

Synthetic Models for Low-Molecular-Weight Chromium-Binding Substance: Synthesis and Characterization of Oxo-Bridged Tetranuclear Chromium(III) Assemblies

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The structural and spectroscopic properties of a series of tetranuclear chromium–oxo complexes are reported. One example, $[\text{Cr}_4\text{O}_2(\text{O}_2\text{CMe})_7(\text{phen})_2]\text{Cl}\cdot 1.5\text{CH}_2\text{Cl}_2\cdot 6\text{H}_2\text{O}$ (**1**) crystallizes in the orthorhombic space group $C222_1$ with $a = 18.652(4)$ Å, $b = 25.200(7)$ Å, $c = 12.559(3)$ Å, $V = 5903.23$ Å³, and $Z = 4$. The structure was refined with 2043 reflections having $F > 3.0\sigma(F)$, giving final R factors of 0.0609 and 0.0623 for R and R_w , respectively. The $[\text{Cr}_4\text{O}_2]^{8+}$ core consists of a “butterfly” arrangement and is structurally akin to other recently reported $[\text{M}_4\text{O}_2]^{8+}$ ($M = \text{Fe}, \text{Mn}$) complexes. These complexes were synthesized by heating a PhCN solution of a bidentate ligand and a trinuclear complex of the composition $[\text{Cr}_3\text{O}(\text{O}_2\text{CR})_6\text{L}_3]^{n+}$. A combination of ¹H and ²H NMR studies allows for assignment of all proton (deuteron) resonances. A π -spin delocalization mechanism is the dominant contributor to the ¹H and ²H chemical shifts. Fast atom bombardment mass spectrometry has been shown to be a valuable tool in the characterization of the chromium–oxo assemblies. The results of electronic and room temperature magnetic studies and the biological relevance of these materials is discussed.

Introduction

Interest in multinuclear chromium–carboxylate assemblies stems from several areas including serving as models of the metal center of the protein Low-Molecular-Weight Chromium-Binding Substance (LMWCr) and as sources of fundamental information about magnetic exchange in multinuclear assemblies. Cr has been determined to be required for normal mammalian carbohydrate and lipid metabolism.³ Cr deficiency in humans results in symptoms comparable with those associated with adult-onset diabetes and cardiovascular disease.⁴ Yet as much as 90% of the American population have a daily intake less than the recommended safe and adequate quantities of Cr.⁵ Despite its importance, essentially nothing is known about the composition and structure of the biologically active form of Cr. The best and perhaps only current candidate is LMWCr. LMWCr is an anionic, carboxylate-rich polypeptide which possesses a molecular weight of ca. 1500 and binds four chromic ions.⁶ Charge balance and other considerations suggest that LMWCr possesses an anion-bridged, multinuclear Cr–carboxylate assembly.⁷ Trinuclear oxo-centered carboxylate assemblies of the general composition $[\text{M}_3\text{O}(\text{O}_2\text{CR})_6\text{L}_3]^{n+}$ (especially where $M = \text{Cr(III)}$) have been of intense interest for three decades as they have served as models to test theories of magnetic coupling between metal ions in multinuclear systems.⁸ Larger, more complex systems are required to further test and extend these theories. This is especially important as assemblies become appreciably larger such that the paramagnet/superparamagnet/

ferromagnet boundaries can be studied.⁹ Discrete, multinuclear oxo-bridged Mn and Fe carboxylate assemblies have been found to approach properties of superparamagnetism;^{9,10} a series of well-studied high nuclearity assemblies with different electron counts could lead to a better understanding of this phenomena. With these goals in mind, this laboratory has recently turned its attention to the synthesis and characterization of such tetranuclear assemblies.

Experimental Section

Syntheses. All manipulations were performed under aerobic conditions, and all chemicals were used as received. Elemental analyses were performed by Galbraith Laboratories, Knoxville, TN. $[\text{Cr}_3\text{O}(\text{OAc})_6(\text{H}_2\text{O})_3]\text{Cl}$,¹¹ $[\text{Cr}_3\text{O}(\text{OAc})_6(\text{py})_3]\text{Cl}$,¹¹ $[\text{Cr}_3\text{O}(\text{O}_2\text{CCD}_3)(\text{py})_3]\text{Cl}$,¹² $[\text{Cr}_3\text{O}(\text{O}_2\text{CPh})_6(\text{py})_3]\text{ClO}_4$,¹² and $[\text{Cr}_4\text{O}(\text{OAc})_7(\text{bpy})_2]\text{PF}_6$ ¹³ were prepared as described in the literature or were available from previous work.

Caution! Appropriate care should be taken whenever perchlorate salts are manipulated or heated.

$[\text{Cr}_4\text{O}_2(\text{OAc})_7(\text{phen})_2]\text{Cl}\cdot 1.5\text{CH}_2\text{Cl}_2\cdot 6\text{H}_2\text{O}$ (1**).** A solution of 1.75 g (2.84 mmol) of $[\text{Cr}_3\text{O}(\text{OAc})_6(\text{H}_2\text{O})_3]\text{Cl}$ and 1.05 g (5.83 mmol) of 1,10-phenanthroline in 60 mL of PhCN was heated to reflux for 4 h. After the resulting slurry was allowed to cool, a gray solid was isolated by filtration. This material was dissolved in CH_2Cl_2 and layered with hexanes to give black crystals in 42% yield (based on Cr). Anal. Calcd (found) for $\text{C}_{39.5}\text{H}_{52}\text{N}_4\text{O}_{22}\text{Cl}_4\text{Cr}_4$: C, 36.93 (37.18); H, 4.08 (4.35); N, 4.36 (3.95); Cl, 11.04 (11.72); Cr, 16.19 (16.65). Selected IR data: 3400 (br), 1610 (s), 1560 (m), 1230 (m), 1150 (m), 1110 (w), 1030 (m), 880 (m), 850 (m), 775 (w), 725 (vs), 675 (s), 620 (s), 570 (m) cm^{-1} .

