Multiple Reversible Protonations of the Adamantane-Shaped {Mn₄O₆}⁴⁺ Core: Detection of Protonation Stereoisomers at the {Mn₄O₄(OH)₂}⁶⁺ Level

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Polynuclear manganese−oxo complexes have been studied extensively as models of the manganese center in the water oxidase active site of photosystem II (PS II).[1] Biophysical studies suggest that the oxygen evolving center (OEC) includes four manganese ions in higher oxidation states organized as a tetranuclear, magnetically coupled core.[2] During the catalytic cycle, water molecules must be deprotonated, and it is likely that a change in the protonation state of the bridged metal cluster also occurs.[3] Modulation of the redox properties of manganese aggregates by protonation/deprotonation or by the extent of hydrogen bonding may play an important role in effective catalysis. While synthetic complexes have provided some insight into the consequences of protonation of a single oxo-bridge,[4−6] only recently were the effects of two successive protonation steps at a di-oxo-bridged dimanganese(IV,IV) core delineated.[7] In this report, we describe the spectroscopic and magnetic properties of the first stable, multiply protonated, tetranuclear Mn(IV) complex ([Mn₄O₄(OH)₂(tacn)₄](CF₃SO₃)₆, **1**H₂(CF₃SO₃)₆) formed by successive protonation of the adamantane-like {Mn₄O₆}⁴⁺ core.[8] This is of particular interest with regard to the PS II OEC, owing to the parity of core nuclearity. Remarkably, **1**H₂(CF₃SO₃)₆ is a nearly equal mixture of the *cis* and *trans* protonation isomers, each with dramatically different magnetic characteristics based on their NMR properties.

Previously, we showed that reversible protonation of a single oxo-bridge of **1**(CF₃SO₃)₄[9] is possible in either acetonitrile or water.[6] Here, successive protonation of **1**(CF₃SO₃)₄ by CF₃SO₃H in acetonitrile under argon to form **1**H₂(CF₃SO₃)₆[10] was initially demonstrated spectrophotometrically, as shown in Figure 1. Quantitative reversibility of the first and second

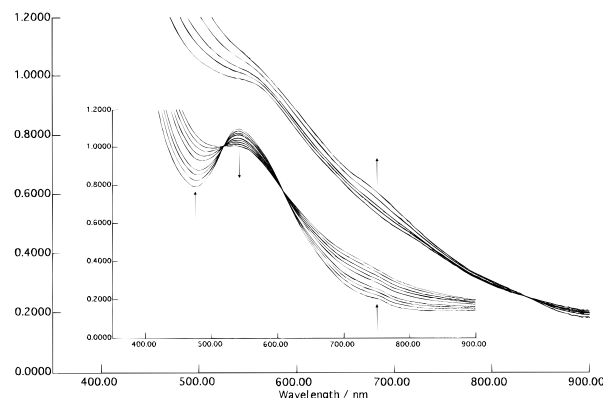**Figure 1.** Spectrophotometric titration of **1**H(CF₃SO₃)₅ with CF₃SO₃H (isosbestic point at 825 nm). Inset, left: titration of **1**(CF₃SO₃)₄ with CF₃SO₃H (isosbestic points at 530 nm and 620 nm). Conditions: 0.423 mM in CH₃CN under argon at 21 °C.

protonation steps was verified by spectrophotometric back titration with Et₃N. The first pK_a value for **1**(CF₃SO₃)₄ of 11.2 in acetonitrile[11] determined in this study agrees with reported values.[6,12,13] A pK_a value of 3.10 in acetonitrile for the second protonation to form **1**H₂(CF₃SO₃)₆[11] reflects a decrease of the effective basicity of the core of **1**H(CF₃SO₃)₅ by 8 orders of magnitude. This drop in pK_a from first to second protonation is significantly larger than the 3−5 unit change observed for successive protonation of [Mn(X-salpn)(μ-O)]₂ in acetonitrile[7] or the 4−5 unit change between first and second pK_a values of several [Cr^{III}(μ-OH)L]₂⁴⁺ complexes in water.[14]

The magnetic and structural consequences of protonation of **1**(CF₃SO₃)₄ were investigated using ¹H NMR. A titration of **1**(CF₃SO₃)₄ with triflic acid in CD₃CN followed by ¹H NMR shows that each protonation state is easily distinguished (Figure 2), and no degradation products are observed. The observation of distinct ¹H NMR spectra for each protonated complex is a consequence of the slow rate of the proton self-exchange of **1**(CF₃SO₃)₄, **1**H(CF₃SO₃)₅, and **1**H₂(CF₃SO₃)₆ on the NMR time scale, consistent with data for other metal−oxo complexes.[12,15,16] The pK_a values of 11.0 and 2.9 for the first and second protonations, respectively, determined by the ¹H NMR titration,[17] are in good agreement with the aforementioned values determined by spectrophotometry.

