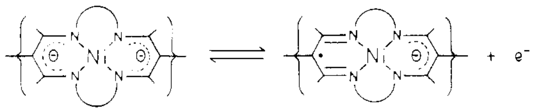
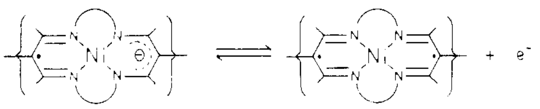


(1)



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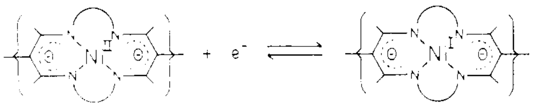

(3)

oxidation waves that were irreversible in solution now are reversible. The Ni(II/I) couple would also demonstrate reversible surface behavior, were it not for the presence of the prewave.

Conclusion. The electropolymerization of nickel tetraazaannulenes on electrode surfaces is a unique method to add to electropolymerization techniques currently used to modify electrode surfaces.[29] These tetraazaannulene, surface-modified electrodes are important from a number of viewpoints. Thin, homogeneous films can be deposited on the electrode surface, and the surface potentials can be controlled by varying the substituents on the ligand, the metal center, and/or the ligands themselves. Since the polymerization is ligand-centered, it should be possible to prepare copolymer films coupling the appropriate tetraazaannulenes that conduct over a large potential region. It should also be possible to design rectifiers and diodes by the sequential polymerization of the appropriate tetraazaannulenes on the electrode surface. These surface-modified electrodes should then find use in catalysis and fuel cells and could serve as electronic devices. We currently are extending our studies into these areas and plan to report our results in the near future.

Acknowledgment. This work was supported by the Office of Naval Research and the North Carolina Biotechnology Center. D.P.R. thanks the American Society of Engineering Education for a 1983 Summer Faculty Fellowship with the Department of the Navy. Thanks also are given to Sador S. Black at N. C. State for the AA analyses, Steve Simko at UNC-Chapel Hill for the XPS film analyses, and Eddie Stokes at UNCC for the SEM work. This is paper No. 7 from the North Carolina Biomolecular Engineering and Materials Application Center.

Registry No. Ni[Me_4Bzo_2[14]tetraeneN_4], 51223-51-9; Ni[Me_4($CH_3Bzo)_2$[14]tetraeneN_4], 74834-16-5; Ni[Me_4(ClBzo$)_2$[14]tetraeneN_4], 92396-74-2; Ni[Me_4($CO_2CH_3Bzo)_2$[14]tetraeneN_4], 92396-70-8; Ni[Me_4($NO_2Bzo)_2$[14]tetraeneN_4], 92396-72-0; Ni[Me_4($CO_2C_3H_7Bzo)_2$[14]tetraeneN_4], 92396-71-9; [Ni(Me_4Bzo_2[14]tetraeneN_4)]$_2$($ClO_4)_2$, 100570-25-0; [Ni(Me_4($CH_3Bzo)_2$[14]tetraeneN_4)]$_n$, 100485-73-2; [Ni(Me_4Bzo_2[14]tetraeneN_4)]$_n$, 100485-74-3; [Ni(Me_4(ClBzo$)_2$[14]tetraeneN_4)]$_n$, 100485-75-4; [Ni(Me_4($CO_2CH_3Bzo)_2$[14]tetraeneN_4)]$_n$, 100485-76-5; [Ni(Me_4($CO_2C_3H_7Bzo)_2$[14]tetraeneN_4)]$_n$, 100485-77-6; [Ni(Me_4($NO_2Bzo)_2$[14]tetraeneN_4)]$_n$, 100485-78-7; Cu(DIM)$^{2+}$, 80502-49-4; Cu(DIM)$^+$, 80502-50-7; Bu_4NPF_6, 3109-63-5; Et_4NClO_4, 2567-83-1; SnO_2, 18282-10-5; Pt, 7440-06-4; carbon, 7440-44-0; *o*-dinitrobenzene, 528-29-0.

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[29] Murray, R. W. *Annu. Rev. Mater. Sci.* **1984**, *14*, 145 and references therein.

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Cascade Halide Binding by Multiprotonated BISTREN and Copper(II) BISTREN Cryptates

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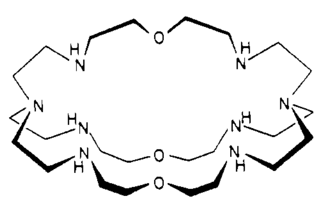
The macrobicyclic ligand 7,19,30-trioxa-1,4,10,13,16,22,27,33-octaazabicyclo[11.11.11]pentatriacontane, BISTREN, has been synthesized in sufficient quantity to carry out a detailed investigation of halide binding to its protonated forms and to its mononuclear and binuclear Cu(II) complexes. Potentiometric investigations were conducted at 1.000 M ionic strength at 25.0 °C in supporting electrolytes consisting of 1.000 M $NaClO_4$ and NaF, 1.000 M NaCl, 1.000 M NaBr, and 1.000 M NaI, in the absence and in the presence of 1 and 2 mole ratios of Cu(II) to ligand. Some combinations of the supporting halide electrolytes with $NaClO_4$ to a total ionic strength of 1.000 M were also employed. A special procedure was required for the system containing Cu(II) and I^-. On the basis of the assumption of no binding to perchlorate, by comparison of the macroscopic protonation and Cu(II) formation constants, in the presence and absence of the halide ions, quantitative calculations of the halide binding constants were carried out. Results are reported for binding by the protonated ligand of HF_2^-, F^-, Cl^-, Br^-, and I^- and for the binding of all four halide ions to the protonated mononuclear Cu(II) cryptate and to the binuclear Cu(II) cryptate.

Introduction

BISTREN is a macrobicyclic ligand that can coordinate one to six protons and/or one or two metal ions in aqueous solution. It consists of two 2,2′,2″-triaminotriethylamine (TREN) moieties tied together with five-atom diethyl ether bridges. Although it contains eight amino groups, the tertiary bridgehead nitrogens are so weakly basic, because of Coulombic repulsion of adjacent protonated nitrogens, that the hexaprotonated form is the most acid species in aqueous solution under the conditions that can be employed for potentiometric measurements. Therefore, BISTREN may be designated an H_6L^{6+} ligand, corresponding to the form generally employed (the hexahydrobromide) for potentiometric investigations.



