

Preparation of the Macrobicyclic Ligand 17-Oxa-1,5,8,12-tetraazabicyclo[10.5.2]nonadecane: Characterization of Copper(II) Intermediates in a Template Synthesis

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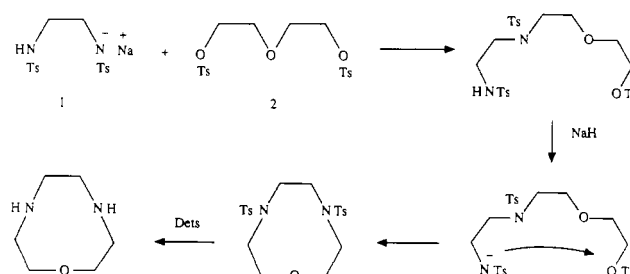
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The synthesis is reported of the pentadentate macrobicyclic ligand 17-oxa-1,5,8,12-tetraazabicyclo[10.5.2]nonadecane (L_2), where attached to the cyclam (1,4,8,11-tetraazacyclotetradecane (14-ane N_4)) framework is a pendant ether group deriving originally from the macrocycle 1-oxa-4,7-diazacyclononane. The reaction sequence used involves the condensation of [N,N' -bis(3-aminopropyl)-1-oxa-4,7-diazacyclononane]copper(II), [$Cu(4)$] $^{2+}$, with glyoxal followed by reduction and demetalation. The process represents one of only a few successful ring closures of this type at a copper center. In addition to characterization by X-ray crystallography of the complex ion [$Cu(L_2)$] $^{2+}$, structures have also been refined of two intermediates isolated in the condensation/reduction reactions. The amidol complex ion [$Cu(L_1)$] $^{2+}$ may be derived from a precursor imine-carbinolamine. When the reduction reaction is carried out in less than the required amount of BH_4^- , not only is the copper complex of the saturated ligand formed but also the macrocyclic enamine [$Cu(L_3)$] $^{2+}$ ion is formed as a result of a favorable equilibrium involving the usually more stable imine. Demetalation of the saturated ion [$Cu(L_2)$] $^{2+}$ in the presence of Na_2S leads to the title ligand. This species has been characterized structurally as the tetrahydrop perchlorate salt [$H_4(L_2)$](ClO_4) $_4 \cdot H_2O$. The perchlorate salt of [$Cu(L_1)$] $^{2+}$ crystallized in the space group $P2_1/c$ (No. 14) ($a = 10.367$ (3), $b = 13.104$ (5), $c = 16.079$ (6) Å; $\beta = 93.28$ (3) $^\circ$). Refinement converged at $R = 0.0838$ for 280 parameters with 1908 reflections with $I > 3\sigma(I)$. The complex is square pyramidal and contains the coordinated amidol function ($C=N = 1.31$ (3) Å). The ion [$Cu(L_2)$] $^{2+}$ crystallized as the diperchlorate in the space group $P2_1/n$ (No. 14) ($a = 13.880$ (2), $b = 15.122$ (3), $c = 10.463$ (2) Å; $\beta = 97.95$ (1) $^\circ$). Refinement converged at $R = 0.079$ for 271 parameters with 1470 reflections with $I > 2\sigma(I)$. In this case the C(10)–C(11) bond in the macrocyclic ring is 1.51 (2) Å considerably longer than the corresponding C=C bond of enamine [$Cu(L_3)$] $^{2+}$ at 1.34 (2) Å. The latter ion, which was investigated as the perchlorate salt, crystallized in the orthorhombic space group $Pbca$ (No. 61) ($a = 16.494$ (3), $b = 18.188$ (3), $c = 14.330$ (2) Å). Refinement converged at $R = 0.0655$ for 271 parameters with 1878 reflections with $I > 2\sigma(I)$. X-ray-quality crystals of [$H_4(L_2)$](ClO_4) $_4 \cdot H_2O$ were obtained from strongly acidic media. The material crystallized in the space group $P2_1/n$ (No. 14) ($a = 13.717$ (3), $b = 20.152$ (5), $c = 10.110$ (2) Å; $\beta = 94.46$ (2) $^\circ$). During refinement there was found to be unresolvable disorder associated with two of the perchlorates. For this reason, $R = 0.117$ for 361 parameters with 2241 reflections with $I > 3\sigma(I)$. ESR data for the copper(II) complexes are consistent with the principal CuN_4 plane dominating in these five-coordinate complex ions.

A continuing feature of interest in coordination chemistry is the stability imparted to organic functional groups when bonded to a metal center.^{1–4} This is true especially of macrocyclic complexes, which may contain unsaturated (e.g., imine) linkages.^{5–8} Recent studies in these laboratories^{9,10} have been directed toward the formation of bicyclic ligands in which a substituted triaza-cyclononane (9-ane N_2X) ($X = S, NH, O$) is “fused” to the 14-membered-ring cyclam 14-ane N_4 (1,4,8,11-tetraazacyclotetradecane). Strategies toward formation of such species have involved (a) extrapolation of derivatives of 9-ane N_2X via Michael addition of acrylonitrile and reduction to the *bis*(aminopropyl) pendant-arm species, followed by (b) ring closure at a complexed copper(II) center. Such reactions are of interest in that they represent some of the few examples of successful cyclization by glyoxal¹¹ and reduction (BH_4^-) at metal complexes of this type. In the corresponding exclusively 14-membered-ring systems, similar reduction results in the formation of metallic copper.¹²

A noteworthy feature of template syntheses in which there are five coordination sites has been the identification and characterization of unexpected intermediates in the cyclization process. In the system where $X = NH$,¹⁰ an imidate (imino ether) has been

Scheme I



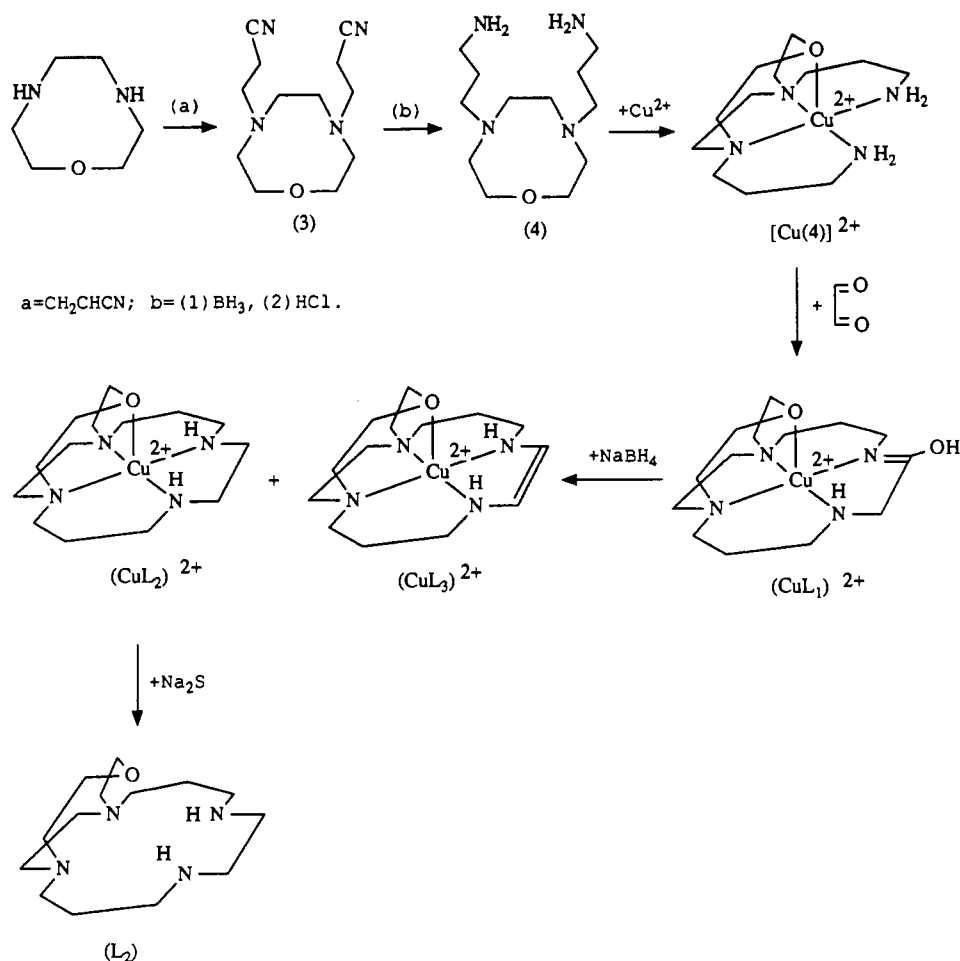
isolated that exhibits remarkable kinetic stability toward acid hydrolysis, presumably owing to the binding of the imino nitrogen to the copper center. Also, as a result of incomplete reduction with borohydride ion, an enamine cation was isolated and characterized crystallographically.

In the present paper we describe the synthesis of a macrobicyclic in which the apical donor is an oxygen atom. There is interest as to whether this ether oxygen would be as effective a coordinator as S or N.¹³ Previous studies on these and related systems¹⁴ are consistent with square-pyramidal configurations at Cu(II). However, in the case of nickel(II),^{3,15} a sixth (perchlorate) ligand is coordinated weakly. Other potentially quinquedentate ligands¹⁶ with O donors have also displayed a tendency for four-coordination of the macrocycle if other sufficiently strongly ligating groups are present. In contrast, the present findings demonstrate that the oxygen donor, as a result of ligand geometry, may be held in a bonding position for interaction with the metal center. Thus, a

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Scheme II



template reaction sequence ensues, which provides further information on the mechanistic aspects of reactions of coordinated ligands of this type.

Experimental Section

All materials were of reagent grade, except where otherwise indicated.

Infrared spectra were obtained as KBr disks with a Perkin-Elmer 283 grating spectrometer. High-field ¹H and ¹³C spectra were obtained by using a Bruker WM 250 instrument. All chemical shifts are reported in δ relative to tetramethylsilane (TMS). ESR spectra were measured on a Varian E6S spectrometer with diphenylpicrylhydrazyl (dppH, g = 2.0037) as a reference standard. UV-visible spectra were run on either a Cary 17 or a Perkin-Elmer Lambda 4B dual-beam spectrometer.

