Effect of the Ligating Anion on the Catalase Activity of Dinuclear Manganese(II) Complexes of Schiff-base Macrocycles

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Synthesis and catalase activity of a series of dinuclear manganese(II) complexes $[Mn_2(X\text{–}L^n)(Y)](ClO_4)$, where $H_2(X\text{–}L^n)$ denotes a Schiff-base macrocycle formed by 2 : 2 condensation of 4-X-2,6-diformylphenol and bis(ω-aminoalkyl)methylamine, are reported, together with the X-ray structure of one complex (X = Me, Y = Cl, n = 2); the catalytic activity depends on the nature of the ligating anion Y^-, and it is proposed that the dissociation of Y^- should be involved in the rate determining step.

A number of manganese-containing enzymes are known,[1] among which Mn catalases are of particular importance.[2] These enzymes catalyse the disproportionation of hydrogen peroxide to dioxygen and water, and are thought to contain a dinuclear Mn^{III} active site. Recently, several reports have appeared on the catalyse activity of synthetic manganese complexes,[3–8] and some of them present interesting proposals about the reaction mechanism. However, our knowledge about the mechanistic details of the catalase activity of these model complexes is insufficient to help us understand the natural catalase systems.

Recently, we reported the synthesis of a series of dinuclear manganese complexes $[Mn_2(X\text{–}L^2)(\mu\text{-}RCO_2)](ClO_4)$, where '$X\text{–}L^n$' is a macrocyclic Schiff-base ligand, and discussed the effect of the substituents X and R on the electrochemical properties of the complexes.[9] In this report, we present the synthesis and structure of several other compounds with a similar composition, and to compare their catalase activity.

Bis(2-aminoethyl)methylamine (3 mmol), $MnCl_2{\cdot}4H_2O$ (3 mmol), and 2,6-diformyl-4-methylphenol (3 mmol) were reacted in boiling methanol for 30 min. After addition of $NaClO_4$ (6 mmol) and heating for several minutes, a yellow precipitate **1** formed. After cooling, the yellow solids were collected and washed with methanol (yield 47%). Use of $MnBr_2{\cdot}4H_2O$ in place of $MnCl_2{\cdot}4H_2O$ afforded **2**. Compound **3** (or **4**) was prepared by the reaction of $Mn(ClO_4)_2{\cdot}6H_2O$ (3 mmol), 2,6-diformyl-4-methylphenol (3 mmol), bis(2-aminoethyl)methylamine (3 mmol) and NaN_3 (or NaSCN) (3 mmol) in boiling methanol. Compounds **10** and **11** were prepared by similar procedures as those for **5**–**9**.[9]

Single crystals of **1** suitable for X-ray diffraction studies were obtained by the vapour diffusion of Et_2O into the DMF solution of **1**.† The structure (Fig. 1) consists of binuclear cations $[Mn_2(Me\text{–}L^2)(\mu\text{-}Cl)]^+$, perchlorate anions, and DMF molecules (two per formula unit). The cation possesses crystallographically imposed C_2 symmetry. The two manganese ions are bridged by the two phenolic oxygens from $Me\text{–}L^2$ and the chloride (located on the C_2 axis). The overall structure of the $Mn_2(Me\text{–}L^2)$ unit resembles that of compound **5**,[9] with highly deformed octahedral coordination to each Mn ion. The shorter Mn–Mn distance (3.086 compared with 3.239 Å in **5**) is attributed to the presence of the μ_2, η^1-bridging chloride in place of the μ_2, η^2-bridging acetate in **5**. From comparison of the structures of **1** and **5**, we can suppose that the $Mn_2(Me\text{–}L^2)$ unit should be sufficiently rigid to retain the structural similarity in these complexes, and that all the compounds **1**–**9** should contain the binuclear cations with similar structures, with the $Mn_2(X\text{–}L^2)$ core and the bridging Y anion.

The catalase activity of **1**–**11** was examined. An H_2O_2 solution (7.5 mol dm^{-3} in MeCN, 1 ml) was added to a solution of the complex (*ca.* 5 × 10^{-3} mol dm^{-3} in MeCN,

