Development of Metallacrown Ethers: A New Class of Metal Clusters

Crown ethers have been used for over twenty years as selective binding agents for alkali metal and alkaline earth ions. Although there have been many modifications to the crown ether core, none is so dramatic as to substitute heteroatoms into the positions normally occupied by carbon atoms. In this article we describe a new class of metal clusters which incorporate trivalent metal ions and nitrogen atoms into molecules that structurally and functionally mimic the behavior of crown ethers. These *metallacrown* ethers can be prepared in high yield in only a couple of steps and lead to molecules that may have utility in analytical chemistry, catalysis and new polymeric materials.

Key Words: *crown ethers, metal sequestration, chiral clusters*

INTRODUCTION

The crown ethers are the paradigm of the molecular class of poly-ether metal sequestration agents.[1,2] These neutral, cyclic molecules form a metal binding cavity composed of ether oxygen atoms. Specificity for alkaline metal and alkali earth cations can be achieved by adding methylene spacers or additional oxygen atoms which increase the cavity size and potential denticity of the ligand.[3] To a first approximation these compounds show selectivity based on a match between the ligand cavity size and the ionic radius of the cation to be encapsulated.[4,5] Crown ether complexes of transition metal ions are rare, presumably because the donor capacity of a

neutral oxygen atom to a transition metal ion is poor. For this reason, variants of crown molecules containing other heteroatoms have been prepared.[6-9] The metal complexes of these ligands exhibit interesting properties (e.g., the stabilization of low spin Co(II)) and altered preferences for transition metal ions. Although analogues that substitute sulphur (crown thiaethers[7]) or nitrogen (cyclams[9]) for the ring oxygen atoms are well known, comparable systems that substitute heteroatoms for the ring carbons have not been explored to any extent. In this contribution we provide an entry into a new class of sequestration agents called metallacrown ethers. These novel clusters are conceptually related to 9-crown-3 and 12-crown-4 as illustrated in Fig. 1. A ring structure of ethereal like oxygen atoms are linked by two atom bridges of nitrogen and transition metal ions. This distinction leads to altered metal binding
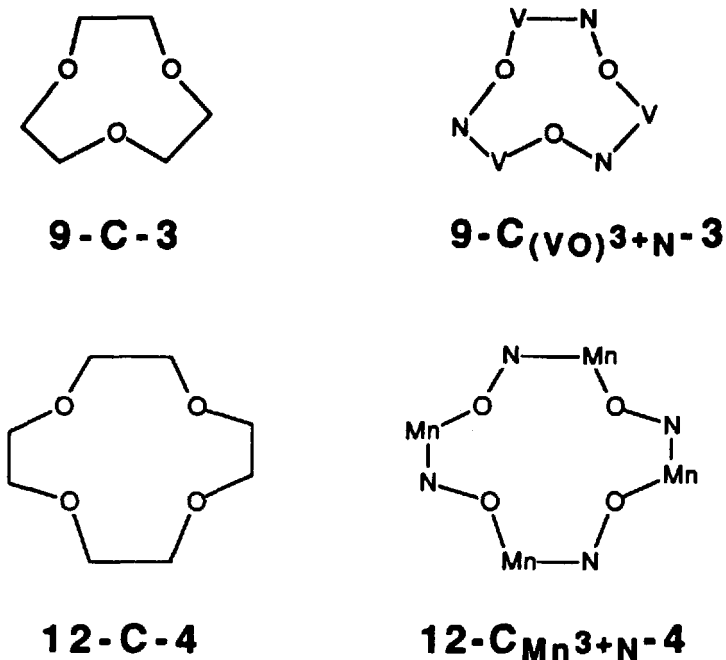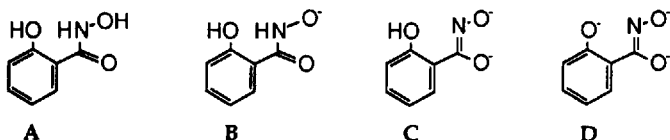

FIGURE 1 Diagram of the conceptual analogy between crown ethers and metallacrown ethers. The methylene carbon positions have been substituted by a nitrogen atom and a trivalent transition metal in the metallacrowns.

character and may provide an entry into selective anion and cation detection agents, catalysts and precursors for new polymeric materials.

The concept of metallacrowns arises from a fusion of the organic metal recognition agents described above and microbial metal ion sequestration agents (siderophores).[10,11] The siderophores are a group of low molecular weight Fe(III) chelating agents that primarily employ hydroxamate or catecholate moieties to sequester and transport ferric ion into bacterial cells. This suggested a biomimetic approach to trivalent transition metal binding using phenolate, catecholate and hydroxamate ligands. The formation constants[12,13] of these ligands with ferric ion are truly impressive with hydroxamates such as Desferal, having $\beta_{110} = 10^{32}$, and catecholates such as enterobactin, exhibiting the astounding $\beta_{110} = 10^{52}$. This high affinity, coupled with the relative specificity for Fe(III), has been exploited in selective iron decorporation therapy in the treatment of β-thallesemia. On this basis, one might expect metal selectivity for high valent transition metal ions (e.g., Fe(III), Mn(III), V(V)O^{3+} or Ga(III)) using a ligand such as salicylhydroxamic acid that contains two of these functional groups.

We found salicylhydroxamic acid (H$_3$SHI, shown below) to be a particularly interesting ligand for two reasons.
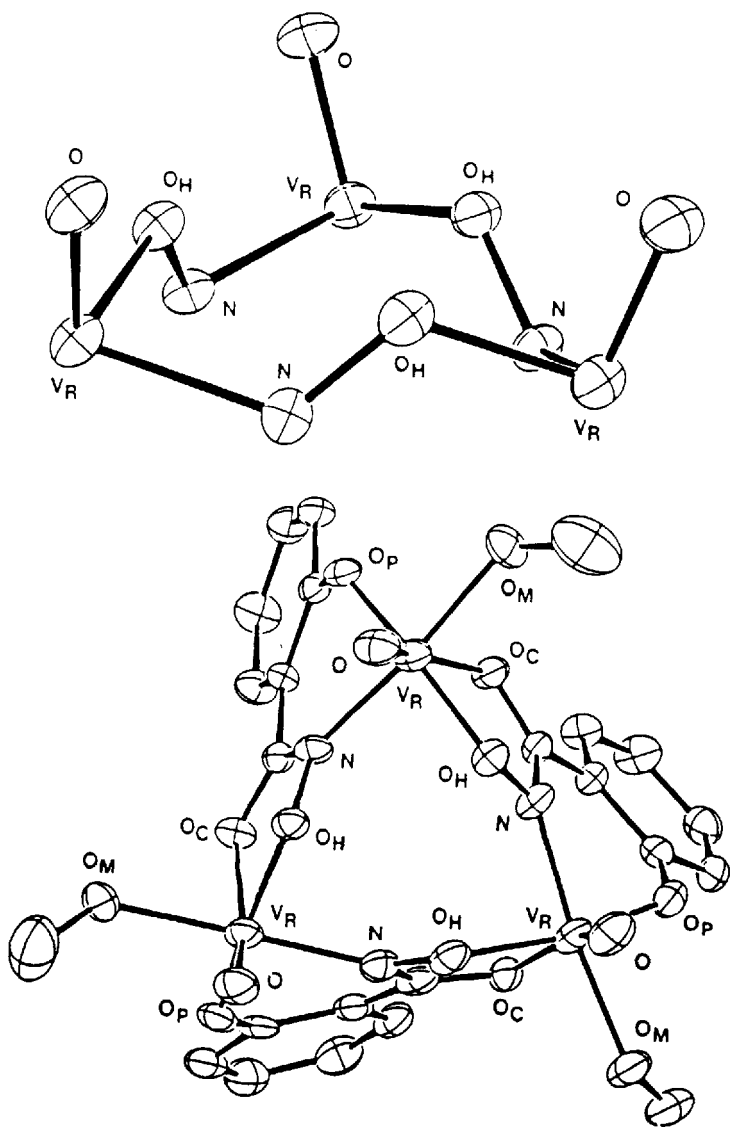

First, there are three protonation states available[14]: the singly deprotonated hydroxamate (B), the doubly deprotonated hydroximate (C) and the triply deprotonated hydroximatophenolate (D). Second, all four heteroatoms are potential metal ligands in D. When fully utilized, one metal can bind in a five membered chelate ring formed through the hydroximate group while a second metal can bind to the 6 membered substituted iminophenolate ring. This leads to metal cluster formation with M_A–N–O–M_B networks linking the sequestered metals. As we show below, it is D with two like metals bound that forms the basis for the metallacrowns.

