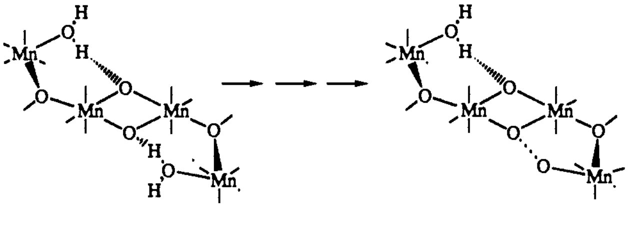


Figure 1. Structure of $[Mn_4O_2(TPHPN)_2(H_2O)_2(CF_3SO_3)_2]^{3+}$ showing the 40% probability thermal ellipsoids and atom-labeling scheme. Hydrogen atoms are omitted for clarity. Unlabeled atoms are related to labeled ones by an inversion operation. Selected interatomic distances (Å) and angles (deg) are as follows: Mn(1)–O(2), 1.818 (3); Mn(1)–O(2′), 1.848 (3); Mn(1)–O(1), 1.937 (3); Mn(1)–N(1), 2.116 (4); Mn(1)–N(2), 2.068 (3); Mn(1)–N(3), 2.135 (4); Mn(2)–O(1), 2.227 (3); Mn(2)–O(3), 2.109 (3); Mn(2)–O(6), 2.251 (4); Mn(2)–N(4), 2.228 (4); Mn(2)–N(5), 2.298 (3); Mn(2)–N(6), 2.201 (5); Mn(1)···Mn(1′), 2.724 (1); Mn(1)···Mn(2), 3.874 (1); O(2)···O(2′), 2.454 (5); O(2)···O(3), 2.596 (5); Mn(1)–O(2)–Mn(1′), 96.0 (2); Mn(1)–O(1)–Mn(2), 136.9 (1); O(2)–Mn(1)–O(2′), 84.0 (1).

Scheme I



The solid-state structure of **1** (Figure 1) consists of an inversion-symmetric cationic tetranuclear complex with two of the triflate anions coordinated directly to manganese atoms. Taking into account that there are five anions per four Mn atoms, and assuming that O(2) is an oxide group (O^{2-}) and that O(3) is in an H_2O molecule (not OH^-), one concludes that complex **1** has an average manganese oxidation state of +2.75. The two obvious choices for oxidation-state assignments are (i) $Mn^{II}Mn^{III}Mn^{IV}Mn^{II}$ and (ii) $Mn^{II}Mn^{III}Mn^{III}Mn^{III}$. For the latter oxidation state assignment (ii), either **1** is actually a valence-trapped species and the outer Mn atoms (Mn(2), Mn(2′)) are statically disordered Mn^{II} and Mn^{III} ions or the odd electron is delocalized, perhaps over the entire molecule. For the former oxidation-state assignment (i), the outer manganese atoms would be Mn^{II} and the inner core would be a mixed-valence $Mn^{III}Mn^{IV}$ pair, with these latter atoms being either (a) valence delocalized or (b) trapped and statically disordered in the crystal lattice. Bond distances to Mn(2) are as expected for Mn^{II},[6] and there is precedent for crystallographically disordered $\{Mn_2O_2\}^{3+}$ cores;[10] thus currently we prefer

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[1] Abbreviations used: HTPHPN, *N,N,N′,N′*-tetrakis(2-pyridylmethyl)-2-hydroxypropane-1,3-diamine; PSII OEC, photosystem II oxygen-evolving complex; bpy, 2,2′-bipyridine.

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[6] (a) Chan, M. K.; Armstrong, W. H. *J. Am. Chem. Soc.* **1989**, *111*, 9121–9122. (b) This complex was also reported by Suzuki et al.: Suzuki, M.; Sugisawa, T.; Senda, H.; Oshio, H.; Uehara, A. *Chem. Lett.* **1989**, 1091–1094.

[7] Elemental analysis of $[Mn_4O_2(TPHPN)_2(H_2O)_2(ClO_4)_2](ClO_4)_3 \cdot 2H_2O$. Calcd for $C_{54}H_{66}Cl_5Mn_4N_{12}O_{28}$: C, 37.53; H, 3.85; Cl, 10.26; Mn, 12.72; N, 9.72. Found: C, 37.60; H, 4.04; Cl, 9.51; Mn, 11.90; N, 9.93.

[8] Yields were typically in the 30–40% range.