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[Cr₄O₂(OAc)₇(bpy)₂]Cl (2). A slurry of 3.50 g (4.38 mmol) of [Cr₃O(OAc)₆(py)₃]Cl and 2.10 g (17.3 mmol) of 2,2'-bipyridine in 60 mL of PhCN were heated to reflux for 4 h. A purple microcrystalline solid was collected by filtration; additional microcrystalline material could be recovered by addition of Et₂O to the filtrate followed by storage at ca. 4 °C. Combined yield was ca. 75% (based on Cr). Recrystallization can be accomplished from CH₂Cl₂/hexanes. The nature of the cation was established by comparison of UV/visible spectra, ¹H NMR spectra, and mass spectra with those of [Cr₄O₂(OAc)₆(bpy)₂]PF₆.¹³ Selected IR data: 1610 (vs), 1560 (s), 1170 (m), 1040 (m), 775 (s), 735 (vs), 680 (s), 625 (s), 450 (m) cm⁻¹. [Cr₄O₂(O₂-CCD₃)₇(bpy)₂]Cl was prepared in an analogous fashion using [Cr₃O(O₂-CCD₃)₆(py)₃]Cl as starting material. Selected IR data: 1610 (s), 1265 (m), 1170 (m), 1100 (m), 1070 (w), 1050 (s), 1000 (m), 930 (m), 850 (m), 760 (s), 740 (s), 640 (s), 620 (s), 550 (m) cm⁻¹.

[Cr₄O₂(OAc)₇(4,4'-Me₂bpy)₂]Cl^{3/4}·CH₂Cl₂·6H₂O (3). A solution of 1.75 g (2.84 mmol) of [Cr₃O(OAc)₆(H₂O)₃]Cl and 1.05 g (5.70 mmol) of 4,4'-dimethyl-2,2'-bipyridine in 60 mL of PhCN was heated to reflux for 4 h, and the resulting solution was allowed to cool. Et₂O was added until precipitation of a grayish solid was complete; after storage overnight at ca. 4 °C, the solid was collected by filtration. Recrystallization was accomplished by layering a CH₂Cl₂ solution with hexanes. The yield was ca. 38% (based on Cr). Anal. Calcd (found) for C_{38.75}H_{58.5}N₄O₂₂Cl_{2.5}Cr₄: C, 16.92 (16.28); H, 7.21 (6.26); N, 4.56 (5.29); Cl, 7.21 (6.26); Cr, 16.92 (16.28). Selected IR data: 3450 (br), 1610 (vs), 1560 (m), 1250 (m), 1035 (s), 925 (m), 835 (m), 725 (vs), 670 (s), 620 (s), 570 (m), 555 (m), 530 (m), 450 (m) cm⁻¹.

[Cr₄O₂(O₂CPh)₇(bpy)₂]ClO₄^{1/4}·CH₂Cl₂·4H₂O (4). A slurry of 2.47 g (2 mmol) of [Cr₃O(O₂CPh)₆(py)₃]ClO₄ and 0.94 g (6 mmol) of 2,2'-bipyridine in 60 mL of PhCN was heated to reflux for 6 1/2 h. After the solution was allowed to cool, Et₂O was added until precipitation of a gray solid was complete. The solid was collected by filtration and recrystallized by layering a dichloromethane solution with hexanes, giving gray-green needle-like crystals. The yield was ca. 80% (based on Cr). Anal. Calcd (found) for C_{69.25}H_{59.5}N₄O₂₄Cl_{1.5}Cr₄: C, 52.22 (52.68); H, 3.76 (3.74); N, 3.52 (3.30); Cl, 3.34 (3.14); Cr, 13.06 (12.84). Selected IR data: 3400 (br), 1610 (s), 1580 (s), 1555 (m), 1180 (m), 1160 (m), 1085 (s), 1030 (m), 770 (m), 720 (vs), 680 (s), 620 (s), 550 (m), 510 (s), 415 (w) cm⁻¹.

X-ray Crystallography and Structure Solution. Data were collected on a Picker four-circle diffractometer at -167 °C; details of the diffractometry, low temperature facilities, and computational procedures employed by the MSC are available elsewhere.¹⁴ A systematic search of a limited hemisphere of reciprocal space yielded a set of reflections having orthorhombic diffraction symmetry. The observed general condition $h + k = 2n$ for all hkl identified the lattice as C-centered. The observed extinction of 001 for $l = 2n + 1$ uniquely identified the space group as C222₁ (No. 20). This choice was confirmed by the subsequent solution and refinement of the structure. Following standard data reduction and averaging of equivalent reflections, a unique set of 2043 reflections ($F > 0.3\sigma(F)$) was obtained. The structure was solved using a combination of direct methods (SHELXS-86)¹⁵ and difference Fourier techniques. All non-hydrogen atoms were readily located and were well behaved except those of the disordered anion and the disordered solvate molecules. All non-hydrogen atoms were refined anisotropically except the solvate atom and anion, which were refined isotropically. Almost all of the hydrogen atoms were visible in a difference Fourier map phased on the non-hydrogen atoms; all hydrogens were included in fixed, idealized positions for the final stages of full-matrix least-squares refinement. All reflections were included in the refinement, but reflections having ($F < 3.0\sigma(F)$) were given zero weight. The final difference map was essentially featureless, the largest peak being 0.59 e/Å³ in the immediate vicinity of C(35). No absorption correlation was performed. Final R (R_w) values are listed in Table 1.

