The Preparation, Stereochemistry and Reactions of Some $[Co(cyclen)(NH_3)X]^{3+/2+}$ Complexes (X = OH_2, Cl, N_3, OH)

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A number of new $[Co(cyclen)(NH_3)X]^{3+/2+}$ complexes have been prepared (X = OH_2, Cl, N_3, OH), and their stereochemistries, interconversions, and substitution reactions have been explored. All have the *syn*,*anti* configuration about the two meridional amine centers of the *cis*-coordinated cyclen ligand (*syn*(NH_3),*anti*(X)- and *syn*(X),*anti*(NH_3)-isomers for X = OH_2, Cl, N_3, OH; designated as **1**-X and **2**-X respectively) but a *syn*,*syn* intermediate is proposed for a number of the reactions. OH^--catalyzed hydrolysis (base hydrolysis) dominates the substitution chemistry in aqueous solution ($k_{OH}/M^{-1}\ s^{-1}$ values reported) and results from deprotonation at one of the relatively very acidic meridional N*H* centers ($k_H/M^{-1}\ s^{-1}$ values reported). A *syn* orientation of the N*H* proton in the reactant is considered important in these reactions, with the resulting lone pair assisting in the displacement of X, and with this proton being transferred to X = OH to facilitate an unusually fast and spontaneous solvent replacement reaction ($k_{ex} = 8 \pm 2\ s^{-1}$, $I = 1.0$ M ($NaClO_4$), 25 °C). Anation by N_3^- has been studied, and this proceeds largely via **2**-OH for both isomers. A crystal structure of *syn*(NH_3),*anti*(N_3)-[Co(cyclen)(NH_3)N_3]$Cl_{0.5}(ClO_4)_{1.5}\cdot H_2O$ is reported; monoclinic, $P2_1/n$ (No. 14), $a = 9.008(6)$ Å, $b = 28.690(15)$ Å, $c = 14.528(7)$ Å, $a = 90°$, $\beta = 104.12(7)°$, $\gamma = 90°$, $Z = 8$, $R = 0.0695$.

Introduction

Although many $[Co(cyclen)(A)X]^{n+}$ complexes have been reported recently,[1] little is known about their substitution chemistry. Because of its small "hole size" cyclen (1,4,7,10-tetraazacyclodecane) forms only *cis*-octahedral complexes,[2] but available information[1e,f,3] indicates that even in this configuration the macrocycle is under considerable strain. Could this strain result in unusual reactivity? Previous studies in this area may be summarized as follows. Hay and Norman[4] have shown that base hydrolysis of $[Co(cyclen)Cl_2]^+$ occurs at the fastest rate ($k_{OH} = 2.1 \times 10^7\ M^{-1}\ s^{-1}$, $I = 1.0$ M, 25 °C) of any *cis*-dichloro complex containing a saturated macrocycle,[5] and Sosa and Tobe[6] subsequently showed that this was due, at least in part, to a particularly labile meridional N*H* proton. Further, the *cis*-$[Co(cyclen)(OH_2)OH]^{2+}$ cation[7] has been found to catalyze the hydration of CH_3CN and a number of other nitriles[8] and to promote the hydrolysis of bis(4-nitrophenyl)phosphate[9] and *N*-formylmorpholine.[10] Such reactions have been interpreted in terms of *cis*-coordinated OH^- inducing the rapid release of coordinated OH_2 by an internal CB mechanism,[11] followed by attachment of substrate. It is clear that considerable substrate and product lability is involved. However, the spontaneous aquation of Cl^- in $[Co(cyclen)Cl_2]^+$ is slow and normal,[4] and we have shown recently that $[Co(cyclen)(O_2CO)]^+$ is remarkably stable toward hydrolysis in acid solution.[1g] Also, $[Co(cyclen)(OC(H)NMe_2)_2]^{3+}$ undergoes only slow, two-stage, aquation.[1c,12]

During a recent investigation using cyclen[13] and Mecyclen[14] complexes of Co(III), we found that both coordinated Cl^- and NH_3 were remarkably labile in neutral aqueous solution but were quite stable in acid. This raised the question as to whether reactivity resulted from a very labile meridional N*H* proton, as suggested by Sosa and Tobe,[6] or from inherent strain in the

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(1) (a) (*syn*,*syn*)-$[Co(cyclen)Cl_2]ClO_4$, Castillo-Blum, S. E.; Sosa-Torres, M. E. *Polyhedron* **1995**, *14*, 223. (b) $[Co(cyclen)(OH_2)_2](ClO_4)_3$, Kim, J. H.; Britten, J.; Chin, J. *J. Am. Chem. Soc.* **1993**, *115*, 3618; $[Co(cyclen)(OH_2)_2](ClO_4)_2NO_3$, Clark, C. R.; Buckingham, D. A. *Inorg. Chim. Acta* **1997**, *254*, 339. (c) $[Co(cyclen)(OC(H)NMe_2)_2](CF_3SO_3)_3$, Curtis, N. J.; Hendry, P.; Lawrance, G. A. *J. Chem. Soc., Dalton Trans.* **1988**, 47. (d) *syn*(N),*anti*(S)- and *syn*(S),anti(N)-[Co(cyclen)(S-$NH_2CH_2CH(CH_3)S$]($ZnCl_4$) isomers, Kojima, M.; Nakabayashi, K.; Ohba, S.; Okumoto, S.; Saito, Y.; Fujita, J. *J. Bull. Chem. Soc. Jpn.* **1986**, *59*, 277. (e) $[Co(cyclen)L]Cl_3\cdot xH_2O$ (L = en, pic, pn, chxn, tn, bn). (f) $[Co(cyclen)(alaO)](ClO_4)_2\cdot 0.5H_2O$, Nonoyama, N.; Kurimoto, T. *Polyhedron* **1985**, *4*, 471. (g) $[Co(cyclen)(O_2CO)]ClO_4\cdot H_2O$, Buckingham, D. A.; Clark, C. R. *Inorg. Chem.* **1994**, *33*, 6171.

