

A Complexation Study of Novel Triaza and Hexaaza Macrocycles
for the Use of Analytical Reagents

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Abstract: Novel macrocyclic ligands modified with pendant arms, N,N',N'',N''', N''''', N''''''-hexakis(2-aminoethyl)-1,4,7,10,13,16-hexaazacyclotadecane [L₃, Fig.1] and 1,4,7-tris(3-(o-hydroxyphenyl)propyl)-1,4,7-triazacyclononane [L₄, Fig.1] have been synthesized, and the protonation of L₃ and L₄ and stability constants of L₃ with bivalent transition metal ions and rare earth metal ions were determined by a potentiometry. The obtained results show that the complex formation of L₃ depends on the metal ligand ratios, and the stability of the metal complexes does not depend on the sizes of the metal ions, but on the nature of the metal ions. The structures of the rare earth complexes for L₄ were characterized by an X-ray absorption spectrometry(XAFS).

Keywords: Appended Triaza Macrocycles, Appended Hexaaza Macrocycles, Complex Formation, Potentiometry, XAFS

1. Introduction

Since macrocyclic polyamines possess reactive secondary amines, their derivatives with appended side chains were also prepared and their complexing abilities toward metal ions were investigated[1].

Macrocyclic polyethers, crown ethers, have oxygen donors which have strong

affinity for hard acids, especially, the alkali and alkaline earths groups. While, macrocyclic polyamines have nitrogen donors, softer base than oxygen and strong affinity for soft acids d-transition metals. There exists strong interests of complexing abilities and reactivities of macrocyclic polyamines toward rare earth

metals, f-transition metals for the field of not only analytical chemistry but also biochemistry[2,3].

For the purpose of making clear the specific complexing ability of macrocyclic polyamines toward bivalent transition metal ions and rare earth ions we have reported on the preparation and characterization of 1,5,9,13,17,21-hexaazacyclo-tetraeicosane [L₁,Fig.1] and its bivalent transition metal complexes[4], and of 1,4,7-tris(3-o-hydroxyphenylpropionyl)-1,4,7-trisazacyclononane[L₂,Fig.1] and its Ni(II), Eu(III), and Yb(III) complexes[5].

In the present study, novel macrocyclic ligands modified with pendant arms, L₃ and L₄ have been synthesized, and measured the complex formation abilities with bivalent transition metal ions and rare earth metal ions. The structures of the complexes were also characterized by an X-ray absorption spectrometry(XAFS).

2.Experimental

Preparation of ligands L₃ and L₄

L₃-A solution of 1,4,7,10,13,16-hexaazacyclooctadecane in acetonitrile was added to a solution of N-tosylaziridine in acetonitrile. The refluxed mixture solution was evaporated to dryness to give the white solid. The white solid N,N',N'',N''',N''''',N''''''-hexakis(2-N-tosylamino-ethyl)-1,4,7,10,13,16-hexaazacyclooctadecane was refluxed with a mixture of hydrobromic acid and acetic acid. The filtered solution was concentrated to dryness, and added to an ethanol. The

precipitate obtained was dissolved in water and eluted through a column of anion-exchange resin. The solution containing free amine L₃ was distilled to dryness.

L₄-A solution of diborane in tetrahydrofuran was added to a solution of L₂ in tetrahydrofuran under nitrogen atmosphere, and the mixed solution was refluxed at 70°C. A hydrochloric acid solution was added to the resulting solution, and the mixing solution was filtered off. The filtrate was evaporated to dryness under reduced pressure.

pH-metric measurement

The pH-metric titrations were carried out in a potassium nitrate solution at 25°C, by using a Horiba Digital pH meter and a Horiba combination glass electrode. For the determination of the protonation constants the cell was filled with about 20 ml of 1.0 mol dm⁻³ KNO₃ solution containing ca.1.0 mmol of samples and ca.9.0 mmol HNO₃ in excess. For the titration the KOH solution was dispensed from a Metrohm auto burette. The ionic product of water was determined in a 1.0 mol dm⁻³ KNO₃ aqueous solution at 25°C and found to be 13.75. The hydrogen ion concentration was obtained from the measured pH values by the method suggested by Irving et al.[7]. The protonation constants and complex formation constants were evaluated on the basis of the pH-metric titration data using the computer program PSEQUAD[8]. The initial concentrations of the reagents and the range of pH used for each titration curve are shown in Table 1.

