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Oxydiacetic Acid and Copper(II) Complexes of a New Hexaaza Macrocyclic Dinucleating Ligand

Antoni Llobet,[†] Joseph Reibenspies, and Arthur E. Martell*

Department of Chemistry, Texas A&M University, College Station, Texas 77845-3255

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The synthesis of a new hexaaza macrocyclic ligand 3,7,11,19,23,27-hexaazatricyclo[27.3.1.1^{13,17}]tetratriaconta-1(32),13,15,17(34),29(33),30-hexaene, Mc, by hydrogenation of the corresponding Schiff base is described. The crystal structure of its hexabromide salt, determined by means of X-ray analysis, is also reported. The compound with the empirical formula $C_{28}H_{52}N_6Br_6$ was obtained as a colorless plate crystallizing in the space group $P1$ as a triclinic crystal with the cell dimensions $a = 7.966$ Å, $b = 16.083$ Å, $c = 7.8870$ Å, $\alpha = 93.45°$, $\beta = 97.26°$, and $\gamma = 102.28°$, with one molecule per unit cell. Protonation constants and metal ion stability constants of the mononuclear and dinuclear copper(II) macrocyclic complexes have been measured potentiometrically and are compared with those of analogous ligands. The different protonated forms of the basic ligand Mc recognize oxydiacetic acid and its anions forming nine strongly bound complexes. The formation constants for those complexes were determined with the use of potentiometric methods, and the nature of these complexes is discussed and compared with other analogous host−guest interactions.

Introduction

In recent years, a large body of dinucleating ligands capable of binding two metal ions in close proximity has appeared in the literature as a result of their relevance to various aspects of coordination chemistry.[1] Of special interest among this growing body of complexing agents are the macrocyclic ligands because they can impose a high degree of preorganization on metal complex formation.[2] Furthermore, macrocyclic ligands also constitute an excellent basis for the study of the molecular recognition type of phenomena since their cavity size, shape, and components can be readily varied.[3] In this paper the synthesis and characterization of a new hexaaza macrocyclic dinucleating ligand 3,7,11,19,23,27-hexaazatricyclo[27.3.1.1^{13,17}]-tetratriaconta-1(32),13,15,17(34),29(33),30-hexaene, Mc, its various protonated forms, and the corresponding mononuclear and dinuclear Cu(II) complexes are described. Also reported are the molecular recognition complexes formed between the protonated forms of Mc and those of oxydiacetic acid. The catalytic activities of the Cu(I) and Cu(II) complexes of the Schiff base used in the synthesis of this ligand are described elsewhere.[4]

Experimental Section

Materials. All reagents were ACS reagent grade and were used without further purification.

Carbonate-free solutions of the titrant, KOH, were prepared by dilution of a commercial ampoule of Dilut-It (obtained from J. Baker Chemical Co.) analytical concentrate with demineralized water under a stream of purified nitrogen. The solutions were standardized with potassium acid phthalate (dried powder), and the extent of the carbonate accumulation was checked periodically by titration with a standard hydrochloric acid solution.[5]

3,7,11,19,23,27-hexaazatricyclo[27.3.1.1^{13,17}]tetratriaconta-1(32),2,11,13,15,17(34),18,27,29(33),30-decaene ($(MX)_2(IBP)_2 \cdot H_2O \cdot 0.5CH_3CN$, 1). A solution of 3,3′-iminobis(propylamine) (3.57 mL, 25.0 mmol) in CH_3CN:CH_3OH, 19:1, (950 mL) was added dropwise from a dropping funnel to a stirred solution of 97% *m*-phthalaldehyde (3.46 g, 25.0 mmol) in 375 mL of CH_3CN:CH_3OH, 19:1 (375 mL) in a 2 L round-bottomed three-neck flask over 12 h at room temperature. A small amount of a white solid formed slowly and was filtered out. Upon reducing the volume of the filtrate to dryness, under reduced pressure at 80 °C, an oil appeared. This oil was washed with ether and then redissolved in 50 mL of CH_3CN. Evaporation to dryness again, under the same conditions as previously, resulted in the formation of a bulky crystalline pale-yellowish solid which was dried under vacuum at 50 °C for 12 h. Yield: 3.94 g, 66.1%. The ^1H and ^{13}C NMR spectra in $CDCl_3$ are complex. MS (FAB): *m/e* 459 (M + 1). Anal. Calcd for $C_{29}H_{41.5}N_{6.5}O$: C, 70.09; H, 8.36; N, 18.33. Found: C, 70.00; H, 8.31; N, 18.36.