[9] X-ray analysis: Compound **1** $(CF_3SO_3)_3 \cdot 3CHCl_3$ crystallizes in the monoclinic space group $C2/c$, with a = 32.297 (6) Å, b = 14.426 (3) Å, c = 20.964 (3) Å, β = 113.10 (2)°, V = 8986 (6) Å^3, and Z = 4. Data collection at 160 K out to 50° in 2θ provided 5181 reflections with $I > 3\sigma(I)$. The structure was solved by direct methods (SHELXS 86, G. Sheldrick) and refined by using 626 parameters to final R (R_w) values of 5.29% (5.62%).

[10] See, for example: Stebler, M.; Ludi, A.; Burgi, H.-B. *Inorg. Chem.* **1986**, *25*, 4743.

[11] (a) Libby, E.; Webb, R. J.; Streib, W. E.; Folting, K.; Huffman, J. C.; Hendrickson, D. N.; Christou, G. *Inorg. Chem.* **1989**, *28*, 4037–4040 and references threin. (b) Goodson, P. A.; Hodgson, D. J. *Inorg. Chem.* **1989**, *28*, 3606–3608. (c) Goodson, P. A.; Glerup, J.; Hodgson, D. J.; Michelsen, K.; Pedersen, E. *Inorg. Chem.* **1990**, *29*, 503–508. The oxidation states for the Mn atoms in the di-oxo-bridged core of **1** are not readily assigned on the basis of comparison to other compounds in the preceding three references.

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the $Mn^{II}Mn^{III}Mn^{IV}Mn^{II}$ oxidation-state assignment. Supporting this assignment is the electronic spectrum of **1** in CH_3CN, which, in the visible region, closely resembles other species that contain the $\{Mn_2O_2\}^{3+}$ core.[15] As was the case for $\{[Mn_2(TPHPN)(O_2CCH_3)(H_2O)]_2O\}^{4+}$,[6] the N_3 ends of the TPHPN ligands bind in a meridional manner. The $Mn^{III}–O_{oxo}$ bond distances in the inner $Mn_2(\mu\text{-}O)_2$ core of **1** are comparable to corresponding parameters in several crystallographically characterized di-μ-oxo dimers.[11] Shortening of the $Mn–O_{oxo}$ bonds is accompanied by elongation along the N(1)–Mn(1)–N(3) axis.[12] The Mn(2)–O(3) bond length (2.109 (3) Å) is 0.065 Å shorter than the $Mn^{III}–H_2O$ distances in $[Mn_2O(O_2CCH_3)_2(H_2O)_2(bpy)_2]^{2+}$.[13] Furthermore, the coordinated water molecules in **1** are involved in an intermolecular hydrogen bonding interaction to the bridging oxo moieties (O(2)), with contacts of 2.596 (5) Å.[14] Both H atoms of the H_2O ligand were located on a difference Fourier map. It is interesting to note that the O(2)⋯O(2′) contact (2.454 (5) Å) is actually somewhat shorter than the O(2)⋯O(3) separation.

Cyclic voltammetry of **1** in CH_3CN solution, using $(Et_4N)(ClO_4)$ as supporting electrolyte, reveals two quasi-reversible redox waves with $E_{1/2}$ values of 0.36 V ($E_{p,a} - E_{p,c} = 0.24$ V) and 0.87 V ($E_{p,a} - E_{p,c} = 0.27$ V) vs SSCE. On the basis of spectroelectrochemical studies,[15] the wave at 0.87 V is assigned to an oxidation of **1** and the wave at 0.36 V is assigned to a reduction to the $Mn^{III}{}_2Mn^{II}{}_2$ oxidation level. Magnetic susceptibility measurements on a solid sample of **1** indicate a moment of 8.7 μ_B per molecule at 279 K, decreasing to 6.6 μ_B at 7 K. Since the spin-only moment for four magnetically uncoupled manganese ions is 10.4 μ_B ($2 \times Mn^{II} + Mn^{III} + Mn^{IV}$), the above values are consistent with net antiferromagnetic interactions within the tetranuclear aggregate.

