Synthesis and reactivity of the macrobicyclic complexes (1,5,8,12-tetraaza-17-oxabicyclo[10.5.2]nonadecane)cobalt(III) perchlorate ([$Co(L_1)(CIO_4)$]-($CIO_4)_2$), [(chloro(1,4,8,11-tetraaza-17-oxabicyclo-[9.5.3]nonadecane)cobalt(III) perchlorate ([$Co(L_2)$ -(CI)](CIO_4)₂), (4,8-dimethyl-1,4,8,11-tetraaza-17oxabicyclo[9.5.3]nonadecane)cobalt(III) perchlorate ([$Co(L_3)(CIO_4)$](CIO_4)₂), and (5,8-dimethyl-1,5,8,12tetraaza-17-oxabicyclo[10.5.2]nonadecane)cobalt(III) perchlorate ([$Co(L_4)(CIO_4)$](CIO_4)₂) — Crystal structure of the L₂ complex¹

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Abstract: The potentially penta-coordinating ligands L_2 and L_3 have been synthesized by reaction of the 10-membered macrocycle 1,5-diaza-8-oxacyclodecane with either 1,9-dichloro-3,7-diazanonane-2,8-dione, and subsequent reduction of the diamide (**3**), or with 1,9-dichloro-3,7-(dimethyl)diazanonane-2,8-dione and reduction (L_3). A similar procedure is outlined for the dimethylated macrobicycle (L_4), based on the corresponding nine-membered 1,4-diaza-7-oxacyclononane. The Co(III) complexes of these ligands and of 1,5,8,12-tetraaza-17-oxabicyclo[10.5.2]nonadecane (L_1) have been prepared. Spectrophotometric determinations on the L_1 complex ion confirm the presence of two hydrogen ion related equilibria, one of which ($pK = 2.2 \pm 0.2$) is associated with the proposed replacement of the apical ether oxygen by a water molecule that is bound to the metal centre and hydrogen bonded to the ether. The species derived from L_1 and L_2 exhibit remarkable kinetic stability. Studies on the anation of the [Co(L_1)(H_2 O)](ClO₄)₃ with chloride ions in acidic media are consistent with the reaction of both the proton-related complex and the [Co(L_1)(H_2 O)]³⁺ ion. Whilst complex ions containing two secondary NH groups maintain the metal-ion coordination in strongly acidic media, corresponding species with ligands containing all four tertiary amine sites are subject to attack by protons leading to a relatively facile demetallation of the complexes. The latter finding is supported by kinetic studies and mass spectrometric fragmentation patterns of the ions.

Key words: cobalt(III), macrobicycle, hydrolysis, anation, spectroscopic analysis.

Résumé : Les ligands L_2 et L_3 qui pourraient donner lieu à une pentacoordination ont été synthétisés en faisant appel à la réaction du macrocycle à dix chaînons 1,5-diaza-8-oxacyclodécane avec la 1,9-dichloro-3,7-diazanonane-2,8-dione

Received 3 December 2004. Published on the NRC Research Press Web site at http://canjchem.nrc.ca on 23 July 2005. Reposted on the Web site with correction on 16 August 2005.

It is a pleasure to recognize the many contributions to chemistry in Canada by colleague and friend Howard Alper.

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¹This article is part of a Special Issue dedicated to Professor Howard Alper. ²Corresponding author (e-mail: amcauley@uvic.ca). et réduction subséquente du diamide cyclique (**3**) ou avec la 1,9-dichloro-3,7-(diméthyl)diazanonane-2,8-dione suivie d'une réduction (L₃). On décrit une méthode semblable pour le macrobicycle diméthylé (L₄) qui est basée sur le composé à neuf chaînons 1,4-diaza-7-oxacyclononane. On a préparé les complexes du cobalt(III) avec ces ligands et avec le 1,5,8,12-tétraaza-17-oxabicyclo[10.5.2]nonadécane (L₁). Des déterminations spectrophotométriques sur le complexe L₁ confirment la présence de deux équilibres apparentés des ions hydrogènes, dont l'un (p*K* = 2,2 ± 0,2) est associé au remplacement proposé de l'oxygène de l'éther apical par une molécule d'eau qui est liée au centre métallique et relié à l'éther par une liaison hydrogène. Les espèces qui dérivent des ligands L₁ et L₂ présentent une stabilité cinétique remarquable. Des études d'anation du [Co(L₁)(H₂O)](ClO₄)₃ avec des ions chlorures en milieu acide sont en accord avec une réaction du complexe lié par un proton et l'ion [Co(L₁)(H₂O)]³⁺. Alors que les ions complexes comportant deux groupes NH secondaires maintiennent la coordination métal-ion en milieu fortement acide, les espèces correspondantes comportant des ligands sur chacun des quatre sites amines tertiaires sont sujettes à des attaques par des protons ce qui conduit à une démétallation relativement facile des complexes. Cette dernière observation est supportée par des études cinétiques et par les patrons de fragmentation en spectrométrie de masse des ions.

Mots clés : cobalt(III), macrobicycle, hydrolyse, anation, analyse spectroscopique.