BISTREN (free base)

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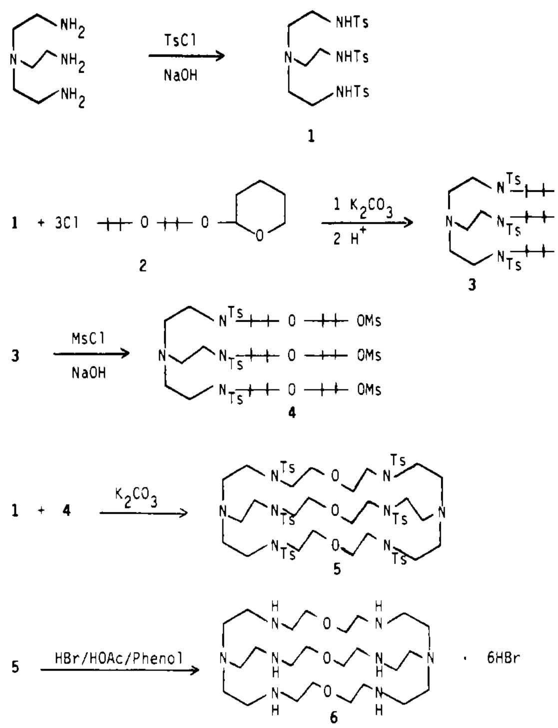
[‡] Kyushu University.

Scheme I



The binding of several anions to polyprotonated BISTREN species has already been measured by NMR.[1] More recently, potentiometric studies[2-4] of dilute aqueous solutions were employed to determine equilibrium constants for Cl^- binding to H_6L^{6+} (L = BISTREN), H_5L^{5+}, H_4L^{4+}, MH_3L^{5+} (M = Cu(II)), MH_2L^{4+}, and M_2L^{4+} at an ionic strength of 0.10 M. Similar binding of NO_3^- to H_6L^{6+}, H_5L^{5+}, and H_4L^{4+} had also been reported.[2] The secondary binding of anions by metal complexes of BISTREN has been termed "cascade" anion binding. In the NMR[4] method the anion-binding studies were confined to H_6L^{6+} species. More extensive work on this interesting ligand had been hampered by the lack of material. Now, with a new source of BISTREN, described in this paper, it is possible to extend the potentiometric measurements over a wider range of concentration and to additional anions.

In this investigation halide binding constants were determined by measuring protonation equilibria potentiometrically by using 1.000 M rather than 0.100 M halide salts as supporting electrolytes. This change made possible the variation of the halide ion concentration over a wide range, thus making possible the detection of polynuclear halide complexes. Previous potentiometric studies were restricted to a single concentration (0.100 M), so that effects resulting from the binding of more than one anion could not be detected easily.

Experimental Section

General Procedures. A stock solution of copper(II) perchlorate was prepared from the reagent grade salt and standardized against standard EDTA by using Murexide indicator in a procedure outlined by Welcher.[5] The base used was carbonate-free 0.1000 M NaOH made up with 0.900 M $NaClO_4$ so that the ionic strength would not change upon addition to the experimental solution. Base was standardized with potassium acid phthalate. NaCl, NaBr, NaI, NaF, and $NaClO_4$ were reagent grade materials dried to constant weight and were of >99.9% purity. Water was doubly distilled ($KMnO_4$).

BISTREN was synthesized by a modification of the general synthetic pathway shown in Scheme I, first outlined by Dietrich et al.,[6] which constitutes an improvement of the method described earlier.[7] The procedures employed for the individual synthetic steps were modeled from methods described in the literature. Compounds **1** and **5** were prepared by the methods of Martin and Bulkowski.[8] Hydrolysis of **5** to give BISTREN (**6**) was carried out by the method of Piper and Johnston.[9]

Tris[2-((*p*-tolylsulfonyl)amino)ethyl]amine (1). Tris(2-aminoethyl)amine tetrahydrobromide (23.5 g, 0.05 mol) was dissolved in 100 mL of water containing 15 g (0.35 mol) of sodium hydroxide. To this was added dropwise *p*-toluenesulfonyl chloride (29 g, 0.15 mol) in 80 mL of ether with vigorous stirring at room temperature. Stirring was continued for 1 h after the addition, and the mixture was allowed to stand overnight. The white solid was collected by filtration, washed with water, and recrystallized from methanol: yield 25.4 g (80%); mp 99–102 °C.

Anal. Calcd for $C_{27}H_{36}N_4O_6S_3 \cdot H_2O$: C, 51.73; H, 6.12; N, 8.94. Found: C, 51.76; H, 6.12; N, 8.87.

1-Chloro-3-oxa-5-(tetrahydropyran-2-yloxy)pentane (2). Dihydropyran (18.5 g, 0.22 mol) was added dropwise with stirring to 2-(2-chloroethoxy)ethanol (25 g, 0.2 mol) containing two drops of concentrated hydrochloric acid. The reaction temperature was kept at 30–35 °C by cooling with cold water. The mixture was further stirred for 1 h at room temperature and dried over a mixture of anhydrous potassium carbonate and magnesium sulfate. The liquid was fractionally distilled, and the fraction with bp 114–115 °C was collected; yield 30 g (72%).

Anal. Calcd for $C_9H_{17}O_3Cl$: C, 50.79; H, 8.23. Found: C, 51.25; H, 8.18.

Tris[2-(*p*-tosyl(5-hydroxy-3-oxapentyl)amino)ethyl]amine (3). The tritosylated TREN (**1**) (7.6 g, 0.013 mol) was dissolved in 200 mL of dry DMF, and anhydrous potassium carbonate (25 g, 0.18 mol) was added. The mixture was heated at 100–110 °C, and to this was added **2** dropwise (8 g, 0.038 mol) in 1 h with vigorous stirring. The heating and stirring were continued for 5 h, and the reaction mixture was allowed to stand at room temperature overnight. The insoluble material was filtered off, and the pale brown filtrate was concentrated to ca. 30 mL by means of a rotary evaporator. A large amount of water was added, and the oily layer was extracted with ether. The ether solution was washed with water and dried over anhydrous sodium sulfate, and the solvent was evaporated to give a pale yellow oil, yield 13.5 g.

The oil (13.5 g, 0.010 mol) was dissolved in 100 mL of 95% ethanol, benzenesulfonic acid (3 g, 0.017 mol) was added, and the solution was refluxed for 5 h. After the solvent was removed under reduced pressure, the pale yellow oily residue was dissolved in 200 mL of dichloromethane. The solution was washed with water and dried over anhydrous potassium carbonate, and the solvent was evaporated off by means of a rotary evaporator to give **3** as a pale yellow oil (10.3 g). This was used for the next reaction without further purification.

Tris[2-(*p*-tosyl(5-mesyloxy-3-oxapentyl)amino)ethyl]amine (4). The crude **3** (10.3 g, 0.10 mol) and triethylamine (5.4 g, 0.053 mol) were dissolved in dry dichloromethane (60 mL), and the solution was chilled to −5 °C. Mesyl chloride (4.5 g, 0.04 mol) in 10 mL of dichloromethane was added dropwise with stirring while the temperature was kept below 0 °C. After the solution was stirred for an additional 1 h at 0 °C, ice water was added and the organic layer was successively washed with 10% hydrochloric acid, with saturated aqueous sodium chloride, with aqueous sodium bicarbonate, and with aqueous sodium chloride and then dried over anhydrous potassium carbonate. The solvent was removed by means of a rotary evaporator below 30 °C, and **4** was obtained as a pale yellow sticky mass, yield 11.2 g.