THE STRUCTURAL ANALOGY

Schematic diagrams of 9-crown-3 (9-C-3), 12-crown-4 (12-C-4) and the analogous cores of the metallacrown ethers 9-MC_{Mn-N}-3 and 12-MC_{Mn-N}-4 are shown as Fig. 1. Two important structural parameters of these molecules are the cavity sizes and bite distances. The cavity size,[14] estimated using CPK models, for 9-C-3 and 12-C-4 and 0.25 Å and 0.60 Å, respectively, while the bite distance is ≈ 2.79 Å for both molecules. Therefore, 12-C-4 can accommodate larger metal ions into its central cavity.
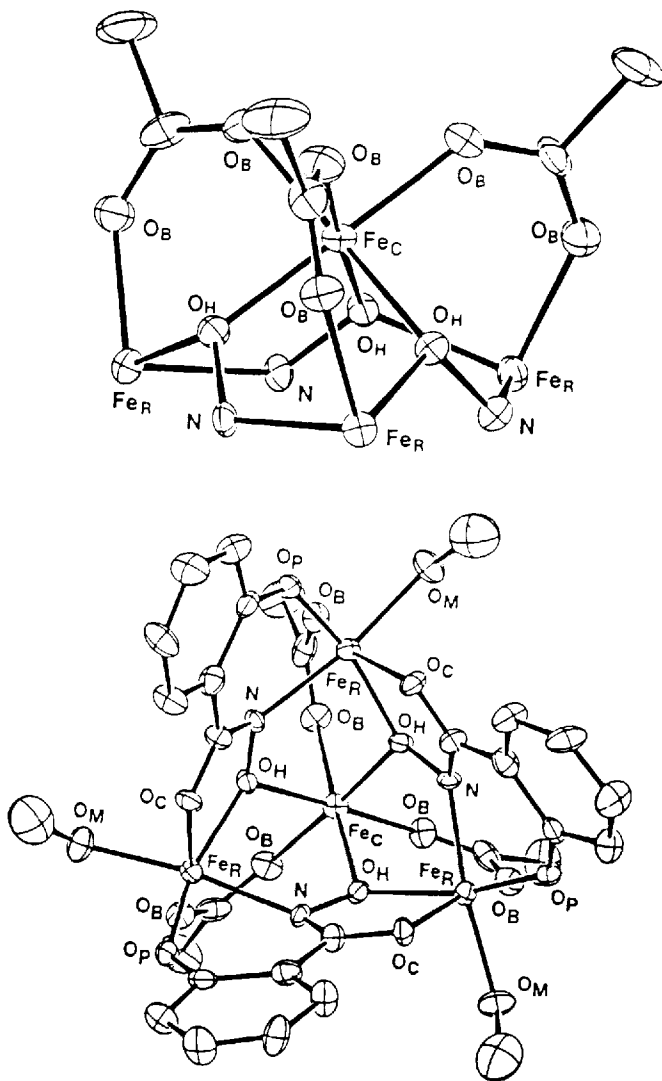
The prototype demetalated metallacrown,[15] $[(VO)^{3+}(SHI)\cdot(CH_3OH)]_3$ {**1**, 9-$MC_{VO^{3+}-N}$-3}, is illustrated in Fig. 2. This trinuclear cluster mimics the conformation of 9-C-3 by forming a 9 membered ring with an endo configuration of three ethereal like oxygen atoms. While these oxygen atoms are joined by ethylene groups in the crowns, metallacrowns are constructed through M^{3+}-N linkages. In this case, the metal position is occupied by the complex ion, VO^{3+}. Naively, one might expect that the difference between metal heteroatom bonds (V–N = 2.02 Å; V–O = 1.86 Å) and carbon bonds (C–O = 1.35 Å; C–C = 1.45 Å) would lead to a significant alteration of the metal binding cavity. Yet, the cavity radii of 9-$MC_{VO^{3+}-N}$-3 (0.35 Å) is only 0.1 Å larger than the organic parent. This similarity is a result of the large changes in bond angles in the linking atoms of the 9-C-3 and 9-$MC_{VO^{3+}-N}$-3 molecules. Typical C–C–O and C–O–C angles are nearly tetrahedral (109.5°), while the V–N–O, N–O–V and O–V–N angles in **1** are 121°, 120° and 86°, respectively. The V(V) ions are separated by 4.66 Å.

Although neither 9-C-3 nor 9-$MC_{VO^{3+}-N}$-3 have been shown to bind transition metal ions, a slight modification of the 9-$MC_{M^{3+}-N}$-3 assembly successfully achieved this goal.[16] The Fe(III)[Fe(III)·(SHI)(OAc)(CH$_3$OH)]$_3$ {**2**, Fe(9-$MC_{Fe^{3+}-N}$-3)}, illustrated as Fig. 3, differs from the 9-$MC_{VO^{3+}-N}$-3 in three significant ways. First, the three ethereal like oxygen atoms define a facial chelate for a capping, octahedral, high spin Fe(III). Second, the ring iron does not contain a terminal oxo group. This leaves a coordination site available for another ligand which leads to the third difference. The remaining three coordination sites of the capping iron are filled by oxygen atoms from a carboxylate that forms bridges to the ring metals via these vacated coordination sites. In **2** we see two potential advantages of the metallacrowns

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FIGURE 2 ORTEP diagrams of $[(VO)^{3+}(SHI)(CH_3OH)]_3$, **1**. (Top) $(VO)^{3+}$ (9-MC$_{VO3+N}$-3) core showing potential cavity for metal binding. (Bottom) Complete structure of **1**.

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FIGURE 3 ORTEP diagrams of Fe(III)[Fe(III)(SHI)(OAc)(CH₃OH)]₃, **2**. (Top) Fe(III)(9-MC$_{Fe3+N}$-3) core. (Bottom) Complete structure of **2**.

over their organic relatives. First, the coordinated oxime is a far better ligand for transition metal ions than an ether oxygen. Second, the captured metal is stabilized by the acetate bridges to the ring metal ions, a recognition mode that is unavailable for unmodified crowns. Such recognition only appears when one expends the synthetic effort to prepare lariat ethers[17] or supramolecules[6] that can impart this additional stability to the coordinated metal. Metal complexation by the 9-C-3 or 9-$MC_{M^{3+}-N}$-3 apparently is too weak to be observed without such stabilization. It is interesting to note that the cavity radius of **2** is identical to 9-C-3 (0.25 Å) and 0.1 Å less than **1**. Furthermore, the ring Fe(III)–ring Fe(III) distance (4.85 Å) is within 0.2 Å of the ring metal separations in **2**. Therefore, transition metal sequestration need not be accompanied by significant expansion of the metallacrown core. The capping Fe(III) is 1.18 Å above the hydroximate oxygen plane and 1.89 Å above the plane formed by the ring Fe(III). The capping Fe(III) to ring Fe(III) distance is 3.42 Å.