The magnetic susceptibility characteristics of each protonation state in solution were determined by the NMR method.[18] Values of μ_{eff}/Mn for **1**(CF₃SO₃)₄ and **1**H(CF₃SO₃)₅ of 4.36 μ_B and 3.14 μ_B, respectively, at 22 °C reflect the change in overall

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(8) Abbreviations: AnH⁺CF₃SO₃⁻ = anilinium triflate; tacn = 1,4,7-triazacyclononane.

(9) A 0.160 g (0.85 mmol) portion of KCF₃SO₃ in 1 mL of water was added to 0.250 g (0.20 mmol) of [Mn₄O₆(tacn)₄]Br₄·5.5H₂O (**1**Br₄·5.5H₂O) (Wieghardt, K.; Bossek, U.; Gebert, W. *Angew. Chem., Int. Ed. Engl.* **1983**, *22*, 328−329) in 3 mL of water. Complex **1**(CF₃SO₃)₄ precipitated in >95% yield and was recrystallized from acetonitrile/chloroform.

(10) The electrospray ionization mass spectrum (Supporting Information) supports this formulation and thus core integrity at the doubly protonated level.

(11) pK_{a1} for **1**(CF₃SO₃)₄ was determined in acetonitrile using AnH⁺-CF₃SO₃⁻ (pK_a =10.6). pK_{a2} for **1**(CH₃SO₃)₄ was determined in acetonitrile using CF₃SO₃H (pK_a =2.60). pK_a values were calculated according to K_a(complex) = K_a(acid)/K_{eq}, where K_{eq} = [complexH⁺][A⁻]/[HA][complex]. K_a(acid) for the acids in CH₃CN are given by Izutsu (Izutsu, K. *Acid-Base Dissociation Constants in Dipolar Aprotic Solvents*; Blackwell Scientific Publications: Oxford, 1990; pp 17−35).

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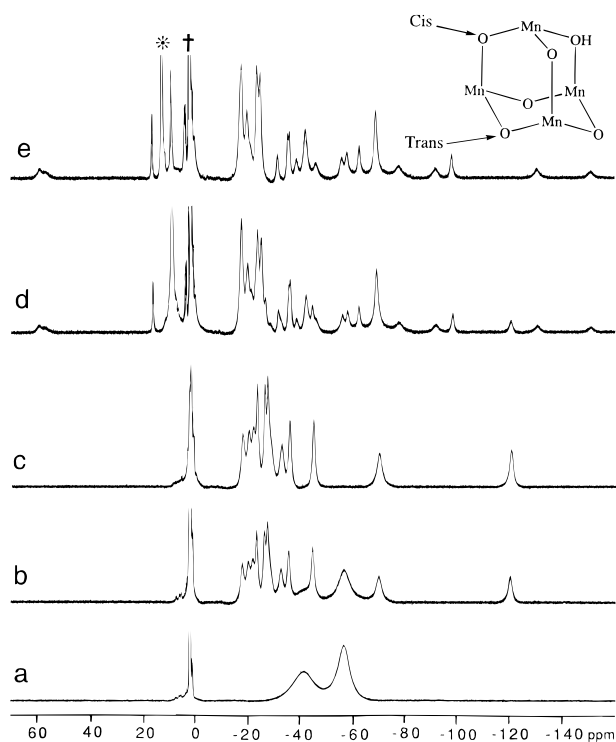
Communications to the Editor

J. Am. Chem. Soc., Vol. 118, No. 44, 1996 10911

Figure 2. ^{1}H NMR titration of **1**(CF$_3$SO$_3$)$_4$ with CF$_3$SO$_3$H: (a) **1**(CF$_3$-SO$_3$)$_4$, (b) +0.5 equiv of H$^+$, (c) +1.0 equiv of H$^+$ (spectrum of **1**H(CF$_3$-SO$_3$)$_5$), (d) +2.9 equiv of H$^+$, (e) +6.5 equiv of H$^+$ (spectrum of *cis*- and *trans*-**1**H$_2$(CF$_3$SO$_3$)$_6$. Inset: **1**H(CF$_3$SO$_3$)$_5$ core showing *cis* and *trans* positions. Conditions: 8.00 mM in CD$_3$CN at 22 °C under argon; 299.95 MHz frequency. An * denotes CF$_3$SO$_3$H; † denotes CD$_2$HCN.

coupling from ferromagnetic to moderately antiferromagnetic[19] and are in good agreement with the corresponding solid state values.[6] The doubly protonated complexes show on average even stronger overall antiferromagnetic coupling for an observed μ_{eff}/Mn of 2.58 μ_B. Although this μ_{eff} for **1**H$_2$(CF$_3$SO$_3$)$_6$ is a composite of two complexes (*vide infra*), the spectral range of resonances for each complex (211 ppm *cis*, 51 ppm *trans*, see Supporting Information) suggests that the *cis* doubly protonated complex experiences much weaker antiferromagnetic coupling than the *trans* doubly protonated complex. The trend from net ferromagnetic to increasingly overall antiferromagnetic coupling with successive protonation of the tetranuclear complex **1**(CF$_3$-SO$_3$)$_4$ is opposite to the trend reported for successive protonation of the oxo-bridges of [Mn(X-salpn)(μ-O)]$_2$.[7] The net ferromagnetism of **1**(CF$_3$SO$_3$)$_4$ has previously been ascribed[20] to "spin frustration",[21] however, intrinsic pairwise ferromagnetism cannot be ruled out.