Hexatosyl-BISTREN (5). Complex **1** (6.2 g, 0.1 mol) was dissolved in 300 mL of dry DMF, and anhydrous potassium carbonate (21 g, 0.15 mol) was added. The mixture was heated at 100–110 °C under nitrogen, and to this was added **4** (11.2 g, 0.01 mol) in 100 mL of DMF during 2–3 h with vigorous stirring. After additional heating and stirring for 2 h, the insoluble material was filtered off at room temperature, the filtrate was treated twice with hot water and dissolved in 100 mL of dichloromethane, and more insoluble material was filtered off. The filtrate was dried over anhydrous sodium sulfate and treated with active charcoal to give a pale yellow solution (ca. 100 mL).

The solution was treated with 40 g of silica gel (for chromatography, 100 mesh) and filtered. The gel was again treated with 100 mL of

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(1) Lehn, J. M.; Sonveaux, E.; Willard, A. K. *J. Am. Chem. Soc.* **1978**, *100*, 4914.

(2) Motekaitis, R. J.; Martell, A. E.; Dietrich, B.; Lehn, J. M. *Inorg. Chem.* **1984**, *23*, 1588.

(3) Motekaitis, R. J.; Martell, A. E.; Lehn, J. M.; Watanabe, E. I. *Inorg. Chem.* **1983**, *22*, 4253.

(4) Dietrich, B.; Guilhem, J.; Lehn, M. M.; Pascard, C.; Sonveaux, E. *Helv. Chim. Acta* **1984**, *67*, 91.

(5) Welcher, R. J.; Johnson, F. "The Analytical Uses of Ethylenediaminetetraacetic Acid"; Van Nostrand-Reinhold: Princeton, NJ, 1958.

(6) Dietrich, B.; Hosseini, M. W.; Lehn, J. M.; Sessions, R. B. Composes Macrocycliques, Colloque International de CNRS Strasbourg, 1982.

(7) Lehn, J. M.; Pine, S. H.; Watanabe, E. I.; Willard, A. K. *J. Am. Chem. Soc.* **1977**, *99*, 6766.

(8) Martin, A. E.; Bulkowski, J. P. *J. Org. Chem.* **1982**, *47*, 415.

(9) Piper, J. P.; Johnston, T. P. *J. Org. Chem.* **1968**, *33*, 636.

Table I. Logarithms of the Protonation Constants $(K^{H}{}_{n})^{a}$ of BISTREN (μ = 1.00 M, t = 25.0 °C)

n	1 M $NaClO_4$	0.5 M NaCl + 0.5 M $NaClO_4$	1 M NaCl	1 M NaBr	1 M NaI	0.05 M NaF + 0.95 M $NaClO_4$	0.025 M NaF + 1.00 M $NaClO_4$
1	10.384	10.217	10.136	10.290	10.262	10.38	10.26
2	9.815	9.736	9.691	9.751	9.778	9.81	9.88
3	9.010	8.935	8.894	8.978	8.958	9.05	9.18
4	8.404	8.525	8.653	8.589	8.427	8.80	8.52
5	7.444	7.907	8.065	7.930	7.596	8.5^{b}	8.17
6	6.954	7.318	7.454	7.216	6.785	8.1^{b}	7.26
7							5.02

$^{a}K_n{}^{H} = [H_nL^{n+}]/[H][H_{n-1}L^{(n-1)+}]$. ^{b}Diminished accuracy due to presence of insoluble HF salts of ligand.

dichloromethane, and combined filtrates were evaporated to dryness under reduced pressure. The sticky residue was treated with 50 mL of hot ethanol, and **5** was obtained as a hard glassy material (4 g).

BISTREN Hexahydrobromide (6). The crude **5** (4 g) was dissolved in 30% hydrogen bromide in acetic acid (80 g) at room temperature, and phenol (10 g) was added. The red-brown solution was kept in a flask tightly stoppered for 3 weeks at room temperature (10–13 °C). A white precipitate began to deposit after 1 week. To the reaction mixture was added twice its volume of water, the water layer was washed several times each with 50 mL of ether, the pale yellow solution was concentrated to near dryness under reduced pressure, and a large amount of ethanol was then added. The resulting solid was recrystallized from dilute ethanol; yield 1.1 g (39%).

Anal. Calcd for $C_{24}H_{54}N_8O_3{\cdot}6HBr$: C, 29.16; H, 6.13; N, 11.34. Found: C, 29.13; H, 6.11; N, 11.53.

Potentiometric Equilibrium Measurements. A typical solution for potentiometric equilibrium studies consisted of the following: 0.0500 mmol of ligand, 0.0500 (or 0.1000) mmol of Cu^{2+}, 50.00 mmol of background electrolyte ($NaClO_4$, NaCl, NaI, or NaBr) or a combination of the above salts to total 50.0 mmol, diluted to 50.00 mL initial volume. The F^- experiments contained only 1.25 and 2.50 mmol of NaF with $NaClO_4$ added to make μ = 1.000 M. NaI/Cu(II) experiments were carried out by back-titration starting with the fully formed complexes, to prevent reaction between aquocopper(II) and I^-.

The Corning Model 130 pH meter, a Jena Glass (S-30050-15C Sargent Welch) glass electrode, and a calomel reference electrode system were calibrated with dilute standard acid solution at 1.000 M ionic strength. In the basic region known amounts of standard alkali at 1.00 M ioic strength were employed. Thus pH is interpreted as $-\log[H^+]$, the advantage being the avoidance of dealing with buffers and a_{H^+}. $-\log K_w$ was determined to be 13.69 in 1.00 M $NaClO_4$. The temperature was maintained at 25.00 ± 0.05 °C, and an inert atmosphere of prepurified CO_2-free nitrogen was maintained before and during measurements.

Computations. Both proton association constants and stability constants were calculated by the general, interactive Fortran program BEST[11] with either the PDP 11/44 or the VAX 11/780 computer of the Chemistry Department of Texas A&M University. Species distributions were computed on a Micromation Dual Disk Microcomputer with a program written in Fortran based on the algorithm taken from program BEST. the species diagrams were generated with a Houston Instruments Model 29 Hiplot multipen plotter with software written in CP/M Basic.

Results

Synthesis of BISTREN. With the general scheme described by Dietrich et al.,[6] the BISTREN sample employed in this research was prepared and made available for study in Aug 1984. Very recently, after this paper was written, details of the procedures for the synthesis of BISTREN and analogous ligands appeared in the literature.[10] The synthetic procedures described for the preparation of BISTREN were modeled on the procedures described for the synthesis of other compounds[8,9] as well as of BISTREN.[6] This work was carried out independently and resulted in definite improvements in some of the synthetic steps. A comparison of these procedures with the work of Dietrich et al.[10] recently published shows differences in reaction conditions and yields, and differences in some of the intermediates. Closely parallel procedures were found only for the cyclization step itself, reaction **1** + **4** → **5**.