(2) (a) Melson, G. A. In *Coordination Chemistry of Macrocyclic Compounds*; Plenum Press: New York, 1979. (b) Hung Y.; Busch, D. H. *J. Am. Chem. Soc.* **1977**, *99*, 4029, 4977.

(3) X-ray structures have been reported for $[Co(cyclen)(O_2CO)]ClO_4\cdot H_2O$, Loehlin, J. H.; Fleischer, E. B. *Acta Crystallogr.* **1976**, *B32*, 3063; $[Co(cyclen)(acac)](ClO_4)_2\cdot H_2O$ and $[Co(cyclen)(Br\text{-}acac)](ClO_4)_2\cdot 0.5H_2O$, Matsumoto, N.; Hirano, A.; Hara T.; Ohyoshi, A. *J. Chem. Soc., Dalton Trans.* **1983**, 2405; *syn*(S),*anti*(N)-[Co(cyclen)(S-$NH_2CH_2CH(CH_3)S$)]$ZnCl_4\cdot H_2O$ (green isomer), Kojima, M.; Nakabayashi, K.; Ohba, S.; Okumoto, S.; Saito, Y.; Fujita, J. *Bull Chem. Soc. Jpn.* **1986**, *59*, 277. The structures of a number of alkyl-substituted cyclen complexes have also been reported.

(4) Hay, R. W.; Norman, P. R. *J. Chem. Soc. Chem Commun.* **1980**, 734.

(5) Tobe, M. L. *Adv. Inorg. Bioinorg. Mech.* **1983**, *2*, 1.

(6) Sosa, M. E.; Tobe, M. L. *J. Chem. Soc., Dalton Trans.* **1985**, 475.

(7) The water-exchange rate in this ion has been shown to be 11 s^{-1} (25 °C, $I = 1.0$ M), Buckingham, D. A.; Clark, C. R.; Rogers, A. J., unpublished data.

(8) Kim, J. H.; Britten, J.; Chin, J. *J. Am. Chem. Soc.* **1993**, *115*, 3618.

(9) Chin, J.; Banaszczyk, M.; Jubian, V.; Zou, X. *J. Am. Chem. Soc.* **1989**, *111*, 186.

(10) Takasaki, B. K.; Kim, J. H.; Rubin, E.; Chin, J. *J. Am. Chem. Soc.* **1993**, *115*, 1157.

(11) Jackson, W. G. *Inorg. Chim. Acta* **1974**, *10*, 51.

(12) These authors, ref 1c, assumed, incorrectly, that the two dimethylformamide ligand sites were equivalent.

(13) Buckingham, D. A.; Clark, C. R.; Rogers, A. J.; Simpson, J. *Aust. J. Chem.*, in press.

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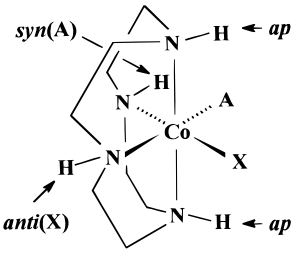

Figure 1. Representation of a *syn*(A),*anti*(X)-[Co(cyclen)(A)X]$^{n+}$ ion designating the *syn,anti* and *ap*-N*H* protons.

cyclen chelate. If a labile N*H* proton was involved, could it be located, and was its stereochemistry important? This article considers such aspects. Most of the complexes considered here have not been reported previously.

Experimental Section

All details of experimental methods, instrumentation, materials, and syntheses are available as Supporting Information.

Results

The starting material for synthesis was [Co(cyclen)Cl_2]Cl, and this was prepared directly from $CoCl_2 \cdot 6H_2O$ and cyclen·4HCl by air oxidation in an improvement on methods previously described.[6,8,15] The complex has the *syn,anti* configuration about the two meridional N*H* centers in its usual form,[6] although the *syn,syn*-isomer has recently been isolated in admixture with the *syn,anti* form.[1a] Substitution of coordinated Cl^- by other ligands occurs easily in neutral aqueous solution, but the complex (ClO_4^- salt) is reported to be quite stable in DMSO;[1a] this is probably due to the nonlability of the N*H* protons in this solvent. Figure 1 shows the *syn,anti*- and *ap*-N*H* (*ap* = apical) proton designation in [Co(cyclen)(A)X]$^{n+}$ complexes.

***syn*(NH$_3$),*anti*(Cl)- and *syn*(Cl),*anti*(NH$_3$)-[Co(cyclen)(NH$_3$)Cl](ClO$_4$)$_2$ (Isomers 1 and 2, Respectively).** These two isomers were prepared following controlled hydrolysis of [Co(cyclen)$(NH_3)_2$]$^{3+}$,[16] anation with HCl, and I. E. chromatographic separation. The same isomers were produced in the same ratio (60 ± 3% **1,** 40 ± 3% **2**) by anation of isolated [Co(cyclen)$(NH_3)OH_2$]$(ClO_4)_3$ complexes (vide infra, either isomer) at pH 7−8 (1 M NaCl, 25 °C). From these and other experiments, it was shown that the above distribution represents the equilibrium mixture, eq 1, K_{Cl} (= [**1**]/[**2**]) = 1.5 ± 0.2 (I = 1.0, ca. 25 °C). Care was required when recovering these

$$\textbf{2}\text{-[Co(cyclen)(NH}_3\text{)Cl]}^{2+} \overset{K_{Cl}}{\rightleftharpoons} \textbf{1}\text{-[Co(cyclen)(NH}_3\text{)Cl]}^{2+} \quad (1)$$

complexes from the ion exchange column as the fastest moving band (isomer **2**) contained any [Co(cyclen)(OH_2)Cl]$^{2+}$ present in the reaction mixture, and the slower band (isomer **1**) needed to be removed without delay as slow aquation occurred on the column (even in the presence of 2−3 M HCl). Isomer configuration (**1**, **2**) and N*H* identification were established by NOE and COSY spectroscopy. No evidence (reversed-phase HPLC analysis) was found in any of these experiments for other isomers (syn,syn or anti,anti).