Table 1. Crystallographic Data for Complex 1·1.5CH₂Cl₂·6H₂O

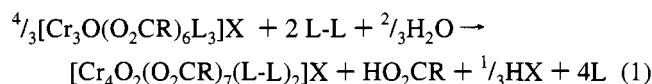
chem formula: C ₃₈ H ₅₇ C ₄ N ₄ O ₁₆ ^a	fw = 1013.71 ^a
$a = 18.652(4)$ Å	space group: C222 ₁ (No. 20)
$b = 25.200(7)$ Å	$T = -167$ °C
$c = 12.559(3)$ Å	$\lambda = 0.71069$ Å ^b
$V = 5903.23$ Å ³	$\rho_{\text{calcd}} = 1.141$ g cm ⁻³
$Z = 4$	$\mu = 7.516$ cm ⁻¹
	$R = 0.0609$ ^c
	$R_w = 0.0623$ ^c

^a Excluding anion and solvate. ^b Graphite monochromator. ^c $R = \sum||F_o| - |F_c||/\sum|F_o|$. $R_w = [\sum w(|F_o| - |F_c|)^2/\sum w|F_o|^2]^{1/2}$, where $w = 1/\sigma^2(|F_o|)$.

Physical Measurements. Infrared spectra (Nujol mull) were recorded on a Perkin-Elmer 283B spectrophotometer. ¹H and ²H NMR spectra were obtained using a Bruker AM-360 and a Bruker AM-500 spectrometer, respectively at ca. 23 °C. Chemical shifts are reported on the δ scale (shifts downfield are positive) using the solvent protio- and deutero-impurity signal(s) as a reference. A Hewlett-Packard 8451A spectrophotometer was used to record ultraviolet-visible spectra. Fast atom bombardment mass spectra were obtained using a VG Autospec high resolution mass spectrometer. Solution susceptibility measurements were obtained using the Evans NMR method,¹⁶ employing hexamethyldisiloxane as the reference peak; solid state susceptibilities were acquired using a Johnson Matthey susceptibility balance. Diamagnetic corrections were employed using Pascal's constants.

Results

Improved Synthesis of Cr₄O₂ Assemblies. Previous to efforts in this laboratory, one complex of the general form [Cr(III)₄O₂(O₂CR)₇(L-L)₂]ⁿ⁺ (where L-L represents a bidentate ligand) had been reported, where R = Me, L-L = 2,2'-bipyridine, and $n = 1$.¹³ This complex was prepared by heating mononuclear Cr(OAc)₃·6H₂O or trinuclear [Cr₃O(OAc)₆(H₂O)₃]Cl in molten bipyridine. This reaction using the molten bidentate ligand as solvent is limited to bidentate ligands with appropriate melting points. In an effort to identify a more general synthetic procedure, the reaction of trinuclear oxo-centered complexes of the form [Cr(III)₃O(O₂CR)₆(L)₃]⁺X⁻ (where L = a monodentate ligand) with bidentate ligands in organic solvents was examined. The method has previously been shown to be effective in the synthesis of tetranuclear Mn(III) complexes.¹⁷ Treatment of green solutions of the starting trinuclear species in PhCN with bpy, 4,4'-Me₂bpy, or phen followed by heating to reflux results in a color change to purple, indicative of the formation of the tetranuclear unit. The procedure is summarized in eq 1. The balanced equation suggests involvement of H₂O



from solvent unless L = H₂O. The Cr₃O parenthood of the Cr₄O₂ core appears to be reflected in its structure (vide infra). The procedure is not limited to neutral bidentate ligands; the use of [NEt₃H][picolinate] and [Cr₃O(O₂CPh)₆(H₂O)₃]NO₃ results in the production of the tetranuclear anion [Cr^{III}₄O₂(O₂CPh)₇(picolinate)₂]⁻.¹⁸

Description of Structure. The structure of the cation of complex 1 is shown in Figure 1. Selected atomic coordinates and interatomic distances and angles are listed in Tables 2 and

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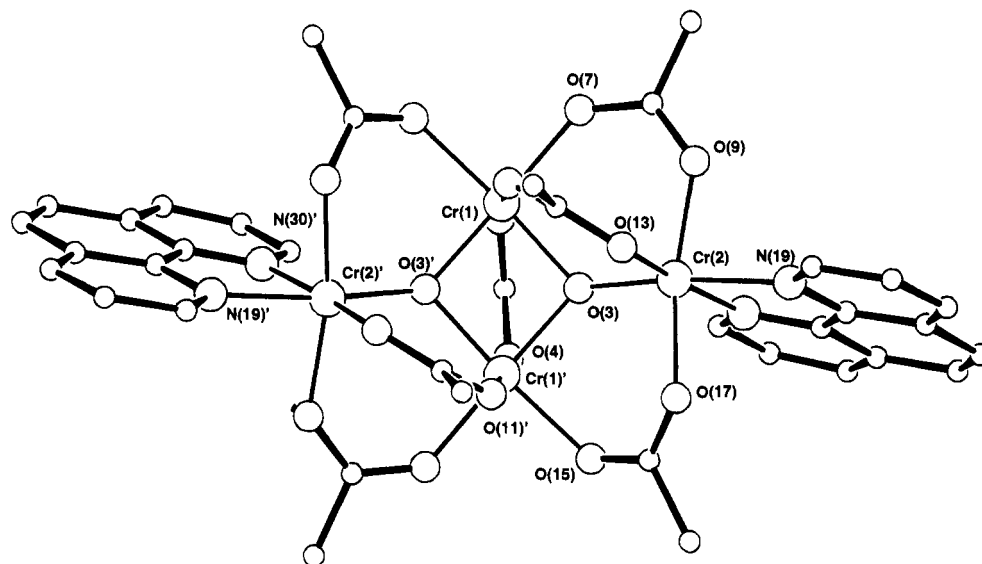


Figure 1. Structure of cation of complex 1 showing the atom labeling scheme. Primed and unprimed atoms are related by the crystallographic C_2 axis. Carbon atoms are labeled consecutively from N and O atoms. H atoms have been removed for clarity.