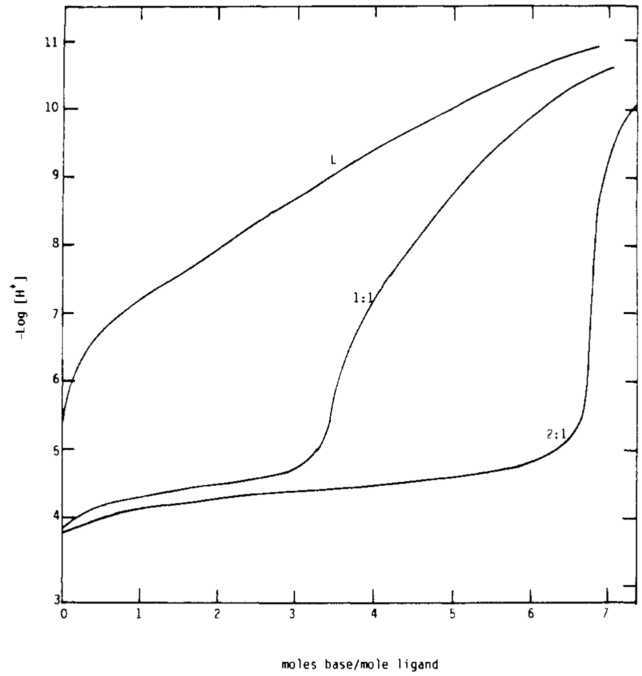

Figure 1. Potentiometric equilibrium curves for 0:1, 1:1, and 2:1 molar ratios of Cu(II) to BISTREN (μ = 1.000 M ($NaClO_4$), t = 25.0 °C, [BISTREN] = 1.000 × 10^{-3} M).

BISTREN Protonation Equilibria. It had been previously established[3] that the perchlorate ion does not bind significantly to the various protonated and coordinated forms of BISTREN at 0.1 M levels, and therefore perchlorate was chosen as the background electrolyte for all comparisons in this study. The ionic strength was set at 1.00 M in this work in order to increase the sensitivity of the observed effects as the concentration of the background electrolyte was changed in composition. It was assumed that at this concentration perchlorate does not significantly bind with the BISTREN species. At worst, this assumption would constitute a base line for the calculated results that could be easily corrected if new evidence indicating some binding by perchlorate should be reported at a later date.

The potentiometric equilibrium curve obtained for BISTREN as a function of $-\log[H^+]$ in 1.000 M $NaClO_4$ is shown in Figure 1, and the calculated logarithms of the protonation constants are presented in Table I. The corresponding potentiometric equilibrium curve is shown in Figure 2 for BISTREN measured in a 1.000 M NaCl medium, and the logarithms of its protonation constants were also computed and are given in Table I. The differences in the metal-free curves are especially pronounced in the first half of each long 6-equiv buffer region in that the pH values of the NaCl curve (Figure 2) are considerably higher than those for the perchlorate medium, a reflection of the stabilizing effect of Cl^- ion on multiprotonated BISTREN species.

Protonation constants were also measured in other media, and comparisons with those in $NaClO_4$ were the basis for the computation of the specific anion binding constants of the particular anion of the protonated BISTREN species. Thus chloride binding was determined in an intermediate concentration of 0.500 M NaCl (+0.500 M $NaClO_4$), and the protonation constants obtained are listed in Table I. BISTREN was also measured in 1.000 M NaBr and in 1.000 M NaI, and the results are also summarized in Table

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(10) Dietrich, B.; Hosseini, M. W.; Lehn, J. M.; Sessions, R. B. *Helv. Chim. Acta* **1985**, *68*, 289.

(11) Motekaitis, R. J.; Martell, A. E. *Can. J. Chem.* **1982**, *60*, 2403.

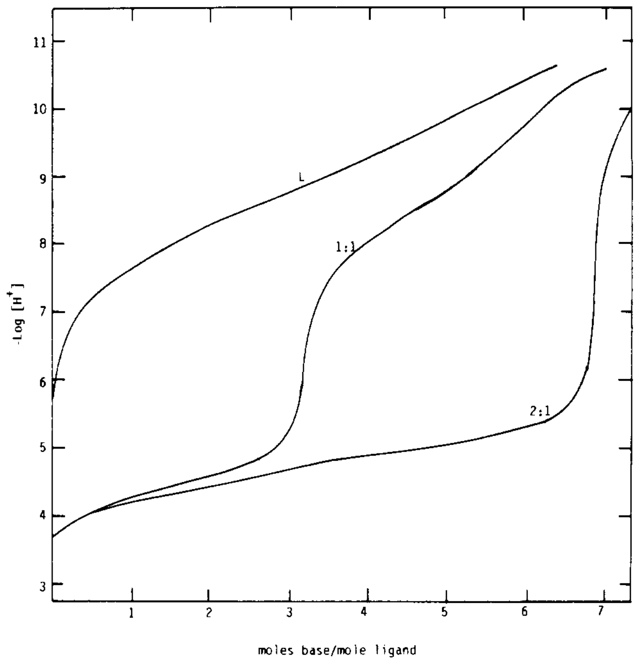

Figure 2. Potentiometric equilibrium curves for 0:1, 1:1, and 2:1 molar ratios of Cu(II) to BISTREN (μ = 1.000 M (NaCl), t = 25.0 °C [BISTREN] = 1.000 × 10^{-3} M).

I. It was found that some forms of BISTREN·xHF are insoluble. Becuase of this the potentiometric equilibrium curves were determined from both the acid and base sides in order to obtain data in the supersaturated regions near a = 0–2. Because the effects of fluoride binding were found to be rather large, the measurements were confined to the relatively dilute 0.025–0.050 M NaF range, with the remaining supporting electrolyte made up with $NaClO_4$. In addition, excess acid was added to reach "negative" a values in order to detect the possible presence of the coordinated FHF^- anion and to determine its binding constants. All the macroscopic protonation constants obtained from the various halide-containing systems are listed in Table I.

Although the first three protonation constant values are of similar magnitude for all supporting electrolytes, the remaining three constants show differences, relative to 1.000 M $NaClO_4$, which in most cases are quite marked. The 0.050 M NaF protonation reactions are very much enhanced for the sixth protonation step relative to those in pure perchlorate medium. However, in the experiments with 0.050 M F^- the soluble region is considerably narrower and the fifth and sixth protonation constants are less accurate. This effect was considerably less serious for the 0.025 M case. Because the observed differences were large in going from 0.050 to 0.025 M, multiple F^- ion binding seemed a definite possibility for the highly protonated forms of BISTREN. Since the FHF^- species is known to be stable in acidic HF solutions, FHF^- was considered a strong possibility for the form of the species with difluoride ion binding. Strong evidence for such a species was found by the addition of excess acid, which gave an additional protonation step, corresponding to the formation of H_7L^{7+} in fluoride media. It should be added that the bridgehead nitrogens on each end of BISTREN are not protonated under these conditions since they are not sufficiently basic to support protonation when the adjacent secondary amino groups are protonated. TREN itself supports this behavior.

