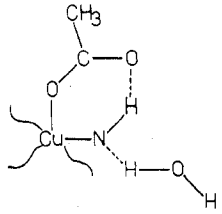


Figure 11. Proposed intramolecular hydrogen bonding and concerted inversion of nitrogen in $[Cu(tet\,a)(OAc)(blue)]^+$.

the copper(II) complex are of two types: (1) those that are weak bases such as Cl^-, Br^-, and I^- and (2) those coordinated ligands such as N_3^- and NCS^-, which lack another lone pair in the vicinity of the N–H group. The latter contains lone pairs, which are too far away to react with the N–H group that must be inverted during the blue-to-red reaction.

In the case of the coordinated anions that contain another lone pair in the vicinity of the amine hydrogen, the value of the resolved rate constant k_L increases as the basicity of the anionic ligand increases as shown by the data given in Table IV. The trend, $k_{NO_2} < k_{OAc} < k_{SH} < k_{OH}$, led us to think that there must be a relation between the proton basicity factors and the resolved rate constants of the anions. Plotting the basicity constant defined as $\log([HL]/[H^+][L^-])$ or pK_a as abscissa and $\log k_L$ as ordinate, we obtain a straight line relationship as shown in Figure 10. The magnitude of the slope, 0.40, suggests that the hydrogen is partially removed from the nitrogen to the coordinated base in the activated complex as shown in Figure 11. The hydrogen-bonded ring structure may be important in helping to maintain an activated species long enough to permit the five-membered and six-membered rings to twist and the nitrogen to attract a proton from a solvent molecule on the opposite site of the coordinated base, thus leading to the inversion.

On the basis of these results we are able to conclude that the kinetics shows a strong preference for the reaction of coordinated bases which contain another lone pair in the vicinity of the amine hydrogen over free bases. The hydrogen is partially removed from the nitrogen in the activated complex. A concerted mechanism is proposed in which intramolecular hydrogen bonding, nitrogen inversion, and ring conformation changes occur.

Acknowledgment. The authors are grateful to the Chemistry Research Center, National Science Council of the Republic of China, for financial support.

Registry No. $[Cu(tet\,a)(blue)]^{2+}$, 73464-68-3; $[Cu(tet\,a)(red)]^{2+}$, 73464-69-4; $[Cu(tet\,a)(OH)(blue)]^+$, 73464-70-7; $[Cu(tet\,a)(SH)(blue)]^+$, 73395-63-8; $[Cu(tet\,a)(OAc)(blue)]^+$, 73384-40-4; $[Cu(tet\,a)(NO_2)(blue)]^+$, 73384-33-5; $[Cu(tet\,a)Cl(blue)]^+$, 73464-66-1; $[Cu(tet\,a)Br(blue)]^+$, 73464-67-2; $[Cu(tet\,a)I(blue)]^+$, 73493-86-4; $[Cu(tet\,a)(SCN)(blue)]^+$, 73384-34-6; $[Cu(tet\,a)N_3(blue)]^+$, 73384-35-7; OH^-, 14280-30-9; Cl^-, 16887-00-6; Br^-, 24959-67-9; I^-, 20461-54-5; N_3^-, 14343-69-2; SCN^-, 302-04-5; OAc^-, 71-50-1; NO_2^-, 14797-65-0; SH^-, 15035-72-0.

Contribution from the Department of Chemistry, College of General Education, Hirosaki University, Bunkyo, Hirosaki 036, Japan, and Institute of Pharmaceutical Sciences, Hiroshima University School of Medicine, Kasumi, Hiroshima 734, Japan

Effects of Axial Ligation on Molecular Oxygen Binding by Donor Atoms Built in Saturated Macrocycles. Equilibrium and Kinetic Study with Cobalt(II) Complexes of Macrocyclic Pentaamines and Oxatetraamine

MUTSUO KODAMA[1a] and EIICHI KIMURA*[1b]

Received August 3, 1979

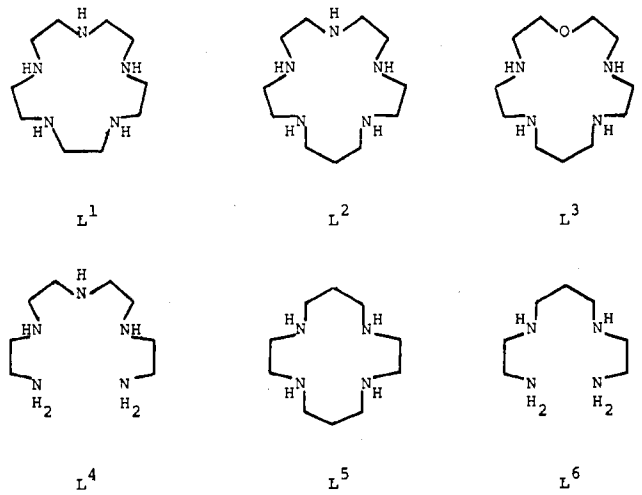
Cobalt(II) complexes of two 16-membered macrocyclic homologues 1,4,7,10,13-pentaazacyclohexadecane (L^2) and 1-oxa-4,7,11,14-tetraazacyclohexadecane (L^3) are capable of coordinating molecular oxygen at pH ~5 to form μ-peroxo-bridging complexes $(CoL)_2O_2$. A comparison with a 14-membered tetraamine L^5 suggests that an extra ligation at an axial position with the fifth N or O donor atom built in the macrocyclic structure appreciably promotes the rates and equilibrium of O_2 uptake, in particular with the N donor. The equilibrium and kinetic results for L^2 are compared with the relevant data reported for a linear pentaamine homologue L^4.