Table 2. Selected Fractional Coordinates ($\times 10^4$)^a and Isotropic Thermal Parameters ($\times 10$) for the Complex $1 \cdot 1.5\text{CH}_2\text{Cl}_2 \cdot 6\text{H}_2\text{O}$

atom	x	y	z	$B_{\text{iso}}, \text{\AA}^2$
Cr(1)	10614(1)	1633(1)	1865(1)	26
Cr(2)	9182(1)	1239(1)	545(1)	25
O(3)	9612(3)	1596(3)	1661(6)	28
O(4)	10519(4)	2415(3)	2033(7)	36
C(5)	10000*	2648(7)	2500*	47
C(6)	10000*	3240(7)	2500*	82
O(7)	10875(4)	1733(3)	345(6)	38
C(8)	10551(6)	1600(4)	-496(10)	34
O(9)	9923(4)	1399(2)	-540(6)	30
C(10)	10937(8)	1676(7)	-1515(11)	57
O(11)	10709(3)	844(3)	1626(5)	26
C(12)	10295(5)	494(4)	1270(8)	22
O(13)	9672(3)	566(3)	864(5)	24
C(14)	10554(5)	-74(5)	1348(9)	32
O(15)	11666(4)	1630(3)	2207(6)	35
C(16)	11974(6)	1310(5)	2835(10)	35
O(17)	8325(4)	1055(3)	1405(6)	25
C(18)	12761(7)	1226(7)	2681(16)	72
N(19)	8563(4)	910(3)	-687(7)	25
C(20)	8555(6)	432(5)	-1057(9)	34
C(21)	8050(6)	251(5)	-1834(10)	35
C(22)	7574(7)	590(5)	-2220(9)	38
C(23)	7569(6)	1125(5)	-1850(10)	37
C(24)	7078(7)	1534(5)	-2208(11)	46
C(25)	7085(7)	2027(5)	-1826(12)	50
C(26)	7602(6)	2168(4)	-1037(10)	36
C(27)	7660(7)	2680(5)	-609(11)	45
C(28)	8190(7)	2795(5)	114(11)	46
C(29)	8636(6)	2377(5)	446(11)	40
N(30)	8593(5)	1893(3)	68(8)	29
C(31)	8091(5)	1789(4)	-676(9)	30
C(32)	8065(6)	1261(5)	-1073(9)	31

^a Parameters marked with an asterisk were not varied.

3, respectively. Complex 1 crystallizes in orthorhombic space group $C222_1$ with a 2-fold axis passing through the center of the cation and thus has C_2 symmetry. Atoms C(5) and C(6) of a bridging acetate ligand are located on the 2-fold axis. The hydrogen atoms on C(6) are disordered around the 2-fold axis.

The cation contains a $[\text{Cr}_4\text{O}_2]^{8+}$ core with peripheral ligation provided by seven bridging acetate groups and two terminal phen groups. The core can be thought of as being derived from two edge-sharing Cr_2O units; however, the resulting arrangement is not planar but has a butterfly structure with Cr(1) and Cr(1)' in the "hinge positions and Cr(2) and Cr(2)' in the "wingtip"

Table 3. Selected Interatomic Distances (\AA) and Angles (deg) for Complex $1 \cdot 1.5\text{CH}_2\text{Cl}_2 \cdot 6\text{H}_2\text{O}$

(a) Distances			
Cr(1)–O(3)	1.888(7)	Cr(2)–O(3)	1.849(7)
Cr(1)–O(3)'	1.901(7)	Cr(2)–O(9)	1.983(7)
Cr(1)–O(4)	1.991(7)	Cr(2)–O(13)	1.967(7)
Cr(1)–O(7)	1.986(8)	Cr(2)–O(17)	1.984(7)
Cr(1)–O(11)	2.018(7)	Cr(2)–N(19)	2.101(9)
Cr(1)–O(15)	2.010(7)	Cr(2)–N(30)	2.069(9)
Cr(1)···Cr(1)'	2.791(2)	Cr(1)···Cr(2)'	3.423(3)
Cr(1)···Cr(2)	3.297(2)		
(b) Angles			
Cr(1)'–O(3)–Cr(1)	94.9(3)	Cr(1)–O(3)–Cr(2)	123.8(4)
Cr(1)'–O(3)–Cr(2)	131.8(4)	O(3)–Cr(2)–O(9)	96.9(3)
O(3)–Cr(1)–O(3)'	84.8(3)	O(3)–Cr(2)–O(13)	93.6(3)
O(3)–Cr(1)–O(4)	88.6(3)	O(3)–Cr(2)–O(17)	92.9(3)
O(3)'–Cr(1)–O(4)	85.8(3)	O(3)–Cr(2)–N(19)	171.5(3)
O(3)–Cr(1)–O(7)	96.8(3)	O(3)–Cr(2)–N(30)	93.6(3)
O(3)'–Cr(1)–O(7)	175.3(4)	O(9)–Cr(2)–O(13)	89.50(27)
O(3)–Cr(1)–O(11)	91.0(3)	O(9)–Cr(2)–O(17)	169.6(3)
O(3)'–Cr(1)–O(11)	96.6(3)	O(9)–Cr(2)–N(19)	87.5(3)
O(3)–Cr(1)–O(15)	174.5(3)	O(9)–Cr(2)–N(30)	90.5(3)
O(3)'–Cr(1)–O(15)	90.5(3)	O(13)–Cr(2)–O(17)	93.59(27)
O(4)–Cr(1)–O(7)	89.9(3)	O(13)–Cr(2)–N(19)	93.8(3)
O(4)–Cr(1)–O(11)	177.5(3)	O(13)–Cr(2)–N(30)	172.8(3)
O(4)–Cr(1)–O(15)	93.9(3)	O(17)–Cr(2)–N(19)	82.3(3)
O(7)–Cr(1)–O(11)	87.8(3)	O(17)–Cr(2)–N(30)	85.2(3)
O(7)–Cr(1)–O(15)	88.1(3)	N(19)–Cr(2)–N(30)	79.0(3)
O(11)–Cr(1)–O(15)	86.7(3)		

positions. The cation is thus a member of a rapidly growing class of tetranuclear complexes of the form $[\text{M}(\text{III})_4\text{O}_2(\text{O}_2\text{CR})_7(\text{L}-\text{L})_2]^{n+/}$ where L-L represents a bidentate ligand and $\text{M} = \text{Cr, Fe, or Mn}$.^{13,17–19}