Because the FHF^- moiety is apparently encapsulated in H_6L^{6+}, it is reasonable to expect that H_5L^{5+} and maybe even H_4L^{4+} also interact in the same way. Detailed computations taking into account the aqueous equilibria for the formation of the HF and the F_2H^- species in aqueous solution support the equilibria described by 1 and 2.

$$H_6L^{6+} + F_2H^- \rightleftharpoons H_6L{\cdot}F_2H^{5+} \quad \log K = 6.25 \qquad (1)$$

$$H_5L^{5+} + F_2H^- \rightleftharpoons H_5L{\cdot}F_2H^{4+} \quad \log K = 8.11 \qquad (2)$$

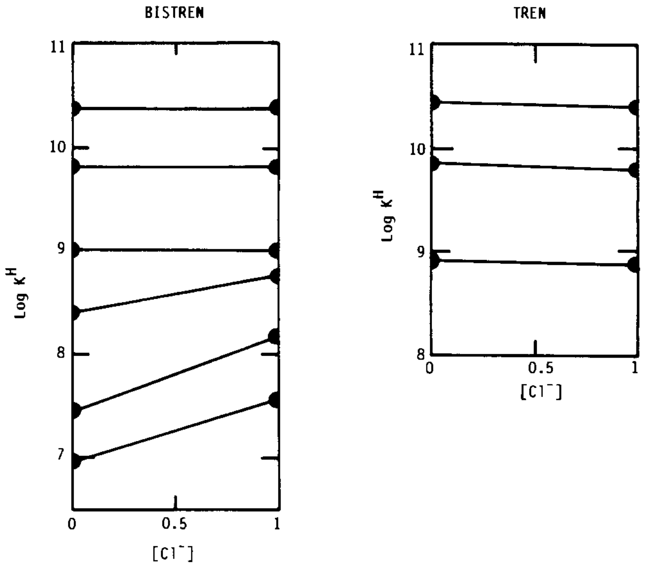

Figure 3. Influence of ion type on the adjusted protonation constants (log K^H) of BISTREN and on the protonation constants of TREN (μ = 1.00 M, t = 25.0 °C) through the replacmeent of $NaClO_4$ as supporting electrolyte by NaCl.

The larger magnitude of (2) is probably related to the spatial requirements of the entering F_2H^- moiety. This calculation also gives rise to the protonation constant defined by eq 3, which

$$H^+ + H_5L{\cdot}F_2H^{4+} \rightleftharpoons H_6L{\cdot}F_2H^{5+} \quad \log K = 5.10 \qquad (3)$$

compares well with the observed (Table I) constant of 5.02. However, the data are inconsistent with eq 4, and therefore it

$$H_4L^{4+} + F_2H^- \rightleftharpoons H_4L{\cdot}F_2H^{3+} \qquad (4)$$

appears that the HF_2^- moiety enters only the H_6L^{6+} and H_5L^{5+} cages. Dietrich et al.[4] made a study of fluoride binding under different conditions but did not report bifluoride participation in the equilibria.

Chloride and bromide also show effects of anion binding on protonation constants, but iodide seems to influence the protonation constants only slightly. Because the anions of the various supporting electrolytes differ so much in size and softness, small differences in observed constants should be intepreted with caution, because of some uncertainty in the apportionment of the differences between real anion binding effects and the specific ion effects of the supporting electrolyte.

Equation 5 was employed for computing the anion binding constants K^X, where X = Cl^-, Br^-, or I^- and where β's are the particular overall macroscopic protonation constants.

$$(\beta^{X}/\beta^{ClO_4} - 1)/[X^-] = K^x \qquad (5)$$

Before eq 5 could be applied to the data in Table I, it was necessary to apply a supporting-electrolyte correction to bring all the constants to a common base, since the differences in the first protonation step could not possibly be due to anion binding. This adjustment was made by graphical extrapolation of lines fitted through the first three protonation constants, which do not involve halide binding, to the last three. The function plotted vs. $1/n^2$ was $1/\Delta$, where $\Delta_n = \log K_n^H(NaClO_4) - \log K_n^H(NaX)$. This relationship provided the noncomplexing supporting electrolyte effect for the fourth, fifth, and sixth protonation constants, on which were based the calculations of the anion binding constants by means of eq 5. Figure 3 shows plots of the corrected values for log K_n^H against the chloride concentration, with horizontal or nearly horizontal plots for the first three protonation constants. The slopes of the fourth, fifth, and sixth protonation plots are a reflection of anion binding with the medium effect eliminated. The horizontal plots for all three protonation constants of TREN are an indication of complete lack of anion binding by this ligand.

Table II. Logarithms of the Constants of Binding of the Monohalide to Protonated Forms of BISTREN[a] (μ = 1.000 M)

n	F^-	Cl^-	Br^-	I^-
6	4.1	1.7	1.0	−0.3
5	2.8	1.1	0.7	
4	1.5	0.1	−0.2	
3	0.2			

[a] Corrected for bulk electrolyte effect relative to perchlorate.

Table III. Comparison of Protonation Constants of BISTREN at μ = 1.00 and 0.100 M (t = 25.0 °C)

n	1.0 M $NaClO_4$	0.10 M $NaClO_4$	Δ	1.0 M NaCl	0.10 M KCl
1	10.38	9.89	0.49	10.14	9.89
2	9.82	9.23	0.59	9.69	9.17
3	9.01	8.29	0.72	8.89	8.26
4	8.40	7.65	0.75	8.65	7.89
5	7.44	6.64	0.80	8.06	7.28
6	6.95	6.01	0.94	7.45	6.60

The results of these calculations are summarized in Table II. The hexaprotonated form of BISTREN is by far the most effective in binding halide ions, and fluoride ion is by far the most strongly bound of the halides. Because of its weak interactions with polycationic BISTREN ions, it was possible to calculate only a small combined (H_6L^{6+} and H_5L^{5+}) constant for the iodide ion. However, the strongly hydrogen-bonding F^- ion shows evidence of binding to protonated BISTREN containing as little as three protons.

Protonation constants in chloride media and chloride binding constants obtained in this research are compared with the corresponding constants of BISTREN reported previously[2] for 0.1000 M ionic strength. The results show that, whereas the effects on the log K values are stronger (and thus more easily measured) in the more concentrated electrolyte medium, the log K values themselves are much smaller. This effect is not unexpected, because of the stabilizing influence of strong electrolyte media of individual ionic species (a reflection of reduced activity coefficient) relative to complexes formed from the component ions in cases where charge neutralization occurs.

Table III also provides a comparison under comparable conditions of the protonation constants measured in 1.000 M $NaClO_4$ and 0.100 M $NaClO_4$. The observed differences in the logarithms of the protonation constants are largest for the reactions involving the formation of the most highly charged species H_6L^{6+}. The constants representing the first protonation reaction show about half the increment of the most highly charged species. Thus it appears that in addition to the charge neutralization effect, the absolute magnitudes of the charges of the ionic species involved also have an influence on the protonation constants observed, assuming no binding of perchlorate in the 1.000 M perchlorate medium.