The modes and capabilities by which cobalt(II)–tetraamine (N_4) complexes bind molecular oxygen[2] are subjected to characteristic modification by the tetraamine ligand cyclization and the cyclized ring size.[3] Although the ring closure of triethylenetetramine (trien)[4,5] with ethylene (into 12-membered N_4) or propylene (into 13-membered N_4) does not alter the stoichiometry of the μ-dioxygen-μ-hydroxo products (represented by $(CoL)_2O_2OH$), it introduces stereochemical constraint to make the O_2 uptake less favorable kinetically and thermodynamically.[3] A most dramatic consequence of the cyclized structure occurs at 14-membered homologue 1,4,8,11-tetraazacyclotetradecane (L^5), where the oxygenation product takes a different $(CoL)_2O_2$ structure lacking a μ-hydroxo bridge.[3,6,7] This implies that rigid planarity around Co(II) is imposed by the 14-membered cyclic structure with one of the axial positions used for interaction with O_2 and the remaining axial site left open (or more likely, for interaction with H_2O solvent). The oxygenation product and the kinetics leading to it (first order in $[CoL^{2+}]$ and in $[O_2]$) for the saturated 14-membered N_4 are analogous to those for unsaturated 16-membered macrocyclic N_4 porphyrins.[8,9] Because of the "nonfrilled" structure, L^5 offers excellent advantages for the study of properties associated with the macrocyclic structure characterizing the natural macrocyclic ligands.

This paper continues the oxygenation study promoted by cobalt(II) complexes of macrocyclic ligands, 1,4,7,10,13-pentaazacyclopentadecane (L^1), 1,4,7,10,13-pentaazacyclohexadecane (L^2), and 1-oxa-4,7,11,14-tetraazacyclohexadecane

(1) (a) Hirosaki University. (b) Hiroshima University.
(2) G. McLendon and A. E. Martell, *Coord. Chem. Rev.*, **19**, 1 (1976).
(3) M. Kodama and E. Kimura, *J. Chem. Soc., Dalton Trans.*, 327 (1980).
(4) F. Miller and R. G. Wilkins, *J. Am. Chem. Soc.*, **92**, 2687 (1970).
(5) R. Nakon and A. E. Martell, *J. Am. Chem. Soc.*, **94**, 3026 (1972).
(6) B. Bosnich, C. K. Poon, and M. L. Tobe, *Inorg. Chem.*, **5**, 1514 (1966).
(7) G. McLendon and M. Mason, *Inorg. Chem.*, **17**, 362 (1978).
(8) D. V. Stynes, H. C. Stynes, J. A. Ibers, and B. R. James, *J. Am. Chem. Soc.*, **95**, 1142 (1973).
(9) B. R. James, "The Porphyrins", Vol. 5, D. Dorphin, Ed., Academic Press, New York, 1978, p 205.

0020-1669/80/1319-1871$01.00/0



(L^3). Natural and synthetic complex oxygen carriers are all active in five-coordination.[9,10] The macrocyclic pentaamines and oxatetraamine are potential five-coordinate ligands, probably taking square-pyramid configurations around Co(II), in which the apical base (N or O atom) would be expected to influence the O_2 interaction at the trans axial position. In natural heme proteins, the protein holds an imidazole at the axial position, facilitating the "neighboring group" effect on oxygenation at the trans position. In the present system, cyclic nature would hold a donor atom in place at an axial position.

As an important foundation the present study includes determination of CoL^{2+} complex stability constants, which have not been reported earlier in literature. The chelating tendencies of the linear pentaamine tetraethylenepentamine (L^4) with Co(II) and its oxygenation equilibrium and kinetics had been well investigated.[11,12] The structural relevance of the cyclic ligands L^1 and L^2 to the linear counterpart L^4 would allow a direct comparison of the effectiveness of the pentaamine cyclization on complexation and the complex reactivities.

The pentadentate macrocycles, further, may serve as a model of the active site of anticancer agent bleomycin which comprises five nitrogen donors (of peptide) in square-pyramid geometry around the central metal ion.[13] A mechanism of anticancer activity is postulated as that O_2 first bonded to the axial position would be released as O_2^- to attack the cancer DNA bases in the surroundings.[14] Significance of the five N coordination at the initial oxygenation step might be realized by the macrocyclic pentaamines.