3,7,11,19,23,27-Hexaazatricyclo[27.3.1.1^{13,17}]tetratriaconta-1(32),13,15,17(34),29(33),30-hexaene Hexahydrobromide Dihydrate. ($Mc \cdot 6HBr \cdot 2H_2O$, 2). $NaBH_4$ (6.25 g, 0.165 mol) was added to a solution obtained by dissolving 6.21 g (12.5 mmol) of the Schiff base **1**[4] in 125 mL of absolute ethanol at room temperature. The suspension was magnetically stirred for about 2 h at room temperature and then gently heated to about 60 °C to ensure that the reaction was completed. Then it was allowed to reach room temperature, at which point 5 mL of H_2O were added to remove unreacted $NaBH_4$. The solvent was removed under reduced pressure, and the product was extracted with CH_2Cl_2 from an aqueous solution (CH_2Cl_2/H_2O, 150 mL/20 mL). Evaporation of CH_2Cl_2 under reduced pressure yielded a colorless oil which was then dissolved in 50 mL of 8% HBr. The volume was reduced, under low pressure, until at approximately 5 mL a white crystalline solid precipitated. This solid was then filtered, washed with a small amount of cold water and methanol, and dried under vacuum at 65 °C overnight. Yield: 5.65 g, 45.78%. ^1H-NMR (D_2O): δ (ppm

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[†] Permanent address: Department de Quimica, Universitat de Girona, Plaça Hospital, 6, 17071-Girona, Spain.

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from DSS) 1.6−1.9 (m, 8H, $NCH_2CH_2CH_2N$), 2.7−3.0 (m, 16H, $NCH_2CH_2CH_2N$), 4.15 (s, 8H, CH_2 of *m*-xylyl), 7.2−7.4 (m, 8H, aromatic H). ^{13}C-NMR (D_2O;CH_3OD (1:1)) δ 23.3 ($NCH_2CH_2CH_2N$), 44.1, 44.8 ($NCH_2CH_2CH_2N$), 51.0 (CH_2 of *m*-xylyl), 130.3, 131.0, 131.2, 131.9 (4 nonequivalent aromatic carbons). MS (FAB): *m/e* 473 (M + 1). Anal. Calcd for $C_{28}H_{56}N_6O_2Br_6$: C, 34.03; H, 5.67; N, 8.51. Found: C, 33.80; H, 5.69; N, 8.59.

Potentiometric Titrations. Potentiometric p[H] measurements and computation of the protonation constants, Cu(II) binding constants, and oxydiacetic acid association constants with the saturated hexaaza macrocyclic ligand Mc were carried out by procedures described in detail elsewhere.[5] The p[H] measurements were made at 25.0 ± 0.1 °C and ionic strength $\mu = 0.100$ M adjusted with KCl. Each titration utilized at least eight points per neutralization of a proton or hydrolytic reaction; typical initial volumes were 50 mL. Each p[H] profile was determined by two titrations on approximately 2.0×10^{-4} M macrocyclic ligand and oxydiacetic acid and 2.0 or 4.0×10^{-4} M Cu(II). Oxygen and carbon dioxide were excluded from the reaction mixture by maintaining a slight positive pressure of purified nitrogen in the reaction cell. Standard stock solutions of 0.100 M NaOH, $CuCl_2$, and oxydiacetic acid were prepared from analytical reagents. The p[H] meter−glass electrode system was calibrated to read hydrogen ion concentration directly so that the measured quantity was $-\log[H^+]$, designated as p[H]. Log K_w for the system, defined in terms of $\log([H^+][OH^-])$, was found to be −13.78 at the ionic strength employed and was maintained fixed during refinements. The range of accurate p[H] measurements was considered to be 2−12.

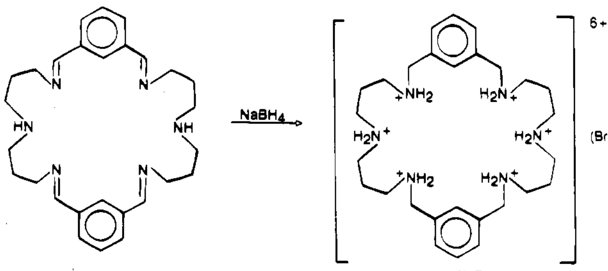
Other Measurements. ^{1}H and ^{13}C NMR were recorded with a Varian XL 200 FT spectrometer operating at 200 MHz. The mass spectra were obtained with the Departmental VG Analytical 70S high-resolution double-focusing magnetic sector spectrometer with an attached VG Analytical 11/250J data system. Elemental analyses were performed by Galbraith Laboratories, Inc., Knoxville, TN.

Preparation of Crystalline Mc·6HBr. Suitable crystals for X-ray analysis were obtained by recrystallizing Mc·6HBr·2H_2O from a mixture of H_2O/CH_3CN (1/5) and allowing it to stand for about 2 weeks in a closed flask at room temperature. The purified crystalline ligand contained no water of crystallization.