The two hinge Cr atoms are bridged by two oxide ligands giving rise to a short $\text{Cr} \cdots \text{Cr}$ separation of 2.791(2) \AA . In contrast the hinge to wingtip separations (3.297(2) and 3.423(3) \AA) are appreciably longer reflecting a single oxide bridging these two type centers. In a manner similar to the previously reported tetranuclear Fe bipyridine complex^{19a} (Table IV), the μ -O atoms

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Table 4. Comparison of Selected Structural Parameters (Å) for Cr, Mn, and Fe Butterflies

param	1	[Cr ₄ O ₂ (O ₂ CPh) ₇ (pic) ₂] ²⁻ ^a	[Cr ₄ O ₂ (OAc) ₇ (bpy) ₂] ⁺	[Mn ₄ O ₂ (OAc) ₇ (bpy) ₂] ⁺	[Fe ₄ O ₂ (OAc) ₇ (bpy) ₂] ⁺
M···M (short)	2.791(2)	2.774(2)	2.7835(8)	2.848(5)	2.855(4)
M···M (long)	3.297(2), 3.423(3)	<i>b</i>	3.4274(8), 3.3163(9)	3.299(5)–3.385(9)	3.439(4), 3.306(4)
M···O (oxide)	1.849(7)–1.901(7)	1.864(3)–1.908(4)	1.852(3)–1.914(2)	1.889(13)–1.930(15)	1.819(5)–1.947(5)
M···O (carboxylate)	1.967(9)–2.018(7)	1.986(4)–2.023(3)	1.952(3)–2.005(3)	1.804(16)–2.259(15)	1.983(5)–2.090(5)
M···N	2.069(9), 2.101(9)	2.069(4)	2.069(4), 2.098(3)	2.021(20)–2.084(18)	2.145(6), 2.185(6)
ref.	this work	18	13	17a	19a

^a pic = picolinate. ^b Not reported.

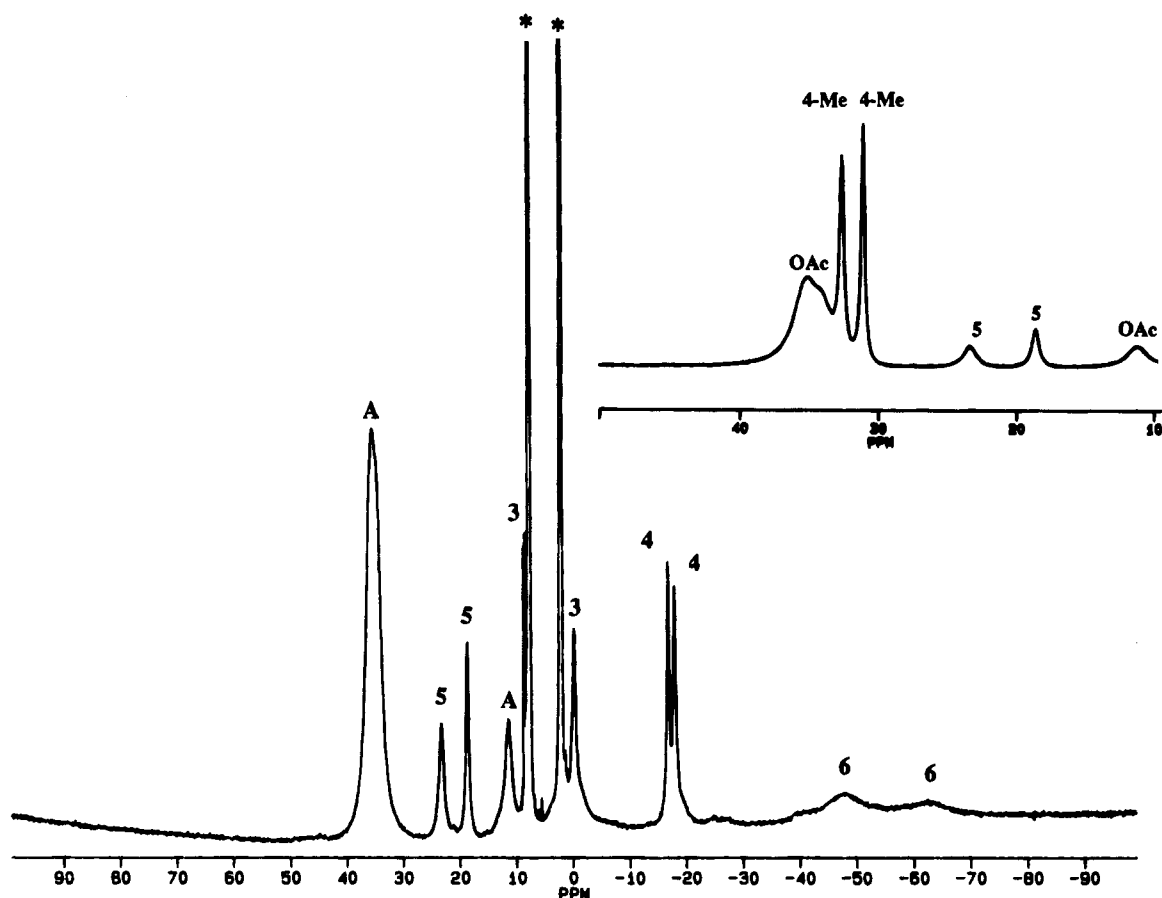


Figure 2. ¹H NMR spectrum of complex **2** in CDCl₃. Key: *, solvent protio impurity and solvate; A, acetate; numbers correspond to position of protons of 2,2'-bipyridine ligands. (The small features at ca. -25 and -40 ppm are probe artifacts.) Inset: Portion of ¹H NMR spectrum of complex **3** in CDCl₃.