3. Result and Discussion

Protonation of L_3 -The stepwise protonation constants for L_3 are given in Table 2, together with those reported for polyazacycloalkane [36]ane $N_{1,2}$ for a comparison [8]. The results show that L_3 behaves as a strong base in the first six steps of protonation and as much weaker base in the last six steps of protonation. The six stronger basic sites are assigned to pendant nitrogen atoms and the six weaker bases to the macrocycle nitrogen atoms. This assignment comes from the fact that nitrogen atom of ethylamine is very basic with $\log K$ of 10.66 and first six steps of protonation occur in the narrow range. From the formation study of tetraaza macrocycles which have 2-aminoethyl groups appended to the 4 nitrogen atoms, Tan et al. [9] drew the same conclusion that the 4 pendant nitrogen atoms are protonated above 7 and further protonations occur to the macrocycle nitrogen atoms.

The macrocycle [36]ane $N_{1,2}$ is less basic than L_3 in almost step of protonation. The behaviour can be due to the electrostatic repulsion among the positive charges on the protonated polyamines. For the macrocycle [36]ane $N_{1,2}$, the positive charges accumulated in the cyclic framework produce stronger repulsion than those accumulated in L_3 . The results indicate that pendant arms in L_3 may relax the electrostatic repulsion in the cyclic framework.

Complexation Constants of L_3 -The formation constants of Ni, Cu, and Zn complexes for L_3 and those of La, Nd, Sm, Gd, and Dy are summarized in Table 3 and 4, respectively. Owing to 12 nitrogen atoms present

in L_3 , many protonated metal complexes are formed in narrow pH region. The most important characteristic of L_3 is the ability to form stable polynuclear complexes. From the equilibrium data obtained for the system Cu-L, the distribution of the complexes formed as a function of pH has been calculated for the 2:1 and 3:1 Cu:L molar ratios, and the results have been plotted in Fig.2. In the case of L_3 there are 12 nitrogen donor atoms. The high value of the stability constant of the trinuclear species and low value of equilibrium constant relative to the addition of some hydrogen ions to the trinuclear species $[Cu_3L]^{6+}$ to form $[Cu_3LH_n]^{6+n}$ ($n=1-5$) indicate that all donor atoms are involved in the complex formation.

From the equilibrium data obtained for the systems Ni-L and Zn-L, the distributions of the complexes formed as a function of pH have been calculated for the 2:1 Ni:L and Zn:L molar ratios, and the results have been plotted in Fig.3. The results of Figs.2 and 3 suggest that the complex formation of L_3 with Ni, Cu, and Zn ions depends on the nature of the metal ions. The order of the stability constants $\log K (M_2L)$ for the Ni, Cu, and Zn dinuclear complexes with L_3 can be expected on the basis of an Irving-William series.

As seen in Table 4, L_3 forms also protonated mononuclear species for La, Nd, Sm, Gd, and Dy. This is similar with that of 1,4,7,10, 13,16-hexaazacyclooctadecane-N,N',N'', N''', N''''',N''''''-hexacetic acid [L_5 , Fig.1], but different with that of L_1 which has only unprotonated mononuclear species. Comparing L_5 appended by carboxyl arms with L_1 , the

Table I. Experimental details of the pH measurements (L=L₃)

	init. concentration, mmol dm ⁻³			pH range		data points
	Metal	L	H ⁺	investigated	computed	
H ⁺		0.4990	4.048	2.3-11.1	3.0 - 11.0	99
Ni ²⁺	0.9200	0.4976	3.943	2.3-11.1	5.1 - 9.2	69
Cu ²⁺	0.9654	0.4981	4.051	2.2-11.2	3.0 - 11.0	133
Cu ²⁺	1.450	0.4981	4.055	2.3-11.0	2.7 - 10.5	86
Zn ²⁺	0.9197	0.4976	3.943	2.2-11.0	5.1 - 8.6	69
La ³⁺	0.2475	0.5023	4.638	2.3-11.3	8.5 - 10.5	146
La ³⁺	0.4966	0.5022	4.636	2.3-11.3	8.5 - 10.5	137
Nd ³⁺	0.2493	0.5023	4.638	2.3-11.2	7.6 - 10.0	74
Nd ³⁺	0.5002	0.5022	4.637	2.3-11.5	7.6 - 10.0	64
Sm ³⁺	0.2536	0.5024	4.638	2.3-11.5	7.1 - 10.2	150
Sm ³⁺	0.5087	0.5022	4.637	2.3-11.3	7.0 - 10.2	138
Gd ³⁺	0.2510	0.5023	4.638	2.3-11.5	7.4 - 10.0	124
Gd ³⁺	0.5036	0.5022	4.637	2.3-11.2	7.4 - 10.0	67
Dy ³⁺	0.2538	0.5023	4.638	2.3-11.5	7.1 - 10.0	137
Dy ³⁺	0.5068	0.5020	4.655	2.3-11.4	7.0 - 10.0	133