The monoanion $[Fe(III)[Fe(III)(SHI)(\mu_2\text{-}SO_4)_{0.5}(CH_3OH)_{1.5}]_4]^-$ {**3**, Fe(III)(12-$MC_{Fe^{3+}-N}$-4)}, illustrated as Fig. 4, demonstrates that stable metallacrowns are not limited to a 9-C-3 motif and need not be neutral clusters.[18] This molecule would be expected to be isostructural with M^{3+}(12-C-4) if such transition metal crown compounds could be prepared and is similar to cyclic tetraaza transition metal complexes. The cavity radii of **3** and 12-C-4 are 0.60 Å. Once again, the difference in oxygen basicity between the metallacrowns and crowns and the ability to stabilize transition metal ions through bridging moieties leads to metal sequestration unprecedented in simple crown ether complexes. Furthermore, we now see *the potential for anion selectivity* as sulfate forms the bridge between ring and captured iron(III) atoms. We will discuss strategies to enhance this selectivity below.

Transition metal encapsulation by metallacrowns can be extended to ions other than Fe(III) as illustrated in Fig. 5 by $Mn(II)[Mn(III)(SHI)(OAc)_{0.5}(DMF)_{1.5}]_4$ {**4**, Mn(12-$MC_{Mn^{3+}-N}$-4)}, which contains Mn(II) in the capping position.[19] Similar to the monoanion **3**, this neutral mixed valent manganese pentamer adopts a 12-C-4 structure. The $(Mn(III)-N-O)_4$ core gives a bite distance of 2.67 Å, a cavity size of 0.57 Å and the Mn(III) ions are separated by 4.64 Å. However, the Mn(II) coordination environment in **4** is
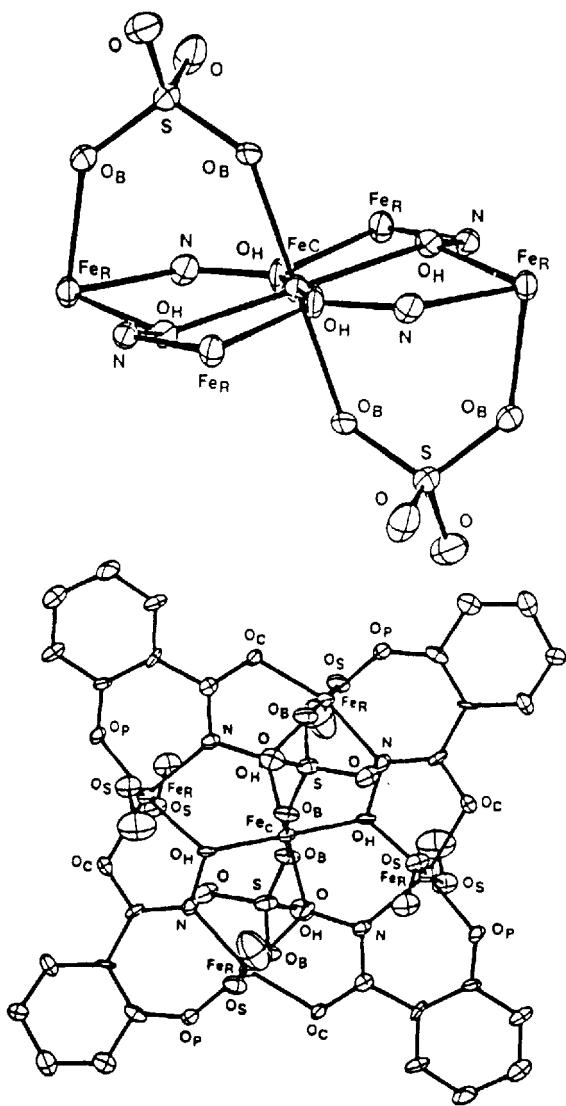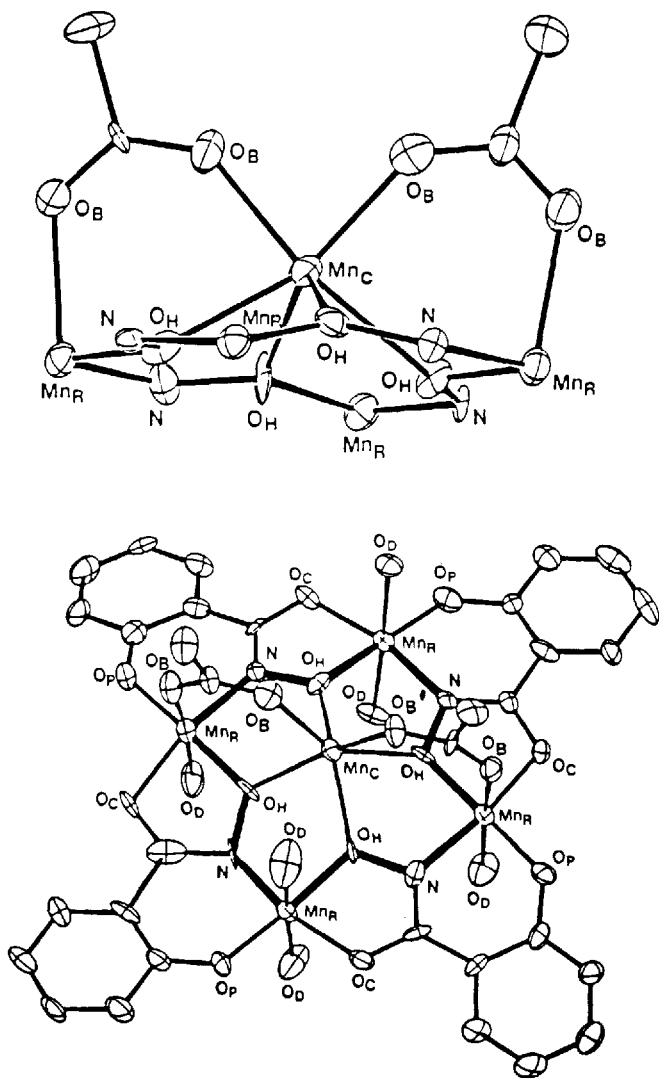
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FIGURE 4 ORTEP diagrams of $[Fe(III)[Fe(III)(SHI)(\mu_2\text{-}SO_4)_{0.5}(CH_3OH)_{1.5}]_4]^-$, **3**. (Top) $Fe(III)(12\text{-}MC_{Fe3+N}\text{-}4)$ core showing *trans-anti* orientation of bridging sulfates and placement of Fe(III) within the four atom oxygen plane. (Bottom) Complete structure of **3**.
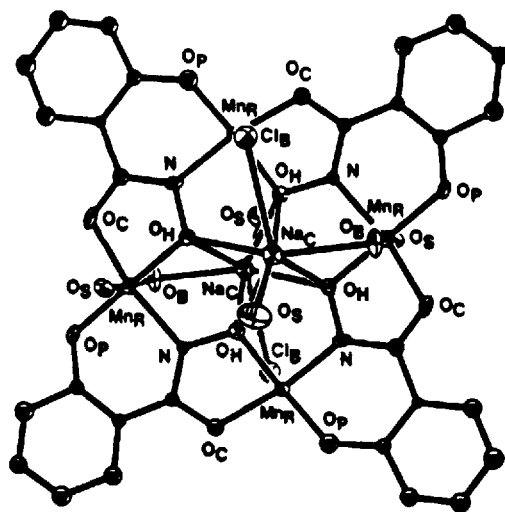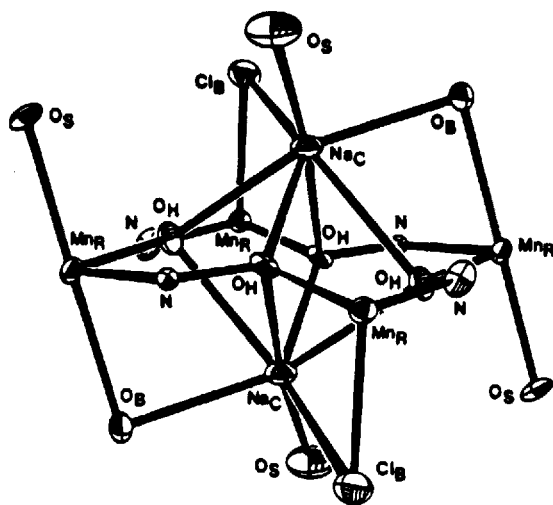
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FIGURE 5 ORTEP diagrams of (A)-$Mn(II)[Mn(III)(SHI)(OAc)_{0.5}(DMF)_{1.5}]_4$, **4**. (Top) $Mn(II)(12$-MC_{Mn3+N}-$4)$ core showing *trans-syn* orientation of bridging acetates and the displacement of Mn(II) above plane of oxygen atoms. The A stereochemistry is defined in Fig. 8 legend. (Bottom) Complete structure of **4**.