bridge somewhat asymmetrically with the bond to the wingtip Cr being somewhat shorter than the others (1.849(7) vs 1.888(7) and 1.901(7) Å). This short Cr(2)–O(3) bond results in a small trans influence on the Cr(2)–N(19) bond (2.101(9) Å), lengthening it in comparison to the Cr(2)–N(30) bond (2.069(9) Å). This asymmetry is also reflected in the bond angles about O(3) with Cr(1')–O(3)–Cr(1) (94.9(3)°) being much smaller than the others, Cr(1)–O(3)–Cr(2) (123.8(4)°) and Cr(1'–O(3)–Cr(2) (131.8(4)°). Similar asymmetry and the associated trans influence is observed in other [Cr₄O₂]⁸⁺ complexes (Table 4). A similar trans influence has been noted in trinuclear oxo-centered chromium assemblies with terminal pyridine ligands; shorter Cr–O (oxide) distances were correlated to longer Cr–N (pyridine) bonds.^{20a} Any trans influence in the tetra Mn bpy analog is masked by Jahn–Teller distortions.¹⁷ However, in general the structures of these [M₄O₂(O₂Cr)₇(L–L)₂]^{n+/–} species

are remarkably uniform given the variation in carboxylate, bidentate ligands, and trivalent metal center (Table 4).

¹H and ²H NMR Spectroscopy. Recent investigations with antiferromagnetically-coupled chromium(III) assemblies in this laboratory have demonstrated the utility of NMR in the characterization of these materials.^{12,20} This technique has also been found to be applicable to these tetranuclear assemblies. For example, complex **2** in CDCl₃ displays a generally well-resolved ¹H NMR spectrum in which all expected resonances for the different protons have been located over the range +40 to -70 ppm (Figure 2). Given the C₂ symmetry of the cation, 12 resonances are expected: eight from bpy ring protons which are all inequivalent and four from inequivalent types of acetate groups. Assignments for the different resonances are given in Table 5. The assignments were based on results of the following: (1) preparation of the O₂CCD₃ derivative which unambiguously allowed assignment of acetate methyl resonances, (2) preparation of the 4,4'-Me₂-bpy derivative which allowed assignment of the bpy 4-position protons, (3) preparation of the phen derivative which allowed assignment of the

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Table 5. ^1H NMR Resonances (ppm) and Assignments

1	2	3
35.4, A ^a	35.3, A	35.1, A 32.6, 4-Me ^c 31.0, 4-Me
18.6, 3/8 ^b	23.1, 5 ^c	23.4, 5
15.2, 3/8	18.6, 5	18.6, 5
11.6, A	11.3, A	11.2, A
2.7, 5/6	7.8, 3	7.8, 3
-17.1, 4/7	-0.33, 3	-0.28, 3
-18.3, 4/7	-16.9, 4	
ca. -56, 2/9	-18.0, 4	
ca. -70, 2/9	-48.7, 6	ca. -48, 6
	-63, 6	ca. -63, 6

^a A = acetate methyl. ^b Numbers correspond to phenanthroline ring positions. ^c Numbers correspond to bipyridine ring positions.

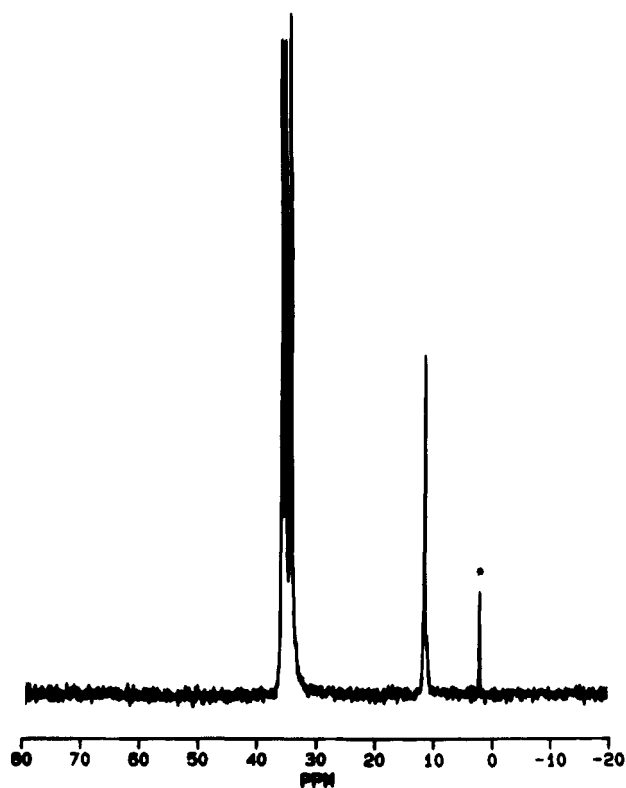


Figure 3. ^2H NMR spectrum of $[\text{Cr}_4\text{O}_2(\text{O}_2\text{CCD}_3)_7(\text{bpy})_2]\text{Cl}$ in CHCl_3 . Key: *, solvent deutero impurity.