[Traduit par la Rédaction]

Introduction

The synthesis of novel macrocyclic and polymacrocyclic ligands and the significant thermodynamic and kinetic stability imparted by them upon metal ion complexation has been a feature of interest for over two decades (1-5). Such species are now found in a variety of chemistries from competitive anion binding sites (6), multimacrocyclic luminescent arrays (7), and polynuclear complexes of pendant-arm ligands with unusual spin states (8). Reports from previous investigations from this laboratory have described macrobicyclic systems involving five-coordinate Cu(II) complexes (9) and sixcoordinate Ni(II) (10, 11) species of L_1 and L_2 , where, in the latter, the d^8 ion, being octahedral, exhibits a single substitution site. Such species exhibit extraordinary kinetic stability, with no detectable decomposition over days even in strongly acidic (4 mol/L) media. In addition, spectroscopic observations are consistent with the formation of nickel(III) species of sufficient lifetimes to permit kinetic measurements not only of redox reactions (12), but also, in some instances, the Ni(III) ions formed are sufficiently stable kinetically to permit rate studies of substitution by chloride (13). Hydrogenion dependences in these investigations are consistent with an unusually strongly acidic proton-related equilibrium associated with the ether linkage (13, 14). In this paper, we present the results of comparable studies of analogous cobalt(III) complexes where the d^6 ion imparts much greater kinetic stability than the nickel(III) ion, providing an opportunity to examine not only kinetic features, but also to spectroscopically identify species involved in the various proton-related equilibria. Included are kinetic observations involving a tetra-N-substituted macrobicycle where the stability in acidic media is diminished owing to protonation at the N-methyl tertiary amines competing with the complexation at the metal centre.

Experimental

The literature method was used to prepare 17-oxa-1,5,8, 12-tetraazabicyclo[10.5.2]nonadecane (L_1) (11). The ligands 17-oxa-1,4,8,11-tetraazabicyclo[9.5.3]nonadecane (L_2), 4,8-dimethyl-1,4,8,11-tetraaza-17-oxabicyclo[9.5.3]nonadecane (L_3), and 5,8-dimethyl-1,5,8,12-tetraaza-17-oxabicyclo-[10.5.2]non-

adecane (L_4) were synthesized as indicated in the following. Acetonitrile (Caledon) was fractionally distilled from CaH₂ and stored under nitrogen. Water, with a specific resistance of >15 M Ω cm was prepared using a MilliQ-Reagent system. $Co(ClO_4)_2 \cdot 6H_2O$ was synthesized from $CoCO_3 \cdot xH_2O$ (Aldrich) through reaction with the stoichiometric amount of HClO₄. The perchlorate salt was recrystallized three times from water, dried under high vacuum for 48 h at room temperature, and stored over CaSO₄ in a desiccator. Ethanol (Commercial Alcohols, 100%), activated charcoal (Sigma, 250–350 mesh), HClO₄ (Allied Chemicals, 70% assay), HCl (Anachemia, 36.5%-38.0% assay), NaClO₄·H₂O (Fisher Scientific), NaOH (BDH), PbO2 (BDH), D2O (Cambridge Isotope Laboratories), and CD₃CN (Cambridge Isotope Laboratories) were all used as purchased. Mass spectra were recorded on a Kratos Concept mass spectrometer in the LSI-MS mode. The matrix employed in all cases was mnitrobenzyl alcohol. Bruker WM-250 and AC-300 NMR spectrometers were used to record the ¹H and ¹³C NMR spectra. ¹³C NMR chemical shifts are referenced to the residual methyl carbon in incompletely deuterated CD₃CN $(\delta (CH_3CN) = 1.30 \text{ ppm})$ and ¹H NMR chemical shifts to the residual protons in incompletely deuterated D_2O (δ (H_2O) = 4.70 ppm). Elemental analyses were performed by Canadian Microanalytical Services, Vancouver, British Columbia, Canada.

Synthesis

(1,5,8,12-Tetraaza-17-oxabicyclo[10.5.2]nonadecane)cobalt(III) perchlorate ($[Co(L_1)(ClO_4)](ClO_4)_2$)

Ligand L_1 (0.299 g, 1.106 mmol) was dissolved in dry, distilled acetonitrile (30 cm³) and an equivalent of cobalt(II) perchlorate hexahydrate (0.405 g, 1.106 mmol) was added with stirring. The solution was acidified to approximately pH 3 with HClO₄ and an excess of lead(II) oxide (0.400 g, 1.672 mmol) added. Upon bubbling the mixture with air overnight, a maroon solution was obtained. The mixture was centrifuged and the excess solid lead(II) oxide filtered leaving the maroon-coloured solution. Concentration of the filtrate to approximately 10 cm³ and cooling in an ice bath resulted in the precipitation of a red solid. Crystallization of the complex was achieved by redissolution of the solid in the minimum amount of acetonitrile and allowing the solution to evaporate slowly. Yield: 0.165 g (24%). ¹³C NMR (D₂O): 75.7 (-*C*H₂-O-), 61.4, 58.0, 55.3, 53.2, 46.9 (-*C*H₂-N-), 24.45 (-C-*C*H₂-C-). Anal. calcd. for $[Co(C_{14}H_{30}N_4O)(CIO_4)](CIO_4)_2$ (%): C 26.79, H 4.82, N 8.93; found: C 26.77, H 4.87, N 9.54.

17-Oxa-1,4,8,11-tetraazabicyclo[9.5.3]nonadecane (L₂)

The synthesis was carried out as shown in Scheme 1.