drastically altered from the captured ferric ion of **3**. Besides the obvious charge difference, the Mn(II) lies 1.2 Å above the best least squares plane of the four ring oxygen atoms while **3** is a centrosymmetric structure with the Fe(III) rigorously in this 4-atom plane. Two acetate anions form bridges from the Mn(II) to ring Mn(III), while sulfate dianions satisfy this requirement in the iron complex. In addition, the acetates of **4** are in a *trans-syn* configuration (same face of crown ring with bridges to *trans* ring Mn) while the sulfates of **3** are in a *trans-anti* orientation (opposite faces of crown with bridges to *trans* ring Fe). The ferric ion co-ordination sphere is nearly a perfect octahedron whereas a distorted trigonal prism (with a 10.5° twist angle) best describes the Mn(II) polyhedron.

The behavior of **3** and **4** is reminiscent of metalloporphyrin compounds where, depending on the oxidation level and spin state of the metal, one can see significant displacements of the bound ion from the porphyrin ring.[20] The ionic radii[21] of the six coordinate, high spin d^5 ions Fe(III) and Mn(II) are 0.645 and 0.83 Å, respectively. Thus, Fe(III) can be accommodated within the metallacrown cavity while Mn(II) is simply too large. This size restriction imparted by the metallacrown core may lead to selective metal sequestration. For example, Mn(II) can be displaced from the core of **4** using Mg(II) to generate the isostructural mixed metal complex with capping magnesium $Mg(II)[Mn(III)(SHI)(OAc)_{0.5}(DMF)_{1.5}]_4$, **5**, or by choice of accompanying anion one can prepare the sodium analogue $\{Na_2[Mn(III)(SHI)(Cl)_{0.5}(DMF)_1]_4(DMF)_2\}$, **6**, illustrated as Fig. 6. The latter complex has the conceptual equivalent of coordinated NaCl.[22] The cation is seven coordinate using four oxygen atoms of the ($12\text{-MC}_{Mn^{3+}N}$-4) ring, two oxygens from DMF molecules and an interaction with the chloride. The Na−Cl distance[23] of 3.00 Å compares favorably with the 2.81 Å separation in NaCl. The Na ion is 1.66 Å above the best four oxygen atom plane. The ($12\text{-MC}_{Mn^{3+}N}$-4) ring is more distorted than in **4** or the analogous Fe(III) crown **3**; however, the Mn(III)−Mn(III) ring separations are comparable (Table I).

One important structural theme that has emerged from these homo- and heteronuclear complexes is that the ring metals always appear as a trivalent cation (Mn^{3+} or Fe^{3+}) or complex ion (VO^{3+}). Therefore, the metallacrown core is neutral in every structure that

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FIGURE 6 ORTEP diagrams of {Na$_2$[Mn(III)(SHI)(Cl)$_{0.5}$(DMF)]$_4$(DMF)$_2$}, **6**. (Top) (NaCl)$_2$(12-MC$_{Mn3+N}$-4) core showing the displacement of Na(I) ions above and below plane of oxygen atoms. (Bottom) Complete structure of **6** illustrating the interaction between sodium and chloride ions.

TABLE I

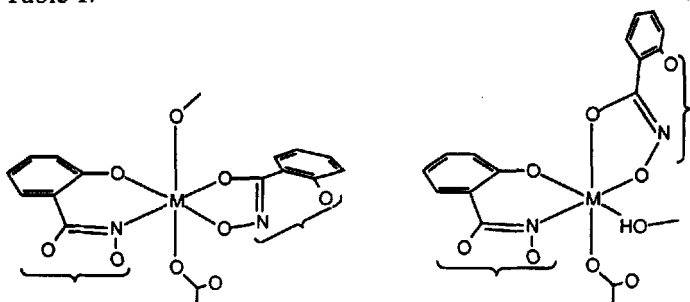Selected separations (Å) and angles (°) for complexes 1–4 and 6.

Separation[a]	1	2	3	4	6
M_R–M_R	4.66	4.85	4.89	4.64	4.59
M_R–M_C	–	3.42	3.46	3.54	3.42
M_R–O_H	1.86	2.06	2.04	1.87	1.90
M_R–O_C	2.12	2.00	1.97	1.97	1.96
M_R–O_P	1.85	1.91	1.88	1.87	1.85
M_R–N	2.02	2.08	2.06	1.97	1.98
M_R–O_B	–	1.99	2.07	2.16	2.42
M_R–Cl_B	–	–	–	–	2.44
M_R–O_S	2.08	2.08	2.09	2.31	2.24
M_R–O	1.59	–	–	–	–
M_C–O_H	–	2.00	1.96	2.24	2.43
M_C–O_B	–	2.01	2.07	2.12	2.45
M_C–Cl_B	–	–	–	–	3.00
M_C–O_{OOP}	–	1.88	0.0	1.20	1.66
CS	0.35	0.25	0.60	0.57	0.56
BD	2.96	2.78	2.77	2.67	2.62
Angle					
N–M_R–O_H	86	96	85	88	88
M_R–O_H–N	120	114	113	116	112
O_H–N–M_R	121	120	122	119	114

[a]Abbreviations used: M_R = ring metal; M_C = encapsulated metal; O_H = hydroximate oxygen; O_C = hydroximate carbonyl oxygen; O_P = phenolate oxygen; O_S = solvent oxygen; O = oxo oxygen; O_B = bridging atom from carboxylate (2,4), sulfate (3) or DMF (6); Cl_B = bridging chloride in 6; M_C–O_{OOP} = out of plane distance for encapsulated metal based on best least squares plane for O_H atoms; CS = cavity size (radius). For reference 9-C-3 = 0.25 Å and 12-C-4 = 0.60 Å.; BD = bite distance. For reference ·9-C-3 = 2.80 Å and 12-C-4 = 2.79 Å.

we have obtained. The final charge of the cluster is dictated by the captured metal ion and type and number of bridging anions.