Elemental analyses were performed by Canadian Microanalytical Services, Vancouver, BC, Canada.

Synthesis. The synthetic route to the macrobicyclic ligand is outlined in reaction Schemes I and II.

1-Oxa-4,7-diazacyclononane, 9-aneN₂O. The cyclic ditosylate was prepared in a manner similar to that described previously.¹⁷⁻¹⁹ An alternate route employed was to react (in 1 L of DMF) 0.1 mol of the monosodium salt of the ditosylate of ethylenediamine (1) with 1 equiv of the ditosylate of bis(2-hydroxyethyl) ether (2). The reaction mixture was maintained at 120 °C overnight before cooling and 1 equiv of sodium hydride added. The solution was heated slowly to 70 °C for 1 h after which no effervescence was observed. The temperature was raised to 120 °C for 4 h before cooling to room temperature. After reduction of the volume to 200 mL, the solution was dropped into 3 L of ice-cold water with vigorous stirring. Following filtration, the white ditosylate was recrystallized from methanol. Yield: 13 g, 30%.

The cyclic ditosylate, 10 g (0.023 mol), was dissolved in 30 mL of concentrated H₂SO₄ at 140 °C, and the mixture was stirred for 5 min. The resulting solution was allowed to cool slowly to room temperature.

Upon addition to a well-stirred solution of ice-cold ethanol, a milky suspension was formed, which separated overnight at 0 °C. The supernatant was further extracted with ether. The resulting solids were dissolved in water (30 mL), the pH adjusted to 12, and the ligand extracted with CH₂Cl₂. After removal of solvent, addition of concentrated HCl (20 mL) in ethanol (200 mL) yielded the dihydrochloride of 9-aneN₂O. (4 g, 86%).

N,N'-Bis(2-cyanoethyl)-1-oxa-4,7-diazacyclononane (3). To a solution of the free ligand 9-aneN₂O (1.3 g, 1 mmol), in CHCl₃, was added K₂CO₃ (2.0 g) and acrylonitrile (20 mL, about 10-fold excess) before refluxing overnight. The K₂CO₃ was filtered off and the solvent removed under reduced pressure. Yield: 2.0 g.

¹H NMR (CDCl₃): 3.7 (t), O-CH₂; 2.8 (m), N-CH₂; 2.45 (t), CH₂CN. Mass spectrum (CI): m/e 237 (M + 1), 265 (M + 29), 277 (M + 41).

N,N'-Bis(3-aminopropyl)-1-oxa-4,7-diazacyclononane (4). The cyanoethyl derivative 3, 2 g (8 mmol), was dissolved in BH₃·thf (1 M in thf, 80 mL), and the solution was brought to reflux for 4 h. Ethanol (40 mL) was added carefully to the cooled solution in order to destroy the excess BH₃. The mixture was taken to dryness under reduced pressure, the solid was subsequently dissolved in a methanolic solution of HCl (4 M, 80 mL), and the solution was refluxed for 1 h. The solvent was again removed under pressure, and the resulting oil was dissolved in 3 M NaOH (40 mL) and extracted into CH₂Cl₂ (5 × 30 mL). The organic layers were combined, dried over Na₂SO₄, and taken to dryness. The resulting oil (2.5 g) contained the desired product.

¹H NMR: 3.7, O-CH₂; 2.8, N-CH₂; 1.6, -CH₂-; 1.4, NH₂. Mass spectrum: m/e 245 (M + 1), 273 (M + 29), 285 (M + 41).

The ligand was purified by crystallization as the corresponding copper(II) salt.

[Cu(4)](ClO₄)₂·H₂O. To a solution of the oil (1 g) containing 4 in water (50 mL) was added Cu(ClO₄)₂·6H₂O (5.2 g, 17 mmol). The solution turned blue immediately but was heated to 80 °C for 1 h to ensure complete complexation. Upon cooling, purplish blue crystals were produced. The product was filtered out rinsed with ethanol and then ether, and air-dried. Yield: 1.6 g.

IR: NH₂ stretch, 3260, 3290 cm⁻¹; NH₂ scissor, 1600 cm⁻¹; perchlorate stretch, 620, 1100 cm⁻¹. Anal. Calcd for [Cu(C₁₂H₂₆N₄O)]-

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(Cl₂O₆)·H₂O: C, 27.44; H, 5.76; N, 10.68. Found: C, 27.59; H, 5.37; N, 10.62.

(6-Hydroxy-1,5,8,12-tetraaza-17-oxabicyclo[10.5.2]nonadec-5-ene)-copper(II) Perchlorate ([Cu(L₁)](ClO₄)₂). To a solution of [Cu(4)]-(ClO₄)₂ (400 mg, 0.8 mmol) in methanol/water (9/1, 600 mL) was added glyoxal (40% solution in water, 0.16 mL, ~1.1 mmol) and the pH adjusted to about 4. The mixture was refluxed overnight, the color becoming slightly more purplish blue. After the reaction mixture was taken to dryness under reduced pressure, the product was recrystallized from hot water (7 mL) acidified with concentrated HClO₄ (1 mL). The crystals obtained, some of which were of X-ray quality, were rinsed with ethanol and ether and air-dried. Yield: 350 mg, 83%.

Anal. Calcd for [Cu(C₁₄H₂₈N₄O₂)](ClO₄)₂: C, 30.67; H, 5.15; N, 10.23. Found: C, 30.56; H, 5.06; N, 10.09. IR: NH stretch, 3260 cm⁻¹; -C(=N)O-, 1420, 1670 cm⁻¹; perchlorate, 620, 631, 1100 (br) cm⁻¹.

(1,5,8,12-Tetraaza-17-oxabicyclo[10.5.2]nonadecane)copper(II) Perchlorate ([Cu(L₂)](ClO₄)₂). To a solution of [Cu(4)](ClO₄)₂·H₂O (760 mg, 1.5 mmol) in methanol/water (9/1, 750 mL) was added glyoxal (40% solution in water, 0.3 mL, 2 mmol). The mixture was refluxed overnight, after which the cooled solution was treated with NaBH₄ (240 mg, 4.4 mmol) and heated to reflux for 2 h. The reaction mixture was taken to dryness under reduced pressure. The product was recrystallized from hot water (ca. 15 mL) acidified with concentrated HClO₄ (1 mL). The magenta crystals were filtered out, rinsed with ethanol, and air-dried. Yield: 650 mg (81%).

Anal. Calcd for [Cu(C₁₄H₃₀N₄O)](ClO₄)₂: C, 31.54; H, 5.68; N, 10.52. Found: C, 31.50; H, 5.56; N, 10.46. IR: NH stretches, 3080, 3140, 3220, 3285 cm⁻¹; perchlorate, 622, 634, 1100 (br) cm⁻¹.

(1,5,8,12-Tetraaza-17-oxa-bicyclo[10.5.2]nonadec-6-ene)copper(II) Perchlorate ([Cu(L₃)](ClO₄)₂). A sample of the reaction mixture from [Cu(L₂)]²⁺ (see above) was eluted on a Sephadex column (CM C-25). When the column was washed with 0.2 M NaCl, three bands appeared. The first band eluted was confirmed as [Cu(L₁)]²⁺, and the second principal segment was [Cu(L₂)]²⁺. The third blue-purple band was taken to dryness and, after removal of NaCl, the material was recrystallized from water (5 mL) containing 1 mL of 9 M HClO₄. The dark blue crystals formed were filtered out, washed with ethanol, and air-dried. On some occasions this band was not observed. However, when present, the material could also be derived by fractional crystallization from the reaction mixture, since the dark blue color was distinguishable from the magenta [Cu(L₂)]²⁺ ion.

Anal. Calcd for [Cu(C₁₄H₂₈N₄O)](ClO₄)₂: C, 31.65; H, 5.32; N, 10.56. Found: C, 31.25; H, 5.53; N, 10.32. IR: NH stretches, 3420, 3495 cm⁻¹; perchlorate, 628, 638 cm⁻¹.

17-Oxa-1,5,8,12-tetraazabicyclo[10.5.2]nonadecane (L₂). To a solution of [Cu(L₂)](ClO₄)₂ (480 mg, 0.9 mmol) in water (100 mL) was added a solution of Na₂S (2 g, 8.3 mmol, 25 mL). The mixture was refluxed overnight whereupon the reddish blue color of the complex had disappeared. The CuS precipitate was filtered off by use of a fine glass frit, and the supernatant was taken to one-fourth of the original volume under reduced pressure. Sodium hydroxide was added (ca. 3 g) to give a NaOH concentration of approximately 3 M and the ligand extracted into CH₂Cl₂ (5 × 20 mL). The organic layers were combined and dried with Na₂SO₄, and the solvent was removed, leaving a colorless hygroscopic oil. Yield: 0.2 g, 82%.

Mass spectrum (CI): *m/e* 271 (M + 1), 299 (M + 29), 311 (M + 41). ¹H NMR: 1.7, CH₂; 2.8, N-CH₂; 3.7, O-CH₂; 1.3, NH. ¹³C NMR (CDCl₃): 77.0, C-CH₂-C; 54.6, 58.4, 58.9, N-CH₂-C; 47.8, 49.0, NH-CH₂; 26.8, C-CH₂-C.

Caution! Transition-metal perchlorates are known to be hazardous and must be treated with care, especially in the presence of organic solvents.

Crystallography. The experimental parameters for the three metal complexes and the hydroperchlorate salt of the free ligand are presented in Table I, with additional information in Table S1 (supplementary material). Crystals were mounted in glass Lindemann tubes and the unit cells and space groups determined by using Weissenberg and precession photography, after which the crystals were transferred to a Picker four-circle diffractometer automated with a PDP11/10 computer. In the case of the ligand salt, the data were collected on a Nonius CAD4 instrument.