The ^{1}H NMR spectra of **1**(CF$_3$SO$_3$)$_4$ and **1**H(CF$_3$SO$_3$)$_5$ can be understood in terms of the core symmetry displayed in their solid state structures and the difference between their magnetic properties. Lack of a symmetry operation relating the two protons of any given methylene group results in their magnetic inequivalence.[22] Solution structural symmetry analogous to that of the solid state structure[6] and a change in overall coupling from ferromagnetic to antiferromagnetic thus predicts two broad

resonances of equal area for **1**(CF$_3$SO$_3$)$_4$ and 12 sharper resonances of equal area for **1**H(CF$_3$SO$_3$)$_5$. Deconvolution[17] and integration of ^{1}H NMR spectra of **1**(CF$_3$SO$_3$)$_4$ and **1**H(CF$_3$-SO$_3$)$_5$ indeed gives two broad equal area peaks and 12 sharper equal area peaks, respectively.

The second protonation can occur at an oxo-bridge either *cis* or *trans* to the first protonated bridge. On one hand, *trans* protonation is favored since the *trans* oxo-bridge should be the most basic following a redistribution of electrons from the oxo-bridges and because of lower Coulombic repulsion of *trans* hydroxo-bridge protons. On the other hand, *cis* protonation is favored since there are four *cis* oxo-bridges and only one *trans* oxo-bridge.[23] The idealized core symmetries of the doubly protonated complexes are D_{2d} for *trans*-**1**H$_2$(CF$_3$SO$_3$)$_6$ and C_s for *cis*-**1**H$_2$(CF$_3$SO$_3$)$_6$, and on this basis one would expect 6 resonances and 24 resonances of equal area for the *trans* and *cis* doubly protonated complexes, respectively.

Following deconvolution of the the ^{1}H NMR spectrum of the doubly protonated complexes into 30 separate resonances (see Supporting Information), peak assignments for the *cis* and *trans* isomers of **1**H$_2$(CF$_3$SO$_3$)$_6$ were made on the basis of relative peak areas and variable temperature NMR. Integration indicates that **1**H$_2$(CF$_3$SO$_3$)$_6$ consists of approximately 50% *trans* isomer and 50% *cis* isomer, implying that pK_a(*cis*) $\approx$ pK_a-(*trans*).

Measurements of the susceptibility difference between S$_1$ and S$_2$ states of O$_2$-evolving PS II core complexes[24] shows that $\mu_{S2}^2 - \mu_{S1}^2$ is 9−17 μ_B^2. This increase in magnetic moment accompanying the S$_1 \rightarrow$ S$_2$ transition has been interpreted as arising from reduced exchange coupling within the cluster.[24b] EXAFS studies at S$_1$ and S$_2$, on the other hand, showed that there is no appreciable structural rearrangement accompanying removal of one electron from the aggregate.[25] The results above demonstrate that a change in the protonation state of the adamantane-like {Mn$_4$O$_6$}$^{4+}$ core has a significant effect on the exchange coupling within the cluster, while causing modest structural change.[6] For instance, $\Delta\mu^2$ for the deprotonation of **1**H$_2$(CF$_3$SO$_3$)$_6$ to give **1**H(CF$_3$SO$_3$)$_5$ is 12.7 μ_B^2, comparable to the observed increase accompanying the S$_1 \rightarrow$ S$_2$ transition. The observed increase in magnetic moment following deprotonation of our tetranuclear manganese complex suggests that changes in the protonation state of water-derived bridging ligands accompanying S state changes could play an important role in determining changes in the electronic structure of the manganese aggregate in the water oxidase active site.

Supporting Information Available: Summary of ^{1}H NMR chemical shifts, peak widths (FWHM) and peak intensities for *cis*- and *trans*-**1**H$_2$(CF$_3$SO$_3$)$_6$ and electrospray ionization mass spectrum of the tetranuclear manganese complex in the doubly protonated form (3 pages). See any current masthead for ordering and Internet access instructions.

(19) The terms overall or net antiferromagnetic or ferromagnetic are used to indicate a negative or positive deviation from the uncoupled spin-only magnetic moment on a per Mn ion basis. In this case, the Mn ions are considered to be $S = {}^3/_2$, therefore the predicted moment per Mn without coupling is 3.87 μ_B.

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