The formation of 12-$MC_{M^{3+}N}$-4 and 9-$MC_{M^{3+}N}$-3 structures is dependent on the dramatically different stereochemistry of the ring metal ions. As illustrated at left below, the SHI ligands adopt a *trans* configuration in the 12-$MC_{M^{3+}N}$-4 motif while the 9-$MC_{M^{3+}N}$-3 compounds result from the *cis* propeller configuration on the right. The 12-$MC_{M^{3+}N}$-4 core is inherently achiral whereas absolute stereochemical isomerism can be described for the 9-$MC_{M^{3+}N}$-3 structures (vide infra). Interestingly, ring metal–ring metal and captured metal–ring metal separations are independent of *trans* (12-$MC_{M^{3+}N}$-4) or *cis* (9-$MC_{M^{3+}N}$-3) configurations. De-
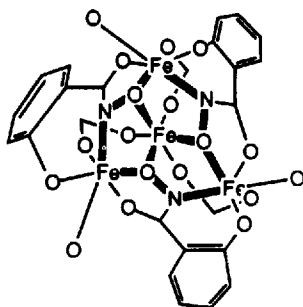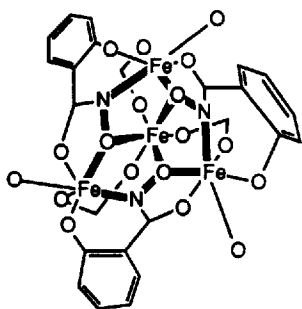
tailed structural information for complexes **1–4** and **6** is provided in Table I.
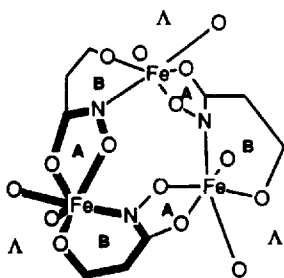

The coordination preference of the ring metal ions dictates the resultant 12-$MC_{M^{3+}N}$-4 or 9-$MC_{M^{3+}N}$-3 complexes. Six coordinate Mn(III) ions are susceptible to a Jahn–Teller distortion away from octahedral symmetry because they have a high spin, d^4 configuration. In nearly every case, a tetragonal elongation is observed.[24] The *trans* SHI configuration can easily accommodate an axial extension without destabilizing the metallacrown ring, whereas the propeller configuration must lengthen at least one of the SHI to Mn(III) bonds. Therefore, the 12-$MC_{Mn^{3+}N}$-4 core is the preferred configuration for ring Mn(III) ions. A different conclusion is drawn for the $(VO)^{3+}$ crown. This d^0 complex ion has a strong preference for 4 or 5 coordination. When six coordinate, there is usually a severe distortion away from octahedral symmetry with a slight elongation of the bond *trans* to the oxo atom and, more important in this case, a significant expansion of angles *cis* to the V=O (e.g., $O–V–(HOCH_3) \approx 110°$).[25] The *trans* SHI configuration is best suited to handle the elongation of the bond *trans* to the V=O; however, the twist that would be imparted into the 12-$MC_{VO^{3+}N}$-4 core by the 110° angle is energetically unfavorable. This distortion is less problematic in the propeller configuration and the 9-$MC_{VO^{3+}N}$-3 structure is obtained. Bridging anion type dominates structure determination for Fe(III) since there is no stereochemical preference for this high spin, d^5 ion.

STEREOCHEMISTRY

Both Λ and Δ isomers are possible at each of the ring positions of the 9-$MC_{M^{3+}N}$-3. Our nomenclature for the stereochemistry of the

Ring Iron(III) Chirality
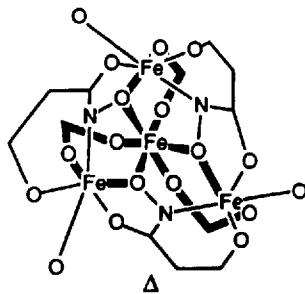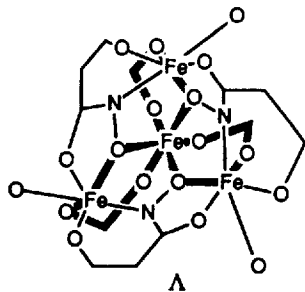

Capping Iron(III) Chirality

FIGURE 7 The two types of absolute stereochemistry for M(9-MC$_{M3+N}$-3) structures. Top row: diagrams of Λ-$\Lambda\Lambda\Lambda$ and Δ-$\Delta\Delta\Delta$ isomers of Fe(9-MC$_{Fe3+N}$-3) highlighting metallacrown ring. Center row: Stereochemistry about ring metal atoms. Bottom row: Stereochemistry about the captured metal ion.

metallacrowns is illustrated in Fig. 7. The 5-membered A ring is formed by the hydroximate group while the six-membered B ring is formed through the substituted oximophenolate. This leads to an asymmetric propeller configuration for the Fe(III). We have designated the isomers in Fig. 7 as Λ or Δ using the skew line convention for compounds with C_2 or pseudo-C_2 axes. Only the $\Lambda\Lambda\Lambda$ and $\Delta\Delta\Delta$ isomers will complete the 9 membered ring system. Therefore, the chirality at one metal center imposes the identical chirality on the remaining two ring metal ions.

The chirality of the ring metals also dictates the stereochemistry of the captured metal ion. To describe the stereocenters in this case, we have defined three identical six-membered chelate rings in order to orient skew lines for compounds with a C_3 axis. The "chelate ring" is connected as captured metal through the acetate bridge to the ring metal and the back to the captured metal via the ethereal like oxygen atom. The chosen ring consists of the fewest number of atoms that contains the bridging acetate and metallacrown ring. Notice that due to the asymmetry about the ethereal like oxygen, nitrogen on one side and metal on the other, there is only one allowed configuration about the captured ion for a particular ring chirality. Using our definition this corresponds to Λ for the $\Lambda\Lambda\Lambda$ or Δ for the $\Delta\Delta\Delta$.

Although the [12-$MC_{M^{3+}N}$-4] core, the centrosymmetric iron pentamer 3 and the mixed metal sodium metallocrown 6 are achiral, stereoisomers can be described for M[12-$MC_{M^{3+}N}$-4] complexes when a single captured metal is displaced out of the four atom oxygen core. This is the case with 4 where the Mn(II) is bound 1.20 Å above the best least squares plane of oxygens. Clockwise (C) and anticlockwise (A) isomers can be defined by relating the rotation of the $M^{3+}-O-N$ units of the metallocrown core with respect to a pseudo-fourfold axis of the complex as is illustrated in Fig. 8. Thus, the isomer illustrated in Fig. 5 is designated as A.

MAGNETOCHEMISTRY

Because of the large number of transition metal ions in these compounds, the metallacrowns have a number of physical properties that distinguish them from organic crowns. Complex 1 is a
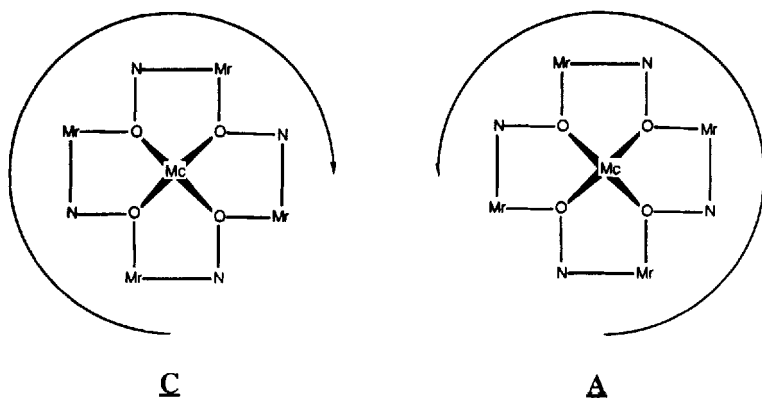
C   **A**