[Cu(L₁)](ClO₄)₂. The unit cell was refined by using 12 pairs of reflections in the 2θ range 17–45°. The intensity measurements were made by scanning in the θ/2θ mode using 200 steps of 0.01° in 2θ counting for 0.25 s/step. Background counting was introduced for 25 s at the end of each scan. A set of three standard reflections preceded each batch of 50 measurements, with no noticeable change of intensity observed during the collection.

Solution of the phase problem was achieved by direct methods with SHELX76.²⁰ The atomic scattering factors were those included in the

Table I. Crystallographic Data

[Cu(L ₁)](ClO ₄) ₂	
chem formula: CuC ₁₄ H ₂₈ N ₄ O ₁₀ Cl ₂	V = 2180.9 Å ³
fw: 546.8	Z = 4
space group: P2 ₁ /c (No. 14)	T = 22 ± 2 °C
a = 10.367 (3) Å	λ = 0.710 69 Å
b = 13.104 (5) Å	ρ _{obs} = 1.659 g cm ⁻³
c = 16.079 (6) Å	ρ _{calcd} = 1.665 g cm ⁻³
α = 90°	μ = 12.40 cm ⁻¹
β = 93.28 (3)°	transm coeff = 0.775–0.836
γ = 90°	R(F _o) = 0.0838
	R _w = 0.0899
[Cu(L ₂)](ClO ₄) ₂	
chem formula: CuC ₁₄ H ₃₀ N ₄ O ₉ Cl ₂	Z = 4
fw: 532.8	T = 22 ± 2 °C
space group: P2 ₁ /n (No. 14)	λ = 0.710 69 Å
a = 13.880 (2) Å	ρ _{obs} = 1.629 g cm ⁻³
b = 15.122 (3) Å	ρ _{calcd} = 1.627 g cm ⁻³
c = 10.463 (2) Å	μ = 12.31 cm ⁻¹
α = 90°	transm coeff = 0.811–0.915
β = 97.95 (1)°	R(F _o) = 0.079
γ = 90°	R _w = 0.073
V = 2175.2 Å ³	
[Cu(L ₃)](ClO ₄) ₂	
chem formula: CuC ₁₄ H ₂₈ N ₄ O ₉ Cl ₂	T = 22 ± 2 °C
fw: 530.8	λ = 0.710 69 Å
space group: Pbcn (No. 61)	ρ _{obs} = 1.621 g cm ⁻³
a = 16.494 (3) Å	ρ _{calcd} = 1.646 g cm ⁻³
b = 18.188 (3) Å	μ = 13.37 cm ⁻¹
c = 14.330 (2) Å	transm coeff = 0.716–0.779
α = β = γ = 90°	R(F _o) = 0.0655
V = 4298.9 Å ³	R _w = 0.0698
Z = 8	
[H ₄ (L ₂)](ClO ₄) ₄ ·H ₂ O	
chem formula: C ₁₄ H ₃₆ N ₄ O ₁₈ Cl ₂	V = 2786.2 Å ³
fw: 690.3	Z = 4
space group: P2 ₁ /n (No. 14)	T = 22 ± 2 °C
a = 13.717 (3) Å	λ = 0.710 69 Å
b = 20.152 (5) Å	ρ _{obs} = 1.637 g cm ⁻³
c = 10.110 (2) Å	ρ _{calcd} = 1.645 g cm ⁻³
α = 90°	R(F _o) = 0.117
β = 94.46 (2)°	R _w = 0.125
γ = 90°	

SHELX76 program together with the Cu *f* curve from ref 21. The program used for absorption correction was a local modification of an existing procedure.²² Completion and refinement of the structure were carried out by difference electron density maps and least-squares techniques. All atoms were refined anisotropically except for the hydrogen atoms, only some of which were observed. The refinement converged with a maximum shift/esd of 0.104 on the final cycle for all atoms except H (but including one of the perchlorate oxygens (O(8)) and a maximum peak of 1.53 e Å⁻³. Exclusion of the oxygen atom reduced the shift/esd value to 0.028. Various attempts were made to examine the poor temperature factors on C(10) but without success.

[Cu(L₂)](ClO₄)₂. The unit cell was refined by using 21 pairs of reflections in the 2θ range from 16 to 38°. The intensity measurements were obtained by scanning in the θ/2θ mode using 200 steps of 0.01° in 2θ counting for 0.25 s/step. Background counting was introduced for 25 s at the end of each scan. Three standard reflections preceded each batch of 50 measurements, with no decomposition during the collection. Details of the solution are similar to those given above. The refinement converged with a maximum shift/esd of 0.017 on the final cycle and a maximum peak of 0.58 e Å⁻³.

[Cu(L₃)](ClO₄)₂. The unit cell was refined by using 17 pairs of reflections in 2θ from 17 to 42°. The intensity measurements were obtained by scanning in the θ/2θ mode using 200 steps of 0.01° in 2θ counting for 0.25 s/step. Background counting was introduced for 25 s at the end of each scan. Three standard reflections that preceded each batch of 50 measurements showed no change of intensity during the collection.

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Table II. $[\text{H}_4(\text{L}_2)]^{4+}$ Fractional Atomic Coordinates and Temperature Parameters^a

atom	<i>x/a</i>	<i>y/b</i>	<i>z/c</i>	$U_{\text{eq}}^b \text{ \AA}^2$
Cl(1)	28121 (28)	4387 (21)	15709 (41)	572 (15)
Cl(2)	36149 (24)	28622 (21)	14709 (39)	538 (15)
Cl(3)	-10213 (27)	14522 (23)	23214 (43)	580 (15)
Cl(4)	-4270 (31)	40690 (25)	17441 (52)	716 (18)
O(1)	2054 (11)	885 (8)	1580 (16)	125 (7)
O(2)	3096 (21)	307 (9)	402 (18)	219 (15)
O(3)	3464 (17)	685 (15)	2446 (25)	243 (16)
O(4)	2502 (11)	-183 (8)	2049 (19)	143 (9)
O(5)	4616 (6)	2843 (5)	1109 (10)	56 (4)
O(6)	3681 (10)	2810 (8)	2852 (11)	120 (7)
O(7)	3088 (11)	2352 (8)	843 (17)	136 (8)
O(8)	3207 (10)	3459 (7)	1151 (16)	116 (7)
O(9)	-1339 (11)	1014 (9)	1291 (19)	147 (9)
O(10)	-1757 (14)	1814 (12)	2763 (22)	189 (11)
O(11)	-384 (22)	1173 (13)	3242 (27)	272 (17)
O(12)	-566 (26)	1927 (15)	1747 (27)	254 (18)
O(13)	543 (9)	3801 (8)	1909 (13)	117 (7)
O(14)	-958 (15)	3714 (18)	820 (25)	229 (17)
O(15)	-307 (22)	4563 (15)	664 (30)	236 (17)
O(16)	-739 (25)	4423 (15)	2579 (21)	272 (19)
O(17)	7006 (8)	503 (5)	4913 (10)	69 (4)
O	5381 (8)	4258 (5)	1639 (12)	73 (5)
N(1)	5860 (8)	3288 (6)	3425 (11)	45 (4)
N(2)	6491 (8)	3386 (6)	465 (11)	51 (5)
N(3)	5607 (9)	996 (6)	3077 (13)	62 (5)
N(4)	6347 (10)	1118 (6)	-494 (12)	60 (5)
C(1)	6887 (9)	3331 (8)	2994 (14)	50 (5)
C(2)	6979 (9)	3028 (7)	1640 (15)	49 (5)
C(3)	6800 (14)	4101 (8)	354 (19)	77 (7)
C(4)	5992 (17)	4553 (11)	762 (25)	121 (11)
C(5)	5599 (18)	4510 (11)	2987 (24)	113 (11)
C(6)	5442 (13)	3951 (8)	3930 (17)	70 (7)
C(7)	5799 (12)	2768 (8)	4565 (15)	64 (6)
C(8)	6104 (11)	2064 (7)	4179 (16)	58 (6)
C(9)	5296 (10)	1695 (7)	3363 (15)	52 (5)
C(10)	6231 (11)	967 (8)	1906 916	62 (6)
C(11)	5657 (11)	1064 (8)	618 (15)	59 (6)
C(12)	6920 (13)	1755 (9)	-489 (17)	74 (7)
C(13)	6230 (11)	2317 (7)	-988 (14)	54 (6)
C(14)	6738 (12)	3026 (8)	-861 (16)	65 (7)

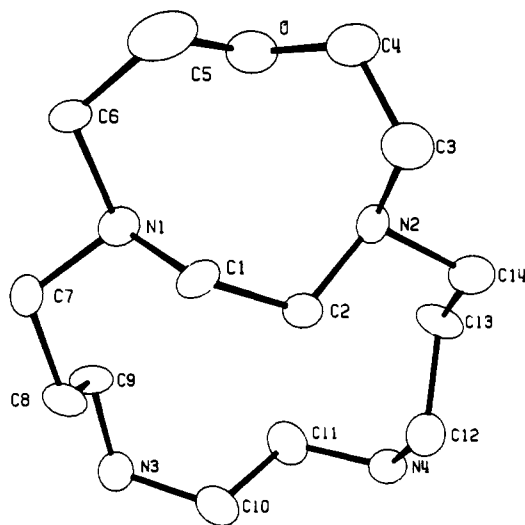
^a Estimated standard deviations are given in parentheses. Coordinates $\times 10^4$, where $n = 5, 4, 4$, and 4 for Cl, O, N, and C. Temperature parameters $\times 10^4$, where $n = 4, 3, 3$, and 3 for Cl, O, N, and C. ^b $U_{\text{eq}} = \frac{1}{3} \sum_i U_{ii}$ is the equivalent isotropic temperature parameter. $U_{\text{eq}} = \frac{1}{3} \sum_i \sum_j U_{ij} a_i^* (a_j^*)$. Primed values indicate that U_{iso} is given. $T = \exp(-8\pi^2 U_{\text{iso}} (\sin^2 \theta) / \lambda^2)$.

The structure was solved for the heavy atoms by using MULTAN²³ and refined by least-squares using SHELX76.²⁰ Other procedures were similar to those described above. The refinement converged with a maximum shift/esd of 0.06 on the final cycle and a maximum peak of 0.698 e \AA^{-3} .