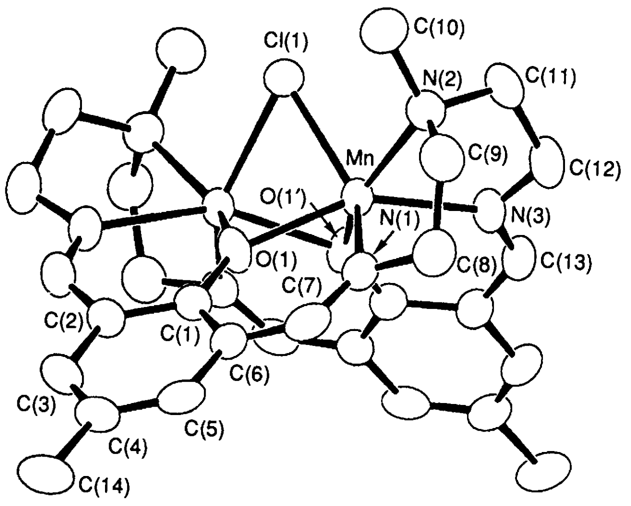
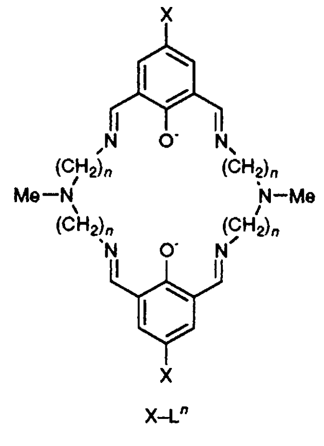


Fig. 1 Selected bond lengths (Å) and angles (°) for $[Mn_2(Me\text{–}L^2)(Cl)]^+$ in **1**: Mn···Mn′ 3.086(2), Mn–Cl(1) 2.524(2), Mn–O(1) 2.181(4), Mn–O(1′) 2.164(4), Mn–N(1) 2.177(5), Mn–N(2) 2.364(5), Mn–N(3) 2.231(5); Cl(1)–Mn–O(1) 80.7(1), Cl(1)–Mn–O(1′) 81.0(1), Cl(1)–Mn–N(1) 142.0(1), Cl(1)–Mn–N(2) 93.9(1), Cl(1)–Mn–N(3) 115.3(1)



X–L^n

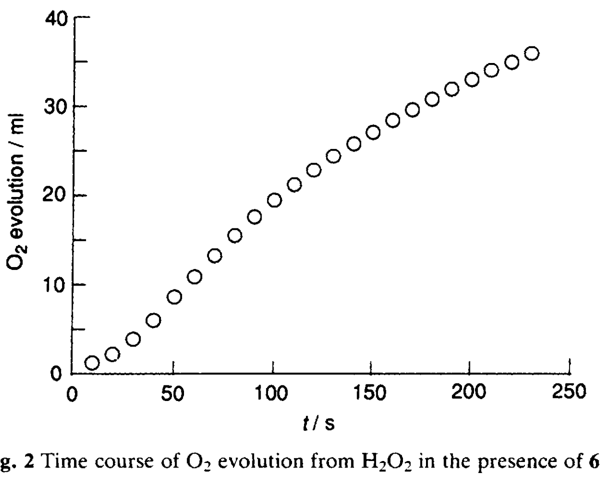


Fig. 2 Time course of O_2 evolution from H_2O_2 in the presence of **6**

Table 1 Maximum rates of O_2 evolution (V_{max}) and first oxidation potentials ($E^1{}_{1/2}$) of $[Mn_2(X\text{-}L^n)(Y)](ClO_4)$ (**1–11**)

	X	*n*	Y	V_{max}/s^{-1}[a]	$E^1{}_{1/2}/V$[b]
1	Me	2	Cl	1.88	0.29
2	Me	2	Br	3.41	0.25
3	Me	2	N_3	4.45	n.d.[c]
4	Me	2	SCN	4.42	n.d.
5	Me	2	$MeCO_2$	0.70	0.15
6	Me	2	CF_3CO_2	2.11	0.27
7	Me	2	CCl_3CO_2	1.13	0.27
8	Br	2	$MeCO_2$	0.29	0.26
9	Br	2	CF_3CO_2	2.36	0.35
10	Me	3	$MeCO_2$	0.14	0.11
11	Me	3	CF_3CO_2	0.20	n.d.

[a] Molecules of O_2 evolved per molecule of catalyst per second. [b] Determined by cyclic voltammetry (in MeCN, 0.1 mol dm^{-3} Et_4NClO_4); potentials with reference to ferrocene–ferricenium couple. [c] n.d. = not determined.

10 ml, kept at 25 °C), and the amount of evolved oxygen was volumetrically measured. The typical time-course profile is shown in Fig. 2. The rate of O_2 evolution was initially zero, rapidly increased to reach a maximum, and then gradually decreased. The presence of a lag period before reaching the maximum rate was already noted by Okawa *et al.*[8] However, they reported a distinct (and important) two-stage character of the time course which seems absent in the present example. Moreover, they reported the colour change of the reaction mixture from yellow to purple, which strongly indicated the formation of a $Mn^{IV}{=}O$ species, whereas in our study all solutions remained yellow, which suggests that the high-valent Mn species, if ever formed, are short-lived and immediately reduced to the pale-coloured Mn^{II} species.