bpy 3-position protons as phen lacks protons in these positions, and (4) consideration of peak widths which allowed assignment of the 6-position protons which are greatly broadened as a result of their close proximity to the chromic centers. The two resonances from the acetate ligands at 35.3 and 11.3 ppm occur in approximately a 6:1 ratio, respectively; consequently, the latter arises from the unique acetate bridging between the two "hinge" chromic ions. ^1H NMR cannot resolve the remaining three sets of acetate ligands; however, the resonances can be resolved by ^2H NMR (Figure 3). The ^2H NMR of the O_2CCD_3 analogue of **2** possesses four distinct resonances in approximately a 2:2:2:1 ratio at 36.1, 35.0, 33.5, and 12.1 ppm. The resolution results from ^2H NMR line widths which can be up to 42 times smaller than those of the corresponding ^1H line widths ($\gamma_{\text{H}}^2/\gamma_{\text{D}}^2 = 42.4$, $\gamma = \text{gyromagnetic ratio}$).²¹

The resonances from the bpy ligands extend over the range ca. +25 to -70 ppm. The 6-position protons are the broadened signals located at the upfield extreme. The 4-position protons

are located at -16.9 and -18.0 ppm as they are not found in the spectrum of **3** and are the sharpest of the bpy proton resonances (of course, being located at the greatest distance from the metal centers). The resonances at +7.8 and -0.28 ppm are missing in the spectrum of complex **1** and are thus assigned to the 3-position protons. By default, the two paramagnetically-shifted resonances at 23.4 and 18.6 ppm are assigned to the 5-position protons. Taken as a whole, the results support retention of the tetranuclear structure of **2** (as well as the other tetranuclear species) in solution.

Each of the four chromic ions, d^3 , has each of its three unpaired electrons occupying a t_{2g} orbital (assuming essentially octahedral coordination), directed between the chromium-ligand bonds. Chromium(III) complexes are hence magnetically isotropic or nearly so, and their dipolar shifts should be quite small or negligible.²² Thus, isotropic shifts should be solely contact in origin to first order. Previous ^1H , ^2H , and ^{13}C NMR studies of oxo-centered trinuclear chromium(III) carboxylates have revealed that a π -delocalization mechanism dominates the paramagnetic shifts.^{12,20} This is consistent with the presence of metal centers where unpaired electrons reside solely in t_{2g} orbitals. A π -delocalization mechanism can readily be shown to dominate in the oxide-bridged tetranuclear chromium carboxylate species. The 4-Me proton resonances of complex **3** (32.6 and 31.0 ppm) are downfield of their diamagnetic position while the 4-position proton resonances of **2** were shifted upfield. This change in sign between the isotropic shifts of the H and Me protons at the 4-position is unambiguous evidence of a π spin-delocalization mechanism. Indeed, Wicholas and Drago have reported that π -delocalization is probably the only component responsible for contact shifts at the 4-position of the bpy ligand; contributions from σ -delocalization should be very attenuated at these large separations from the paramagnetic metal centers.²³ A similar behavior has been observed in the analogous tetranuclear Mn(III) complexes,^{17a} while in the tetranuclear Fe(III) analogues the resonances for both the 4-position and 4-methyl protons are essentially in their diamagnetic positions.^{19a} Further evidence for a dominant π -delocalization mechanism comes from the alternating sense of shifts about the bpy while the 4-position protons resonances are upfield, the 5-position proton resonances are shifted downfield, and the 6-position resonances are shifted upfield. Parallel spin at the chromic ions should result in parallel spin at the 6- and 4-position carbons and in contrast antiparallel spin at the 5- and 3-position carbons. The result in turn should be antiparallel spins at the 6- and 4-position protons (upfield shifts) and parallel spin at the 5- and 3-position protons (downfield shifts).

For complex **1**, the ^1H NMR spectrum has been assigned by comparison with those of the bpy complexes. The spectrum of complex **1** differs by lacking the resonances from the 3-position bpy protons and possessing an additional signal at 2.7 ppm. This signal is assigned to both the 5- and 6-position protons of the phen ligands as it is lacking in the spectrum of the bpy complexes and as its intensity is approximately twice the intensity of the other phen protons.

Mass Spectral Results. FAB mass spectrometry has recently been shown to be a valuable technique in the characterization of oxo-bridged multinuclear Cr assemblies.^{20a,20c} FAB mass spectra of complexes **1-3** (Table 6) reveal a distinctive set of ions with masses corresponding to the parent cation and fragments of the parent derived by loss of carboxylate or

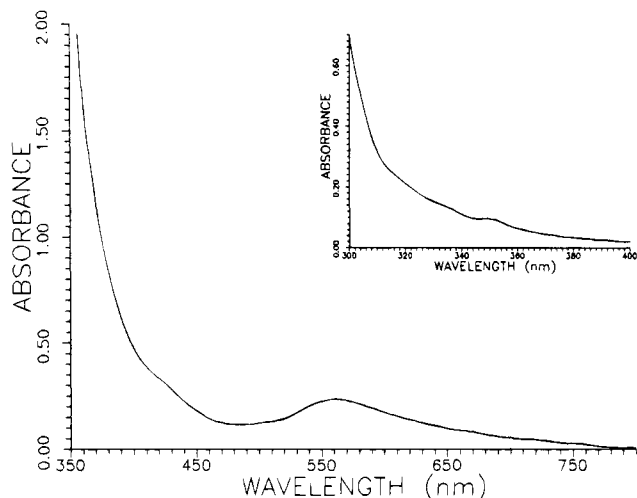
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Table 6. Mass (and Intensity) of Ions in FAB Mass Spectra

ion	R = Me, L-L = phen	R = Me, L-L = bpy ^a	R = Me, L-L = 4,4'- Me ₂ Bpy
[Cr ₄ O ₂ (O ₂ CR) ₇ (L-L) ₂] ⁺	1013 (100)	965 (100)	1021 (100)
[Cr ₄ O ₂ (O ₂ CR) ₆ (L-L) ₂] ⁺	954 (27)	906 (6)	962 (7)
[Cr ₄ O ₂ (O ₂ CR) ₇ (L-L)] ⁺	833 (35)	809 (27)	837 (27)
[Cr ₄ O ₂ (O ₂ CR) ₆ (L-L)] ⁺	774 (19)	750 (11)	778 (11)
[Cr ₄ O ₂ (O ₂ CR) ₅ (L-L)] ⁺	715 (6)	691 (4)	719 (3)