$[\text{H}_4(\text{L}_2)](\text{ClO}_4)_4 \cdot \text{H}_2\text{O}$. Following Weissenberg and precession photography, the crystal was mounted in a Nonius CAD4 diffractometer. The cell was refined by using 25 centered reflections in the range $\theta = 18\text{--}35^\circ$. No decomposition of the crystal was observed during the data acquisition. Parameters were obtained by using scan speed 10 on the instrument. Absorption corrections were made.²² The structure was solved by direct methods.²⁰ The refinement converged with a maximum shift/esd of 0.036 on the final cycle and a maximum peak of 1.29 e \AA^{-3} . Considerable perchlorate disorder was observed in two of the anions.

Results

The macrocyclic ligand was synthesized according to the reaction sequence reported for the analogous SN_4 bicyclic ligand 17-thia-1,5,8,12-tetraazabicyclo[10.5.2]nonadecane¹¹ through the Schiff-base condensation of a diamine with glyoxal, followed by the reduction of the intermediate by borohydride. However, in the present system we have not only isolated a crystalline form of the ligand (Figure 1) but also characterized structurally (Figures 2-4) several intermediates formed owing to stabilization of the organic systems by copper(II) (Scheme II). Relevant data are

**Figure 1.** ORTEP diagram of the ligand cation from the tetrahydroperchlorate salt, showing 25% thermal ellipsoids.**Table III.** $[\text{H}_4(\text{L}_2)]^{4+}$ Interatomic Distances (\AA)^a

C(13)-C(12)	1.535 (21)	C(9)-N(3)	1.507 (19)
C(14)-C(13)	1.591 (21)	C(10)-N(3)	1.515 (20)
C(4)-O	1.400 (21)	C(11)-N(4)	1.528 (19)
C(5)-O	1.464 (23)	C(12)-N(4)	1.505 (20)
C(1)-N(1)	1.508 (16)	C(2)-C(1)	1.512 (19)
C(6)-N(1)	1.555 (18)	C(4)-C(3)	1.517 (25)
C(7)-N(1)	1.564 (18)	C(6)-C(5)	1.504 (29)
C(2)-N(2)	1.502 (17)	C(8)-C(7)	1.539 (21)
C(3)-N(2)	1.508 (20)	C(9)-C(8)	1.523 (19)
C(14)-N(2)	1.583 (19)	C(11)-C(10)	1.481 (21)

^a Estimated standard deviations are given in parentheses.

Table IV. $[\text{H}_4(\text{L}_2)]^{4+}$ Bond Angles (deg)^a

C(5)-O-C(4)	110.6 (18)	C(4)-C(3)-N(2)	109.8 (15)
C(6)-N(1)-(1)	115.1 (12)	C(3)-C(4)-O	113.7 (15)
C(7)-N(1)-C(1)	110.8 (11)	C(6)-C(5)-O	107.5 (17)
C(7)-N(1)-C(6)	106.9 (11)	C(5)-C(6)-N(1)	111.2 (14)
C(3)-N(2)-C(2)	114.0 (12)	C(8)-C(7)-N(1)	113.6 (12)
C(14)-N(2)-C(2)	109.8 (11)	C(9)-C(8)-C(7)	112.8 (12)
C(14)-N(2)-C(3)	107.2 (11)	C(8)-C(9)-N(3)	110.8 (11)
C(10)-N(3)-C(9)	111.9 (12)	C(11)-C(10)-N(3)	112.8 (13)
C(12)-N(4)-C(11)	114.2 (12)	C(10)-C(11)-N(4)	109.9 (12)
C(2)-C(1)-N(1)	112.6 (10)	C(13)-C(12)-N(4)	108.6 (14)
C(1)-C(2)-N(2)	117.3 (12)	C(14)-C(13)-C(12)	112.4 (13)
		C(13)-C(14)-N(2)	111.0 (11)

^a Estimated standard deviations are given in parentheses.

presented in Tables II-XIV, with supplementary material provided in Tables S1-S21. ESR (Table XIV) and electrochemical studies have also been made. In the latter, there is evidence for both Cu(I) and Cu(III).

Discussion

Whereas in Schiff-base condensations of this type the expected primary product would be the diimine, evidence has been presented previously^{9,12} for imine-carbinolamine species. Hydrated material produced from a nickel(II) amine/glyoxal reaction, which was difficult to characterize, gave infrared data consistent with an imine-carbinolamine.¹² However, in the present study, while an intermediate dicarbinolamine must be formed, the initial complex identified was an amidol species $[\text{Cu}(\text{L}_1)]^{2+}$ (Scheme II), which is tautomeric with an amide. This species is similar to the imidate complex formed in methanolic media in the condensation of the corresponding pentaaza system (N_4NH).⁹ Incomplete reduction of the amidol with BH_4^- results in the enamine $[\text{Cu}(\text{L}_3)]^{2+}$. Further reaction with an excess of reductant yields the macrocyclic ion $[\text{Cu}(\text{L}_2)]^{2+}$.

Molecular Structures. The structures of the free ligand and the various copper complexes are shown in Figures 1-4.

Table V. $[\text{Cu}(\text{L}_1)]^{2+}$ Atomic Coordinates and Temperature Parameters^a

atom	<i>x/a</i>	<i>y/b</i>	<i>z/c</i>	<i>U</i> _{eq} ^b Å ²
Cu(1)	-20482 (13)	37389 (10)	31616 (9)	483 (5)
Cl(1)	78333 (37)	10997 (27)	14019 (25)	723 (13)
Cl(2)	30431 (39)	34588 (35)	3177 (25)	827 (16)
O(1)	7027 (19)	1683 (13)	883 (10)	184 (9)
O(2)	8651 (24)	549 (18)	967 (11)	232 (12)
O(3)	8470 (17)	1713 (16)	2006 (11)	186 (9)
O(4)	7135 (16)	441 (15)	1888 (12)	194 (10)
O(5)	1756 (17)	3631 (23)	285 (14)	284 (16)
O(6)	3702 (17)	4248 (13)	169 (16)	236 (13)
O(7)	3044 (16)	2709 (18)	-252 (13)	227 (12)
O(8)	3429 (31)	3180 (24)	1051 (13)	376 (20)
O	-2495 (8)	5238 (6)	3776 (5)	66 (3)
O(10)	1692 (15)	2965 (11)	3526 (10)	150 (7)
N(1)	-3997 (10)	3586 (9)	3250 (6)	66 (4)
N(2)	-2479 (11)	4528 (8)	2096 (6)	59 (4)
N(3)	-1618 (13)	2878 (15)	4157 (9)	118 (7)
N(4)	-156 (12)	3657 (10)	3020 (10)	100 (6)
C(1)	-4686 (15)	4006 (15)	2478 (10)	101 (7)
C(2)	-3766 (13)	4077 (12)	1795 (8)	75 (6)
C(3)	-2639 (17)	5643 (11)	2286 (10)	85 (6)
C(4)	-2108 (18)	5947 (12)	3146 (12)	97 (7)
C(5)	-3816 (16)	5300 (13)	3963 (11)	94 (7)
C(6)	-4348 (15)	4218 (13)	4008 (11)	90 (7)
C(7)	-4342 (15)	2461 (13)	3359 (11)	95 (7)
C(8)	-3679 (22)	1943 (13)	4101 (12)	110 (9)
C(9)	-2234 (22)	1834 (16)	4086 (11)	111 (9)
C(10)	-205 (22)	2925 (24)	4368 (11)	164 (13)
C(11)	416 (14)	3216 (13)	3668 (20)	129 (11)
C(12)	465 (17)	3782 (15)	2232 (13)	106 (8)
C(13)	-179 (19)	4617 (14)	1711 (12)	101 (8)
C(14)	-1539 (16)	4348 (13)	1427 (9)	80 (6)

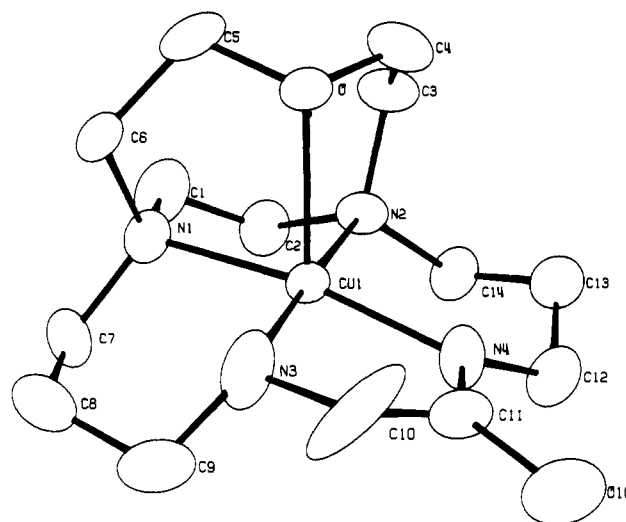
^a Estimated standard deviations are given in parentheses. Coordinates $\times 10^4$, where $n = 5, 5, 4, 4$, and 4 for Cu, Cl, O, N, and C. Temperature parameters $\times 10^4$, where $n = 4, 4, 3, 3$, and 3 for Cu, Cl, O, N, and C. ^b See footnote b in Table II.

Table VI. Complex Ion $[\text{Cu}(\text{L}_1)]^{2+}$ Interatomic Distances (Å)^a

O-Cu(1)	2.259 (8)	N(3)-Cu(1)	1.987 (12)
N(1)-Cu(1)	2.044 (10)	N(4)-Cu(1)	1.991 (12)
N(2)-Cu(1)	2.029 (9)		

^a Estimated standard deviations are given in parentheses.