Structure Determination. A colorless plate (0.04 mm × 0.20 × 0.28 mm) was mounted on a glass fiber with epoxy cement at room temperature. Preliminary examination and data collection were performed on a Rigaku AFC5R X-ray diffractometer. Cell parameters were calculated from the least-squares fit of the setting angles for 25 reflections. Omega scans for several intense reflections indicated acceptable crystal quality. Data were collected for $5.0° \le 2\theta \le 50.0°$ at 293 K. Scan width for data collection was $1.52 \pm 0.30 \tan(\theta)$, with a variable scan rate of 8.08 to 15.63 deg min^{-1}. Three control reflections, collected every 150 reflections, showed no significant trends. Background measurement was made by the stationary crystal and stationary counter technique at the beginning and end of each scan for 0.50 of the total scan time.

Lorentz and polarization corrections were applied to 3730 reflections. A semiempirical absorption correction was applied. A total of 1752 unique reflections ($R_{int} = 0.02$), with $|I| \ge 2\sigma(I)$, were used in further calculations. The structure was solved by Direct Methods (SHELXS, SHELXTL-PLUS program package[6]). Full matrix least-squares anisotropic refinements for all non-hydrogen atoms (SHELXLS, SHELXTL-PLUS program package[6]), number of least-squares parameters = 181, quantity minimized $\Sigma w(F_o - F_c)^2$; $w^{-1} = \sigma^2 F + gF^2$, $g = 0.000\,33$, yielded $R = 0.051$, $R_w = 0.051$, and $S = 1.31$ at convergence. Hydrogen atoms were placed in idealized positions with isotropic thermal parameters fixed at 0.08 Å^2. Neutral atom scattering factors,[7] and anomalous scattering corrections terms were taken from ref 8.

Scheme 1



1 $(H_2)_{-4}$Mc

2 Mc·6HBr

Table 1. Summary of Crystal Structure Results[a]

empirical formula	$C_{28}H_{52}N_6Br_6$
space group	triclinic, *P*1
unit cell dimensions	$a = 7.966(2)$ Å
	$b = 16.083(5)$ Å
	$c = 7.8870(10)$ Å
	$\alpha = 93.45(2)°$
	$\beta = 97.260(10)°$
	$\gamma = 102.28(2)°$
volume	975(1) Å^3
formula units/cell	1
formula weight	952.2
density (calc)	1.621 g/cm^3
absorption coefficient (μ)	61.4 cm^{-1}
radiation	Mo Kα (λ = 0.710 73 Å)
temperature	293 K
final residuals (obs data)	$R(F_o) = 5.06\%$; $R_w = 5.07\%$

[a] $R(F_o) = \Sigma||F_o| - |F_c||/\Sigma|F_o|$. $R_w = \Sigma||F_o| - |F_c||w^{1/2}$. $W^{-1} = \sigma^2(F_o) + 0.0003(F_o)^2$.

Results and Discussion

Synthesis. Reaction of 3,3′-iminobispropylamine with *m*-phthalaldehyde formed the Schiff base $(H_2)_{-4}$Mc, **1**, the Cu(I) and Cu(II) complexes of which are described elsewhere.[4] Hydrogenation of the Schiff base with $NaBH_4$ followed by treatment with diluted HBr leads to the formation of the hexaaza macrocyclic ligand Mc·6HBr in good yield as outlined in Scheme 1.

Structure of Mc·6HBr (2·6HBr). A summary of the results of the crystal structure studies is presented in Table 1. Atomic coordinates and selected bond lengths and angles are given in Tables 2 and 3, respectively. A thermal ellipsoid plot, with 50% probability, of Mc·6HBr together with the atomic labeling scheme is shown in Figure 1. The crystal structure belongs to the space group *P*1 with the crystallographic inversion center located in the macrocyclic cavity. There is only one molecule per unit cell with extensive hydrogen bonding among neighboring molecules. The three nitrogen atoms of each macrocyclic arm are linearly accommodated in a plane which contains the rest of the aliphatic carbons. The planarity is achieved because of a zigzag type of arrangement of successive N and C atoms. The phenyl rings are nearly perpendicular to that plane pointing in opposite directions. All six nitrogens are protonated, and each has one of the two hydrogen atoms directed outside the ring. None of the bromide counterions are situated inside the macrocyclic cavity. The distance between the xylyl planes is 12.89 Å and the perpendicular width of the cavity is 2.68 Å.

Protonation Constants. The potentiometric equilibrium curve for Mc·6HBr is illustrated in Figure 2. The p[H] profile

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[6] All crystallographic calculations were performed with SHELXTL-PLUS rev 4.11, 1990 (G. M. Sheldrick, Institut fur Anorganische Chemie der Universitat, Tammannstrasse 4, D-3400, Gottigen, Federal Republic of Germany) supplied by Siemens Analytical Instruments, Madison WI, on a VAXII minicomputer.