1,9-Dichloro-3,7-diaza-nonane-2,8 dione (1)

Propylenediamine (4.88 g, 0.0567 mol) was added under constant stirring to a mixture of CHCl₃ (69 mL) and H₂O (34 mL) and cooled in an ice bath. A mixture of chloroacetyl chloride (13.9 mL, 0.172 mol) in CHCl₃ (86 mL) and K_2CO_3 (22.36 g, 0.162 mol) in water (860 mL) were added simultaneously under a nitrogen atmosphere over a 1 h period. The reaction mixture was stirred at room temperature for a further 2 h. The CHCl₃ layer was separated, washed with water $(2 \times 100 \text{ mL})$, and dried over MgSO₄. Removal of solvent yielded a colourless oil that was dried in vacuo overnight. Upon addition of CCl₄ and cooling overnight, a white solid precipitated. Filtration and concentration of the solution followed by a further addition of CCl₄ afforded a second crop of material. The diamide (1) was dried under vacuum. Yield: 9.01 g, 70%. The material was used as such. ¹H NMR (D₂O): 7.2 (N-H), 4.1 (-CH₂-C(O)-), 3.4 (CH₂-NH), 1.8 (-C-CH₂-C-). ¹³C NMR (CDCl₃): 170.1 (-C=O), 42.7 (CH₂-NH), 37.4 (-CH₂-C(O)-), 27.9 (-C-CH₂-C-). ¹³C NMR (D₂O): 169.7 (-C=O), 42.2 (CH₂-NH), 37.0 (-CH₂-C(O)-), 27.5 (-C-CH₂-C-).

Cyclization with the free macrocycle, 1,5-diaza-8-oxacyclodecane (2), was carried out in basic acetonitrile. Doubly distilled acetonitrile (2.5 L) was placed in a 5 L four-necked flask fitted with a stirring attachment and a condenser and two septa for syringes. A stream of N2 was attached and Na₂CO₃ (2.402 g, 22.66 mmol, 3.16 equiv.) was added to the bulk CH₃CN. The macrocycle 2 (1.036 g, 7.183 mmol) was dissolved in 200 mL of dry CH₃CN. Diamide 1 showed limited solubility in acetonitrile and only 0.408 g (1.797 mmol) was dissolved in 50 mL of solvent. The CH₃CN-Na₂CO₃ solution was heated to reflux and 50 mL each of the reactant solutions 1 and 2 were added slowly (four portions) over a period of 40 h. Reflux was continued for another 24 h. After filtration of the Na₂CO₃, the acetonitrile was removed in vacuo leaving a yellow, quasi-crystalline solid. Dissolution in CHCl₃ removed the residual amounts of diamide impurity yielding a yellow crystalline solid **3**. Yield: 2.07 g, 96%. ¹³C NMR (CDCl₃): 174.8 (-C=O), 66.7 (CH₂-O-), 62.1, 57.4, 55.9 (CH₂-N), 37.4 (-*C*H₂-CH₂-NH-), 29.8, 27.7 (-C-*C*H₂-C-). MS: 299 (M + 1)⁺.

The fully saturated macrocycle (L_2) was prepared by addition of a solution of BH₃·THF (100 mL) to a solution of **3** (1.002 g, 3.358 mmol) in dry THF (30 mL) and refluxing for 24 h. After cooling to room temperature, excess borane was destroyed with water. Upon removal of the solvent under vacuum, the white solid formed was treated with 6 mol/L HCl and refluxed for 3 h. Upon cooling, basification with KOH pellets to pH 14 and extraction with CHCl₃, the solution was dried, filtered, and the solvent removed, yielding a slightly yellow oil. Yield: 0.742 g, 82%. ¹³C NMR (CDCl₃): 73.6 (-CH₂-O), 58.5, 58.1, 56.9 (CH₂-N), 47.8, 47.3 (-CH₂-CH₂-NH-), 28.2, 28.1 (-C-CH₂-C-).

Scheme 1.



[(Chloro)(1,4,8,11-tetraaza-17-oxabicyclo[9.5.3]nonadecane)cobalt(III)] perchlorate ([Co(L₂)(Cl)](ClO₄)₂)

An aqueous solution of cobalt(II) perchlorate hexahydrate (0.134 g, 0.366 mmol) was added to a refluxing ethanol- H_2O (4:1, 30 cm³) solution of the ligand L_2 (0.099 g, 0.366 mmol). The resulting solution turned green almost instantaneously. A catalytic amount of activated charcoal was then added and the solution refluxed for 2 h. After cooling, air was bubbled through the mixture for several hours yielding a purplish-red solution. The charcoal was filtered off and the solvent removed under reduced pressure. An aqueous solution of the crude complex was purified by passage down a Dowex 50W-x8 (50-100 mesh) exchange column. The complex was eluted with 6 mol/L HCl and the eluate evaporated to dryness, leaving a green solid, which was recrystallized from a hot aq. 0.2 mol/L NaClO₄ (10 cm³) solution, collected, washed with ethanol and diethyl ether, and air dried. Yield: 0.082 g, 40%. ¹³C NMR (D₂O): 82.4 (-CH₂-O-), 67.4, 58.7, 58.0, 52.7, 50.1 (-CH2-N-), 27.8, 24.0 (-C-CH2-C-). Anal. calcd. for $[Co(C_{14}H_{30}N_4O)(Cl)](ClO_4)_2 \cdot H_2O$ (%): C 28.91, H 5.54, N 9.63; found: C 28.94, H 5.24, N 9.64.

Neutralizing an aqueous solution of the monochloride complex with 0.1 mol/L NaOH solution resulted in a colour change from green to orange-red. Leaving the solution open to the atmosphere to allow the solvent to evaporate slowly yielded the purple perchlorate complex, $[Co(L_2)(ClO_4)]$ - $(ClO_4)_2$, which was filtered out, washed with ethanol, and air dried.