Experimental Section

Macrocyclic pentaamines L^1 and L^2 were synthesized as described before.[15] Their mixed protonation constants (log K_i) used for calculation are listed in Table I, together with the corresponding values for the related polyamines. The oxatetraamine L^3 was prepared by treating bis(2-chloroethyl) ether with equimolar 1,4,8,11-tetraazaundecane (L^6) tetratosylate in DMF in the presence of large excess K_2CO_3 at ~110 °C for 3 days. The product was recrystallized from benzene–ethanol as $L^3 \cdot 4Ts$, mp 105 °C. Anal. Calcd for $C_{11}N_4OH_{22} \cdot 4Ts$: N, 6.6. Found: N, 6.4. Hydrolysis of the tosylate with refluxing HBr–HOAc for 1 week precipitated $L^3 \cdot 4HBr$. Anal. Calcd for $C_{11}N_4OH_{26} \cdot 4HBr$ (recrystallized from AcOH–HBr): N, 10.1. Found: N, 10.0. The protonation constants log K_i of L^3 determined potentiometrically are 9.35, 7.90, 4.90, and ~3 at 35 °C. Stock solutions of cobalt(II) were prepared from analytical grade chloride salts and standardized by the method of Schwarzenbach.[16] Potentiometric apparatus and polarographic apparatus were the same as those used previously.[3]

Table I. Ligand Mixed Protonation Constants at 35 °C and $I = 0.2$ M

	log K_1	log K_2	log K_3	log K_4	log K_5
L^1 [a]	10.71	9.45	5.81	<2	<2
L^2 [a]	10.42	9.27	7.06	<2	<2
	(10.64)	(9.49)	(7.28)	(1.71)	(1.45)
L^3 [b]	9.35 ± 0.02	7.90 ± 0.02	4.90 ± 0.02	~3	
L^4 [c]	10.36	9.65	8.50	4.70	2.40
L^5 [d]	11.23	10.30	1.5	0.8	
L^6 [e]	10.34	9.42	8.20	5.58	

[a] Reference 15. The values in parentheses are at 25 °C. [b] This study. [c] D. B. Moss, C. Lin, and D. B. Rorabacher, *J. Am. Chem. Soc.*, 95, 5179 (1973). At 25 °C and $I = 0.1$ M. [d] Reference 3. [e] Literature values (R. Barbucci, L. Fabbrizzi, P. Paoletti, and A. Vacca, *J. Chem. Soc., Dalton Trans.*, 1763 (1973)) are corrected to 35 °C and $I = 0.2$ M by using the given thermodynamic parameters.

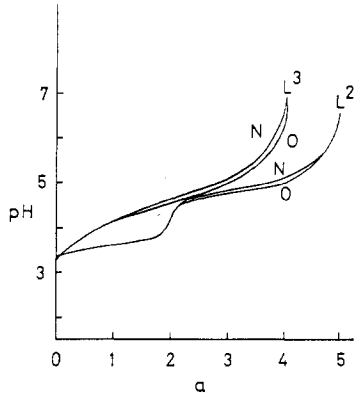


Figure 1. Potentiometric titrations of the 16-membered macrocycles L^2 and L^3 with the presence of equimolar Co(II) in N_2 atmosphere (N) and in air (O).

Potentiometric Measurements. The ligand hydrobromide salts $L^1 \cdot 5HCl$ or $L^2 \cdot 5HBr$ (3×10^{-4} M) and $L^3 \cdot 4HBr$ (10^{-3} M) in 50 mL aqueous solutions were titrated potentiometrically with standard sodium hydroxide solution in the presence of equimolar cobalt(II), and the $-\log [H^+]$ (=pH) values were recorded 35 min (15 min for L^3) after addition of each increment of base. The anaerobic (in N_2) and aerobic formation curves were determined with L^2 and L^3 (see Figure 1) to compute stability constants K_{CoL} and oxygenation constants K_{O_2}, respectively. With L^1 irreversible oxidation rapidly occurs in aerobic conditions to prevent accurate determination of K_{O_2}. Molar concentration of O_2 in air-saturated aqueous solution was taken from the literature: 2.7 (2.3) $\times 10^{-4}$ M at 25 (35) °C.[17] Solutions were adjusted to 0.20 M ionic strength by addition of $NaClO_4$ and maintained at 35.0 ± 0.1 °C.

Kinetic Measurements. Two sets of O_2 (dissolved in aqueous solutions) uptake rates by the L^2 system were measured with a stopped-flow apparatus by observing the increase in absorbance at 320 nm due to the formation of μ-peroxo complex at $I = 0.2$ M and 25 °C. One is the rate for the interactions of Co(II), L, and O_2 in acetate buffer solutions in N_2 atmosphere. No decomposition to Co^{3+} was seen spectrophotometrically during the kinetic measurements. The rate constants were determined by the initial gradient method. The other is the rate of O_2 uptake by CoL^{2+} preformed in anaerobic conditions by mixing Co^{2+} with L (5–7% in excess) in acetate buffer and allowing the mixture to complete equilibration (>60 min). The subsequent oxygenation rate constants were determined from the second-order plots (unequal concentration). Typical rate data for