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Table 2. Atomic Coordinates ($\times 10^4$) and Equivalent Isotropic Displacement Parameters ($Å^2 \times 10^3$) for Mc•6HBr

	x	*y*	*z*	$U(eq)^{a,b}$
Br(1)	−706(2)	1090(1)	4516(1)	60(1)
Br(2)	−389(2)	7107(1)	1690(1)	52(1)
Br(3)	6479(1)	4164(1)	3004(1)	47(1)
N(1)	−121(10)	2116(5)	4347(9)	37(3)
N(2)	2910(10)	4949(5)	2982(9)	33(3)
N(3)	6083(10)	7783(4)	1853(9)	33(3)
C(1)	−3927(12)	1407(5)	1546(11)	33(4)
C(2)	−4671(12)	1233(6)	−145(12)	33(4)
C(3)	−3835(12)	801(6)	−1238(13)	44(4)
C(4)	−2316(14)	576(6)	−630(13)	47(5)
C(5)	−1583(13)	761(6)	1079(13)	41(4)
C(6)	−2423(13)	1178(6)	2189(11)	38(4)
C(7)	−1693(13)	1402(6)	4058(12)	47(4)
C(8)	−206(13)	2840(6)	3288(12)	42(4)
C(9)	1419(13)	3542(6)	3729(12)	42(4)
C(10)	1287(12)	4254(6)	2596(11)	38(4)
C(11)	2933(12)	5677(6)	1870(11)	37(4)
C(12)	4542(12)	6355(6)	2389(11)	35(4)
C(13)	4549(13)	7078(6)	1271(11)	38(4)
C(14)	6347(13)	8509(7)	741(13)	48(4)

[a] Equivalent isotropic *U* defined as one-third of the trace of the orthogonalized U_{ij} tensor. [b] Estimated standard deviations are given in parentheses.

Table 3. Selected Bond Distances (Å)[a] and Angles (deg)[a] for Mc•6HBr

N(1)−C(7)	1.49(1)	N(1)−C(8)	1.48(1)
N(2)−C(10)	1.50(1)	N(2)−C(11)	1.49(1)
N(3)−C(13)	1.48(1)	N(3)−C(14)	1.50(1)
C(1)−C(2)	1.38(1)	C(1)−C(6)	1.37(1)
C(2)−C(3)	1.39(1)	C(2)−C(14A)	1.51(1)
C(3)−C(4)	1.37(2)	C(4)−C(5)	1.39(1)
C(5)−C(6)	1.39(1)	C(6)−C(7)	1.51(1)
C(8)−C(9)	1.51(1)	C(9)−C(10)	1.51(1)
C(11)−C(12)	1.50(1)	C(12)−C(13)	1.50(1)
C(14)−C(2A)	1.51(1)		
C(7)−N(1)−C(8)	115.3(7)	C(10)−N(2)−C(11)	113.9(7)
C(13)−N(3)−C(14)	116.1(7)	C(2)−C(1)−C(6)	123.4(9)
C(1)−C(2)−C(3)	117.3(9)	C(1)−C(2)−C(14A)	120.0(9)
C(3)−C(2)−C(14A)	122.6(8)	C(2)−C(3)−C(4)	120.4(9)
C(3)−C(4)−C(5)	121(1)	C(4)−C(5)−C(6)	119(1)
C(1)−C(6)−C(5)	118.8(8)	C(1)−C(6)−C(7)	119.7(9)
C(5)−C(6)−C(7)	121.5(9)	N(1)−C(7)−C(6)	113.1(8)
N(1)−C(8)−C(9)	111.0(8)	C(8)−C(9)−C(10)	109.0(8)
N(2)−C(10)−C(9)	109.9(7)	N(2)−C(11)−C(12)	110.8(7)
C(11)−C(21)−C(13)	110.5(7)	N(3)−C(13)−C(12)	110.5(7)
N(3)−C(14)−C(2A)	112.0(8)		

[a] Estimated standard deviations are given in parentheses.

of this ligand reveals a six equivalent buffer region from p[H] 6 to 11, indicating that all the amino nitrogens are moderately to strongly basic. Indeed, the resulting calculated[5] protonation constants, which are given in Table 4, range from log values of 6.59 to 10.33. Table 4 also contains the log protonation constants for $(MX)_2(DIEN)_2$[9] or Mc′ (which is the hydrogenated hexaaza neutral macrocyclic ligand obtained from the [2 + 2] condensation of *m*-phthalaldehyde and diethylenetriamine), for purposes of comparison.