4,8-Dimethyl-1,4,8,11-tetraaza-17-oxabicyclo[9.5.3]nonadecane (L_3)

The ligand, with no ionizable protons, was prepared in a manner similar to that shown for L_2 (Scheme 1, vide supra). *N*,*N*'-Dimethylpropylenediamine (5 g, 0.0489 mol) was added



under constant stirring to a mixture of CHCl₃ (69 mL) and H₂O (34 mL) and cooled in an ice bath. A mixture of chloroacetyl chloride (22.11 g, 0.1957 mol) in CHCl₃ (86 mL) and K₂CO₃ (22.36 g, 0.162 mol) in water (860 mL) was added simultaneously under a nitrogen atmosphere over a 1 h period. The reaction mixture was stirred at room temperature for a further 2 h. The CHCl₃ layer was separated, washed with water (2 \times 100 mL), and dried over MgSO₄. Removal of the solvent yielded a colourless oil that was dried in vacuo overnight. Upon addition of CCl₄ and cooling overnight, a white solid precipitated. Filtration and concentration of the filtrate followed by a further addition of CCl₄ afforded a second crop of material. The diamide 4 was washed with ethanol and dried. Yield: 9.5 g, 76%. The NMR spectrum showed the presence of several isomers. ¹³C NMR (CDCl₃): 166.2, 166.7 (-C=O), 45.7, 45.6 (CH₂-NMe), 41.0, 41.4, 41.6 (-CH₂-C(O)-), 24.3, 26.6 (-C-CH₂-C-).

To a solution of the bis(chloro)diamide 4 (1.718 g, 6.73 mmol), in dry distilled CH₃CN (200 mL), was added sodium iodide (5.548 g, 37.01 mmol). The macrocycle 2 (0.971 g, 6.73 mmol) was dissolved in dry distilled CH₃CN (200 mL) and solutions of the reagents 4 and 2 were added very slowly (over a 24 h period) under N₂ in 50 mL batches to a refluxing solution of dry distilled acetonitrile (2.5 L) containing Na₂CO₃ (9.415 g, 88.83 mmol). Heating of the mixture, now orange coloured, was continued for a further 10 h, and the mixture was cooled overnight. Filtration under nitrogen, removal of the solvent, and addition of CHCl₂ (250 mL) yielded an orange solution and an off-white solid. After washing with water and further addition of CHCl₃, the solution was dried (Na₂SO₄), filtered, and the solvent removed yielding an orange-brown oil that was dried under high vacuum overnight. The cyclised diamide, 4,8-dimethyl-1.4.8.11-tetraaza-17-oxabicyclo[9.5.3]nonadecane-2.9-dione (5), solidified as a yellow, crispy honeycomb that was quite hygroscopic. Yield: 2.0 g, 90%. MS: 327 (M + 1)⁺.

The crude diamide **5** (2.5 g, 10.46 mmol) was transferred to a 1 L flask using dry, freshly distilled THF (170 mL). After addition of the BH₃·THF complex (340 mL, 1 mol/L), the solution was refluxed for 24 h and cooled to room temperature. The solution was cooled in ice water to quench the remaining borane. Evaporation to dryness in vacuo gave a cream-coloured solid to which was added 6 mol/L HCI (140 mL), and this solution was heated to reflux for 3 h. Cooling in ice followed by the addition of KOH pellets to pH ~ 14 and extraction with CHCl₃, and filtration, gave a pale-yellow solution of the macrobicycle L₃. Upon drying under high vacuum, a yellow oil formed. The product after work-up (1.944 g, 85%) was observed to be a mixture. Purification was achieved by preparation of the corresponding copper(II) complex³ (0.642 g) followed by decomplexation of the metal ion by use of Na₂S (9). The final yield of **L**₃ was 0.426 g (21% from macrocycle **2**). ¹³C NMR (CDCl₃): 72.1 (CH₂-O), 56.6, 56.2, 56.0, 55.5, 54.7 (CH₂-N), 43.2 (N-CH₃), 26.6, 25.8 (CH₂-CH₂-CH₂). MS: 298 (M⁺), 299 (M + 1)⁺, 327 (M + 29)⁺.

4,8-Dimethyl-1,4,8,11-tetraaza-17-oxabicyclo[9.5.3]nonadecane-cobalt(III) perchlorate $([Co(L_3)(ClO_4)](ClO_4)_2)$

The ligand L₃ (0.132 g, 0.442 mmol) was dissolved in an ethanol-water mixture (48 mL : 12 mL) and heated to reflux. An aqueous solution of $Co(ClO_4)_2 \cdot 6H_2O$ (0.162 g, 0.442 mmol) was added and the solution turned a yellowgreen colour. Several grams of activated charcoal were introduced and the solution was refluxed for 2 h. Air bubbling of the cooled solution (5 h) followed by filtration yielded a pink-red solution. After removal of the residual ethanol and addition of 1 drop of concd. HClO₄, the solution was left to crystallize at 4 °C overnight. The crystals were washed with ethanol, ether, and air dried. Yield: 0.106 g, 37%. ¹³C NMR (D₂O): 66.9 (CH₂-O), 60.9, 55.0, 54.6, 52.3, 51.7 (CH₂-N), 39.0 (N- CH_3), 19.7 (CH₂- CH_2 -CH₂). It appears that there is overlap of the methylene peaks, since only eight and not nine signals were observed. MS (negative ion): 654.05 $([Co(L_3)(ClO_4)](ClO_4)_2]^-$. UV-vis (λ_{max}, nm) : 232 ($\epsilon =$ 5380 (mol/L)⁻¹ cm⁻¹) and 516 ($\epsilon = 17$ (mol/L)⁻¹ cm⁻¹).