(10) F. Basolo, B. M. Hoffman, and J. A. Ibers, *Acc. Chem. Res.*, **8**, 384 (1975).
(11) W. R. Harris, I. Murase, J. H. Timmons, and A. E. Martell, *Inorg. Chem.*, **17**, 889 (1978).
(12) F. Miller, J. Simplicio, and R. G. Wilkins, *J. Am. Chem. Soc.*, **91**, 1962 (1969).
(13) Y. Sugiura and Y. Mino, *Inorg. Chem.*, **18**, 1336 (1979), and references therein.
(14) T. Takita, Y. Muraoka, T. Nakatani, A. Fujii, Y. Iitaka, and H. Umezawa, *J. Antibiot.*, **31**, 1073 (1978).
(15) M. Kodama and E. Kimura, *J. Chem. Soc., Dalton Trans.*, 104 (1978).
(16) G. Schwarzenbach, "Complexometric Titrations", Interscience, New York, 1957, p 82.
(17) "Chemical Handbook of Japan", Chemical Society of Japan, Maruzen, Japan, 1973, p 571.

Table II. Rate Data for the Reactions of $[CoL^2]$ with O_2 at 25 °C and $I = 0.2$ M to Give $(CoL)_2O_2$

$10^3 \times$ $[CoL^2]$, M	$10^3 \times$ $[O_2]$, M	$10^3 \times$ $[AcO^-]$, M	pH	$10^{-5}k_2$, M^{-1} s^{-1}
1.0	0.13_5	100	5.50	2.22
1.0	0.13_5	100	5.00	2.22
1.0	0.13_5	100	4.80	2.19
0.50	0.13_5	100	5.50	2.21
0.25	0.13_5	100	5.50	2.10
1.00	0.13_5	50	5.50	2.12
1.00	0.13_5	200	5.50	2.20
1.00	0.067_5	100	5.50	2.19
1.00	0.033_8	100	5.50	2.20

individual runs are given in Table II.

The kinetics for L^3 was not studied due to the absorption peak (305 nm) of the oxygenation product overlapping with the reactants.

Results and Calculations

Potentiometric Determination of K_{CoL}. The anaerobic formation curves in Figure 1 represent the equilibria

$$H_{i-1}L^{(i-1)} + H^+ \rightleftarrows H_iL^{i+}$$
$$K_i = [H_iL^{i+}]/[H_{i-1}L^{(i-1)+}][H^+] \quad (1)$$

$$Co^{2+} + L \rightleftarrows CoL^{2+} \qquad K_{ML} = [CoL^{2+}]/[Co^{2+}][L] \quad (2)$$

The hydrolysis of $Co^{2+}(aq)$ was neglected taking into account the reported[18] value $10^{3.96}$ of K_{OH} ($=[Co(OH)^+]/[Co^{2+}]\cdot[OH^-]$) and the pH range ($4 < pH < 6$) studied. The metal–ligand stability constants K_{ML} were calculated by using the similar procedures as described previously.[3,19] In essence, the calculation for the pentaamines L^1 and L^2 involves the simultaneous solution of eq 3–6, where C_L and C_M are total

$$C_L = [L]_F + [ML^{2+}] \quad (3)$$

$$C_M = [M^{2+}] + [ML^{2+}] \quad (4)$$

$$C_L = C_M \quad (5)$$

$$\alpha = [H^+] + aC_L = 5[L] + 4[HL^+] + 3[H_2L^{2+}] + 2[H_3L^{3+}] + [H_4L^{4+}] + 5[ML^{2+}] \quad (6)$$

concentrations of ligand and cobalt ion, respectively

$$[L]_F \text{ (=concentration of uncomplexed ligand)} = [L] + [HL^+] + [H_2L^{2+}] + \ldots + [H_5L^{5+}] \quad (7)$$

and α is the sum of hydrogen ($-\log [H] = pH$) and dropped alkaline molar concentration at titration point a. By introduction of the definitions

$$(\alpha_H)_L = [L]_F/[L] = 1 + [H^+]K_1 + [H^+]^2K_1K_2 + \ldots + [H^+]^5K_1K_2K_3K_4K_5 \quad (8)$$

$$\beta_H = 5 + 4[H^+]K_1 + 3[H^+]^2K_1K_2 + 2[H^+]^3K_1K_2K_3 + [H^+]^4K_1K_2K_3K_4 \quad (9)$$

eq 2 is rewritten by (10).

$$K_{CoL} = \frac{[\alpha(\alpha_H)_L - \beta_HC_L][5(\alpha_H)_L - \beta_H]}{(\alpha_H)_L(5C_L - \alpha)^2} \quad (10)$$

K_{CoL} for the oxatetraamine L^3 can be similarly derived as in eq 11. Plots of the numerator vs. denominator in eq 10

$$K_{CoL} = \frac{[\alpha(\alpha_H)_L - \beta_HC_L][4(\alpha_H)_L - \beta_H]}{(\alpha_H)_L(4C_L - \alpha)^2} \quad (11)$$

and 11 (in the range $2.5 < a < 4.5$ for L^1 and L^2 and $1.5 < a < 3.5$ for L^3) showed excellent linear lines passing the origin.