The overall log protonation constant, $\Sigma \log K^{H}_{i}$, for the hexaaza macrocyclic ligand Mc turns out to be 50.10, whereas for the corresponding smaller hexaaza macrocyclic ligand containing diethylenetriamine moieties, Mc′, is 40.63; thus Mc displays a much stronger overall basic character than Mc′. This difference is due to the fact that Mc contains one more methylene unit separating each amino group, helping to separate the positive charges when the corresponding amino groups are protonated. This effect is specially dramatic for the last two protonation constants, K^{H}_{5} and K^{H}_{6}, where the relative differences for the two ligands are more than 3 orders of magnitude. The other protonation constants K^{H}_{i} ($i = 1-4$) differ by less than 1 order

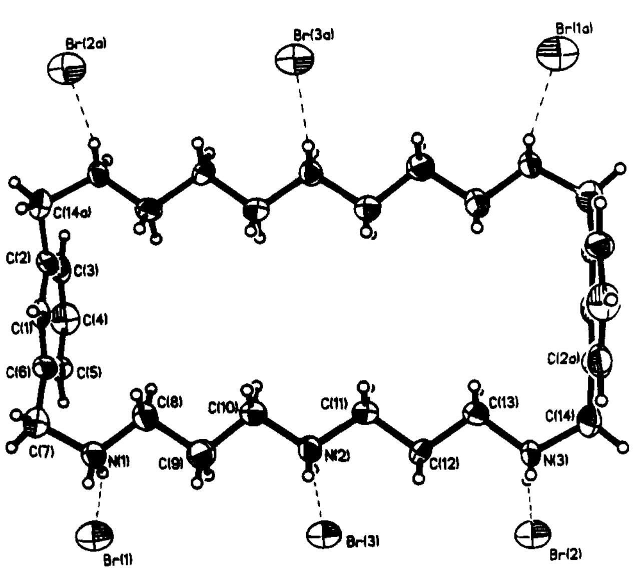

Figure 1. Thermal ellipsoid plot, 50% probability, of Mc•6HBr with atomic labeling scheme.

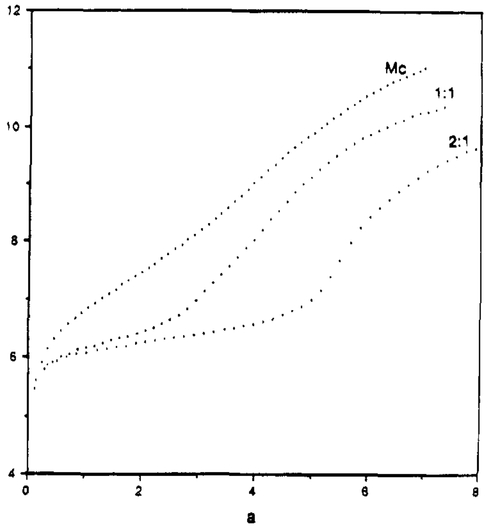

Figure 2. Potentiometric equilibrium curves for 2.02×10^{-4} M Mc•6HBr and for 1:1 and 2:1 molar ratios of Cu(II):Mc•6HBr (*a* = moles of KOH added per mole of ligand; $\mu = 0.100$ M (KCl), $T = 25.0$ °C).

Table 4. Logarithms of the Ligand Protonation Constants for Mc ($\sigma_{fit} = 0.0017$) and Mc′ at 25.0 °C and $\mu = 0.100$ M KCl Ionic Strength

symbol	equilibrium quotient	log K^{H}_{i}	
		L = Mc[a]	L = Mc′[b]
K^{H}_{1}	[HL]/[H][L]	10.33	9.49
K^{H}_{2}	$[H_2L]/[H][HL]$	9.62	8.73
K^{H}_{3}	$[H_3L]/[H][HL_2]$	8.57	8.03
K^{H}_{4}	$[H_4L]/[H][HL_3]$	7.79	7.29
K^{H}_{5}	$[H_5L]/[H][HL_4]$	7.20	3.64
K^{H}_{6}	$[H_6]/[H][HL_5]$	6.59	3.45
ΣK^{H}_{i}	$[H_6L]/[H]^6[L]$	50.10	40.63

[a] Estimated errors are one digit or less in the last decimal place shown. [b] Mc′, **6**, is the diethylenetriamine analog of Mc.

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Table 5. Logarithms of Cu(II) Binding Constants for Mc (L:Cu 1:1, $\sigma_{fit} = 0.0204$; L:Cu 1:2, $\sigma_{fit} = 0.0212$) and Mc′ at 25.0 °C and $\mu = 0.100$ M KCl Ionic Strength

symbol	equilibrium quotient	log K^X_{Mi} L = Mc[a]	log K^X_{Mi} L = Mc′[b]
K^M_{ML}	[ML]/[M][L]	11.46	13.79
K^H_{MHL}	[MHL]/[H][ML]	8.85	8.69
$K^H_{MH_2L}$	[MH_2L]/[H][MHL]	8.09	7.32
$K^H_{MH_3L}$	[MH_3L]/[H][MH_2L]	6.27	
$K^M_{M_2L}$	[M_2L]/[M][ML]	8.28	9.68
$K^{OH}_{M_2(OH)L}$	[$M_2(OH)L$][H]/[M_2L]	−8.85	−7.26
$K^{OH}_{M_2(OH)_2L}$	[$M_2(OH)_2L$][H]/[$M_2(OH)L$]	−9.61	−8.40

[a] Estimated errors are one digit or less in the last decimal place shown. [b] Mc′, **6**, is the diethylenetriamine analog of Mc.