$[\text{H}_4(\text{L}_2)](\text{ClO}_4)_4$. X-ray-quality crystals were obtained from a strongly acidic (HClO_4) solution of the ligand. The structure is shown in Figure 1. Unfortunately during refinement it was found that there was unresolvable disorder associated with two of the perchlorates, centered on C(13) and C(14). For this reason, the final *R* value of 0.117 ($R_w = 0.125$) is very high. Relevant data are provided in Tables II-IV. However, sufficient information on the structure is provided that it may be used as a perspective of the framework into which the metal ion is incorporated. There are also surprisingly few ligand structures of this type of ligand available. The closest comparisons are in the cage macrobicycles 5-*X*-12,17-dimethyl-1,9,12,17-tetraazabicyclo-[7.5.5]nonadecane ($X = \text{NH}, \text{O}$), where the axially binding atom is located in the bridge spanning the two tertiary nitrogens of the 12-membered ring. In that pentaaza system,²⁴ the macrocycle has been shown to take up three hydrogen ions, behaving in the first protonation step as a proton sponge. The structure proposed for the protonated ion involves two hydrogen ions incorporated into the macrocycle as part of a network comprising all five nitrogen centers. Where $X = \text{O}$,²⁵ there is evidence for the proton located as a "quasi metal" complexing agent. These structures are in marked contrast to the present ion, where all four of the nitrogens are protonated. The rings show considerable puckering, with some distortion round the tertiary nitrogens N(1) and N(2). In this case, the angles C(6)-N(1)-C(1) (115.1 (12)°) and C-

**Figure 2.** ORTEP diagram of the cation $[\text{Cu}(\text{L}_1)]^{2+}$, showing 25% thermal ellipsoids.**Table VII.** Complex Ion $[\text{Cu}(\text{L}_1)]^{2+}$ Bond Angles (deg)^a

N(1)-Cu(1)-O	80.0 (4)	N(4)-Cu(1)-N(2)	95.8 (5)
N(2)-Cu(1)-O	83.4 (4)	N(4)-Cu(1)-N(3)	83.4 (5)
N(2)-Cu(1)-N(1)	86.5 (4)	C(11)-Cu(1)-O	107.5 (5)
N(3)-Cu(1)-O	100.6 (6)	C(11)-Cu(1)-N(1)	150.3 (7)
N(3)-Cu(1)-N(1)	93.7 (5)	C(11)-Cu(1)-N(2)	122.6 (7)
N(3)-Cu(1)-N(2)	175.9 (7)	C(11)-Cu(1)-N(3)	56.8 (7)
N(4)-Cu(1)-O	109.0 (5)	C(11)-Cu(1)-N(4)	26.8 (7)
N(4)-Cu(1)-N(1)	170.9 (5)		

^a Estimated standard deviations are given in parentheses.

(3)-N(2)-C(2) (114.0 (12)°) are much larger than the tetrahedral angle in contrast to the other angles around these atoms. However, the lack of precise information on the location of the hydrogens, unavailable owing to perchlorate disorder, limits detailed analysis, especially for the other nitrogen centers where slightly larger angles are again observed.

$[\text{Cu}(\text{L}_1)]^{2+}$. X-ray-quality crystals were obtained from a solvent mixture of acetonitrile/ether. The structure of the five-coordinate ion is shown in Figure 2. Relevant crystal data are presented in Tables V-VII. The crystal structure consists of a complex ion packed with two perchlorate counterions. The coordination geometry at the copper center is square pyramidal and very similar to that of $[\text{Cu}(\text{daptacn})]^{2+}$ ²⁶ (daptacn = 1,4-bis(amino-propyl)-1,4,7-triazacyclononane) apart from the additional chelate ring. The ion is virtually identical with the imidate intermediate formed in the pentaaza system from the daptacn precursor.⁹ It represents the first example of an amidol complex of this type and the immediate product of the dehydration of the dicarbinolamine formed in the Schiff-base condensation. The N(4)-C(11) distance (1.31 (3) Å) is much shorter than the other N-C bonds in the ion (1.46 (2)-1.53 (2) Å) and must be regarded as a double bond. The distance is almost identical with that in the imidate complex investigated previously⁹ (1.28 (2) Å) and is also very similar to the values (1.29, 1.30 Å) found for the C=N bonds in a conjugated diimine derived from nickel(II) cyclam, where there is multiple-bond character.²⁷ The bond angles at both C(11) and N(4) also reflect unsaturation. Around C(11), two of the angles are 124° and the other 111 (2)°. The latter, N(4)-C(11)-O(10), is probably influenced by a hydrogen bond between O(10) and O(7) of one of the perchlorates. Although the hydrogen was not locatable, the O(10)-O(7) link (2.507 Å) is consistent with a strong hydrogen bond. At N(4), there is some asymmetry with two angles at 125° and 123° and the C(11)-N(4)-Cu angle of 109 (1)°. The larger angles may reflect the pull exerted by C(10) to allow for formation of the five-membered chelate ring. The

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Table VIII. $[\text{Cu}(\text{L}_3)]^{2+}$ Fractional Atomic Coordinates and Temperature Parameters^a

atom	<i>x/a</i>	<i>y/b</i>	<i>z/c</i>	<i>U</i> _{eq} ^b , Å ²
Cu(1)	12676 (7)	40914 (5)	25524 (7)	412 (4)
Cl(1)	-6632 (17)	19689 (14)	-3056 (18)	630 (10)
Cl(2)	33460 (18)	-4280 (15)	77703 (20)	677 (10)
O	154 (4)	3419 (3)	2113 (4)	57 (2)
O(1)	175 (5)	1954 (5)	-54 (5)	97 (4)
O(2)	-1139 (5)	1941 (5)	512 (6)	106 (4)
O(3)	-836 (7)	2616 (3)	-790 (7)	134 (5)
O(4)	-814 (5)	1355 (5)	-879 (6)	106 (4)
O(5)	2881 (6)	-955 (5)	8302 (8)	134 (5)
O(6)	3549 (8)	-709 (7)	6930 (7)	163 (6)
O(7)	4021 (6)	-307 (7)	8321 (7)	145 (6)
O(8)	2841 (6)	181 (4)	7680 (6)	108 (4)
N(1)	1766 (6)	3055 (4)	2556 (6)	68 (3)
N(2)	1461 (5)	4089 (4)	1147 (5)	58 (3)
N(3)	1260 (6)	4153 (4)	3962 (6)	68 (3)
N(4)	661 (6)	5047 (4)	2582 (6)	74 (4)
C(1)	2098 (8)	2902 (7)	1586 (8)	93 (5)
C(2)	2217 (6)	3630 (6)	1093 (7)	72 (4)
C(3)	778 (7)	3724 (7)	610 (7)	72 (4)
C(4)	2 (6)	3680 (6)	1164 (7)	70 (4)
C(5)	349 (7)	2631 (5)	2165 (8)	77 (5)
C(6)	1056 (8)	2554 (6)	2800 (9)	83 (5)
C(7)	2476 (8)	2972 (7)	3210 (8)	92 (5)
C(8)	2239 (8)	3148 (8)	4246 (9)	96 (6)
C(9)	2041 (9)	3931 (8)	4446 (7)	96 (6)
C(10)	1082 (12)	4948 (8)	4178 (10)	124 (8)
C(11)	509 (10)	5208 (9)	3626 (11)	137 (8)
C(12)	996 (7)	5649 (7)	1958 (13)	97 (6)
C(13)	1021 (8)	5425 (8)	972 (11)	98 (6)
C(14)	1670 (8)	4840 (6)	765 (8)	83 (5)

^a See footnote *a* in Table V. ^b See footnote *b* in Table II.

sum of the angles at each center is 359 and 358°, respectively, indicating planarity. Mean plane calculations involving atoms Cu, N(4), C(11), C(12), C(10), and O(10) show extensive planarity with the most significant deviation (0.14 Å) at N(4).

Including the data for the free ligand for the C–O distances observed at the apical oxygen, the average lengths in all the systems under consideration are C(5)–O = 1.45 (3) Å and C(4)–O = 1.44 (2) Å. However, in this ion, the C(11)–O(10) bond (1.39 (2) Å) is significantly shorter. This reflects a π-bond character from a resonance form with more amide contribution.

The four equatorial nitrogens do not form a truly ideal plane, with N(2) and N(3) above and N(1) and N(4) below. The ligand structure is similar to that found in previous complexes of this type. The Cu–N(1) and Cu–N(2) bonds to the tertiary nitrogens, 2.04 (1) and 2.03 (1) Å, respectively, are longer than those to the secondary centers (Cu–N(3) = Cu–N(4) = 1.99 (1) Å). The longest bond to copper is the apical Cu–O, which at 2.259 (8) Å is somewhat longer than the corresponding Cu–N (2.21 (1) Å) in the pentaaza imidate ion.⁹ This may reflect the weaker ligating tendency of the ether oxygen. In the present complex ion, the copper is positioned 0.114 (10) Å above the N₄ plane toward the apical oxygen, much less than the 0.21 (2) Å observed for the N₅ imidate.⁹ The angle between the Cu–O(ap) vector and the normal to the N₄ plane is 15.2°. This tilting of the apical atom away from the position directly above the copper is a feature of all the ions studied and is the result of the inability of the ligand to completely reach over and occupy the orthogonal site.

An unsatisfactory feature of the structure is the rather poor temperature factor associated with atom C(10), for which the origin is not known at present. Of interest, however, is the fact that another form of this ion was found under slightly differing experimental conditions. At neutral pH, the ion exists as a dimer where there is deprotonation of one of the amidol hydrogen atoms and a strong hydrogen bond (O(10)–O(10)' = 2.45 Å) between the two inverted complex ions. Structural parameters are virtually identical with those described above with the exception that the C(10)–C(11) distance is 1.45 Å, closer to the single-bond value anticipated. Again, of the three perchlorates required for electroneutrality, one is badly disordered. A figure of this ion is

Table IX. Complex Ion $[\text{Cu}(\text{L}_3)]^{2+}$ Interatomic Distances (Å)^a

O–Cu(1)	2.335 (6)	N(3)–Cu(1)	2.023 (8)
N(1)–Cu(1)	2.065 (8)	N(4)–Cu(1)	2.020 (7)
N(2)–Cu(1)	2.041 (7)		

^a Estimated standard deviations are given in parentheses.