The maximum rates of O_2 evolution (V_{max}) were measured for compounds **1–11** (Table 1). Comparison of V_{max} values for **2**, **6**, **7** and **8** confirms that the oxidation potentials are not important in determining V_{max}. Instead, it seems that the nature of the bridging anion Y^- is closely related with V_{max}. This idea is supported by several considerations. (1) The more basic Y^- is, the smaller the activity (**5–7**). (2) Nevertheless, **3** and **4** have higher acitivity than **6** in spite of the greater basicity of Y^-, because in these compounds Y^- should bind (perhaps) in a μ_2, η^1-manner and therefore less tightly. (3) Examination of the two series, **5**, **8** and **10** and **6**, **9** and **11**, reveals that the compounds **10** and **11** have much lower activity; it is possible that the $(CH_2)_3$ chains in **10** and **11** should allow the more stable conformation of the $Mn_2(Me\text{-}L^3)$ core which should bind Y^- more tightly.

We propose that dissociation of Y^- is involved in the rate-determining step in the catalytic decomposition of H_2O_2 by **1–11**. This is quite reasonable as these complexes have six-coordinate (saturated) Mn centres, in contrast with the Okawa's compound which has five-coordinate Mn centres.[8] This important difference might have led to the apparently different behaviour of our compounds from theirs.

The authors are grateful to the Instrument Center of the Institute for Molecular Science for assistance in obtaining the X-ray diffraction data. This work was supported by a Grant-in-Aid for Encouragement of Young Scientists (No. 05854051).

Received, 24th August 1993; Com. 3/05113G

Footnote

Crystal data for: $[Mn_2(Me\text{-}L^2)(Cl)](ClO_4)\cdot 2(CH_3)_2NCHO$, **1**: $C_{34}H_{50}N_8O_8Cl_2Mn_2$, $M = 879.60$, monoclinic, space group *P*2/*a*, $a = 13.927(5)$, $b = 10.121(3)$, $c = 15.147(7)$ Å, $\beta = 109.40(2)°$, $U = 2013(1)$ Å^3, $Z = 2$, $D_c = 1.45$ g cm^{-3}, $F(000) = 916$, μ(Mo-Kα) = 8.17 cm^{-1}.

Data collection and reduction. Single crystals were obtained by a vapour diffusion of Et_2O into a DMF solution of **1**. A crystal with approximate dimensions 0.4 × 0.4 × 0.2 mm was mounted on a glass fibre and coated with an epoxy resin. All measurements were made on a Rigaku AFC5R diffractometer with graphite monochromated Mo-Kα radiation ($\lambda = 0.71073$ Å) at 25 °C. Cell parameters were obtained from a least-squares fit to 19 reflections in the range $29 < 2\theta < 30°$. The data were collected using the ω-2θ scan technique with scan width of $(1.42 + 0.50 \tan\theta)°$ at a speed of 6.0° min^{-1} (in ω). The intensity data were corrected for Lorentz and polarization factors. Three standard reflections were monitored every 150 reflections, which showed decrease by −5.2%. A linear decay correction and an empirical absorption correction based on psi-scans of three reflections were applied (transmission factors 0.71–1.00). A total of 3939 reflections were collected in the range $2 < 2\theta < 50°$, and 2624 with $F > 3\sigma(F)$ were observed.

Structure solution and refinement. The structure was solved by MITHRIL84 direct methods. Refinement was carried out by the full-matrix least-squares method. The function minimized was $\Sigma w(|F_o| - |F_c|)^2$ where $w = 1/\sigma^2(F_o)$. All the non-hydrogen atoms were refined anisotropically. The hydrogen atoms of the macrocyclic ligand were located at the calculated positions and refined isotropically except for those of the methyl group on the phenol ring, which were fixed. The final refinement cycle with 314 variable parameters yielded the values of R and R_w of 0.069 and 0.064, the maximum shift being 0.28 times its esd. The maximum and minimum peaks on the final difference Fourier map were 1.00 and −0.64 e^- Å^{-3}. All calculations were performed using the TEXSAN crystallographic software package.

Atomic coordinates, bond lengths and angles, and thermal parameters have been deposited at the Cambridge Crystallographic Data Centre. See Information for Authors, Issue No. 1.

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