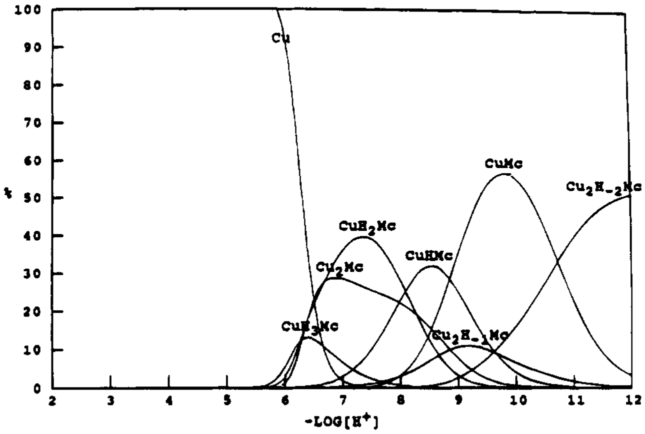


Figure 3. Species distribution diagram showing the species formed as a function of p[H] when 2.02×10^{-4} M Mc·6HBr and 2.12×10^{-4} M copper(II) are equilibrated at 25.0 °C, $\mu = 0.100$ M KCl. Only copper-containing species are shown.

of magnitude but with the Mc protonation constants always being larger than protonation constants of Mc′, as expected.

Cu(II) Binding and Hydroxide Bridging. The potentiometric investigation of the Cu(II) binding constants of Mc as obtained by KOH titration of Mc·6HBr or Mc·6HBr in the presence of Cu^{2+} produced a p[H] profile that is shown in Figure 2. The potentiometric equilibrium curves for the 1:1 and 2:1 molar ratios of Cu(II) to Mc clearly show that both mononuclear and dinuclear complexes are formed. The buffer regions beyond $a = 6$ likewise indicate the formation of metal chelate hydroxy species. The buffer region corresponding to the formation of the dinuclear copper(II) complex overlaps the buffer region corresponding to the formation of the hydroxo species. This is further supported by the excellent fitting of the curve with the postulated hydroxo species. This system parallels the behavior of analogous types of copper(II) complexes.[9] The calculated Cu(II) binding constants are exhibited in Table 5, along with those of Mc′.

On the basis of the equilibrium data displayed in Table 5, the distributions of individual metal complex species were calculated as a function of p[H]. Figure 3 displays the species distribution diagram for the 1:1 system. The CuH_xMc (x = 0−3) species are formed within the p[H] range 5.5−12. The 1:1 fully deprotonated species, $CuMc^{2+}$, predominates over the p[H] range 9−10.5 (a maximum is reached at p[H] = 9.8 where the percentage of $CuMc^{2+}$ is 56.4 with respect to the total analytical concentration of the ligand). The formation of dinuclear species is also significant in this 1:1 system, especially for Cu_2Mc^{4+} (maximum at p[H] 6.9, 28.7%) and $Cu_2Mc(OH)_2^{2+}$ (maximum at p[H] 12.0, 50.6%).

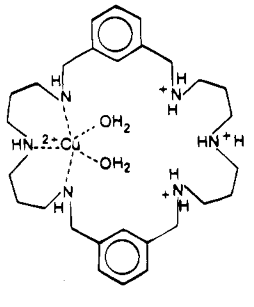
Figure 4 displays the species distribution diagram for the 2:1 system. The dinuclear complex Cu_2Mc^{4+} is the predominant species over the p[H] range 6.5−8.5 (maximum at p[H] 7.6, 85.9%). As the p[H] is increased the predominant species becomes $Cu_2Mc(OH)^{3+}$ (maximum at p[H] 9.2, 51.1%). A further increase in the p[H] leads to the formation of $Cu_2Mc(OH)_2^{2+}$ (maximum at p[H] 12.0, 96.2%), which is the predominant species from p[H] 9.7 to 12. The mononuclear species have low concentrations, CuH_2Mc being the most important (maximum at p[H] 6.6, 22.8%).

In summary, the distribution diagrams in Figures 3 and 4 show that Mc has a strong tendency to form the dinuclear species Cu_2Mc^{4+} which easily forms hydroxo complexes, at high p[H], as illustrated by formula **4**.

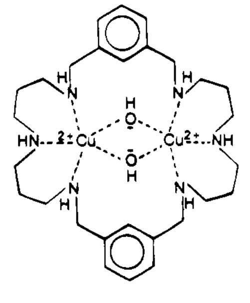
It is interesting to note that the Mc formation constants for the mononuclear and dinuclear copper(II)−Mc complexes are relatively low, while the sixth and fifth Mc protonation constants are relatively high. Thus, the potentiometric titrations of the copper(II) complex had to be performed under highly dilute conditions in order to avoid copper(II) hydroxide formation.