Table X. $[\text{Cu}(\text{L}_3)]^{2+}$ Bond Angles (deg)^a

N(1)–Cu(1)–O	81.6 (3)	N(4)–Cu(1)–N(2)	96.0 (4)
N(2)–Cu(1)–O	82.1 (3)	N(4)–Cu(1)–N(3)	85.9 (4)
N(2)–Cu(1)–N(1)	86.3 (3)	C(2)–Cu(1)–O	96.2 (3)
N(3)–Cu(1)–O	107.0 (3)	C(2)–Cu(1)–N(1)	59.2 (3)
N(3)–Cu(1)–N(1)	92.9 (3)	C(2)–Cu(1)–N(2)	32.9 (3)
N(3)–Cu(1)–N(2)	170.6 (3)	C(2)–Cu(1)–N(3)	140.8 (4)
N(4)–Cu(1)–O	92.6 (3)	C(2)–Cu(1)–N(4)	124.9 (4)
N(4)–Cu(1)–N(1)	173.4 (4)		

^a Estimated standard deviations are given in parentheses.

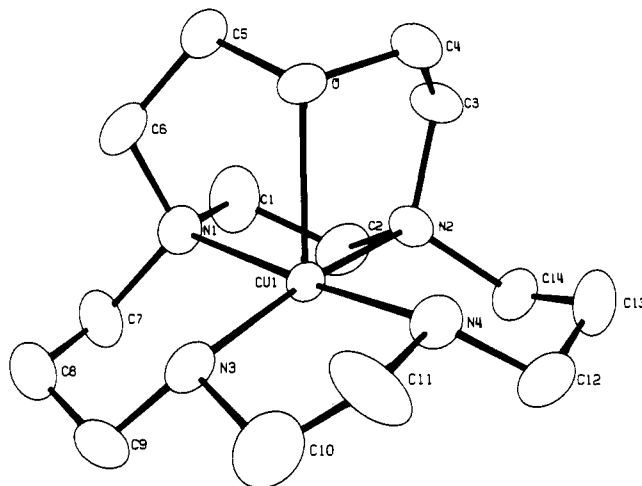


Figure 3. ORTEP diagram of the cation $[\text{Cu}(\text{L}_3)]^{2+}$, showing 25% thermal ellipsoids.

provided with the supplementary material submitted with this paper.

$[\text{Cu}(\text{L}_3)]^{2+}$. Crystals of the perchlorate salt were grown from a solution of the complex in acetonitrile in an ether atmosphere. The atomic coordinates, bond lengths, and angles are listed in Tables VIII–X. The structure consists of a five-coordinate copper complex and two perchlorate counterions. The molecular structure of the cation is shown in Figure 3.

The coordination geometry at the copper center may be described as square pyramidal with a weak interaction between the copper and O(8) of one of the perchlorate ions (2.98 Å). As was seen in the amidol complex above, the bond lengths to the tertiary nitrogens (Cu–N(1) = 2.065 (8) Å and Cu–N(2) = 2.041 (7) Å) are somewhat longer than those to the secondary atoms (Cu–N = 2.021 (7) Å (average)). The distance between the metal ion and the apical oxygen, 2.335 (6) Å, is longer than that found for the other two cations. The angles subtending atoms in the propyl bridges, e.g., C(9)–N(3)–Cu, are all uniformly in the range 113–114°, significantly different from those (105.0 (7) and 105.5 (7)°) within the five-membered ring containing the double bond. The value of 1.34 (2) Å for the C(10)–C(11) distance is consistent with unsaturation within this ring.

Of the three copper complexes examined in this study, the four “planar” nitrogens in this cation are the most distorted toward a pseudotetrahedral arrangement. In the enamine, the copper center is only 0.0325 Å above the N(4) plane, which is less than the nitrogens forming the base of the square pyramid. The degree of tugging of the apical oxygen is reflected by the angle of incidence between the Cu–O vector and the mean N₄ plane at 14.8°.

$[\text{Cu}(\text{L}_2)]^{2+}$. The structure of this ion is shown in Figure 4. The atomic coordinates, bond lengths, and angles are listed in Tables XI–XIII. In this case, the four atoms of the N₄ plane show only minor deviations (0.006 Å maximum) from coplanarity. The

Table XI. $[\text{Cu}(\text{L}_2)]^{2+}$ Fractional Atomic Coordinates and Temperature Parameters^a

atom	<i>x/a</i>	<i>y/b</i>	<i>z/c</i>	$U_{\text{eq}}^b \text{ \AA}^2$
Cu(1)	-6678 (13)	24536 (14)	27528 (17)	405 (6)
Cl(1)	20712 (39)	2442 (32)	30757 (48)	647 (20)
Cl(2)	62747 (36)	20683 (36)	23817 (46)	658 (20)
O(1)	2625 (9)	-360 (8)	3887 (14)	91 (6)
O(2)	1257 (14)	-190 (11)	2418 (15)	150 (9)
O(3)	1694 (9)	897 (8)	3821 (13)	95 (6)
O(4)	2629 (16)	584 (12)	2272 (20)	209 (14)
O(5)	7253 (11)	2315 (11)	2299 (17)	141 (9)
O(6)	6295 (11)	1560 (11)	3499 (14)	122 (8)
O(7)	5971 (11)	1559 (11)	1314 (13)	126 (8)
O(8)	5694 (12)	2811 (10)	2429 (15)	135 (8)
O	921 (7)	2834 (7)	2781 (10)	55 (4)
N(1)	-881 (10)	3750 (9)	2200 (14)	60 (6)
N(2)	-520 (12)	2207 (10)	868 (13)	75 (7)
N(3)	-858 (9)	2674 (8)	4624 (11)	48 (5)
N(4)	-513 (9)	1164 (8)	3248 (14)	60 (6)
C(1)	-1371 (15)	3651 (15)	849 (18)	83 (9)
C(2)	-742 (16)	3051 (15)	107 (17)	88 (9)
C(3)	569 (13)	1944 (13)	844 (18)	72 (8)
C(4)	1239 (13)	2645 (13)	1527 (16)	73 (8)
C(5)	911 (12)	3781 (10)	3133 (17)	63 (8)
C(6)	74 (13)	4242 (12)	2274 (18)	69 (8)
C(7)	-1589 (14)	4269 (12)	2887 (20)	75 (9)
C(8)	-1285 (13)	4242 (11)	4347 (20)	68 (8)
C(9)	-1517 (14)	3375 (13)	4994 (19)	82 (9)
C(10)	-1198 (14)	1811 (12)	5131 (18)	72 (8)
C(11)	-532 (12)	1115 (12)	4706 (19)	71 (8)
C(12)	-1239 (13)	594 (13)	2450 (22)	80 (9)
C(13)	-1032 (16)	550 (16)	1048 (25)	103 (12)
C(14)	-1214 (16)	1457 (19)	320 (18)	96 (11)

^a See footnote *a* in Table V. ^b See footnote *b* in Table II.**Table XII.** Complex Ion $[\text{Cu}(\text{L}_2)]^{2+}$ Interatomic Distances (\AA)^a

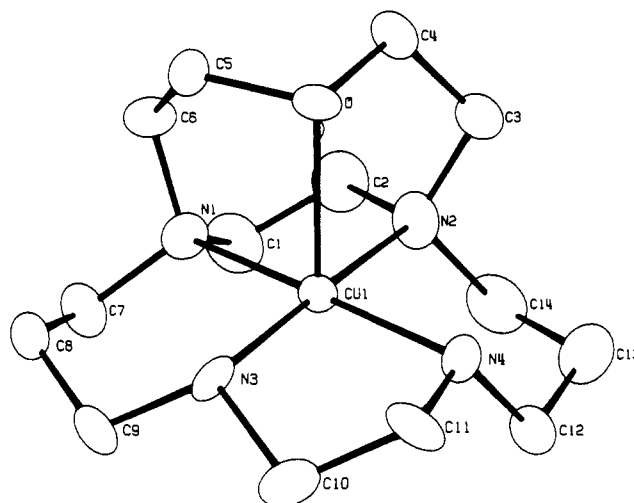
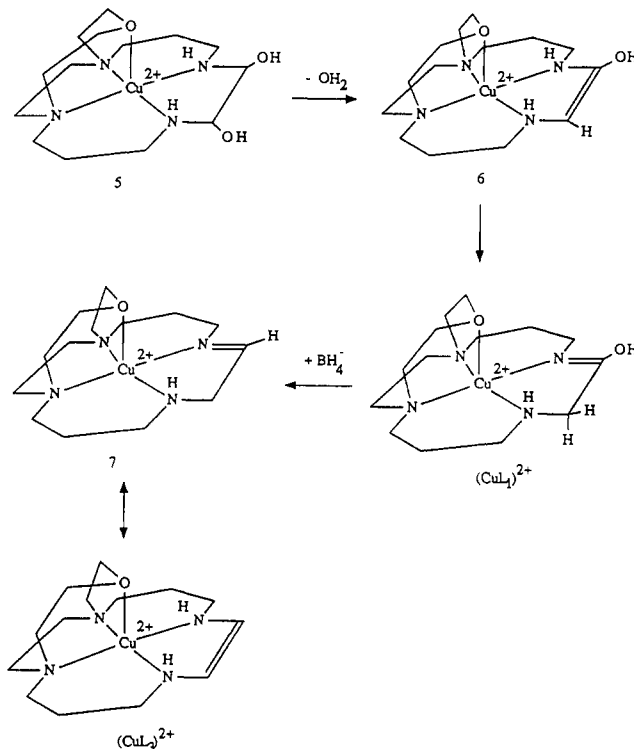
O-Cu(1)	2.275 (9)	N(3)-Cu(1)	2.038 (12)
N(1)-Cu(1)	2.054 (12)	N(4)-Cu(1)	2.021 (13)
N(2)-Cu(1)	2.045 (14)		

^a Estimated standard deviations are given in parentheses.**Table XIII.** Complex Ion $[\text{Cu}(\text{L}_2)]^{2+}$ Bond Angles (deg)^a