^a Cl⁻ anion.**Figure 4.** Visible spectrum of complex **1** in CH₂Cl₂ solution ($c_{Cr} = 5$ mM). Inset: Ultraviolet spectrum of complex **1** in CH₂Cl₂ solution ($c_{Cr} = 0.2$ mM).

bidentate ligand. The parent ion always represents the most intense feature of the spectrum. Similar terminal ligand loss has recently been observed in electrospray mass spectrometric studies of trinuclear Cr(III) assemblies.²⁴ Loss of carboxylate ligands was only observed in collisionally activated mass spectrometric studies,²⁴ but has previously been observed in FAB mass spectral studies of these trimers.^{20a,20c}

Magnetic Studies. The effective magnetic moment of complex **1** at room temperature (298 K) in solution (MeCN-*d*₃) and in the solid state has been determined. The values per Cr of 2.72 and 2.69 μ_B , respectively, indicate that the cation of **1** maintains its integrity in solution and that it is overall antiferromagnetically coupled (μ_{spin} only for Cr³⁺ = 3.87 μ_B). The values are nearly identical to those reported for the anion [Cr₄O₂(O₂CPh)₇(picolinate)₂]⁻, i.e. (2.65 and 2.56 μ_B , respectively),¹⁸ and slightly smaller than the solid state moment reported for [Cr₄O₂(O₂CMe)₇(bpy)₂]⁺, $\mu = 3.02 \mu_B$ (281.5 K).¹³ The similar coupling between the chromic centers of these tetranuclear species is reflected by the high degree of similarity in their ¹H NMR spectra (vide supra).

Electronic Spectra. The electronic spectrum of complex **1** is shown in Figure 4. The visible spectrum is dominated by overlapping spin-allowed d → d transitions from the chromic ions. The energy and shape of the broad feature with maximal absorption at 560 nm ($\epsilon/Cr = 47 \text{ M}^{-1} \text{ cm}^{-1}$) is distinctive of these [Cr₄O₂]⁸⁺ species. A similar feature has been reported for [Cr₄O₂(O₂CMe)₇(bpy)₂]⁺ (562 nm ($\epsilon = 55 \mu^{-1} \text{ cm}^{-1}$))¹³ and [Cr₄O₂(O₂CPh)₇(picolinate)₂]⁻ (564 nm ($\epsilon = 89.8 \text{ M}^{-1} \text{ cm}^{-1}$)).¹⁸ Several weak, low energy bands between 650 and 800 nm result from formally spin-forbidden d → d transitions which become allowed as a result of exchange interactions. Of particular

interest are near-ultraviolet bands at 348 and 332 nm; the position and relative sharpness of the bands suggest they arise from simultaneous pair excitation (SPE) transitions,²⁵ also made allowed by exchange interactions between the chromic ions. The energy of these transitions suggest the double excitations are of the low energy formally spin-forbidden transitions. Similar SPE transitions have been identified in numerous oxo-bridged multinuclear Cr(III) complexes,^{20a,25} but they have not previously been identified in a tetranuclear Cr(III) complex.

Discussion

Biological Significance. LMWCr is an anionic polypeptide which binds four chromic ions; its organic portion is apparently comprised solely of glycine, cysteine, and glutamic and aspartic acids (and/or their amines), with the two acids corresponding to over half of the total amino acid composition.⁶ The binding affinity for Cr is great, as LMWCr binds Cr tighter than the metal transport protein transferrin and can accept Cr from Cr-transferrin.²⁶ The polypeptide also displays appreciable biological activity in *in vitro* assays (the ability to potentiate the effects of insulin on glucose metabolism in rat adipocytes or adipose tissue); this activity is directly related to the amount of bound Cr.²⁷ In binding four Cr³⁺ ions, the protein acquires 12 positive charges while remaining overall anionic. After the possible sources of negative charge are maximized the polypeptide alone cannot account for enough negative charge to compensate for the acquired positive charge to remain anionic overall. Additionally given that each of the four trivalent Cr desire hexadentate coordination, the four Cr³⁺ ions (given this number is correct) probably reside in a multinuclear assembly bridged by small anionic ligands and supported by carboxylates provided by the polypeptide.⁷ Unfortunately to date, LMWCr has only been isolated in submilligram quantities, insufficient for characterization of the material at a molecular level using spectroscopic and magnetic techniques.

Well-characterized chromium–small anion assemblies supported by carboxylate ligands are few with the exception of those possessing the “basic acetate” type structure [Cr₃O(O₂CR)₆L₃]⁺.⁸ However, prior to work in this laboratory, two such tetranuclear assemblies had been reported: [Cr₄S(O₂CMe)₈(H₂O)₄]²⁺²⁸ and [Cr₄O₂(O₂Me)₇(bpy)₂]⁺.¹³ The aim of this laboratory is to extend the type and number of such complexes to accumulate a pool of spectroscopic and magnetic data for comparison with LMWCr (as techniques for isolation of larger quantities are developed) to aid in the elucidation of its structure, function, and mode of action.

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Supplementary Material Available: A presentation of the data collection and solution of the structure for **1**, giving tables of crystallographic data, fractional coordinates, thermal parameters, and bond distances and angles for **1** and an ORTEP diagram of the [Cr₄O₂(OAc)₇(phen)₂]⁺ cation and labeling scheme (12 pages). Ordering information is given on any current masthead page.

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