N*H* exchange rate data was obtained in dilute DCl or buffered D_2O solution, Table 1. The three N*H* signals corresponding to the *syn,anti*- and *ap*-N*H* protons are clearly differentiated in d_6-DMSO; but for isomer **1** in dilute DCl, the *anti*(Cl)- and *ap*-N*H* signals overlap, and only two resonances are apparent, Figure S1 (Supporting Information). However, the ca. 10-fold difference in the rates of exchange at these sites means that the processes are easily distinguished. For both isomers, the fastest exchanging proton is that *trans* to Cl^- (isomer **1**, *syn*(NH_3); isomer **2**, *anti*(NH_3)) and the values of their similar rate constants, k_H = (2.0 ± 0.5) × 10^9 M^{-1} s^{-1}, suggest reaction rates at, or close to, the diffusion controlled limit.[17] Such rate constants are among the largest known for N*H* exchange in a 2+ Co(III) complex.[5,18] The remaining N*H* protons are less labile with, for isomer **1**, the *anti*(Cl) proton being some 10 times faster to exchange than the two equivalent *ap*-N*H* protons. For this isomer, both the meridional and apical N*H* exchanges are faster than base hydrolysis of Cl^- (cf. Table 2, D_2O, k_{OD}(**1**) = 6 × 10^5 M^{-1} s^{-1}). For isomer **2**, only exchange of the *anti*(NH_3)-N*H* proton is appreciably faster than base hydrolysis, with both the *syn*(Cl)-N*H* and *ap*-N*H* protons having exchange rates not too different from that for base hydrolysis (cf. Table 2, D_2O, k_{OD}(**2**) = 7.2 × 10^6 M^{-1} s^{-1}). It was, therefore, of interest to see whether the latter exchanges occur in the NH_3/Cl reactant or whether they result from faster (subsequent) exchange in the NH_3/OH^- product. This was decided by an NMR experiment on isomer **2** carried out at pD 4.35 which showed that over a time period corresponding to 1 × $t_{1/2}$ for base hydrolysis (ca. 27 min), the *anti*(NH_3)-N*H* proton had completely disappeared, consistent with its very fast exchange (2.0 × 10^9 M^{-1} s^{-1}, Table 1), the *syn*(Cl)-N*H* was partly exchanged (ca. 50%), whereas the *ap* protons remained. Details are given in Figure S2 (Supporting Information). It is therefore clear that the k_H rate constant for the *syn*(Cl) proton of isomer **2** (cf. Table 1, 9 × 10^6 M^{-1} s^{-1}) corresponds only in part to exchange in the NH_3/Cl reactant (ca. 50%), and it must also contain a similar contribution from base hydrolysis and exchange in the hydrolysis product. The somewhat smaller k_H value for *ap*-N*H* exchange (Table 1, 6 × 10^6 M^{-1} s^{-1}) must then refer only to exchange in the NH_3/OH product. Further consideration of such matters will be taken up in the discussion below. No H/D exchange was found for the NH_3 protons of either **1**- or **2**-[Co(cyclen)(NH_3)Cl]$^{2+}$ prior to, or immediately subsequent to, base hydrolysis of Cl^-. Such protons cannot therefore be responsible for base hydrolysis. Aquation of coordinated Cl^-

Table 1. Rate Data for N*H* Exchange in the Two [Co(cyclen)(NH_3)Cl]$^{2+}$ Isomers (D_2O, I = 1.0 M, $NaClO_4$, 25 °C)[a]

N*H* (ppm)	[D$^+$]/M or pD	10^{12}[OD$^-$][b]/M	10^4k_{obs}/s^{-1}	k_H[c]/M^{-1} s^{-1}
	syn(NH_3),*anti*(Cl)-isomer **1**			
syn(NH_3) (6.30)	0.0087	0.53	9.6	1.8 × 10^9
	0.017	0.27	5.5	2.0 × 10^9
anti(Cl) (6.60)	3.51	8.6	4.1	4.8 × 10^7
ap (6.65)	4.71	137	8.2	6.0 × 10^6
	4.9[d]	26	1.2	4.6 × 10^6
	syn(Cl),*anti*(NH_3)-isomer **2**			
anti(NH_3) (6.34)	0.017	0.27	4.2	1.6 × 10^9
	0.035	0.13	2.7	2.1 × 10^9
	4.96	0.13	3.0	2.3 × 10^9
syn(Cl) (6.81)	4.93	227	21.4	9.4 × 10^6
	4.96	243	20.3	8.4 × 10^6
ap (6.68)	4.93	227	14.2	6.3 × 10^6
	4.96	243	13.6	5.6 × 10^6

[a] [Co] ≅ 0.02 M. [b] [OD$^-$] = $10^{(pD - 14.81)}/\gamma_{\pm}$; $\gamma_{\pm}$ = 0.58. [c] $k_H = k_{obs}$/[OD$^-$]. [d] No added electrolyte (I = ca. 0.2 M).