Table II. Protonation Constants of the Macrocycle L in 0.5 mol dm⁻³ KNO₃ Aqueous Solution (L=L₃)

	L	[36]aneN ₁₂ ^a
log K ₁	10.16(5) ^b	9.75
log K ₂	10.30(2)	9.65
log K ₃	9.24(8)	8.88
log K ₄	9.85(2)	8.96
log K ₅	8.67(4)	8.12
log K ₆	8.97(1)	7.82
log K ₇	7.20(1)	5.66
log K ₈	5.10(2)	4.27
log K ₉	4.20(2)	3.58
log K ₁₀	2.59(2)	2.62
log K ₁₁	2.0 ^c	2.3
log K ₁₂	1.0 ^c	1.0 ^c

^aFrom ref. 8. ^bEstimated standard deviations on the last significant digits are in parentheses. ^c Estimated

Table III. Formation Constants of Nickel(II), Copper(II) and Zinc(II) Complexes for the Macrocycle L in 0.5 mol dm⁻³ KNO₃ Aqueous Solution at 25 °C (L=L₃)

reaction	log K		
	M=Ni ²⁺	M=Cu ²⁺	M=Zn ²⁺
2M ^a + L = M ₂ L	29.00(1)	34.3(2)	26.38(2)
2M + L + H = M ₂ LH	38.26(1)	45.6(1)	35.14(1)
2M + L + 2H = M ₂ LH ₂	45.70(1)	54.7(1)	41.97(1)
2M + L + 3H = M ₂ LH ₃	51.96(1)	63.38(9)	48.47(1)
2M + L + 4H = M ₂ LH ₄	57.50(1)	69.04(4)	54.51(1)
2M + L + 5H = M ₂ LH ₅	61.58(2)	72.93(2)	
2M + L + H ₂ O = M ₂ LOH + H		23.6(1)	
3M + L = M ₃ L		48.8(2)	
3M + L + H = M ₃ LH		57.9(1)	
3M + L + 2H = M ₃ LH ₂		64.56(5)	
3M + L + 3H = M ₃ LH ₃		68.81(9)	
3M + L + 5H = M ₃ LH ₅		76.96(2)	
3M + L + H ₂ O = M ₃ LOH + H		38.5(2)	
3M + L + 2H ₂ O = M ₃ L(OH) ₂ + H		27.8(2)	
M ₂ L + H = M ₂ LH	9.62	11.3	8.76
M ₂ LH + H = M ₂ LH ₂	7.44	9.1	6.83
M ₂ LH ₂ + H = M ₂ LH ₃	6.27	8.7	6.50
M ₂ LH ₃ + H = M ₂ LH ₄	5.53	5.66	6.03
M ₂ LH ₄ + H = M ₂ LH ₅	4.08	3.89	
M ₂ L + OH = M ₂ LOH		3.1	
M ₃ L + H = M ₃ LH		9.1	
M ₃ LH + H = M ₃ LH ₂		6.7	
M ₃ LH ₂ + H = M ₃ LH ₃		4.25	
M ₃ LH ₃ + 2H = M ₃ LH ₅		8.15	
M ₃ L + OH = M ₃ LOH		3.5	
M ₃ LOH + OH = M ₃ L(OH) ₂		3.0 ^a	