(18) J. A. Bolzen and A. J. Aruia, *Electrochim. Acta*, 7, 589 (1962).
(19) M. Kodama and E. Kimura, *J. Chem. Soc., Dalton Trans.*, 1081 (1978).

Table III. Equilibrium Constants for CoL^{2+} Complex Stability and for Oxygenation of CoL^{2+} in Aqueous Solution[a]

ligand	log K_{CoL}	log K_{O_2} [b]	log K'_{O_2} [c]
L^1	16.76 ± 0.05		
L^2	15.95 ± 0.05	39.77 ± 0.05	7.87 ± 0.05
L^3	11.42 ± 0.05	27.48 ± 0.05	4.64 ± 0.05
L^4 [d]	13.66	43.15	15.83
L^5 [e]	12.71	27.08	1.66
L^6 [f]	12.93		

[a] Unless otherwise noted all values were determined at 35 °C and $I = 0.20$ M ($NaClO_4$). [b] K_{O_2} defined by eq 12. [c] K'_{O_2} defined by eq 21. [d] From ref 11 at 25 °C and $I = 0.1$ M (KNO_3). [e] From ref 3. [f] M. Kodama and E. Kimura, unpublished results.

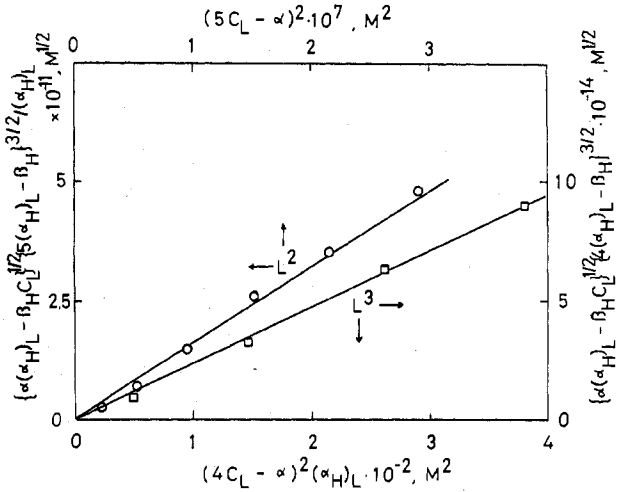


Figure 2. Determination of oxygenation constants K_{O_2} by plots of eq 17 (for L^2) and eq 18 (for L^3).

The K_{CoL} values obtained from the gradients are listed in Table III.

Potentiometric Determination of Oxygenation Constants K_{O_2}. As for K_{CoL}, simultaneous solution of eq 12–16 leads to eq 17 for the pentaamine L^2 system. Similarly, K_{O_2} for oxatetraamine L^2 was derived as (18). The K_{O_2} values for L^2 and L^3

$$2M^{2+} + 2L + O_2 \overset{K_{O_2}}{\rightleftarrows} (ML)_2O_2^{4+}$$
$$K_{O_2} = [(ML)_2O_2]/[M^{2+}]^2[L]^2[O_2] \quad (12)$$

$$C_M = 2[(ML)_2O_2] + [M^{2+}] \quad (13)$$

$$C_L = 2[(ML)_2O_2] + [L]_F \quad (14)$$

$$C_M = C_L \quad (15)$$

$$\alpha = [H^+] + aC_L = 5[L] + 4[HL^+] + 3[H_2L^{2+}] + 2[H_3L^{3+}] + [H_4L^{4+}] + 10[(ML)_2O_2] \quad (16)$$

$$K_{O_2} = \frac{[\alpha(\alpha_H)_L - \beta_HC_L][5(\alpha_H)_L - \beta_H]^3}{2(5C_L - \alpha)^4(\alpha_H)_L^2[O_2]} \quad (17)$$

$$K_{O_2} = \frac{[\alpha(\alpha_H)_L - \beta_HC_L][4(\alpha_H)_L - \beta_H]^3}{2^3(4C_L - \alpha)^4(\alpha_H)_L^2[O_2]} \quad (18)$$

determined graphically (see Figure 2) are summarized in Table III.

Polarographic Measurements of Oxygenation Stoichiometry. A reduction wave height of free O_2 (3.0×10^{-4} M) dissolved in 25 mL of aqueous solution containing Co^{2+} (2×10^{-4} M) and $[AcO^-]$ (10^{-1} M) at pH 5.15, $I = 0.2$ M, and 20 °C (where the complexation with L can occur with or without O_2) was 8.40 cm. An addition of $L^2 \cdot 5HBr$ (10^{-3} M) lowered the O_2 reduction wave height (after >60 min of equilibration time) to 6.5 cm. The dimunition of free O_2 in the solution due to

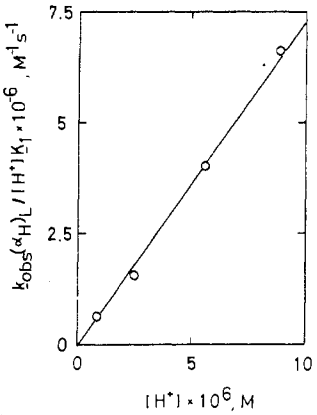


Figure 3. Resolution of the observed second-order rate constant by plots of eq 20 at $[Co^{2+}] = [L^2] = 10^{-3}$ M, $[O_2] = 2.7 \times 10^{-4}$ M, $[OAc^-] = 10^{-2}$ M, $I = 0.2$ M, and 25 °C.