(15) Collman, J. P.; Schneider, P. W. *Inorg. Chem.* **1996**, *5*, 1380.
(16) For the preparation of this complex see: Buckingham, D. A.; Clark, C. R.; Rogers, A. J. *Inorg. Chim. Acta* **1995**, *240*, 125.
(17) Ridd, J. H. *Adv. Phys. Org. Chem.* **1978**, *16*, 1.
(18) Buckingham, D. A.; Clark, C. R.; Rogers, A. J. *J. Am. Chem. Soc.* **1997**, *119*, 4050.

Table 2. Rate Data for Hydrolysis of the Two [Co(cyclen)(NH$_3$)Cl]$^{2+}$ Isomers[a] (25.0 °C, I = 1.0 M (NaClO$_4$))

pH (or pD)	10^8[OH$^-$] (or[OD$^-$])[h]	k_{obs}/s^{-1}	$10^{-5}k_{OH}$[i]/ M^{-1} s^{-1}
	syn(N),*anti*(Cl)-isomer **1**		
4.90[b]	0.137	2.81×10^{-4}	2.1
4.98[b]	0.165	4.53×10^{-4}	2.8
7.17[c]	25.5	7.2×10^{-2}	2.8
7.64[c]	75.3	2.42×10^{-1}	3.2
8.06[c]	198	6.55×10^{-1}	3.3
8.32[c]	360	1.05	2.9
8.95[c]	1540	4.95	3.2
8.07[f,g]	31.4	1.85×10^{-1}	5.9
8.60[f,g]	106	0.64	6.0
8.84[f,g]	185	1.15	6.2
	syn(Cl),*anti*(N)-isomer **2**		
7.82[d]	114	4.80	42
8.19[d]	267	12.1	45
8.92[d]	1430	57	40
9.09[e]	2120	92.5	44
8.09[f,g]	32.8	2.52	77
8.61[f,g]	109	8.09	74
8.86[f,g]	193	12.9	67

[a] [Co] = 2 mM, 300 nm. [b] 0.10 M acetate buffer. [c] 0.10 M HEPES buffer. [d] 0.10 M TRIS buffer. [e] 0.10 M CHES buffer. [f] 0.05 M TRIS buffer, 530 nm. [g] D_2O. [h] [OH$^-$] = $10^{(pH-14.00)}/(\gamma_\pm)$ for pH data; [OD$^-$] = $10^{(pD-14.81)}/(\gamma_\pm)$ for pD data; $\gamma_\pm$ = 0.58. [i] k_{OH} (k_{OD}) = k_{obs}/[OH$^-$] (or [OD$^-$]).

under acidic conditions (1.0, 0.1 M HClO$_4$), eq 2, was found to be slow for both isomers (spectrophotometric rate data not given) with k_{aq}(**1**) = (2.0 ± 0.1) × 10^{-5} s^{-1}, k_{aq}(**2**) = (3.9 ± 0.2) × 10^{-6} s^{-1} (I = 1.0 M, NaClO$_4$; 25 °C). Isomer **1** thus aquates

$$\textbf{1}\text{- or }\textbf{2}\text{-[Co(cyclen)(NH}_3\text{)Cl]}^{2+} + H_2O \xrightarrow{k_{aq}} \textbf{1}\text{- or }\textbf{2}\text{-[Co(cyclen)(NH}_3\text{)OH}_2\text{]}^{3+} + Cl^- \quad (2)$$

some 5 times faster than isomer **2**. The isomeric purity of the NH$_3$/OH$_2$ product was not established with any certainty since isomerization between the two aqua ions occurs at a comparable rate (vide infra). However, since the faster reverse anation reaction in acid solution occurs with full retention of configuration (vide infra), it can be assumed that spontaneous hydrolysis also occurs with stereochemical retention.

On the other hand, base hydrolysis is fast, even in neutral solution, eq 3, Table 2, with k_{OH}(**1**) = (3.0 ± 0.3) × 10^5 M^{-1} s^{-1}, k_{OH}(**2**) = (4.2 ± 0.3) × 10^6 M^{-1} s^{-1} (I = 1.0 M, NaClO$_4$; 25 °C). Isomer **2** thus hydrolyzes some 14 times faster than **1**

$$\textbf{1}\text{- or }\textbf{2}\text{-[Co(cyclen)(NH}_3\text{)Cl]}^{2+} + OH^- \xrightarrow{k_{OH}} \textbf{2}\text{-[Co(cyclen)(NH}_3\text{)OH]}^{2+} + Cl^- \quad (3)$$

(the k_{OH}/k_{aq} ratio ca. 10^{12} M^{-1} for **2** appears to be the largest known for a Co(III)-chloro complex). The different k_{OH} values means that **1**-Cl and **2**-Cl do not rapidly interconvert prior to hydrolysis and this was easily checked for faster reacting **2**-Cl by quenching after ca. 1 × $t_{1/2}$ (2.5 min, pH 4.80) and examining recovered reactant by reversed-phase HPLC; no **1**-Cl was found (<0.5%). A similar experiment using isomer **1** required choosing a time such that **2**-Cl, if produced, would be present in maximum amount.[19] This experiment (12.5 s reaction time at pH 6.19, I ≈ 0.1 M)[20] also failed to demonstrate the presence of **2**-Cl (<0.5% of Co$_T$) in the quenched reaction mixture; some 7% would have been expected at this time if prior isomerization **1**-Cl → **2**-Cl had occurred.[19] Under most conditions, the [Co(cyclen)(NH$_3$)OH]$^{2+}$ product was found to have its equilibrium distribution (75% **1**, 25% **2**, vide infra) since, as we shall see below, interconversion between them is fast in neutral to alkaline solution. However, by choosing an appropriate pH, and by acid quenching before substantial isomerization could take place, the **immediate** NH$_3$/OH$^-$ product could be found. Hydrolysis of **1**-Cl (pH 8.66 for 100 ms, ~20% reaction); and ion exchange separation of the quenched [Co(cyclen)(NH$_3$)-OH$_2$]$^{3+}$ product gave on spectrophotometric examination an extinction coefficient ratio A_{490}/A_{347} of 1.28. Exactly the same ratio was obtained for the quenched aqua product in an identical experiment starting with **2**-Cl (pH 8.66 for 100 ms, 5 × $t_{1/2}$ for base hydrolysis; no ion exchange separation necessary). This extinction ratio corresponds exactly to that for pure **2**−OH$_2$, so that base hydrolysis of **both** chloro isomers leads to only *syn*(OH),*anti*(NH$_3$)-[Co(cyclen)(NH$_3$)OH]$^{2+}$ (i.e., **2**-OH, experimental uncertainty ±10%). Over time (16 h) the two acidified (pH 1−2) solutions relaxed to give A_{490}/A_{347} = 1.40, corresponding to that for the fully equilibrated aqua isomers (vide infra).