N(1)-Cu(1)-O	82.2 (5)	N(4)-Cu(1)-N(2)	92.9 (6)
N(2)-Cu(1)-O	80.3 (5)	N(4)-Cu(1)-N(3)	86.3 (5)
N(2)-Cu(1)-N(1)	86.1 (6)	C(1)-Cu(1)-O	95.1 (5)
N(3)-Cu(1)-O	101.6 (4)	C(1)-Cu(1)-N(1)	31.8 (6)
N(3)-Cu(1)-N(1)	94.7 (5)	C(1)-Cu(1)-N(2)	59.9 (6)
N(3)-Cu(1)-N(2)	178.0 (6)	C(1)-Cu(1)-N(3)	120.3 (6)
N(4)-Cu(1)-O	99.9 (4)	C(1)-Cu(1)-N(4)	146.1 (6)
N(4)-Cu(1)-N(1)	177.5 (6)		

^a Estimated standard deviations are given in parentheses.

trans-basal angles are $\text{N}(3)\text{-Cu-N}(2) = 178.0 (6)$ and $\text{N}(1)\text{-Cu-N}(4) = 177.5 (6)^\circ$, respectively. The copper atom is located 0.0396 \AA above the plane, but there is a strong bond with the apical oxygen ($2.275 (9) \text{ \AA}$), confirming the square-pyramidal nature of the complex cation. As in the enamine case, there is a weak interaction between O(5) of one of the perchlorates and the sixth site of the copper coordination sphere (2.866 \AA). This is shorter than the corresponding electrostatic interaction in the $[\text{Cu}(\text{L}_3)]^{2+}$ ion, presumably owing to the closer coplanarity of the copper in the fully saturated ring. Unlike the other two copper complex ions under consideration, the Cu-N bonds are all 2.04 \AA within experimental error. This is identical with the average distances found for the $[\text{Cu}(\text{N}_4\text{S})]^{2+}$ macrobicycle and is typical of N_4 ligands coordinated in planar fashion around copper(II).²⁸ In other respects, the ion is closely similar to the enamine, except for the lengthening of the C(10)-C(11) bond to $1.51 (2) \text{ \AA}$ consistent with a single bond. The "tugging" angle 13.4° is lower than for the other two ions, presumably owing to the better encapsulation of the copper into the N_4 plane.

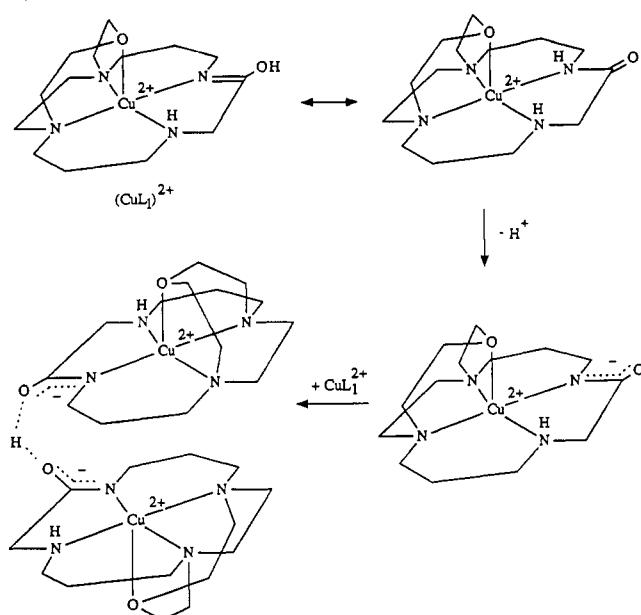
**Figure 4.** ORTEP diagram of the cation $[\text{Cu}(\text{L}_2)]^{2+}$, showing 25% thermal ellipsoids.**Scheme III**

Formation of the Intermediates. The amidol intermediate isolated as the first product is not one of the three products expected for a template condensation of this type.

In Scheme III is presented a mechanism whereby the amidol may be formed. It is proposed that the initial product of the glyoxal condensation is the dicarbinolamine (**5**), which, upon elimination of water, yields an imine-carbinolamine (not shown). Subsequent base-catalyzed proton shifts yield the unsaturated enolic species **6**, which is converted to the $[\text{Cu}(\text{L}_1)]^{2+}$ ion by a tautomeric proton rearrangement. Alternatively, **5** loses a water molecule as shown to yield the $\text{C}=\text{C}$ bond, which then undergoes tautomeric change. The ionization of methylene protons adjacent to an imine in a five-membered ring is well documented.²⁹ The amide may be produced under basic conditions (Scheme IV). In this regard it is similar to the system observed for the $[\text{Cu}(\text{N}_5)]^{2+}$ ion formed on base hydrolysis of the corresponding imidate.⁹ Interaction with a second mole of $[\text{Cu}(\text{L}_1)]^{2+}$ results in the for-

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Scheme IV



mation of the hydrogen-bonded dimer, the structure of which is presented as supplementary material. Reduction of an imidate (and, by extension, an amidol) by BH_4^- results in the formation of secondary amines. The mechanism suggested³⁰ involves the formation of an imine, which is generally not observed, indicating that the imine reduction is a faster process than the initial reaction of the amidol (Scheme III). In the present system, the imine **7**, which is formed under conditions of deficiency of BH_4^- , can rearrange to the enamine $[\text{Cu}(\text{L}_3)]^{2+}$. The imine–enamine equilibrium would normally favor the former. However, in the system under study, the energy associated with the formation of 120° bonds at the coordinated imine is sufficiently great to promote rearrangement to the enamine.

There is an interesting comparison between the amidol species and the monooxo–tetraamine complexes described previously by Kimura.³¹ In the case of monooxocyclam, where the ring contains one amido group, there is no evidence for the amidol, and a significant thermodynamic preference is observed for the square-planar forms of the nickel(II) and copper(II) complexes, even in the presence of potential axially coordinating donors. In the present system, although the ether oxygen is a weak binder, it is a sufficiently good σ donor, both in the copper case and in the corresponding nickel(II) complex, which is high spin,²⁷ that coordination is observed. Perhaps it is noteworthy that there is no ready deprotonation of the amide, implying a weaker in-plane ligand field than the amido nitrogen. What is clear is that there are subtle effects of the ring field that can be transmitted to the metal center and that are exhibited by the facility to change coordination number. A weak Cu–O(ether) bond (2.47 (2) Å) has been reported in the copper(II) complex of the potentially ditopic receptor 1,4,7,10-tetraoxa-13,16,19,22-tetraazacyclotetradecane,³² which is considerably longer than the corresponding bonds (2.25–2.33 Å) found in the present study.

The present ligand framework is related to the ligand 1-oxa-4,7-diazacyclononane (9-ane N_2O , L_4). Thermodynamic studies¹⁷ show that there is considerable stabilization relative to other similar systems. It is suggested that this relates to the conformation of the 9-membered ring favoring coordination to the octahedral face of a small metal ion. Of the first-row elements, Cu^{2+} forms the strongest complex, $\log K_2([\text{Cu}(\text{L}_4)_2]^{2+}) = 10.86$.¹⁷ In this system both ether oxygens are bound to the copper ion. However, with

Table XIV. ESR Parameters for Various Copper(II) Ions

complex ion	g_{\parallel}	A_{\parallel} , G	g_{\perp}	A_{\perp} , G
$[\text{Cu}(\mathbf{4})]^{2+}$ (DMF/ H_2O , 1/1)	2.220	190	2.060	30
$[\text{Cu}(\text{L}_1)]^{2+}$ ($\text{CH}_3\text{CN}/\text{DMF}$, 1/1)	2.194	188	2.043	42 (2)
$[\text{Cu}(\text{L}_1)]^{2+}$ (1.5 M HNO_3)	2.182	200	2.050	<i>a</i>
$[\text{Cu}(\text{L}_1)]^{2+}$ (1 M NaOH/DMF , 1/1)	2.180	195	2.061	40
$[\text{Cu}(\text{L}_2)]^{2+}$ (1.5 M HNO_3)	2.189	197	2.072	<i>a</i>
$[\text{Cu}(\text{L}_2)]^{2+}$ ($\text{CH}_3\text{CN}/\text{DMF}$, 1/1)	2.204	190	2.047	35 (4)
$[\text{Cu}(\text{L}_3)]^{2+}$ ($\text{H}_2\text{O}/\text{DMF}$, 1/1)	2.197	196	2.056	42 (2)
$[\text{Cu}(\text{L}_3)]^{2+}$ ($\text{CH}_3\text{CN}/\text{DMF}$, 1/1)	2.190	193	2.050	42 (2)
$[\text{Cu}(\text{cyclam})]^{2+}$ (DMF)	2.194	206	2.02	29 ^{b,c}
$[\text{Cu}(\text{cyclam})]^{2+}$ (DMF)	2.200	205	2.050	30 ^{b,d}

^a Feature observed but unresolved. ^b Reference 33. ^c Perchlorate salt. ^d Perfluorothiophenolate salt.

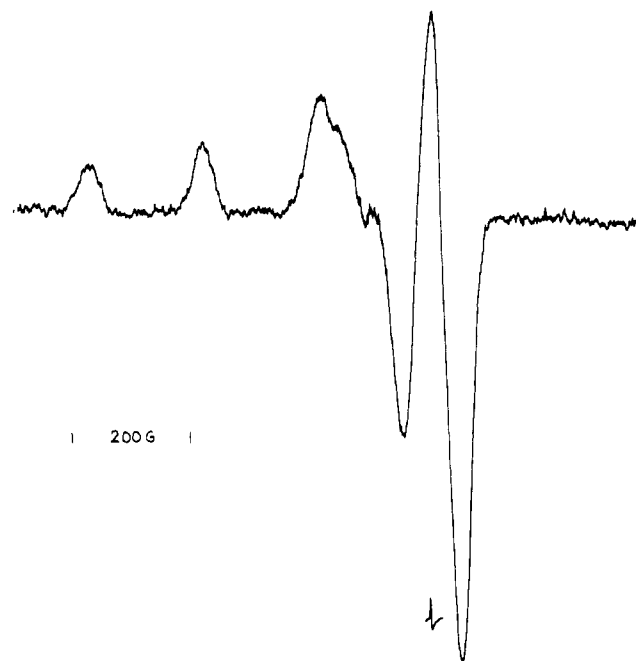


Figure 5. Frozen-solution ESR spectrum of $[\text{Cu}(\text{L}_2)]^{2+}$ at 77 K, in $\text{CH}_3\text{CN}/\text{H}_2\text{O}$ medium.

the additional cyclam framework in the bicyclo ligands, the stability constant for $[\text{Cu}(\text{L}_2)]^{2+}$ undoubtedly will be considerably higher.