The copper(II) formation constants K^M_{CuMc} and $K^M_{Cu_2Mc}$ are 2.33 and 1.40 orders of magnitude smaller than the corresponding constants for Mc′ despite the fact that the former is much more basic. This is attributed to the lower stability of the two adjacent copper(II) six-membered rings, formed upon complexation with the amino groups of Mc, with respect to the more stable five-membered rings formed in the Mc′ case.[10]

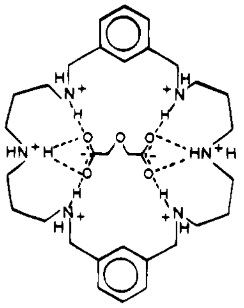
Three protonated mononuclear complexes CuH_iMc (i = 1, 2, 3) are found to be significantly formed in the p[H] range 5−12 with the present system. The protonation constants of the mononuclear complex $CuMc^{2+}$ are slightly lower than those of the corresponding ligand species (Mc), as one would expect because of the presence of the complexed Cu(II). For Mc′ only two CuH_iMc' (i = 1, 2) species could be detected. This is due to the higher acidity of the CuH_3Mc', with respect to CuH_3Mc, because of the higher basicities of the amino groups of Mc compared to Mc′. A probable arrangement of coordinate bonds for CuH_3Mc^{5+} is illustrated in formula **3**.



3 CuH_3Mc^{5+}



4 $Cu_2(OH)_2Mc^{2+}$



5 H_6McOd^{4+}

Finally, the dinuclear complex Cu_2Mc^{4+} is characterized by strong hydrolytic tendencies at high p[H] (see Figures 3 and 4) to form mono- and dihydroxo-bridged complexes. The suggested structure of the latter is illustrated in formula **4**. This behavior parallels that of its analogous $Cu_2Mc'^{4+}$ complex. The formation constants for the species $Cu_2Mc(OH)_x$ ($x = 1, 2$) are more than 1 order of magnitude smaller than those of Mc′. Since the Cu(II) ion is more weakly coordinated in its Mc complex than in the analogous Mc′ complex, one would expect its tendency to form a hydroxo complex to be higher. The observed difference must therefore be related to the fact that the Cu(II)−Cu(II) distance is less in the Mc′ complex and more favorable for hydroxo bridging. This idea is supported by the use of space-filling models.

Recognition of Oxydiacetic Acid by Mc. The oxydiacetic acid (H_2Od) protonation constants were evaluated with the conditions used in this paper and agree with the values previously reported in the literature.[11]

$$Od^{2-} + H^+ \rightleftharpoons HOd^- \qquad \log K^H_1 = 3.91$$

$$HOd^- + H^+ \rightleftharpoons H_2Od \qquad \log K^H_2 = 2.81$$

With the individual protonation constants of oxydiacetic acid and Mc, the potentiometric data of a solution containing an equimolar amount of H_2Od and H_6Mc^{6+} were resolved (σ_{fit} 0.0031) showing the presence of nine equilibrium species

$$H_6Mc^{6+} + H_2Od \rightleftharpoons H_8McOd^{6+} \qquad \log K^R_8 = 3.98$$

$$H_6Mc^{6+} + HOd^- \rightleftharpoons H_7McOd^{5+} \qquad \log K^R_7 = 4.09$$

$$H_6Mc^{6+} + Od^{2-} \rightleftharpoons H_6McOd^{4+} \qquad \log K^R_6 = 4.38$$

$$H_5Mc^{5+} + Od^{2-} \rightleftharpoons H_5McOd^{3+} \qquad \log K^R_5 = 4.04$$

$$H_4Mc^{4+} + Od^{2-} \rightleftharpoons H_4McOd^{2+} \qquad \log K^R_4 = 4.10$$

$$H_3Mc^{3+} + Od^{2-} \rightleftharpoons H_3McOd^{+} \qquad \log K^R_3 = 4.00$$

$$H_2Mc^{2+} + Od^{2-} \rightleftharpoons H_2McOd \qquad \log K^R_2 = 3.94$$

$$HMc^{+} + Od^{2-} \rightleftharpoons HMcOd^{-} \qquad \log K^R_1 = 3.94$$

$$Mc + Od^{2-} \rightleftharpoons McOd^{2-} \qquad \log K^R_0 = 3.88$$

where K^R_i is the recognition constant of protonation degree i and the entries are listed in order of appearance from low to high p[H]. Possible hydrogen bonding for the most stable of these species, H_6McOd^{4+}, is illustrated in formula **5**.

Figure 5 shows the species distribution diagram as a function of p[H] obtained for the 1:1 Mc:Od system. It is interesting to note that over the whole p[H] range studied the predominant species are always the H_iMcOd complexes; the individual species derived from the protonation of the individual Mc molecule and Od^{2-} anion are minor components in all cases.