the uptake by CoL^{2+} was calculated as $(3.0 \times 10^{-4})(8.40 - 6.50)/8.40 = 6.8 \times 10^{-5}$ M. Meanwhile, the concentration of $CoL \cdot O_2$ adduct formed was calculated at 1.34×10^{-4} M from the absorbance of 0.86 at 320 nm, on the basis of the apparent molar absorbance being 6.4×10^3. The stoichiometry of CoL^{2+} to O_2 in the oxygen complex was thus established as 2:1. The same technique showed also the 2:1 stoichiometry for the L^3 system.

Kinetics of O_2 Complexation. Reactions between Co(II) and L^2 in O_2-Dissolved Acetate Buffers. In acetate buffers, the free cobalt(II) ion is present as $Co^{2+}(aq)$, $Co(OAc)^+$, and $Co(OAc)_2$ with the hydrolyses of $Co^{2+}(aq)$ being negligible. At a given pH and $[OAc^-]$, the observed rates k_{obsd} are first order in $[Co^{2+}]_{init}$ and first order in $[L^2]_{init}$ but are independent of $[O_2]_{init}$. The second-order rate constant k_{obsd} at constant pH increases as $[AcO^-]$ increases in proportion to $K_{Co(OAc)} \cdot [OAc^-]/\beta_{AcO^-}$, which indicates that the $Co(OAc)^+$ is a reactive species of cobalt. Here

$$\beta_{AcO^-} = [Co^{2+}]_F/[Co^{2+}(aq)] = 1 + K_{Co(OAc)}[OAc^-] + K_{Co(OAc)}K_{Co(OAc)_2}[OAc^-]^2 \quad (19)$$

The values for $K_{Co(OAc)}$ ($=10^{0.97}$) and $K_{Co(OAc)}K_{Co(OAc)_2}$ ($=10^{1.10}$) were taken from literature[20] and corrected for $I = 0.2$ M.

At constant $[AcO^-]$, k_{obsd} increases as pH increases, which was resolved into specific rate constant k_{iH} terms by use of relation (20). The plots of $k_{obsd}(\alpha_H)_L/[H^+]K_1$ against $[H^+]$

$$k_{obsd}(\alpha_H)_L = k_H[H^+]K_1 + k_{2H}[H^+]^2K_1K_2 + k_{3H}[H^+]^3K_1K_2K_3 + \ldots \quad (20)$$

are linear passing the origin, as shown in Figure 3. The rate constant k_{2H} for diprotonated L was determined from the slope. Small contribution from higher order terms involving tri- or more protonated species was neglected.

Reaction between CoL^{2+} and O_2. The rates were first order in $[CoL^{2+}]$ and first order in $[O_2]$. The second-order rate constants were independent of pH and of buffer concentrations used. All the rate constants are listed in Table IV, along with the relevant values.

Discussion

Protonation Constants and Cobalt Ion Equilibria. The protonation constants of the new ligand L^3 may be compared with those of relevant model compounds (see Table I). The first and second protonation constants of L^3 are low relative to those of L^2 or L^6 and may suggest a strong solvation effect on the coordinated protons by the intramolecularly surrounding O atom. The greater basicity drop in K_3 and K_4 values of L^3 in comparison with the gradual fall of L^6 may illustrate constrained cyclic amine structure for L^3.

Table IV. Rate Constants (All in M^{-1} s^{-1}) for the Formation of Oxygen Adducts at 25 °C and $I = 0.2$ M

	$10^{-2}k_{2H}$[a]	k_2[b]
L^2 [c]	2.4 ± 0.1	$(2.2 \pm 0.1) \times 10^5$
L^4 [d]		$\sim 10^5$
L^5 [e]		1.1×10^2

[a] See eq 20 in the text. [b] The second-order rate constants for the reaction between $[CoL^{2+}]$ and $[O_2]$. [c] This study. [d] From ref 12. [e] From ref 3.

Titration of the acid salts of the macrocycles in the presence of equimolar Co(II) ion showed the proton-releasing complex formation to commence at $a = 2$ for L^1 and L^2 and $a = 1$ for L^3. An attainment of the acid–base equilibrium in the presence of Co(II) was so slow at 25 °C (especially with L^2 requiring >60 min for each increment of Na OH titrant) that we employed a higher temperature of 35 °C (then the time was shortened to ca. 35 min). The metal complex formation equilibria measured under nitrogen were quantitatively expressed solely in terms of eq 2, precluding the chelate protonation (to form $CoHL^{3+}$) or hydrolysis (to $Co(OH)L^+$).