***syn*(NH$_3$),*anti*(OH$_2$)- and *syn*(OH$_2$),*anti*(NH$_3$)-[Co(cyclen)-(NH$_3$)OH$_2$](ClO$_4$)$_2$NO$_3$ (Isomers 1 and 2, Respectively).** These two complexes were prepared directly from the amino-chloro complexes via the Hg^{2+}-catalyzed removal of Cl$^-$ under acidic conditions, eq 4. This reaction is nearly always stereo-

$$\textbf{1}\text{- or }\textbf{2}\text{-[Co(cyclen)(NH}_3\text{)Cl]}^{2+} + Hg^{2+} + H_2O \rightarrow \textbf{1}\text{- or }\textbf{2}\text{-[Co(cyclen)(NH}_3\text{)OH}_2\text{]}^{3+} + HgCl^+ \quad (4)$$

retentive,[21] and so it is here; re-anation of the recovered crystalline products (6 M HCl, 40−60 °C) gave back the pure NH$_3$/Cl isomers.

This latter reaction in acid solution is distinguished from the anation reaction under neutral to alkaline conditions (vide infra), and the result implies no isomerization **1** ⇌ **2** in the spontaneous displacement of either Cl$^-$ (aquation) or OH$_2$ (anation). As with other NH$_3$/OH$_2$ complexes,[22] the mixed ClO$_4^-$/NO$_3^-$ salt proved to be the most suitable for isolation and recrystallization purposes. However, it was found necessary to keep all solutions acidic (ca. 0.1−1.0 M HClO$_4$) and cold to prevent anation by NO$_3^-$. ^{1}H-spectra in acidified d_6-DMSO, Figure S3 (Supporting Information), together with NOE data, were used for structural assignment.

Isomerization rate data (Table S1**,** Supporting Information), eq 5, is plotted vs [OH$^-$] in Figure 2. This shows a first-order

$$\textbf{1}\text{-[Co(cyclen)(NH}_3\text{)OH}_2\text{/OH]}^{2+/3+} + OH^- \underset{k_l(\mathbf{2}) + k'_l(\mathbf{2})}{\overset{k_l(\mathbf{1}) + k'_l(\mathbf{1})}{\rightleftharpoons}} \textbf{2}\text{-[Co(cyclen)(NH}_3\text{)OH}_2\text{/OH]}^{2+/3+} + OH^- \quad (5)$$

dependence on [OH$^-$] in the acid region (pH < 6.5) and again above pH ≈ 8, but is clearly [OH$^-$]-independent from pH 6.5−8.0 (i.e., about the pK_a of the OH$_2$ ligand).

(19) The maximum amount of **2**-Cl (i.e., $100\kappa^{\kappa/(1-\kappa)}$%) can be expected after a time given by t_{max} = ln κ/k_{obs}(**1**)(κ − 1), where κ = k_{obs}(**1**)/k_{obs}(**2**); cf. Frost, A. A.; Pearson, R. G. In *Kinetics and Mechanism*; Wiley and Sons: New York, **1953**; p 155.

(20) We found k_{obs} (I = 0.1 M) ≈ 2k_{obs} (I = 1.0 M) for **1**-Cl.

(21) Posey, F. A.; Taube, H. *J. Am. Chem. Soc.* **1957**, *79*, 255. Buckingham, D. A.; Olsen, I. I.; Sargeson, A. M. *J. Am. Chem. Soc.* **1968**, *90*, 6654. However, see Jackson, W. G. *Inorg. Chim. Acta* **1974**, *10*, 51.

(22) Buckingham, D. A.; Clark, C. R.; Webley, W. S. *Aust. J. Chem.* **1980**, *33*, 263.

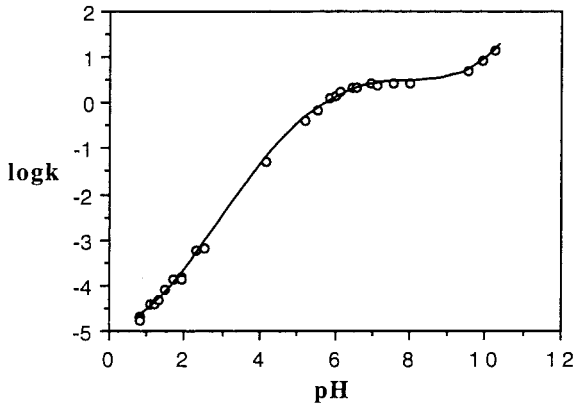

Figure 2. Plot of log k_{obs} vs pH for isomerization of *syn*(OH_2),*anti*(NH_3)-[Co(cyclen)(NH_3)OH_2]$^{3+}$ (**2**-OH_2), I = 1.0 M ($NaClO_4$), 25 °C. The curve represents the best fit to eq 6 using $k_I = 1.4 \times 10^8$ M^{-1} s^{-1}, $k'_I = 4 \times 10^4$ M^{-1} s^{-1}.