The recognition constant values obtained for this system lay within the range of previously reported host−guest interactions with hexaaza macrocyclic amines and dicarboxylic acids.[12,13]

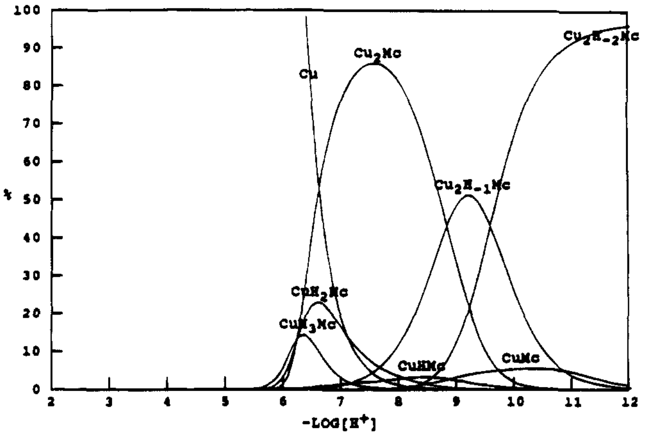


Figure 4. Species distribution diagram showing the species formed as a function of p[H] when 1.05 × 10^{-4} Mc·6HBr and 2.04 × 10^{-4} M copper(II) are equilibrated at 25.0 °C, $\mu = 0.100$ M KCl. Only copper-containing species are shown.

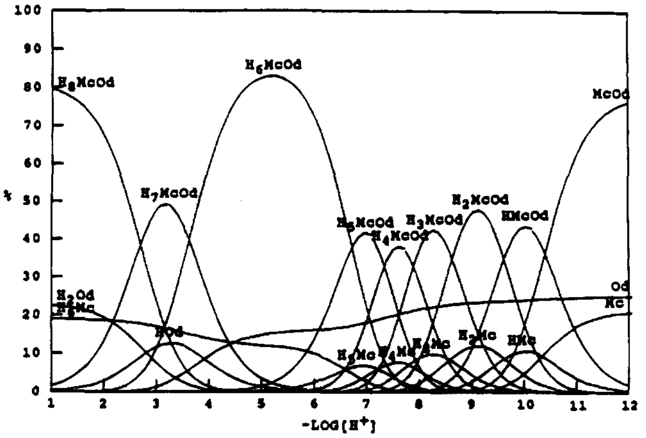


Figure 5. Species distribution diagram showing the species formed as a function of p[H] when 1.94 × 10^{-3} M Mc·6HBr and 2.01 × 10^{-3} M oxydiacetic acid (Od) are equilibrated at 25.0 °C, μ = 0.100 M KCl.

For example, the recognition of ketomalonate by protonated forms of OBISDIEN (1,4,7,13,16,19-hexaaza-10,22-dioxacyclotetracosane)[12a] produces K^R_i's in the range of 3.39−5.12.

The highest equilibrium constant for the present ternary recognition complexes H/Mc/Od corresponds to formation of the species H_6McOd^{4+}, $\log K^R_6 = 4.38$. This complex can be formally described as an H_6Mc^{6+} positive ion bonded to an Od^{2-} anion by Coulombic forces and hydrogen bonds. In this complex the Coulombic interactions and hydrogen bonding forces reach a maximum.

There is a gradual decrease of K^R_x, from $x = 6$ to $x = 8$, where the Coulombic interactions decrease as well as the potential hydrogen-bonding contributions. From $x = 6$ to $x = 0$, K^R_x decreases corresponding to a decrease of both potential H-bonding and formal Coulombic interactions between host and guest. K^R_4 is an exception which might be due to some kind of conformational rearrangement of the species being formed. Comparing with other host−guest systems involving hexaaza macrocycles and dicarboxylic acids,[11−13] the present system offers a numerically much closer series of k^R_i's. This suggests that in this case, besides Coulombic interactions, other Mc−Od interactions also play an important role in the overall host−

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guest bonding. This closeness in the numerical values of the constants implies that the various protonated Mc and Od species tightly complement each other both in size and shape, probably because of the high flexibility of oxydiacetic acid and its anionic forms.

Because of the interesting questions raised by these research results, it would be of interest in future work to study the binding of other guests, such as oxalate and mesoxalate anions, by this macrocyclic host. It would also be of interest to investigate other stoichiometries, such as two guests to one host, in addition to the 1:1 ratio used in this study.

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Supplementary Material Available: Figures S1, distribution of species present as a function of p[H] in a 1.71 × 10^{-3} M solution of H_6Mc^{6+} at 25.0 °C and $\mu = 0.100$ M (KCl), Table SI, anisotropic displacement parameters for Mc·6HBr, Table SII, hydrogen atom coordinates, and Table SIII, a complete table describing the crystallographic data and procedure (5 pages). Ordering information is given on any current masthead page.