The isomeric macrobicyclic ligand, 5,8-dimethyl-1,5,8,12tetraaza-17-oxabicyclo[10.5.2]nonadecane (L_4), was prepared⁴ in a manner similar to that outlined previously using *N*,*N*'-dimethylethylenediamine and 3-chloropropionyl chloride as initial reactants. Further reaction of the resultant bis(chloro)diamide with the macrocycle 1,4-diaza-7oxacyclononane yielded the bicyclic diamide that upon reduction, as described previously, yielded ligand L_4 . For the Co(III) complex [Co(L_4)(Cl)](ClO₄)₂ calcd. (%): C 32.48, H 5.79, N 9.47; found: C 32.87, H 5.84, N 9.57. UV-vis (λ_{max} , nm): 461 ($\epsilon = 16$ (mol/L)⁻¹ cm⁻¹).

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

Crystallography

$[Co(L_2)(Cl)](ClO_4)_2$

X-ray quality crystals were grown by slow evaporation of an aqueous solution containing the complex and NaClO₄. The experimental parameters for the complex are listed in Table 1.

A crystal of dimensions 0.10 mm × 0.15 mm × 0.40 mm was mounted in a glass Lindemann tube and optically centred in an Enraf-Nonius CAD-4 diffractometer employing graphite-monochromated MoK α radiation. The unit cell was refined by using 24 reflections in the 2 θ range 25°–33°. The diffraction data were collected using the $\omega/2\theta$ scan mode. A total of 3554 reflections were collected. The structure solution and refinement were completed using the PC version of

³T. Rodopoulos. Unpublished observations.

⁴M. Rodopoulos. Unpublished observations.

Table 1. Experimental crystallographic data for $[Co(L_2)Cl](ClO_4)_2$.

Formula	CoC ₁₄ H ₃₀ N ₄ O ₉ Cl ₃
Formula mass	563.7
Crystal colour	Green
Crystal system	Monoclinic
Space group	$P2_1/n$
Cell dimensions	
a (Å)	9.8483(7)
<i>b</i> (Å)	13.1344(9)
<i>c</i> (Å)	16.6774(12)
α (°)	90
β (°)	90.6830(10)
γ (°)	90
$D_{\text{calcd.}}$ (Mg m ⁻³)	1.707
$V(A^3)$	2194.0(7)
Ζ	4
<i>F</i> (000)	1168
λ (Å)	0.7093
$\mu (mm^{-1})$	1.2
Cryst. dim. (mm ³)	$0.10 \times 0.15 \times 0.40$
Transmis. factors	0.839-0.999
2θ Range (°)	25-33
No. refls. meas.	3554
No. unique refls.	3432
No. refls. with $I_{\text{net}} > 3.00\sigma(I_{\text{net}})$	1740
$R(F_0)$	0.062
R _w	0.061

the NRCVAX system (15–18). Of the 3432 unique reflections observed, 1740 reflections with $I_{\text{net}} > 3.00\sigma(I_{\text{net}})$ were included in the final least-squares refinement for 61 atoms and 280 parameters. Absorption corrections were made and all non-hydrogen atoms were refined anisotropically. Min and max transmission factors were estimated to be 0.839 and 0.999, respectively. All hydrogen atoms were placed in calculated positions ($D_{\text{C-H}} = 1.08$ Å), and were given isotropic thermal parameters based upon the atom to which they were bonded. The refinement converged with a max shift to estimated standard deviation (esd) of 0.009 in the final cycle, and a maximum peak of 0.640 e Å⁻³ at an $R(F_0)$ value of 0.062 ($R_w = 0.061$).

UV-vis (pK_a measurements)

UV-vis spectra were recorded on a Varian Cary 5 spectrophotometer. Small increments of NaOH solutions (varying concentrations) were added with a Gilson Pipetman P200 micropipette to approximately 1 mol/L HClO₄ solutions of the cobalt(III) complexes in quartz UV-vis cuvettes. The pH of the solutions was measured after each addition of base with a Fisher glass electrode connected to a Fisher Scientific Accumet pH meter 915 followed by the immediate recording of their UV-vis spectra. Measurements were made over the pH range 0.5-10.

Fig. 1. ORTEP diagram of the $[Co(L_2)(Cl)]^{2+}$ ion with 25% thermal ellipsoids.



Kinetic studies

Anation reactions of $[Co(L_1)(H_2O)](ClO_4)_3$ with chloride ions under pseudo-first-order conditions were followed at 25–40 °C using a Shimadzu UV-160A spectrophotometer at 240 nm. The rates of anation were determined by reaction with a series of LiCl solutions ranging in concentrations of 50–400 molar excess. The experiments were carried out at eight different HClO₄ concentrations between 0.11 and 0.96 mol/L (I = 1.0 mol/L, LiClO₄). Prior to mixing, the solutions were pre-equilibrated at the required temperature and were controlled to within ±0.1 °C. A minimum of three kinetic runs was collected for each pair of solutions, prior to signal averaging with kinetic analysis by nonlinear, leastsquares fitting methods.

Although metal-ion complexes of ligands L_1 and L_2 were shown to be kinetically stable, with no detectable decomposition in 1 mol/L media over a >24 h period, the complexes incorporating L_3 and L_4 , if left overnight in 1 mol/L acidic media, exhibited complete decomposition. Studies on $[Co(L_3)(ClO_4)](ClO_4)_2$ were undertaken at 25 °C at 232 nm where the rates of absorbance decrease over a range of acidities confirmed the acid dependence.