The pK_a was found to be 6.02 for the isomeric mixture (potentiometric titration). No "spontaneous" (i.e., acid-independent) pathway could be found even in 0.1 M H^+, and this is in keeping with the observed retention on anation by Cl^- in aqueous HCl. The rate data fit the rate law

$$k_I(\text{obs}) = k_I K_a [OH^-]/(K_a + [OH^-]) + k'_I[OH^-] \quad (6)$$

where k_I corresponds to the second-order rate constant for OH^--catalyzed isomerization in the X = OH_2 ions, $k_I = k_I$(**1**) + k_I(**2**) = (1.4×10^8 M^{-1} s^{-1}, I = 1.0 M $NaClO_4$, 25 °C) and k'_I to the similar rate constant for isomerization in the X = OH ions ($k'_I = k'_I$(**1**) + k'_I(**2**) = 4×10^4 M^{-1} s^{-1}, I = 1.0 M $NaClO_4$, 25 °C). Equilibrium concentrations of the two X = OH_2 ions (65 ± 2% **1**, + 35 ± 2% **2**) were found by allowing the isomers (both **1** and **2**) to stand overnight in 0.1 M $HClO_4$ (I = 1.0 M $NaClO_4$, 25 °C) giving $K_{H_2O} = k_I$(**2**)/k_I(**1**) = 1.9 ± 0.1, and the separate forward and reverse rate constants for isomerization k_I(**1**) = 4.8×10^7 M^{-1} s^{-1}, k_I(**2**) = 9.2×10^7 M^{-1} s^{-1}. Alternatively, the rate data may be analyzed in terms of spontaneous isomerization in the X = OH^- ions giving k_I = 2.5 s^{-1}. Again, equilibration of these ions (pH 8.2, 10 s; giving 75 ± 2% **1** plus 25 ± 2% **2**, K_{OH} = 3.0 ± 0.1, I = 1.0 M $NaClO_4$) allows the separate rate constants k_I(**1**) = 0.63 s^{-1}, k_I(**2**) = 1.9 s^{-1} to be evaluated. The two mechanisms will be considered further below, but it is clear that isomerization in the X = OH^- ions is fast. Also, from the above equilibrium data, the individual acidities of the two X = OH_2 ions may be evaluated; pK_a(**1**) = 5.96, pK_a(**2**) = 6.15.

Rate data for exchange of coordinated OH_2 in [Co(cyclen)(NH_3)$^{17}OH_2$]$^{3+}$ (mixed isomers) with solvent is given in Table S2 (Supporting Information). These were obtained by following the increase in solvent $H_2{}^{17}O$ signal as a function of time by ^{17}O NMR. The method was restricted to $t_{1/2} > 2$ min, but exchange under neutral conditions was shown to be complete within the time of the first observation (1 min). However, the data in acidic solution clearly showed a strict OH^- dependence. This may again be interpreted as involving either OH^--catalyzed loss of coordinated H_2O in [Co(cyclen)(NH_3)OH_2]$^{3+}$, $k_{OH} = (4.5 \pm 1) \times 10^8$ M^{-1} s^{-1}, or as spontaneous loss of OH^- in [Co(cyclen)(NH_3)OH]$^{2+}$, with $k_{ex} = 8 \pm 2$ s^{-1}. This aspect will be taken up again below, but irrespective of mechanism, it is clear that solvent exchange is somewhat faster (ca. 5−10 times) than isomerization **1** ⇌ **2**. It was not possible to determine whether only one or both isomers were responsible for solvent exchange (vide infra).

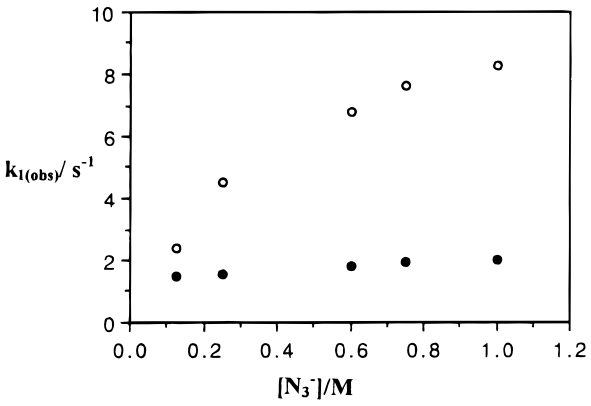

Figure 3. Plots of k_1(obs) vs [N_3^-] for anation of the *syn*(NH_3),*anti*(OH)-(closed circles) and *syn*(OH),*anti*(NH_3)- (open circles) [Co(cyclen)-(NH_3)OH]$^{2+}$ isomers (**1**-OH, **2**-OH, respectively) at pH 7.62, I = 1.0 M ($NaClO_4$), 25 °C.

Anation by Cl^- is slow under acidic conditions (h; 1.0 M, 4.0 M HCl; 25 °C), but is fast at neutral pH (<1 s, 1.0 M NaCl). The [Co(cyclen)(NH_3)Cl]$^{2+}$ product gave the same isomer distribution for both sets of conditions, 60 ± 3% **1**, 40 ± 3% **2**. Qualitatively it was found that the rate of this reversible reaction was OH^--dependent at pH values less than the pK_a of the coordinated OH_2 molecule, but became very fast and independent of pH under conditions where [Co(cyclen)(NH_3)-OH]$^{2+}$ was the dominant species. Clearly, Cl^- anation is associated with the above-mentioned loss of coordinated OH_2 or OH^-.