^aCharges omitted for clarity.Table IV. Formation Constants of Lanthanid(III) Complexes for the Macrocycle L in 0.5 mol dm⁻³ KNO₃ Aqueous Solution at 25 °C (L=L₃)

reaction	log K				
	M=La ³⁺	M=Nd ³⁺	M=Sm ³⁺	M=Gd ³⁺	M=Dy ³⁺
M ^a + L = ML	5.81(5)	8.18(6)	8.61(7)	9.17(9)	9.93(9)
M + L + 2H = MLH ₂	25.02(5)	27.48(3)	27.99(4)	28.34(7)	29.08(6)
M + L + 4H = MLH ₄		44.98(3)	45.53(4)	46.00(5)	46.64(5)
M + L + H ₂ O = MLOH + H	-4.30(6)	-1.82(7)	-1.22(6)	-0.72(9)	0.19(9)
ML + 2H = M LH ₂	19.21	19.30	19.38	19.17	19.15
MLH ₂ + 2H = M LH ₄		17.50	17.54	17.66	17.56
ML + OH = MLOH	3.7	3.8	3.9	3.9	4.0

^aCharges omitted for clarity.

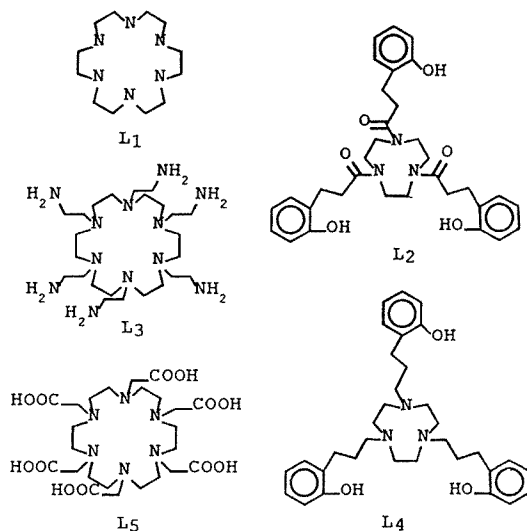


Figure 1. Structure of macrocycles discussed in this paper.

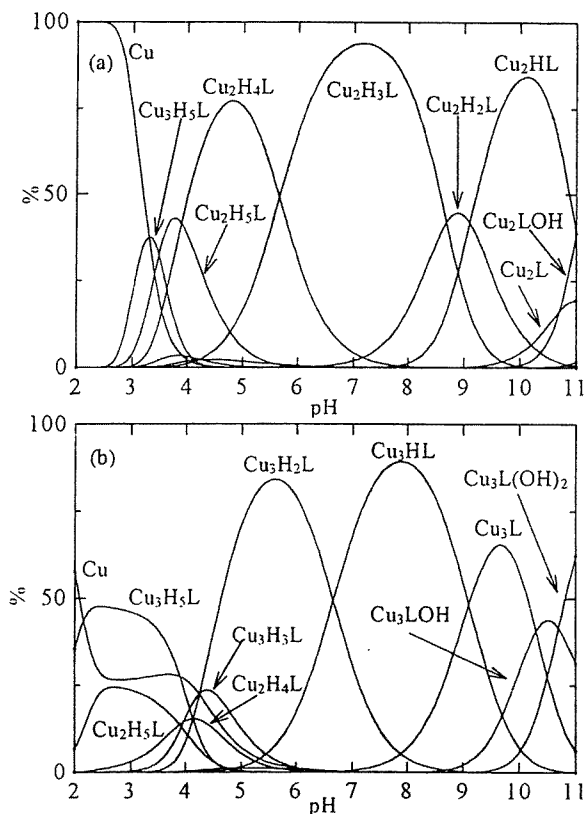


Figure 2. Calculated distribution of the equilibrium species in the systems Cu^{2+}/L in $0.5 \text{ mol dm}^{-3} \text{ KNO}_3$ aqueous solution at 25°C : (a) $C_{\text{Cu}}:C_{\text{L}}=2:1$; (b) $C_{\text{Cu}}:C_{\text{L}}=3:1$ ($\text{L}=\text{L}_3$)