Results

Molecular structure

An ORTEP of the structure of the $[Co(L_2)Cl]^{2+}$ ion is shown in Fig. 1. Collection details are provided in Table 1 and selected bond lengths and bond angles are provided in Table 2. Atomic coordinates are shown in Table S1.⁵ The geometry at the cobalt metal centre is only slightly distorted from an ideal octahedron expected for a d^6 ion, with the L₂ ligand occupying five of the coordination sites and a chloride ion the sixth site. The macrobicyclic ligand L₂ can be

⁵ Supplementary data for this article are available on the Web site or may be purchased from the Depository of Unpublished Data, Document Delivery, CISTI, National Research Council Canada, Ottawa, ON K1A 0S2, Canada. DUD 3689. For more information on obtaining material refer to http://cisti-icist.nrc-cnrc.gc.ca/irm/unpub_e.shtml. CCDC 256926 contains the crystallographic data for this manuscript. These data can be obtained, free of charge, via www.ccdc.cam.ac.uk/conts/retrieving.html (Or from the Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; fax +44 1223 336033; or deposit@ccdc.cam.ac.uk).

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e ()	L (2) 3(4)2
Bond distances (Å)	
Co(1)—Cl(1)	2.219(3)
Co(1)—O(1)	1.924(6)
Co(1)—N(1)	1.979(9)
Co(1)—N(2)	2.007(9)
Co(1)—N(3)	1.949(9)
Co(1)—N(4)	1.978(8)
Bond angles (°)	
Cl(1)-Co(1)-O(1)	178.53(22)
Cl(1)-Co(1)-N(1)	92.5(3)
Cl(1)-Co(1)-N(2)	92.4(3)
Cl(1)-Co(1)-N(3)	88.4(3)
Cl(1)-Co(1)-N(4)	88.3(3)
O(1)-Co(1)-N(1)	86.3(3)
O(1)-Co(1)-N(2)	86.9(3)
O(1)-Co(1)-N(3)	92.8(3)
O(1)-Co(1)-N(4)	92.6(3)
N(1)-Co(1)-N(2)	96.5(5)
N(1)-Co(1)-N(3)	177.0(5)
N(1)-Co(1)-N(4)	87.5(4)
N(2)-Co(1)-N(3)	86.4(5)
N(2)-Co(1)-N(4)	176.0(5)
N(3)-Co(1)-N(4)	89.7(4)

Table 2. Selected interatomic distances $(\text{Å})^a$ and bond angles $(^{\circ})^a$ for $[\text{Co}(\text{L}_2)\text{Cl}](\text{ClO}_4)_2$.

^{*a*}Estimated standard deviations are given in parentheses.

envisaged as the fusion of a 10-membered cyclodecane ring with a 14-membered cyclotetradecane ring. The cyclam ring in L₂ adopts a trans-III configuration according to the terminology of Bosnich et al. (19). Numerous studies have illustrated that for complexes of this type, the trans-III configuration is lowest in energy. In contrast to $[Co(L_2)(Cl)]^{2+}$, the trans-I configuration is adopted by ligands in the macrobicyclic ions $[Cu(L_1)]^{2+}$ and $[Ni(L_1)(ClO_4)]^{2+}$ and in the complexes of the analogous thioether ligand (1,5,8,12-tetraaza-17-thiabicyclo[10.5.2]nonadecane) (L₅) (10). Species such as [Co(L₅)CH₃CN]³⁺ also incorporate nine-membered cyclononane and 14-membered cyclotetradecane rings. In effect, the only structural difference between L_2 and L_n , (where n =1 or 5), other than the type of apical donor atom, is the placement of the five-membered apical bridge. The trans-III configuration results in a greater ability of the ether oxygen in the decane ring of L_2 to reach over and better encapsulate the axial site. The bond to the apical oxygen is quite strong with Co(1)—O(1) = 1.924(6) Å and is significantly shorter than the Co—S distance (2.206 Å) in $[Co(L_5)(CH_3CN)]^{3+,6}$ which displays strain owing to the isomeric ligand structure. Furthermore, the Co(1)—Cl(1) bond length is 2.219(3) Å, which is similar to the Co-Cl distance (2.246 Å) observed in the crystal structure of [Co(daptacn)(Cl)]²⁺ (20), where daptacn is the pentaaza ligand 1,4-di(3-aminopropyl)-1,4,7triazacyclononane. In the latter complex ion, and in the corresponding system, 1,4,7-tri(3-aminopropyl)-1,4,7-triazacyclononane (21), there is a slight distinction between the Co-N(tert) and Co-N(sec) bond distances, with the for-

Fig. 2. Spectra of the individual cobalt(III) ions. A = $[CoHL_1(OH_2)]^{4+}$; B = $[CoL_1(OH_2)]^{3+}$; C = $[CoL_1(OH)]^{2+}$.



mer being slightly greater as expected owing to increased steric repulsion at the tertiary nitrogens. However, in contrast with the relatively more open species above, in the present complex, the distances are much more similar, probably owing to the constraints imposed by the macrobicyclic ligand.