FIGURE 8 Clockwise (C) and anticlockwise (A) isomers of M[12-MC$_{M3+N}$-4]. The designators are derived by examination of the rotation sense of the M^{3+}–O–N unit of the metallacrown core to an axis perpendicular to this core which lies along the pseudo-fourfold axis of the metallacrown. This veiw of the molecule is along this primary axis *with the captured metal ion residing out of the paper toward the observer.* This definition becomes important for M[12-MC$_{M3+N}$-4] where the captured metal is displaced from the plane of metallacrown oxygen atoms.
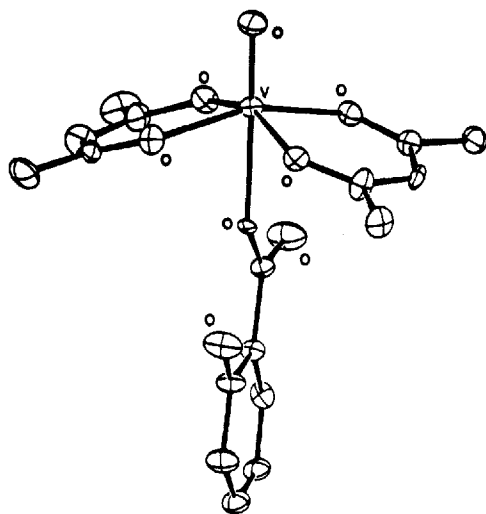
deep blue, **2** and **3** are red and **4** is green-brown. In addition, these clusters can be highly magnetic. Magnetization measurements on solid samples of the metallacrowns were compiled and analyzed by our collaborators Prof. William Hatfield and Martin Kirk at the University of North Carolina.[16] The data collected on compound **2** strongly suggest the presence of an $S = 5$ ground state. Analysis using Heisenberg exchange theory gave best fit values $g = 2$ (fixed), $J_1 = -4.92$ cm^{-1} (capping Fe–ring Fe), $J_2 = 0.47$ cm^{-1} (ring Fe–ring Fe) and $zJ' = -0.16$ cm^{-1}. The variable temperature magnetic behaviors of the other metallocrowns have not yet been examined; however, room temperature susceptibilities are quite high with μ_{eff} values of 9.4, 12.2 and 13.8 $\mu_{B.M.}$ for **2, 3** and **4**, respectively.
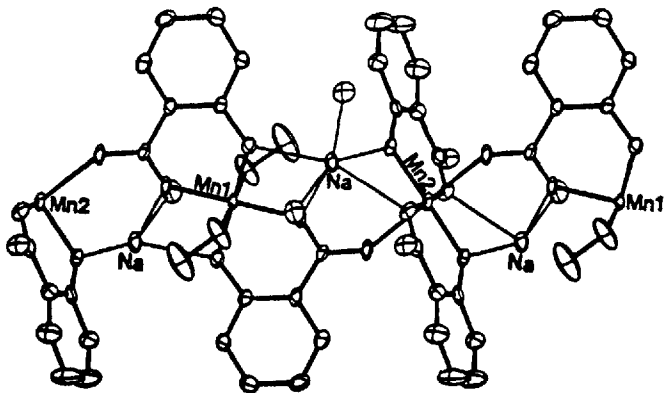
PREPARATION OF METALLACROWNS

Syntheses of the metallacrowns can be accomplished in methanol or DMF. The vanadium compound can be prepared by the reaction of one equivalent of H$_3$SHI with V(III), V(IV), or V(V) salts.

While it is important to include a small amount of base to buffer the reaction, excess hyroxylic bases lead to cluster decomposition. For example, the reaction of V(IV)O(ACAC)$_2$ with SHI and NaOH in methanol yields an $\approx$ 50:50 mixture of **1** and $[(VO)^{2+}(ACAC)_2(salicylic\ acid)]$, **7**, shown in Fig. 9.[26] This ligand hydrolysis to salicylic acid and hydroxylamine is not unique to the vanadium cluster as the addition of excess base in the reaction of Mn(Acetate)$_2$ with H$_3$SHI leads to Na$_2$[Mn$_2$(salicylate)$_4$(CH$_3$OH)$_2$], **8**, shown in Fig. 9. Although the isolated product is an alternating AB chain containing bidentate coordinated salicylate,[27] the same hydrolytic process is occurring. Presumably the coordinated Lewis acid polarizes the hydroximate carbonyl, making it a better center for nucleophilic attack by base. The use of metal acetate salts averts this ligand decomposition pathway.

An important structure determinant is the chosen solvent and the type of acetate used as base. The Fe(III)[Fe(III)(SHI)·(OAc)(CH$_3$OH)]$_3$, **2**, can be obtained by reaction of FeSO$_4$ with H$_3$SHI in either methanol or DMF using sodium acetate as base. However, if, using either solvent, sodium trichloroacetate or tri-fluoroacetate is substituted for sodium acetate, the [Fe(III)·[Fe(III)(SHI) (μ_2-SO$_4$)$_{0.5}$(CH$_3$OH)$_{1.5}$]$_4^-$, **3**, is recovered exclusively rather than the halide substituted Fe(III)(OAcX$_3$)$_3$[9-MC$_{Fe^3 \cdot N}$-3]. We suggest that the anion and structure preference is related to the basicity of the bridging ligands. Acetate is more basic than sulfate which in turn is more basic than trichloro or trifluoroacetates. Thus, **2** is obtained in the presence of acetate but the sulfate bridged **3** is the sole product with the halogenated acetates. The [9-MC$_{Fe^3 \cdot N}$-3] structure can neither accommodate the high charge or steric repulsions of the sulfate oxygens; therefore, the cluster rearranges to the [12-MC$_{Fe^3 \cdot N}$-4] form and orients the bridging groups in the aforementioned *trans-anti* conformation. An even more striking example of the sensitivity of this system is seen in the synthesis of Mn(II)[Mn(III)(SHI)(OAc)$_{0.5}$(DMF)$_{1.5}$]$_4$, **4**. In this case, **4** is recovered from DMF by the reaction of H$_3$SHI and Mn(II) acetate (1:1) or H$_3$SHI:MnCl$_2$:sodium acetate (1:1:2). If run in methanol, no product **4** is recovered under the same reaction conditions. Isolation of a new mixed-metal me-tallacrown {Na$_2$[Mn(III)(SHI)(Cl)$_{0.5}$(DMF)$_2$]$_4$(DMF)$_2$}, **6**, (NaCl)$_2$[12-MC$_{Mn^3 \cdot N}$-4], is achieved by the reaction of H$_3$SHI:MnCl$_2$:sodium trichloroacetate (1:1:2) in DMF while, once

$\underline{7}$

$\underline{8}$

FIGURE 9 Hydrolysis products of metallacrowns. (Top) ORTEP diagram of $(VO)^{2+}(ACAC)_2$(salicylic acid), 7; (Bottom) ORTEP diagram of the alternating chain $Na_2[Mn_2(salicylate)_4(CH_3OH)_2]$, 8.

again, no reactivity is seen in methanol. Thus, judicious choice of solvent and base allows for the controlled modification of structure {[9-MC$_{Fe^{3+}N}$-3] or [12-MC$_{Fe^{3+}N}$-4]} and/or composition (4 or 6). One expects that addition of Fe(III) or Ga(III) to 4-6 would lead to mixed metal metallacrowns isostructural to 3. Such compounds will be described in more detail below.

SOLUTION BEHAVIOR

The sections above described the *structural* analogy of these metal clusters to organic crown ethers and their metal complexes; however, to truly imitate their organic relatives, metallacrowns should have the capacity to sequester free metal ions. Structural integrity of the cluster in solution must be demonstrated before evaluating whether the metallacrowns can achieve this function. A combination of ^{1}H NMR and epr spectroscopy allow us to evaluate both these points.