The molecular structure of each complex ion is best described as a distorted square pyramid. In some instances the copper ion lies above the mean plane of the four nitrogens, with the apical oxygen atom tilted away from a position directly above the copper. In the case of the ion $[\text{Cu}(\text{L}_3)]^{2+}$, the four nitrogen centers are perfectly planar with a displacement of the metal from the plane of 0.0396 Å toward the oxygen donor. The angle between the apical oxygen and the N_4 plane is 13.4° , as a result of the inability of the apical donor to reach over completely and occupy the position normal to the plane. For the saturated ligand and the amidol, the corresponding values are 14.82 and 15.23° , respectively. As the copper ion is located further out of the plane, the degree of tugging increases.

Although the copper–oxygen bonds reflect a reasonably strong interaction, the ESR spectra are quite similar to that of the copper cyclam complex ion. Representative data are provided in Table XIV, and a typical spectrum is shown in Figure 5. There are only minor variations seen in mixed-solvent systems, even such as acetonitrile, which could coordinate in the sixth axial position. As is seen in Figure 5, both the axial and equatorial hyperfine splitting is observed. The values of g_{\parallel} at 2.18 and g_{\perp} at 2.06 (Table XIV) are closely similar to other square-planar copper(II) systems. In the case of $[\text{Cu}(\text{cyclam})](\text{ClO}_4)_2$ and $\text{Cu}(\text{cyclam})(\text{SC}_6\text{F}_5)_2$,³³ the values (Table XIV) fall in the same range.

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The principal CuN_4 "plane" continues to dominate in these five-coordinate ions. The relatively low A_{\parallel} values are consistent with weak z -axial interaction through the oxygen donor.

Electrochemical studies are currently in progress. There is evidence for both oxidation to copper(III) and reduction to copper(I). In acetonitrile media for $[\text{Cu}(\text{L}_2)]^{2+}$, two oxidation features are observed, at 1.34 and 1.745 V, respectively. However, only one reduction peak is seen at -1.1 V. The cyclic voltammograms provide evidence for transient species in intermediate geometry, which may reflect a similar "square" format outlined recently in the electron-transfer reactions of copper(II/I) thioether systems.³⁴

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Supplementary Material Available: Tables S1-S17, containing bond distances and angles, anisotropic temperature parameters, selected intermolecular distances, and experimental crystallographic data for all complexes, and a diagram of the dimeric amidol structure (29 pages); Tables S18-S21, listing calculated and observed structure factors (33 pages). Ordering information is given on any current masthead page.

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Effects of a Bridging Dicarboxylate Ligand on the Synthesis and Physical Properties of (μ -Oxo)bis(μ -carboxylato)diiron(III) Complexes[†]

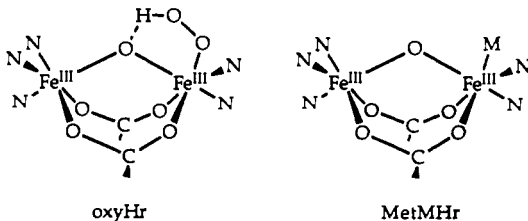
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The molecule *m*-phenylenedipropionic acid (H_2MPDP), in which two carboxylates are part of the same bridging unit, has been used in the synthesis of diiron(III) oxo protein analogues containing the (μ -oxo)bis(μ -carboxylato)diiron(III) core. The dicarboxylate ligand MPDP^{2-} facilitates the self-assembly synthesis of $[\text{Fe}_2\text{O}(\text{MPDP})\{\text{HB}(\text{pz})_3\}_2]$ and $[\text{Fe}_2\text{O}(\text{MPDP})\text{B}_2\text{Cl}_2]$ complexes having terminal bidentate, B, dipyriddy, or bis(1-methylimidazol-2-yl)phenylmethoxymethane (BIPhMe, a polyimidazole nitrogen donor), and monodentate chloride ligands. The structural features and physical properties of $[\text{Fe}_2\text{O}(\text{MPDP})\{\text{HB}(\text{pz})_3\}_2]$ and the two $[\text{Fe}_2\text{O}(\text{MPDP})\text{B}_2\text{Cl}_2]$ complexes, elucidated in single-crystal X-ray diffraction studies, are very similar to those of the acetate analogue, $[\text{Fe}_2\text{O}(\text{O}_2\text{CCH}_3)_2\{\text{HB}(\text{pz})_3\}_2]$, indicating that the coordinated MPDP^{2-} ligand preserves the integrity of the (μ -oxo)bis(μ -carboxylato)diiron(III) core. The multidentate ligand does not impart unusual stability to the $[\text{Fe}_2\text{O}(\text{MPDP})]^{2+}$ core, however, since decomposition to form $[\text{Fe}\{\text{HB}(\text{pz})_3\}_2]$ occurred during attempts to reduce $[\text{Fe}_2\text{O}(\text{MPDP})\{\text{HB}(\text{pz})_3\}_2]$ electrochemically. Small differences between the spectroscopic properties of $[\text{Fe}_2\text{O}(\text{MPDP})\{\text{HB}(\text{pz})_3\}_2]$ and $[\text{Fe}_2\text{O}(\text{MPDP})\text{B}_2\text{Cl}_2]$ complexes can be accounted for by changes in terminal ligation. The coordination of the BIPhMe imidazole nitrogen atoms to the (μ -oxo)bis(μ -carboxylato)diiron(III) center affords a more accurate model of the histidine ligation found in the proteins and more stable complexes than the dipyriddy counterparts. Chloride ion is coordinated cis to the oxo bridge in both $[\text{Fe}_2\text{O}(\text{MPDP})\text{B}_2\text{Cl}_2]$ complexes, the position where exogenous ligands and dioxygen bind in the invertebrate respiratory protein hemerythrin (Hr). The presence of this labile ligand facilitates terminal ligand exchange reactions. Crystal data: $[\text{Fe}_2\text{O}(\text{MPDP})\{\text{HB}(\text{pz})_3\}_2] \cdot 5\text{CH}_2\text{Cl}_2$, triclinic, $P\bar{1}$, $a = 12.878$ (1) Å, $b = 20.301$ (1) Å, $c = 11.906$ (1) Å, $\alpha = 96.28$ (1)°, $\beta = 106.96$ (1)°, $\gamma = 74.33$ (1)°, $Z = 2$; $[\text{Fe}_2\text{O}(\text{MPDP})(4,4'\text{-Me}_2\text{bpy})_2\text{Cl}_2] \cdot 2\text{CH}_3\text{CN}$, triclinic, $P\bar{1}$, $a = 10.941$ (1) Å, $b = 11.328$ (1) Å, $c = 18.781$ (2) Å, $\alpha = 100.34$ (1)°, $\beta = 95.66$ (1)°, $\gamma = 115.56$ (1)°, $Z = 2$; $[\text{Fe}_2\text{O}(\text{MPDP})(\text{BIPhMe})_2\text{Cl}_2] \cdot 3\text{CH}_2\text{Cl}_2 \cdot \text{CH}_3\text{CN}$, triclinic, $P\bar{1}$, $a = 15.446$ (2) Å, $b = 16.077$ (2) Å, $c = 12.453$ (2) Å, $\alpha = 95.41$ (1)°, $\beta = 100.68$ (1)°, $\gamma = 93.17$ (1)°, $Z = 2$.

Introduction

Reversible dioxygen binding, formation of a stable tyrosyl radical, and oxidation of methane are among the remarkable variety of functions performed by dinuclear iron oxo centers in the proteins hemerythrin (Hr),¹ ribonucleotide reductase (RR) from *Escherichia coli*,² and methane monooxygenase (MMO),³ respectively. These proteins bind or activate dioxygen at a vacant or labile coordination site in their reduced, $[\text{Fe}^{\text{II}}\text{Fe}^{\text{II}}]$ forms. Structural⁴ and vibrational spectroscopic⁵ studies have established that Hr binds dioxygen as a terminal hydroperoxide ligand coordinated to one iron of the $\{\text{Fe}_2\text{O}(\text{O}_2\text{CR})_2\}^{2+}$ center, with the remaining terminal sites occupied by histidines:



[†] Abbreviations used in this article: bpy, 2,2'-dipyridine; 4,4'- Me_2bpy , 4,4'-dimethyl-2,2'-dipyridine; $\text{H}_2\text{B}(\text{pz})_2^-$, dihydrobis(1-pyrazolyl)borate; TMEDA, N,N',N'',N''' -tetramethylethylenediamine; BICOH, bis(1-methylimidazol-2-yl)hydroxymethane; H_2MPDP , *m*-phenylenedipropionic acid; $\text{HB}(\text{pz})_3^-$, hydrotris(1-pyrazolyl)borate; BIPhMe, bis(1-methylimidazol-2-yl)phenylmethoxymethane; TMICMe, tris(1-methylimidazol-2-yl)methoxymethane; TICMe, tris(1-imidazol-2-yl)methoxymethane; Me_3TACN , 1,3,7-trimethyl-1,3,7-triazacyclononane; TIEOH, 1,1,2-tris(1-methylimidazol-2-yl)ethanol; TMIP, tris(1-methylimidazol-2-yl)phosphine.

Monodentate (M) anions, including N_3^- , Cl^- , CN^- , OCN^- , and SCN^- , can displace the hydroperoxide ligand, and both the azide adduct and the oxy form of Hr have been crystallographically characterized.^{4,6} By analogy to Hr, the diiron centers in RR and MMO probably function by binding and activating dioxygen at a terminal coordination site.

Discovering the principles by which the protein tunes its diiron center either to bind dioxygen reversibly, as in Hr, or to activate dioxygen, as in RR and MMO, is a major objective of current interest in bioinorganic chemistry. One approach to this problem is to prepare and study small molecule analogues containing the dinuclear iron oxo core. Many features of the structural, magnetic,

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