Cu(II)–BISTREN Ion Binding. The 1:1 and 1:2 formation curves for Cu(II)–BISTREN are quite different depending on whether 1.000 M $NaClO_4$ (Figure 1) or 1.000 M NaCl (Figure 2) is used as the background electrolyte. The 1:1 curve for perchlorate medium has an inflection at a = 3.5 and then gradually reaches high pH values in an extended sloping buffer zone. In contrast, the NaCl curve has an inflection at a = 3.0, resulting in a steeper rise in pH, followed by a sloping buffer region. The 2:1 curves in all cases have inflections at a = 7, but the perchlorate buffer region occurs at lower pH than that of the NaCl medium. Since seven protons are neutralized in both systems and the amine is initially a hexahydrobromide, 1 mol of OH^-/mol of binuclear Cu(II) complex is involved in complex formation, thus providing a hydroxo bridge between the metal ions. The shifts in the potentiometric equilibrium curves are also observed for the other halide supporting electrolytes relative to perchlorate and can be explained in terms of the detailed speciation of the BISTREN–copper(II) complexes formed with and without cascade halide inclusion complexes formed in the corresponding supporting electrolyte media. The observed speciation may also be considered a function of the involvement of the anion of the medium in the stabilization of the various cationic chelated cryptate complexes formed.

The computer-resolved overall logarithms of the formation constants (β values) measured in this research are listed in Table IV. These values were obtained by the iterative refinement of both 1:1 and 2:1 equilibrium data so that all species present were taken into account. The species present were found to be ML^{2+}, MHL^{3+}, MH_2L^{4+}, MH_3L^{5+}, M_2L^{4+}, and M_2OHL^{3+} over a range of pH. However, the species M_2L^{4+} is in most cases an exceedingly minor constituent, and its log β value could not be obtained with the desired precision.

The differences in β values listed in Table IV give the stepwise constants (log K_X) shown in Table V. These constants indicate the differences arising from changes in the supporting electrolyte. Most notable are the stability constants of the pentapositive triprotonated 1:1 Cu(II)–BISTREN complex, CuH_3L^{5+}, and the tetrapositive binuclear complex, Cu_2L^{4+}, which are considerably higher in the chloride medium, reflecting the additional stabilization provided by chloride binding. It is also noted that the effect of fluoride ion, which is present as a relatively minor constituent in the ionic medium, has a major influence on the measured protonation constants.

The microscopic halide binding constants, calculated with equations similar to (5), are listed in Table VI. Fluoride is the most strongly bound both to the binuclear and to all of the protonated mononuclear copper(II) cryptates. The stability constant for fluoride binding to the monoprotonated mononuclear cryptate,

Table IV. Overall Stability Constants for BISTREN and Cu^{2+} (μ = 1.00 M, t = 25 °C)

	0.025 M NaF	1.0 M $NaClO_4$	0.5 M $NaClO_4$ + 0.5 M NaCl	1.0 M NaCl	1.0 M NaBr
log β_{ML}	18.30	18.65	17.85	17.34	18.15
log β_{MHL}	27.90	27.88	27.11	26.43	27.24
log β_{MH_2L}	36.45	36.03	35.61	35.08	35.59
log β_{MH_3L}	43.80	41.78	(42.2)	42.75	42.63
log β_{M_2L}	(32.9)	(30.2)	(31.0)	(30.2)	(29.4)
log β_{M_2LOH}	40.33	40.76	40.33	39.36	40.47

Table V. Logarithms of the Stability Constants for Cu(II)–BISTREN[a] (μ = 1.0 M, t = 25.0 °C)

quotient, Q	1.0 M $NaClO_4$	0.5 M $NaClO_4$ + 0.5 M NaCl	1.0 M NaCl	1.0 M NaBr	0.025 M F^-
K_{ML} = [ML]/[M][L]	18.65	17.85	17.34	18.15	18.30
$K^H{}_{MHL}$ = [MHL]/[ML][H]	9.23	9.26	9.09	9.09	9.60
$K^H{}_{MH_2L}$ = [MH_2L]/[MHL][H]	8.15	8.50	8.65	8.35	8.55
$K^H{}_{MH_3L}$ = [MH_3L]/[MH_2L][H]	5.75	7.57	7.67	7.04	7.35
$K^M{}_{M_2L}$ = [M_2L]/[ML][M]	(11.5)	(13.2)	(12.8)	(11.2)	(14.6)
$K^{-H}{}_{M_2LOH}$ = [M_2LOH][H^+]/[M_2L]	(−3.1)	(−4.4)	(−4.5)	(−2.6)	(−5.3)

[a] log $K^{-H}{}_{M_2LOH}$ = −6.5 at 1.0 M NaI.

Table VI. Anion Binding Constants for Polycationic Complexes of BISTREN (μ = 1.00 M, t = 25.0 °C)

	log Q			
quotient, Q	X = F^-	X = Cl^-	X = Br^-	X = I^-
$[M_2LX]/[M_2L][X]$	4.71	2.11		3.2
$[MH_3LX]/[MH_3L][X]$	3.20	2.27	1.72	
$[MH_2LX]/[MH_2L][X]$	2.00	0.54	−0.2	
$[MHLX]/[MHL][X]$	1.78	−0.7		

Table VII. Hydrolysis Constants of Binuclear Complexes[a] (μ = 1.0 M, t = 25.0 °C)

log K^{OH}	log (K^{OH}/K^X)	medium
(10.6)		1.0 M $NaClO_4$
(9.3)	(7.2)	0.50 M $NaClO_4$ + 0.50 M NaCl
(9.2)	(7.1)	1.0 M NaCl
(11.1)		1.0 M NaBr
(8.4)	(3.7)	0.025 M NaF + 0.975 M $NaClO_4$
(7.2)	(4.0)	1.0 M NaI

[a] $K^{OH} = [M_2LOH]/[M_2L][OH]$; $-\log K_w = 13.7$.

$CuHL^{3+}$, is considerable. The fact that its stability constant is much higher than that of the chloride ion is probably more a reflection of its greater hydrogen-bonding tendency than its greater affinity for Cu(II). Somewhat surprising is the strong binding between iodide ion and the binuclear cryptate. The coordinate-bond strength between Cu(II) and iodide is weaker than those of other halides.[12] Its unusually high affinity therefore seems to be due to other factors, such as a better fit of the iodide ion between the two Cu(II) centers than is possible with the smaller halide ions. The lack of hydrogen-bonding tendency of iodide is evidenced by the fact that its affinity for the protonated mononuclear cryptates is too low to show an effect on the measured protonation constants.