As seen previously with Cu^{2+},[15] Zn^{2+}, etc.,[19] the cyclization of the linear pentaamine L^4 into a 15- (L^1) or 16-membered ring (L^2) enhances the cobalt complex stability with certain ring-size effects. Coordination of pentaamine macrocycles by all five N donor atoms is indicated by the values of the formation constants being much larger than expected for four N coordination as represented by the L^5 or L^6 system. The Co(II) chelates may be considered to adopt a square-pyramidal form, in which relatively rigid five-coordinate binding may be inferred by the lack of the chelate protonation at the complex formation equilibria. By comparison, Cu(II), Zn(II), Cd(II), and Pb(II) macrocyclic pentaamines showed overlapping equilibria with the monoprotonated MHL^{3+}.[15,19] Co(II) complexing with the flexible pentaamine L^4 also accompanies $CoHL^{3+}$ formation.[11]

The stability constant for L^3 is much smaller than for L^2, reflecting weaker donation of the O atom than of the N atom. The fact that the L^3 complex is even less stable than the L^5 or L^6 complex may imply little bonding between Co(II) and the O donor.

Oxygenation Equilibria. In similar fashions to the pink macrocyclic tetraamine L^5 complex,[3] the pink (also indicating high-spin) macrocyclic L^2 and L^3 complexes react with O_2 to form golden brown oxygenated species having ~320-nm absorptions assignable to $O_2 \rightarrow Co$ CT bands (370 nm with L^5), which may identify μ-peroxo complex formation.[2] The potentiometric and polarographic results fit to the μ-peroxo formula $[CoL]_2O_2$.

Comparison of the equilibrium constant K'_{O_2} derived as (21)

$$K'_{O_2} = \frac{[(CoL)_2O_2]}{[CoL]^2[O_2]} = \frac{K_{O_2}}{K_{CoL}{}^2} \quad (21)$$

reveals (see Table III) that the macrocyclic pentaamine L^2 can equip Co(II) with much higher (by orders of 6) oxygen affinity than the macrocyclic tetraamine L^5.[21] This finding is in conformity with the stabilizing effect of trans axial ligation by an extra N of L^2, which in turn supports square-pyramidal N_5 configuration. A good correlation had been reported between the axial ligand basicity and oxygen affinity for L^5,[7] Schiff bases,[22] and the porphyrin system.[23] The intermediate

(20) S. K. Siddhanta and S. N. Banerjee, *J. Indian Chem. Soc.*, **35**, 323 (1958).

(21) Although the O_2 adduct of the L^2 complex survives longer than that of L^5, the former is not yet stable enough (soon decomposes to red Co(III) species) to preclude further characterization.

O_2 affinity by L^3 may be compatible with a square-pyramid structure in which the O donor in the macrocycle may reside at the axial position. The increases in cobalt(III) character by the interaction of O_2 would make the O atom ligation likely, especially the intramolecularly attached one as in L^3, which should exert some stabilizing effect on the trans O_2 bridge.

The μ-peroxo complexes have been well characterized for other pentaamine systems such as $(NH_3)_5$ and L^4.[24] Steric factors may account for less stable μ-peroxo complex with L^2 relative to L^4 (see Table III). Another possible explanation may be weaker electron-donating ability of L^2 (see Table I) which reduces Co → O_2 π-bonding effects.[25]

Oxygen-Uptake Kinetics. A difference in the O_2-uptake rates by linear and macrocyclic N_5 systems was initially observed at the potentiometric titrations where the equilibrating time after each addition of NaOH titrant was ~20 s for L_4, whereas for L^2 it required much longer time, ~35 min. The kinetic studies showed the slower rates of O_2 uptake by the macrocyclic system are ascribable to the extremely slow CoL^{2+} chelate formation.

The equilibrium study has shown that L^2 can form CoL^{2+} chelates and the subsequent O_2 adducts almost simultaneously around pH 5. The stopped-flow measurements of the appearance of the 320-nm peak found the second-order (first order in $[Co(OAc)^+]$ and first order in $[H_2L^{2+}]$) rate laws for the O_2-adduct formation in acetate buffers. This implies a slow formation of CoL^{2+} to be followed by a rapid oxygenation. The same conclusion was drawn for the macrocyclic tetraamine system including L^5.[3] Interestingly, the magnitude of the k_{2H} value is almost comparable to the rate constants k_H (=2.5 × 10^2 and 4.2 × 10^2 M^{-1} s^{-1}) for the 12- and 13-membered macrocyclic tetraamine complex formation between $Co(OAc)^+$ and monoprotonated N_4 observed at the oxygen uptake.[3] The availability of three free nitrogens in the macrocycles gives the similar rates for the interaction with Co(II). A similar situation is known for Cu^{2+}–macrocyclic N_5 and N_4 complex formations: k_{2H} (=2.4 × 10^6 M^{-1} s^{-1} for the reaction of $Cu(OAc)^+$ with diprotonated N_5)[15] is almost the same with k_H (=5.3 × 10^6 M^{-1} s^{-1} for the reaction of $Cu(OAc)^+$ with monoprotonated N_4).[26]