Equilibrium studies

In the case of the ion $[Co(L_1)(ClO_4)]^{2+}$, spectra were measured over the pH range 0.872–9.92. The spectra showed the presence of more than one ion equilibrium (Figs. S1 and S2).⁵ Measurements made at 10 nm intervals over the range 210-310 nm were analysed by a second-order global analysis procedure (22) developed to examine the existence of differing, but spectroscopically similar, species in titrations of this kind that result in an inability to reliably fit a reasonable model to the data. The EQUISPEC program (22) permits a number of titrations with differing initial concentrations of the equilibrium partners to be analysed simultaneously. The result is the determination of not only profiles for each reagent, but also the pK for each equilibrium observed. By use of the data shown in Fig. S1,⁵ the absorption spectra of three species have been determined and are presented in Fig. 2. The concentration profiles and extent of agreement between observed and calculated spectra are presented in Figs. S3 and S4.⁵ It was observed that there is no change in the UVvis spectrum over 24 h under conditions of 1 mol/L [H⁺]. Although there is maintenance of the Co-ether O linkage in the solid state, it is considered that in solution the bond dissociates and the presence of the lone pair on this oxygen provides a template for formation of a hydrogen bond as shown in Scheme 2. In increasingly basic conditions, there is loss of the protonated solvent and, at higher pH, the release of the proton from the trans aqua group with a significant change in the spectrum. The pK values associated with these equilibria are 2.2 ± 0.2 and 4.2 ± 0.2 , respectively.

An alternative scheme could be envisaged in which there is retention of the Co—O (ether) bond and the site of the solvated H^+ interaction would be the remaining lone pair on

Scheme 2.

900



the oxygen. It is not possible to exclude the latter, but the bond formation with the O atom to the Co(III) may be weak in this case.

The value for the first p*K* is higher than that (0.65) for the corresponding strongly oxidizing Ni(III) species (14). However, the second p*K*, not observed in the Ni(III) system owing to decomposition, is similar to that for other *trans* aquotetramminecobalt(III) species (23, 24).

Similar results on the cobalt(III) complex of the dimethylated ligand L_3 showed two spectroscopic changes, the first over the range pH 0.58–0.67, and a second more clearly defined change with $pK \sim 1$. For the corresponding complex of L_4 , only a single $pK \sim 1.05$ is defined. In both cases, however, there is acid decomposition of the complexes owing to the protonation at the tertiary amines (vide infra).

Kinetic measurements

Anation reactions

Substitution reaction kinetics were investigated at 40 °C with chloride concentrations of approximately 50–400 times in excess halide. The rate data for the $[Co(L_1)(H_2O)]^{3+}$ reaction, obtained at 280 nm, are tabulated in Table S2.⁵ In general, the scatter of individual values for k_{obs} was in the order of ±5%. The observed first-order rate constants (k_{obs}) vary linearly with chloride concentration. However, the intercepts and slope of each curve vary roughly inversely with [H⁺]. No evidence was observed for a second substitution step in the anation.

A mechanistic scheme that accounts for the observed acid dependence is described in Scheme 3, where (neglecting all charges) CoHL and CoL represent the complex ions $[CoL(OH_3)(OH_2)]^{4+}$ and $[CoL(OH_2)_2]^{3+}$, and CoHLCl and CoLCl, the corresponding chloro complexes.

The observed rate constant derived from this equilibrium set may be represented as:

[1]
$$k_{obs} = (k_1[H^+] + k_2K_a)[Cl^-]/(K_a + [H^+]) + (k_{-1}[H^+] + k_{-2}K_b)/(K_b + [H^+])$$

As can be seen from eq. [1], approximate inverse proton dependences are predicted for both the intercepts and slopes of plots of k_{obs} vs. [Cl⁻] (eq. [1]). A plot of slope($K_a + [H^+]$) vs. [H⁺] is shown in Fig. 3 and, using the K_a value (6.3 × 10⁻³ mol/L) obtained previously, the rate constants derived are $k_1 = 0.053 \pm 0.002 \text{ (mol/L)}^{-1} \text{ s}^{-1}$ and $k_2 = 3.8 \pm 1.0 \text{ (mol/L)}^{-1} \text{ s}^{-1}$. However, the plots of intercepts ($K_b + [H^+]$) vs. [H⁺] show a slope of zero or are slightly negative

Scheme 3.



Fig. 3. Plot of slope $(K_a + [H^+])$ vs. $[H^+]$ (eq. [1]).



 $(k_{-1} \text{ not statistically discernible})$, with intercept $k_{-2}K_b = 10.4 \pm 1.3 \times 10^{-5} \text{ s}^{-1}$. Assuming $K_a \sim K_b$, then, at 40 °C, $k_{-2} = 1.6 \times 10^{-2} \text{ s}^{-1}$ and $K_2 = 230 \pm 60 \text{ mol/L}$. Comparison with the analogous Ni(III) systems at 25 °C $k_1 = 142 \text{ (mol/L)}^{-1} \text{ s}^{-1}$ and $k_2 = 1400 \pm 300 \text{ (mol/L)}^{-1} \text{ s}^{-1}$ (14) indicates, as expected, a significantly slower process for the d^6 ion.

Decomposition of $[Co(L_3)(ClO_4)](ClO_4)_2$ in acidic media

Although complexes of L_1 and L_2 appeared indefinitely stable, those incorporating the dimethylated ligands decomposed much more readily. Kinetic studies were made at 25 °C (I = 1.0 mol/L) over a range of acid concentrations using absorbance changes at 223 nm. The results are presented in Table S3⁵ and are consistent with the reaction scheme (charges omitted):



for which the observed rate constant may be written in the form: $k_{obs}([H^+] + K_a) = k_1K_a + k_2[H^+]^2$. The data are presented in Fig. 4 and the individual rate constants (derived using the value of $K_a = 0.7$ derived spectroscopically) are consistent with the reaction not only of the neutral species, but also the protonated ion. The increased rate is attributed to protonation at the tertiary nitrogen atoms, leading to a reduction in the macrocyclic coordination and eventual release of the metal ion. A similar considerable increase in lability over the unsubstituted complex has been observed previously for the Ni(II) tetramethyl-cyclam ion (25).