We have shown that compounds 1-4 are soluble in acetonitrile, DMF and methanol. The X-band epr spectrum of 4 in DMF at 100 K shows[19] a six-line signal, the hallmark of uncomplexed Mn(II). A standard curve indicates that this signal arises from 20 ± 10% of the Mn(II) in the sample. Acetonitrile solutions of 4 contain an additional broad derivative shaped resonance centered at $g = 2$ that underlies a very weak six-line signal. The intensity of this broad feature is slightly greater at 4 K than at 110 K, suggesting that it arises from the electronic ground state. We believe that this poorly resolved signal is associated with the intact cluster while this smaller amount of six-line signal in acetonitrile corresponds to less than 5% of the overall spin. Thus, the epr spectra indicate that undissociated 4 appears to be the dominant species in DMF or acetonitrile. In contrast, epr spectra of 4 in methanol are consistent with complete loss of Mn(II) from the crown. We believe the cluster dissociates completely in methanol.

These conclusions are supported by the ^{1}H NMR spectra of 4 in d^4-methanol and d^7-DMF. We have shown previously that the paramagnetically shifted proton resonances of Mn(III) complexes containing phenolates and acetates can be useful probes of manganese cluster structure and reactivity.[28-30] There are no paramagnetically shifted resonances detected for 4 in methanol which is consistent with complete dissociation of the cluster. In contrast,

Fig. 10D illustrates ^{1}H NMR spectra of **4** in d[7]-DMF:d[3]-acetonitrile 1:3. There are three sharp peaks upfield of the diamagnetic region at -14.1, -15.5 and -23.0 ppm and a broader resonance far downfield at $+56.1$ ppm. The downfield signal was assigned to acetate protons by obtaining spectra of **4** prepared using d[3]-acetate (Fig. 10A). Based on the accumulated data for Mn(III) imino-phenolate compounds, the phenolate ring protons are believed to be the origin of the upfield peaks. The lability of the coordinated acetates was tested by the addition of a small amount (<1 eq) of Mn(II)Acetate to the deuterated sample of **4** (Fig. 10B). The recovery of the $+56$ ppm peak, without any other changes to the spectrum, demonstrated that the acetates are exchangeable; however, this experiment did not discern whether the Mn(II) ion was labile. This was demonstrated by the addition of (1 eq) of Mg(II)acetate to a solution of **4**. The recovered crystalline solid (which analyzed for a 7:3 ratio of **4** and **5**) gave the spectrum shown in Fig. 10C. The new acetate resonance at $+34$ ppm is assigned to the isostructural Mg(II)[Mn(III)(SHI)(OAc)$_{0.5}$(DMF)$_{1.5}$]$_4$, **5**. This upfield shift is consistent with the decrease in spin density associated with the substitution of the paramagnetic Mn(II) by the diamagnetic Mg(II). Thus, both the bridging acetates and captured metal are potentially exchangeable.

The preference of the [12-MC$_{Mn^{3+}N}$-4] core for Mn(II) rather than Mg(II) underscores a significant difference in selectivities between the metallacrowns and organic crowns for metal ions. An equal or slightly preferred binding of Mg(II) to [12-MC$_{Mn^{3+}N}$-4] would be predicted[8] based solely on a simple size comparison of Mn(II) (0.83 Å) and Mg(II) (0.72 Å). However, metal complexation by the metallacrowns is assisted by the bridging groups. Therefore, one can alter the inherent binding selectivity of the [12-MC$_{Mn^{3+}N}$-4] by choice of these anions.

Because the [12-MC$_{Mn^{3+}N}$-4] appears to have high affinity for Mn(II), it was prudent to develop a demetallated (i.e., without a captured metal such as **1**) metallacrown or a metallacrown with an easily replaceable cation. Such a compound could then be used as a precursor to a wide variety of mixed metal metallacrowns. The latter was achieved by the preparation of {Na$_2$[Mn(III)(SHI)·(Cl)$_{0.5}$(DMF)]$_4$(DMF)$_2$}, **6** (vide supra). The ^{1}H NMR of this complex is illustrated as Fig. 11A and **4** is redrawn as Fig. 11C. Notice
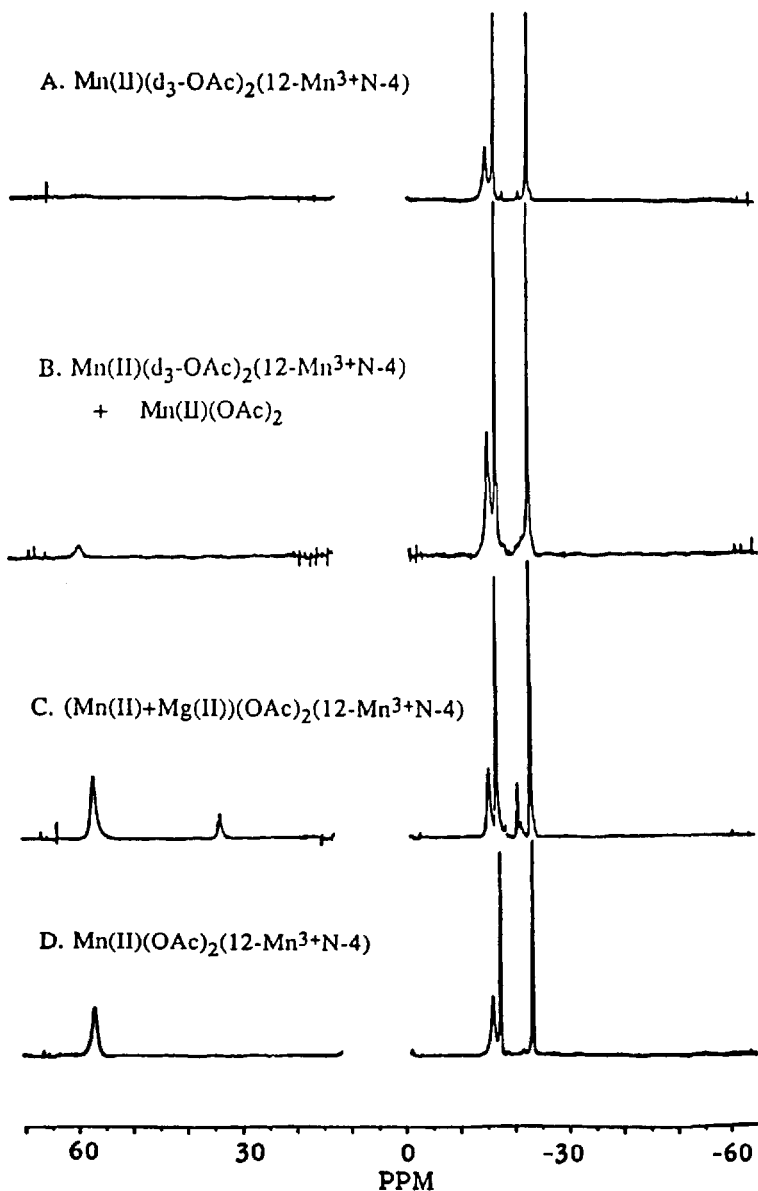
FIGURE 10 ^{1}H NMR spectra of compound **4** in d^7-DMF:d^3-acetonitrile, 1:3. (A) **4** prepared with d^3-acetate; (B) Addition to Mn(II) acetate to the solution in A; (C) Spectrum after 24 hours following addition of Mg(II)(acetate) to **4**; (D) **4**.
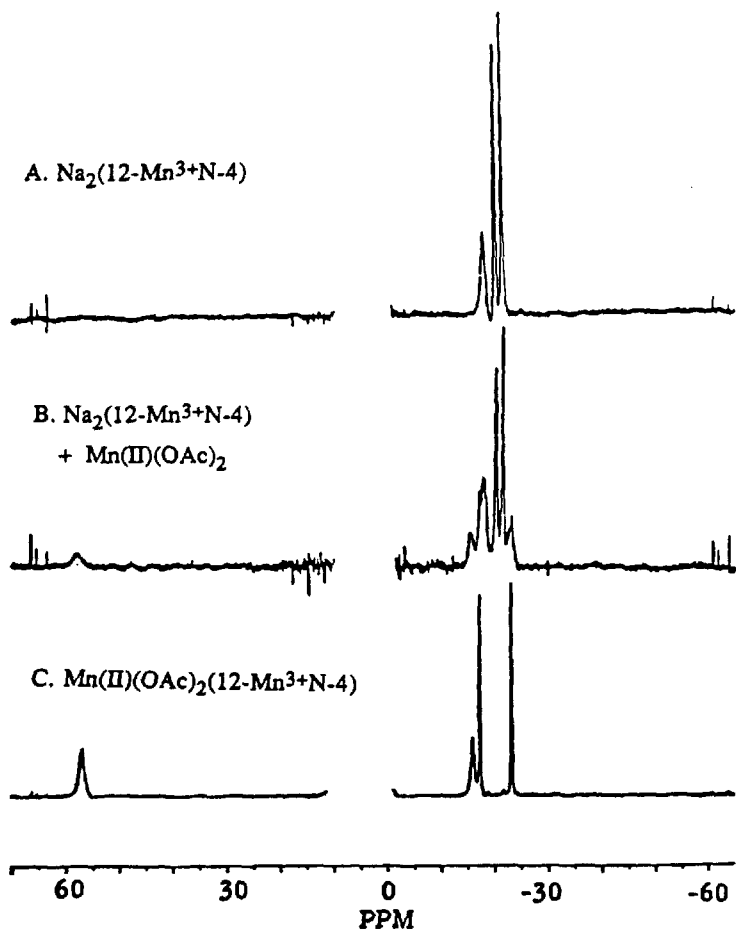
A. $Na_2(12-Mn^{3+}N-4)$