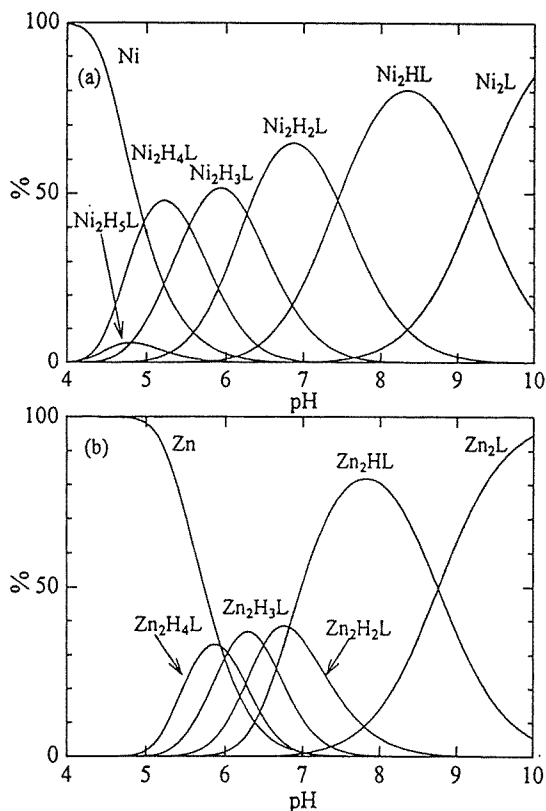


Figure 3. Calculated distribution of the equilibrium species in the systems Ni²⁺/L and Zn²⁺/L in 0.5 mol dm⁻³ KNO₃ aqueous solution at 25°C: (a) C_{Ni}:C_L=2:1; (b) C_{Zn}:C_L=2:1 (L=L₃)

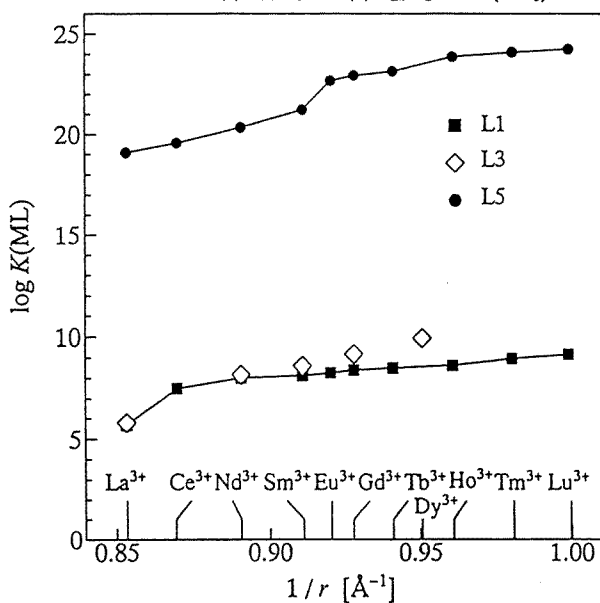


Figure 4. Variation of the stability constants $K(ML)$ of the complexes L1, L3 and L5 with the reciprocal values of the ionic radii of Ln(III)

stability constants of L_5 for rare earth metal ions increase very much. However, this pendant effect cannot recognize in the case of L_3 since hard rare earth metal ions strongly interact with hard oxygen donors. Fig.4 shows the variation of the stability constants of rare earth complexes for L_3 with the reciprocal values of the ionic radii of Ln comparing those for L_1 and L_5 [10].

Protonation Constants of L_4 -The stepwise protonation constants for L_4 are also determined by a potentiometry. The results show that L_4 behaves as a strong base in the first three steps of protonation and as much weaker base in the last three step of protonation. The three stronger basic sites may be assigned to pendant oxygen atoms and three weaker bases to the cycle nitrogen atoms.

Complexation of L_4 - L_4 forms stable mononuclear species for Cu, rare earth ions. The complex formation of these mononuclear species has been characterized by UV-Vis, IR, and XAFS spectrometries. Both XANES and XAFS spectra of the metal complexes for L_4 to Nd and Tb ions comparing with those of Nd complexes for DTPA diethlenetriaminepentacetic acid. XANES and XAFS spectra of the Nd complex for DTPA are different with those of the Nd and Tb complexes for L_4 . This suggests that L_4 forms the same structure for the Nd and Tb complexes.

The aqueous solution of the Tb complex showed very strong fluorescent spectra compared with the aqueous solution of terbium chloride. The result shows the possibility of a fluorescent analysis for the trace amount of Tb.

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