The affinity constants listed in Table VII for the binuclear cryptates in various media (which may be considered hydroxide ion binding constants) were calculated from the values of log β_{M_2L} and log $\beta_{M_2LOH^{3+}}$, with the value of K_w at 0.100 M ionic strength taken as 13.69. All the values listed are approximate and therefore are placed in parentheses because in all cases the degree of formation of M_2L was never large enough for a highly precise determination of its log β value. However, even with this limitation, the data are valuable as a measure of the competition between hydroxide ion and halide ions as bridging groups between two metal ions. The decrease in hydrolysis constant from the high values for perchlorate and bromide, for which no anion binding is assumed, provides a measure of this competition, remembering that the nature of the ionic medium also has some effect. With these hydroxide binding constants, the ratios of hydroxide to halide binding constants were calculated, and the values obtained are also listed in Table VII. The data, though approximate, clearly indicate that, even compared to the isoelectronic fluoride anion, which is the most strongly bound halide, the hydroxide ion is more strongly bound by many orders of magnitude. This large difference, which was at first surprising, is ascribed to the polar nature of the hydroxide ion and the possibility of hydrogen bonding to the ether oxygens of the cryptand.

Species Distributions. Figure 4 illustrates the 1:1 species distribution curves for Cu(II)–BISTREN as a function of pH in 1.000 M $NaClO_4$ solution. The most outstanding observation is the binding of hydroxide ion to form an exceedingly stable M_2LOH^{3+} species, to the virtual exclusion of any other 1:1 cryptate species. Thus, about 80% of the metal ion even in a 1:1 Cu(II)–BISTREN system exists as Cu_2LOH^{3+} above pH 5. It is the formation of this species that is responsible for the initial break at a = 3.5 in Figure 1. Figure 5 further dramatizes this hydroxide-binding cascade effect by showing 100% formation of M_2LOH. Also noteworthy is the ca. 0.5% maximum near pH 4.5 for the binuclear complex M_2L, which is shown to be virtually

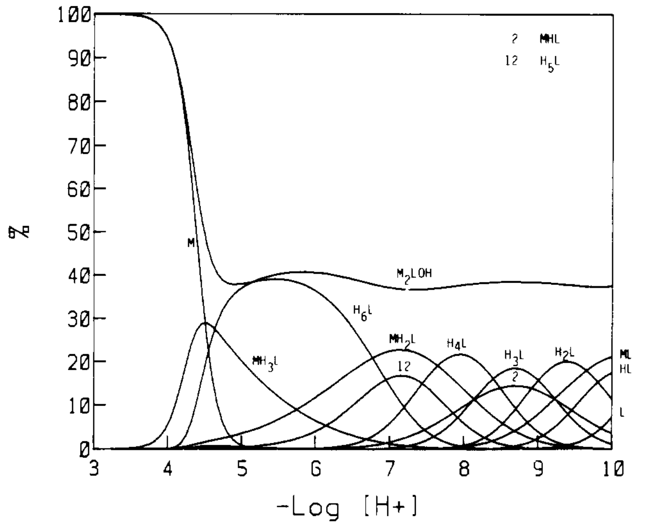

Figure 4. Distribution of species in a solution containing a 1:1 molar ratio of Cu(II) to BISTREN (μ = 1.000 M ($NaClO_4$), t = 25.0 °C, $T_{Cu^{2+}} = T_{BISTREN} = 1.000 \times 10^{-3}$ M).

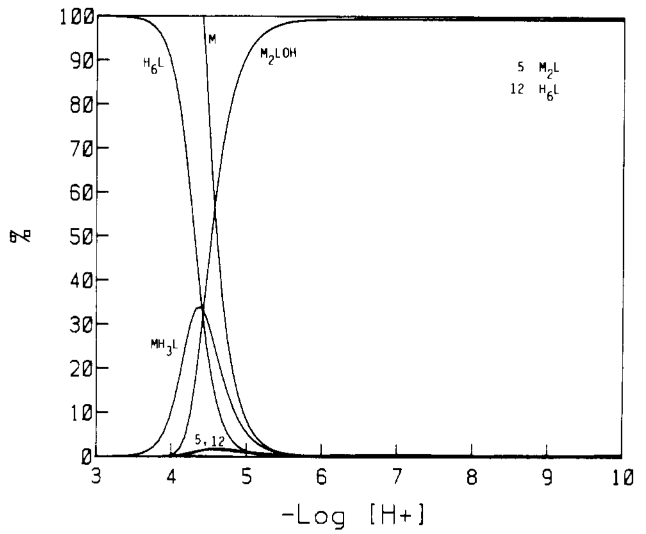

Figure 5. Distribution of species in a solution containing a 2:1 molar ratio of Cu(II) to BISTREN (μ = 1.000 M ($NaClO_4$), t = 25.0 °C, $T_{BISTREN} = {}^1/_2T_{Cu^{2+}} = 1.000 \times 10^{-3}$ M).

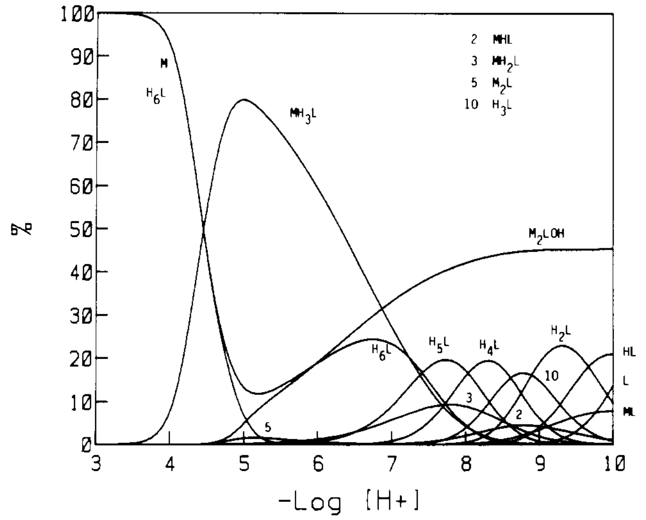

Figure 6. Distribution of species in a solution containing a 1:1 molar ratio of Cu(II) to BISTREN (μ = 1.000 M (NaCl), t = 25.0 °C, $T_{BISTREN} = T_{Cu^{2+}} = 1.000 \times 10^{-3}$ M).

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(12) Ahrland, S. *Struct. Bonding (Berlin)* **1973**, *15*, 167.

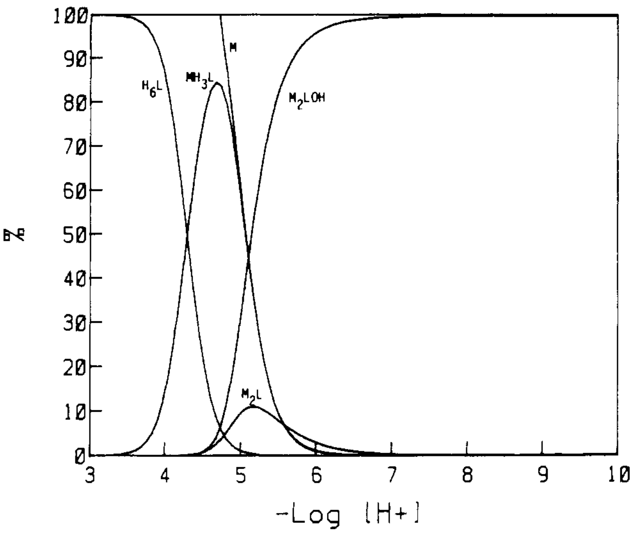


Figure 7. Distribution of species in a solution containing a 2:1 molar ratio of Cu(II) to BISTREN (μ = 1.000 M (NaCl), t = 25.0 °C, $T_{BISTREN} = {}^1/_2T_{Cu^{2+}}$ = 1.000 × 10^{-3} M).