Anation by N_3^- at neutral pH is not reversible for [N_3^-] > 0.05 M. Rate data collected at pH 7.62 is given in Table S3 (Supporting Information) and plotted vs [N_3^-] in Figure 3. Two processes were observed for each isomer. The first involved a large OD increase (at λ_{max} for the azido isomers, 514 nm), and this was followed by a slower and smaller increase. Rate constants (k_{fast}(obs), k_{slow}(obs)) were obtained using a consecutive first-order fitting program. The first reaction results from the initial anation by N_3^-, eq 7, and this is followed by [N_3^-]-independent isomerization in the [Co(cyclen)(NH_3)N_3]$^{2+}$ product (cf. eq 9 below). Thus anation does not give the equilibrium

$$\textbf{1}\text{- or }\textbf{2}\text{-[Co(cyclen)(NH}_3\text{)OH]}^{2+} + N_3^- \rightarrow \textbf{1} + \textbf{2}\text{-[Co(cyclen)(NH}_3\text{)N}_3\text{]}^{2+} + OH^- \quad (7)$$

mixture (48% **1**, 52% **2**, vide infra) but results in considerably more **2** than **1**. From the absorbance changes observed for the two processes, we estimate 61 ± 3% **2**, 39 ± 3% **1**, independent of [N_3^-] and of the starting isomer for the kinetic distribution. However, while the rate constants for production of azido product from **1**-OH are seen to be nearly independent of azide ion concentration those from **2**-OH increase more sharply with increasing [N_3^-]. These differing responses and the observation of a common product distribution are consistent with anation occurring largely via isomer **2**. Isomerization in the hydroxo reactants (**1** ⇌ **2**, k_I = 2.5 s^{-1}) was not directly observed under the experimental conditions (at 514 nm, the extinction coefficients of the hydroxo isomers are very similar and much less (<$^1/_{10}$) than those of the azido products), but the rate at which azido product is generated from **1**-OH largely reflects this isomerization. Superficially this process appears to be pseudo-first-order, but this is likely to be an artifact, especially at low [N_3^-], since an induction period should have been observed. Clearly, the rate of production of azido complex from **1**-OH is such that the associated absorbance change should not follow a

Table 3. Some Properties of the [Co(cyclen)(NH$_3$)X]$^{3+/2+}$ Complexes[a]

complex X	isomer configuration	absorption maxima, nm (ϵ)[b]	NH exchange rates (k_H, M^{-1} s^{-1})	equilibrium ratio (K = [**1**]/[**2**])	spontaneous rate constant (k_{H_2O}, s^{-1})	base hydrolysis rate constant (k_{OH}, M^{-1} s^{-1})	isomerization rate constant (k_I, M^{-1} s^{-1})
OH$_2$	*syn*(NH$_3$),*anti*(OH$_2$)	496 (197), 347 (133)	7.0×10^9	1.86	*i*		4.8×10^7
	syn(OH$_2$),*anti*(NH$_3$)	500 (194), 347 (153)			*i*	4.5×10^8	9.2×10^7
OH	*syn*(NH$_3$),*anti*(OH)			3.0	8	1.0[h]	0.6[d]; 1×10^4
	syn(OH),*anti*(NH$_3$)				8	1.0[h]	1.9[d]; 3×10^4
Cl	*syn*(NH$_3$), *anti*(Cl)	524 (183), 364 (159)	2×10^9, 5×10^7	1.5	2.0×10^{-5}	3.0×10^5	*g*
	syn(Cl),*anti*(NH$_3$)	535 (159), 364 (163)	2×10^9, 9×10^6		3.9×10^{-6}	4.2×10^6	*g*
N$_3$	*syn*(NH$_3$),*anti*(N$_3$)	514 (548)		0.92			1.5×10^5
	syn(N$_3$),*anti*(NH$_3$)	514 (434)				4.0×10^4	1.5×10^5

[a] In 1 M NaClO$_4$, 25 °C. [b] Units: M^{-1} cm^{-1}. [c] Same for both *syn* (7.8 ppm) and *anti* (7.5 ppm) protons. [d] For spontaneous reaction; units: s^{-1}. [e] Combined forward (k'_I(**2**)) and reverse (k'_I(**1**)) rate constant. [f] Not observed. [g] Isomerization not observed prior to base hydrolysis. [h] For hydrolysis of the second NH$_3$ ligand, Buckingham, D. A.; Clark, C. R.; Rogers, A. J., unpublished data. [i] Not observed (<10^{-5} s^{-1}).

single exponential. This is not so for **2**-OH where azido production is significantly faster than reactant isomerization. Here, it would be expected that the rate constants for anation should tend toward independence in [N_3^-] as they approach the solvent exchange rate ($k_{ex} = 8 \pm 2$ s^{-1}), and the data in Figure 3 clearly indicate that this is so. Rate constants for the subsequent (slower) isomerization in the azido product (k_{slow}(obs), Table S3, Supporting Information) are the same, independent of starting isomer (0.31 ± 0.04 s^{-1}), as would be expected. This reaction was also examined separately using the pure azido complexes (vide infra).