The relatively short intramolecular O(2)⋯O(3) interaction in **1** gives rise to the notion that bond formation between these atoms may be promoted by an oxidation/deprotonation process as shown in Scheme I. We suggest that this mechanism represents a plausible pathway by which the key O–O bond-forming step in PSII OEC water oxidation may occur. Compound **1** corresponds to a model for the S_0 oxidation level in the Kok S-state scheme.[16] While heretofore oxidation-state assignments for a given S state generally avoid formulations with both Mn^{II} and Mn^{IV} present, the stability of **1** demonstrates that, with appropriate donors, manganese atoms at these oxidation levels can coexist in the same molecule. Further characterization of **1** and its oxidized and deprotonated derivatives is underway.

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Note Added in Proof. It has come to our attention that Professor M. Suzuki and co-workers have isolated the title complex as a perchlorate salt. We are grateful to them for supplying us with a preprint of their manuscript (submitted to *Chem. Lett.*) which describes this work.

Registry No. **1** $(CF_3SO_3)_3\cdot 3CHCl_3$, 127103-44-0; **1** $(CF_3SO_3)_3$, 127103-43-9; $[Mn_4O_2(TPHPN)_2(H_2O)_2(ClO_4)_2](ClO_4)_3$, 127129-91-3; H_2O, 7732-18-5.

Supplementary Material Available: A fully labeled ORTEP drawing, atomic positional and thermal parameters, and intramolecular distances and angles for $[Mn_4O_2(TPHPN)_2(H_2O)_2(CF_3SO_3)_2](CF_3SO_3)_3\cdot 3CHCl_3$ (14 pages). Ordering information is given on any current masthead page.

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(12) The fact that the elongation is not as pronounced as often observed is presumably due to averaging of the Mn^{III} and Mn^{IV} sites by static disorder in the crystal lattice.

(13) Ménage, S.; Girerd, J.-J.; Gleizes, A. *J. Chem. Soc., Chem. Commun.* **1988**, 431–432.

(14) Hydrogen bonding of the coordinated water molecules to the oxo bridge in **1** is reminiscent of the hydrogen bonding of hydroperoxide to the bridging oxo group in oxyhemerythrin.[3c]

(15) Compound **1** as isolated has an electronic spectrum similar to the spectra of other species that have $\{Mn_2O_2\}^{3+}$ cores (in CH_3CN, λ, nm (ϵ, M^{-1} cm^{-1}): 547 (760), 625 (520)).[11c] When a platinum electrode is poised at −0.1 V vs SSCE in a CH_3CN solution of **1**, current passes and the visible absorption diminishes markedly. On the other hand, when the electrode is held at +1.3 V vs SSCE, the absorption in the visible region increases strongly as current is passed. Both of these processes are reversible on the time scale of approximately 1 h.

(16) Full details of the proposed mechanism will be presented elsewhere.

Synthetic and Mechanistic Studies on Esperamicin A_1 and Calicheamicin γ_1. Molecular Strain Rather Than π-Bond Proximity Determines the Cycloaromatization Rates of Bicyclo[7.3.1] Enediynes

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During the past two years there has been intense interest in the remarkable antitumor antibiotics esperamicin A_1 (**1**) and calicheamicin γ_1 (**2**).[1] These unusual natural products exert their DNA cleaving properties by binding into the minor groove. In some as yet unspecified manner the allylic trisulfide is subsequently cleaved in situ to release the thiol (or thiolate) **3**. The latter undergoes conjugate addition to the proximate α,β-unsaturated carbonyl system (C-1) to give **4**. With sp^3 hybridization at C-1 the bicyclic enediyne no longer violates Bredt's rule; the transition state leading to 1,4-diyl **5** becomes energetically feasible. Hydrogen atom abstraction from the ribose backbone by the biradical results in single- and double-stranded-DNA cleavage and formation of the cycloaromatized adduct **6** (Scheme I).

It has been suggested that rehybridization at C-1 ($sp^2 \rightarrow sp^3$) results in contraction of the C-6/C-11 distance ($r(C_{sp}\text{-}\text{-}\text{-}C_{sp})$) from 3.35 Å to 3.16 Å, causing spontaneous, ambient cycloaromatization to 1,4-diyl **5**. These conclusions were based on a study of monocyclic enediynes.[2] Alternatively, qualitative investigations led us to propose that an overall change in strain energy from enediyne to cycloaromatized adduct furnishes the closure driving force.[3] More recently, we presented computational evidence that factors controlling the ease of cycloaromatization are directly related to strain energy in the transition state rather than to proximity of the acetylenic carbon atoms (r) in the ground state.[4] Quantitative experimental and theoretical data reported herein support the strain attenuation hypothesis.

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