Confirmation of the locus of reaction is provided by a comparison of the NMR spectra in neutral and acidic media. The ¹³C NMR spectrum of $[Co(L_3)(ClO_4)](ClO_4)_2$ in D_2O- CD₃CN is highly symmetrical with only eight distinct lines exhibited (Table S4).⁵ Thus, the complex in solution possesses a time-averaged C_2 axis of symmetry. Addition of a few drops of perchloric acid to the NMR tube containing such a solution $(pH \sim 0)$ resulted in the initial precipitation of the purple complex. However, upon allowing the solution to stand overnight, dissolution occurred with loss of colour. The resultant spectrum reflects a high-symmetry species where significant chemical shifts are seen at atoms C5, C6, and C3 when compared to the Co(III) spectrum (at pH 7), and additional shifts compared to the free ligand noted at C9 and C1 were consistent with demetallation and protonation of the ligand. Bencini et al. (26) observed a similar downfield shift by the resonances of the carbon atoms adjacent to methyl centres upon protonation of the ligand 4,10dimethyl-1,4,7,10-tetraazabicyclo[5.5.2]tetradecane.

Mass spectroscopy

Characterization by LSI-MS indentified both positively and negatively charged ions, providing informative similarities and differences. In the positive-ion spectra of $[Co(L_1) (ClO_4)](ClO_4)_2$, $[Co(L_2)(ClO_4)](ClO_4)_2$, and $[Co(L_3)(ClO_4)]$ - $(ClO_4)_2$ (see Table S5)⁵, there was no evidence for the pseudo-molecular ion $[M + H^+]^+$ where $M = [Co(L_n) (ClO_4)$] $(ClO_4)_2$. The geometric isomers [Co(L_n)(ClO₄)]- $(ClO_4)_2$ (*n* = 1 or 2) gave almost identical positive-ion mass spectra with the highest ion observed at 428 ($[Co(L_n) (ClO_4)$ ⁺) owing to the initial loss of two outer-sphere perchlorate ions with the next highest ion at 328 being due to the subsequent loss of neutral HClO₄ ($[Co^{II}(H_{-1}L_n)]^+$). There is no evidence for any Co(III) fragments in either decay. In contrast, for the molecule $[Co(L_3)(ClO_4)](ClO_4)_2$, while a similar initial loss of two perchlorate ions to give a $[Co^{II}(L_3)(ClO_4)]^+$ fragment at 456 is observed, there is also a fragment at 355, $[Co(H_{-2}L_3)]^+$, in which the cobalt centre remains in the +3 oxidation state. Thus, in the same spectrum, there is evidence for cobalt in both the +2 and +3 oxidation states. The only other significant fragment observed at 299 is assignable to the protonated free ligand HL_3^+ . No extru-

Fig. 4. Rate constants for the decomposition of $[Co(III)(L_3))OH_2)]^{3+}$ in acidic media. Curve fit: $10^5k_1 = 1.1 \pm 0.11 \text{ s}^{-1}$; $10^5k_2 = 9.9 \pm 0.2 \text{ M}^{-1} \text{ s}^{-1}$.



sion of the metal centre was observed in the positive-ion mode spectra of the cobalt(III) complexes with ligands L_1 or L_2 .

In the negative-ion spectra (Table S5),⁵ there is strong evidence for the molecular ion [M]⁻. This is the result of the reduction to Co(II) and maintenance of the outer sphere perchlorates. Again, the geometric isomers $[Co(L_1)(ClO_4)]$ - $(ClO_4)_2$ and $[Co(L_2)(ClO_4)](ClO_4)_2$ gave almost identical mass spectra. Other than [M]⁻, the only other significant fragment observed was at 526 due to the loss of neutral $HClO_4$. As seen in the positive-ion spectrum for $[Co(L_3) (ClO_4)$](ClO₄)₂, the negative-ion spectrum also exhibited fragments with removal of the metal ion. Ions at 597 and 497 correspond to $[(H_2L_3)(ClO_4)_3]^-$ and $[(HL_3)(ClO_4)_2]^-$, respectively. However, there is evidence for cobalt(I) as the fragment at 355 corresponds to $[Co(H_2L_3)]^-$. The differences in mass spectra reflect the kinetic stabilities and reactivities of the methylated and non-methylated complexes. From Table S5,⁵ it can be seen that $[Co(L_2)(ClO_4)](ClO_4)_2$ and the chloro-related complex $[Co(L_2)(Cl)](ClO_4)_2$ gave very similar negative-ion mass spectra when the loss of either $HClO_4$ or HCl from $[M]^-$ is taken into account.

In summary, the Co(III) complexes with ligands L_1 and L_2 are kinetically more stable than their Ni(III) analogues, but exhibit similar proton-related equilibria that are exhibited in the kinetic analysis. Whilst the species with secondary NH groups maintain macrocyclic coordination in acidic media, those incorporating all four tertiary nitrogens are subject to attack by protons leading to an unexpectedly ready demetallation of the complexes, a feature also observed in the mass spectroscopic fragmentation of the complexes.

Acknowledgements

We thank the Natural Sciences and Engineering Research Council of Canada (NSERC) and the University of Victoria for support. TR acknowledges the tenure of an NSERC International Post-doctoral Fellowship, and KI, sabbatical assistance from Waseda University.

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