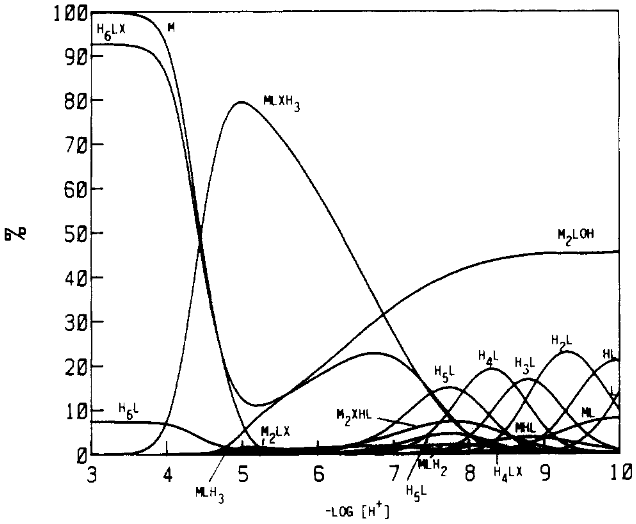


Figure 8. Distribution of microspecies in a solution containing 1.000 × 10^{-3} M BISTREN, 1.000 × 10^{-3} M Cu^{2+}, and 1.00 M NaCl (μ = 1.00 M, t = 25 °C).

absent.

Considerable redistribution of metal cryptate species occurs when halide ions are used in place of perchlorate in the supporting electrolyte. The effect of 0.100 M chloride medium described earlier[2] is greatly amplified in 1.000 M chloride medium, in spite of the fact that the chloride binding constant is reduced considerably at the higher ionic strength. The species distribution curves for the 1:1 Cu(II)–BISTREN system in perchlorate (Figure 4) and chloride (Figure 6) show an increase in degree of formation of the MH_3L species (actually MH_3L + $MClH_3L$) and a corresponding delay in the formation of M_2OHL to higher pH. For the 2:1 Cu(II)–BISTREN systems (Figures 5 and 7), the formation of appreciable binuclear cryptate Cu_2L^{4+} is seen to be depressed to insignificance because of the high stability of the hydroxide ion bridged species $Cu_2(OH)L^{3+}$. In chloride media the Cu_2L^{4+} species (actually Cu_2L^{4+} + Cu_2ClL^{3+}) increases over fivefold relative to perchlorate medium, and chloride complexes over 20% of the Cu(II) at pH 5.2. Here also, the binding of hydroxide ion is many times stronger than that of chloride, so that Cu_2OHL^{3+} becomes the major component above pH 5 and virtually the only component above pH 7. The distribution curves of the microscopic species formed in a 1.000 M sodium chloride medium (Figure 8) demonstrate the involvement of chloride binding in the formation of each type. Comparison with Figure 6, which gives the total (apparent) concentrations of each species, provides a clear picture of chloride participation occurring in these complex systems.

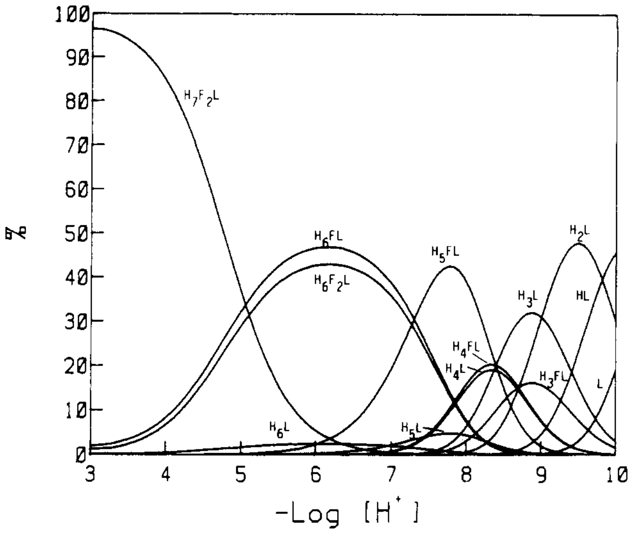
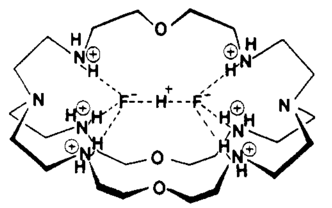


Figure 9. Distribution of microspecies in a solution containing 1.000 × 10^{-3} M BISTREN (μ = 1.000 M (2.50 × 10^{-2} M NaF and 0.975 M $NaClO_4$), t = 25.0 °C).

Figure 9 illustrates the species formed by BISTREN with merely a 20-fold excess of fluoride ion in an otherwise perchlorate medium. The predominant species at low pH is $H_7F_2L^{5+}$, which is in equilibrium with other fluoride complexes, $H_6F_2L^{4+}$ and H_6FL^{5+}. Only a minor concentration of H_6L^{6+} is formed at any pH, with a shallow maximum at pH 6.15. It is also seen that H_5FL^{4+} predominates over H_5F^{5+}. As the degree of protonation decreases, fluoride binding becomes weaker. Thus H_4L^{4+} and H_4FL^{3+} have approximately equivalent concentrations, and H_3L^{3+} forms at higher concentration than H_3FL^{2+}. A schematic representation of the hydrogen bonding that stabilizes the cascade-type HF_2^- anionic complex within the hexaprotonated cryptand H_6L^{6+} is illustrated.



Dietrich et al.[6] have reported the crystal structures of several halide inclusion complexes of BISTREN and found that when a single fluoride ion is bound, it is located at one end of the crypt in a tetrahedral environment. Probably the high solubility of the $H_7F_2L^{5+}$ species precluded the isolation of the bifluoride anion inclusion complex in crystalline form. In this work it was found that in the range of neutralization values of a = 0–1, corresponding to H_6L^{6+}–H_5L^{5+}, a solid phase separates, but the region of insolubility is not extensive enough to preempt the determination of all required potentiometric data when the region is approached from both higher and lower pH values. The existence of insoluble BISTREN hydrofluoride salts that increase in solubility at lower pH is due to the formation of the bifluoride inclusion complex at low pH. Chloride and bromide ions were reported to be located in the center of the crypt in an essentially octahedral environment.[6]

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Registry No. **1**, 98846-92-5; **2**, 54533-84-5; **3**, 98846-94-7; **4**, 98846-95-8; **5**, 64819-96-1; **6**, 89202-71-1; BISTREN, 64819-97-2; HF_2^-, 18130-74-0; F^-, 16984-48-8; Cl^-, 16887-00-6; Br^-, 24959-67-9; I^-, 20461-54-5; tris(2-aminoethyl)amine, 4097-89-6.