Separately, we have measured the rates of O_2 uptake by preformed CoL^{2+} chelates in acetate buffers. The reaction found was first order in [CoL] and first order in $[O_2]$. The same rate law has been reported for polyamines including L^5,[3] L^4,[12,25] or porphyrins.[8,9] The observed oxygenation rate may refer to slow formation of the 1:1 $CoL{\cdot}O_2$ species followed by immediate reaction with another CoL to give the final μ-peroxo products. Another interpretation is that the rapidly formed 1:1 species undergoes slow rearrangement for the fast 2:1 product formation, as invoked for O_2 uptake by cobalt porphyrins.[8,9]

In comparison of the rates in the same acetate buffer conditions, the reaction of CoL with O_2 occurs ca. 1.2 × 10^4 times faster than the prior formation of CoL. Namely, the CoL^{2+} chelate formation has determined the rate of the macrocycle O_2 uptake at the potentiometric titrations.

As seen in Table IV, the second-order rate constant k_2 for L^2 is 10^3 times as much as that for L^5. The fact may support the activation effect for O_2 coordination by the axial N donor atom. Comparison with L^4 indicates the cyclization of the linear pentaamine (although having a big unstabilizing effect on the O_2 uptake equilibrium; see Table III) has a minor retarding effect on the kinetics. In fact, a similar O_2-uptake rate of 10^5 M^{-1} s^{-1} was shown by other Co^{2+} polyamine chelates such as trien and $(en)_2$, which is supposed to be commonly limited by the rate of H_2O exchange.[24] It is yet to be investigated whether other substitution reactions on the macrocyclic L^2 complex show the paralleling rates.

In short, the present study has demonstrated that the compulsive axial ligation by the macrocyclic structures significantly promotes the rates and equilibrium of O_2 uptake of Co(II) surrounded by saturated tetraamines. The effects of such axial N ligation were not estimated from the previous studies using a linear tetraamine (trien)[5] and pentaamine (L^4),[11] due to the different oxygenation product formula. Predictably further studies using the macrocyclic system may find more efficient and biologically significant models.

Registry No. $L^3{\cdot}4Ts$, 73396-35-7; $L^3{\cdot}4HBr$, 73396-36-8; L^3, 73396-34-6; $[CoL']^{2+}$, 73396-74-4; $[CoL^2]^{2+}$, 73396-75-5; $[CoL^3]^{2+}$, 73396-76-6; O_2, 7782-44-7; $L^6{\cdot}4Ts$, 73396-37-9; bis(2-chloroethyl) ether, 111-44-4.

(22) M. J. Carter, D. P. Rillema, and F. Basolo, *J. Am. Chem. Soc.*, **96**, 392 (1974).
(23) M. J. Walker, *J. Am. Chem. Soc.*, **95**, 1154 (1973); D. V. Stynes, H. C. Stynes, B. R. James, and J. A. Ibers, *ibid.*, **95**, 1796 (1973).
(24) R. G. Wilkins, *Adv. Chem. Ser.*, **No. 100**, 111 (1970), and references therein.
(25) G. McLendon and A. E. Martell, *J. Chem. Soc., Chem. Commun.*, 223 (1975).
(26) M. Kodama and E. Kimura, *J. Chem. Soc., Dalton Trans.*, 1472 (1977).

Contribution from the Department of Chemistry,
Texas Christian University, Fort Worth, Texas 76129

Synthesis of New *N*-Silylphosphinimines: Phosphazene Precursors

PATTY WISIAN-NEILSON and ROBERT H. NEILSON*

Received December 5, 1979

The reactions of some bis(trimethylsilyl)aminophosphines with bromine proceeded with elimination of Me_3SiBr to produce the new *P*-bromo-*N*-silylphosphinimines $RR'P(Br)=NSiMe_3$ (**1**, R = R′ = Me; **2**, R = Me, R′ = Ph; **3**, R = R′ = Ph; **4**, R = R′ = OCH_2CF_3). Other new *N*-silylphosphinimines, $R_2R'P=NSiMe_3$ (**5**, R = Me, R′ = NMe_2; **6**, R = OCH_2CF_3, R′ = NMe_2; **7**, R = Me, R′ = OCH_2CF_3), were prepared from **1** and **4** via their reactions with either Me_2NH or $LiOCH_2CF_3$. Compounds **1**–**4** eliminate Me_3SiBr on heating to form cyclic phosphazenes $(RR'PN)_n$ with nearly quantitative yields of $(Me_2PN)_n$ (n = 3, 4, 5) resulting from thermolysis of **1**.

Introduction

In a recent study we reported that the reaction of substituted fluorophosphoranes, $RR'PF_3$, with $LiN(SiMe_3)_2$ resulted in the formation of several new *P*-fluoro-*N*-silylphosphinimines $RR'P(F)=NSiMe_3$.[1] These compounds undergo thermal decomposition, eliminating Me_3SiF and forming cyclic phosphazenes, $(RR'P=N)_n$. On the basis of this fluorosilane

(1) Wisian-Neilson, P.; Neilson, R. H.; Cowley, A. H. *Inorg. Chem.* **1977**, *16*, 1460.

0020-1669/80/1319-1875$01.00/0