B. $Na_2(12-Mn^{3+}N-4)$
   $+ Mn(II)(OAc)_2$

C. $Mn(II)(OAc)_2(12-Mn^{3+}N-4)$

60   30   0   -30   -60
PPM

FIGURE 11 ^{1}H NMR spectra of compounds **6** and **4** in d^7-DMF:d^3-acetonitrile, 1:3. (A) **6**; (B) Addition of Mn(II)acetate to **6**; (C) **4**.

the clean spectrum for **6** and the lack of a low field resonance. This indicates that the basic crown core is intact but that Mn(II) and carboxylates are not bound. The spectrum Fig. 11B results when Mn(II) acetate is added. The +56 ppm signal reappears, the phenolate resonances for the sodium form are depleted and the phenolate peaks of **4** reappear. This demonstrates that the metallacrown can bind Mn(II) from the Na form. Additional stud-

80

ies using Mg(II) and Ga(III) show that these mixed metallacrowns can be prepared in an analogous manner. These experiments illustrate that, in addition to the structural analogy described in the first section, the metallacrowns can selectively sequester metal ions. Therefore, *both a structural and functional analogy to the organic parents has been established.*

POSSIBLE FUTURE APPLICATIONS

Although the metallacrowns are a fascinating new set of clusters, one might ask whether another transition ion sequestering agent is needed. After all, polyaminocarboxylates (e.g., EDTA), siderophores, cyclams and crown thiaethers show selectivity and high affinity for transition metals. However, the unique structure of the metallacrowns potentially provide entry into analytical chemistry, catalysis and new materials that are not easily attained with simpler organic molecules.

Cation detection systems are well advanced, while the development of selective anion sensors has lagged behind. We have already discussed the importance of the bridging anion for altering the prediction of metal selectivity based on cation radius. However, even more exciting is the chemical corollary, that is, synthesis of a series of metallacrowns with different captured metals should lead to *anion* selectivity. Organic molecular receptors[6] can be synthesized that have affinity for some anions (substrates) forming supramolecules; however, the preparation of these compounds is often laborious. In contrast, metallacrowns are isolated in one or two step syntheses (depending on whether one desires homo- or heterometallic clusters). Potentially one can distinguish bidentate anions with different bite distances, charges and Lewis basicities by exploiting the multiple metal centers of the metallacrowns. A good example of this point is the iron metallacrown system. Acetate has a high affinity for the $Fe(III)[9-MC_{Fe^{3+}N}-3]$ structure while sulfate only binds to $Fe(III)[12-MC_{Fe^{3+}N}-4]$ and binding of trichloro- or trifluoro-acetate to either cluster is not observed.

To be useful analytical reagents for anion sensing, the metallacrowns must retain their integrity in the solvents or ion permeable membranes containing the desired analyte. Furthermore, the captured metal must not easily dissociate from the crown cavity. Clearly

this is not true of **4**; however, the central ion in **3** appears quite stable. Furthermore, **3** can be trapped in a poly(vinylchloride) membrane using DMF as the solvent for the polymerization.[31] The resulting membrane can be placed in water for days without any discoloration. We are presently assessing the utility of **3** and mixed metal analogues as anion sensors while **4–6** provide an entry to selective transition metal detectors.

Another important area of analytical chemistry is preparation of new chromatography columns capable of chiral recognition. One may be able to exploit the screw sense isomerism of the [9-MC$_{M^{3+}N}$-3] structures to separate neutral and chiral inorganic complexes by supporting the metallocrown on a solid phase resin. Furthermore, chiral organic molecules with functional groups capable of hydrogen bonding to the ring oxygens of the metallacrowns can, in principle, be resolved.

The application of chiral metal complexes extends beyond separation technology into the realm of catalysis. The metallacrown clusters are potentially useful for chiral induction in organic synthesis in one of two ways. The first would take advantage of the open crown cavity (e.g., **1**) to select a specific small molecule and then carry out a chemical transformation (e.g., epoxidation) using the ring metals. The second could be achieved using heterometallic M'[9-MC$_{M^{3+}N}$-3] clusters (e.g., Fe(III) and Ga(III) analogues of **3–6**) that, due to differences in Lewis acidity and redox capacity, generate bifunctional templates for concurrent nucleophilic and electrophilic center induction in substrate molecules.

Finally, the [12-MC$_{M^{3+}N}$-4] metallacrowns represent potential monomer precursors for the development of one dimensional magnetic and conducting polymers. The coupling of Ga(III)· [12-MC$_{M^{3+}N}$-4] into an infinite chain using anti acetate bridges along the Ga(III) axis, analogous[32] to [Mn(III)[2-OH-SALPN](OAc)$_n$, would result in an oriented assembly of highly magnetic disks stacked along one axes. Each disk would be magnetically insulated from through bond interactions since the direct magnetic exchange must proceed via two diamagnetic ions. However, through space interactions, potentially leading to interesting ferrimagnets may occur.[33] Electrochemical studies of **2** and **4** suggest that the ring metals are not redox active while the captured metals can be reduced (**2**) or oxidized (**4**). For example, a quasi-

reversible one electron reduction of the capping Fe(III) in **2** is observed in DMF at $-330 \, mV$ vs. SCE. If instead of using a redox inactive metal such as Ga(III) in one dimensional polymers, an ion such as Fe(III) is incorporated in the core, one has the possibility of generating a molecular wire surrounded by a static magnetic field.

We have attempted to illustrate in this article how a well established system, metal ion sequestration by organic crown ethers, can be expanded to a new level of utility by a simple concept: utilize metals where once there were carbons. In so doing, we have achieved a new class of interesting metal clusters. Although not yet realized, "dreams" of future applications of the metallacrown ethers in analytical chemistry, catalysis and new materials demonstrate a potentially bright future for these novel inorganic clusters.

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14. There are many different tautomeric structures for B and C since the acidities of phenolate and hydroxamate groups are similar. This scheme shows two of these tautomers, one as the monoanion and one as the dianion, for illustration.

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