***syn*(NH$_3$),*anti*(N$_3$)- and *syn*(N$_3$),*anti*(NH$_3$)-[Co(cyclen)(NH$_3$)N$_3$](ClO$_4$)$_2$ (Isomers 1 and 2, Respectively).** These complexes were prepared by anating either of the [Co(cyclen)(NH$_3$)OH$_2$](ClO$_4$)$_2$NO$_3$ isomers with 0.1 M NaN$_3$ at pH ~ 7 and separating the two products by ion exchange chromatography (pH ~ 3). The complexes were isolated as "mixed" ClO_4^-/NO_3^- salts and converted to their more soluble perchlorates by anion ion exchange chromatography. Isomer configuration (**2** moves fastest on cation ion exchange chromatography or reversed-phase HPLC) was determined by stereoretentive conversion to the aqua ions, eq 8, and by a crystal structure of *syn*(NH$_3$),*anti*(N$_3$)-[Co(cyclen)(NH$_3$)N$_3$]Cl$_{0.5}$(ClO$_4$)$_{1.5}$·H$_2$O. Crystallographic data are given in Tables S4 to S8 and Figures S4 and S5 (Supporting Information). The bond lengths and angles in the structure are unremarkable, with inequality in the N−N bond lengths in the azido ligand being what is usually observed in Co(III)-N$_3$ structures,[23] and with the large differences in C−N−C bond angles for *ap*-NH compared to *syn*- or *anti*-NH centers being in accord with observations on other Co(III)-cyclen complexes.[18]

1-, or **2**-[Co(cyclen)(NH$_3$)N$_3$]$^{2+}$ + HNO$_2$ + H$^+$ →

1- or **2**-[Co(cyclen)(NH$_3$)OH$_2$]$^{3+}$ + N$_2$ + N$_2$O (8)

Isomer interconversion was followed at 514 nm in the presence of added 1.0 M N_3^- (to remove completely the effect of the slower base hydrolysis reaction, vide infra). Rate data are given in Table S9 (Supporting Information) and show strict OH^- catalysis ($k_I = (2.9 \pm 0.2) \times 10^5$ M^{-1} s^{-1}, I = 1.0 M, 25 °C). The data are the same for both isomers. From the final equilibrium distribution 48 ± 2% **1**, 52 ± 2% **2**, determined from experiments carried out in the absence of added N_3^- (0.1 M Pipes buffer, pH 6.32, 10 min, reversed-phase HPLC), the separate isomerization rate constants can be evaluated, eq 9, k_I(**1**) = 1.5×10^5 M^{-1} s^{-1}, k_I(**2**) = 1.4×10^5 M^{-1} s^{-1} (I = 1.0 M, NaClO$_4$; 25 °C). Base hydrolysis of coordinated N_3^-, eq

$$\textbf{2}\text{-[Co(cyclen)(NH}_3\text{)N}_3\text{]}^{2+} + OH^- \underset{k_I(\mathbf{1})}{\overset{k_I(\mathbf{2})}{\rightleftharpoons}} \textbf{1}\text{-[Co(cyclen)(NH}_3\text{)N}_3\text{]}^{2+} + OH^- \quad (9)$$

10, was followed at 305 nm where a large OD decrease occurs; Table S10 (Supporting Information) gives rate data. These show

1- + **2**-[Co(cyclen)(NH$_3$)N$_3$]$^{2+}$ + OH$^-$ →

1- + **2**-[Co(cyclen)(NH$_3$)OH]$^{2+}$ + N_3^- (10)

strict OH^- catalysis with $k_{OH} = (4.0 \pm 0.1) \times 10^4$ M^{-1} s^{-1} (I = 1.0 M, NaClO$_4$; 25 °C) being the same for both isomers consistent with rapid prior isomerization. At the pH values used, subsequent hydrolysis of coordinated NH$_3$ in the [Co(cyclen)(NH$_3$)OH]$^{2+}$ product is slow. The product was identified as the equilibrium mixture (pH 8.0, 1 min, pH-stat control) by recovering the quenched product by ion exchange chromatography (HCl eluent) and examining the subsequently anated [Co(cyclen)(NH$_3$)Cl]$^{2+}$ complex by reversed-phase HPLC. This gave 75% **1** + 25% **2**. Due to the slowness of the base hydrolysis process, which occurs with prior isomerization in the reactant and rapid isomerization in the NH$_3$/OH product, the stereochemistry of this reaction remains unknown.

Selected properties of the [Co(cyclen)(NH$_3$)X]$^{n+}$ complexes are given in Table 3.

Discussion

Base Hydrolysis. Unquestionably, the single most important factor controlling the reactivity of these [Co(cyclen)(NH$_3$)X]$^{3+/2+}$ complexes (X = OH$_2$, Cl, N$_3$, OH) is the enhanced acidity of the two "flat" meridional *sec*-NH centers. Acid ionization at one center leads to a higher than usual concentration of the conjugate base (e.g., **2**-Cl (CB) in Scheme 1), and this extends the S$_N$1CB process[5,24] ($k_{obs} = k_1k_2[OH^-]/(k_{-1} + k_2)$; $K_a = K_w \cdot k_1/k_{-1}$ in Scheme 1) well into the acid region. In the case studied (D$_2$O solution, X = Cl), the quenched hydrolysis product, as well as the unreacted starting material, showed no exchange of N*H*$_3$ and *ap*-N*H* protons so that such centers cannot be involved in the CB mechanism. Also, spontaneous aquation is very slow and normal by the standards of Co(III) substitution chemistry (viz., **1**-Cl, $k_{aq} = 2 \times 10^{-5}$ s^{-1}; **2**-Cl, $k_{aq} = 3.9 \times 10^{-6}$ s^{-1}). Likewise, uncatalyzed exchange of coordinated H$_2$O in [Co(cyclen)(NH$_3$)^{17}OH$_2$]$^{3+}$ is slow ($k_{ex} < 1 \times 10^{-4}$ s^{-1}), so

(23) Palenik, G. J. *Acta Crystallogr.* **1964**, *17*, 360. Restivo, R. J.; Ferguson, G.; Hay, R. W.; Piplani, D. P. *J. Chem. Soc., Dalton Trans.* **1978**, 1131. Comba, P.; House, D. A.; Jackson, W. G.; Marty, M.; Stoeckli-Evans, H.; Zipper, L. *Helv. Chim. Acta* **1992**, *75*, 1130.

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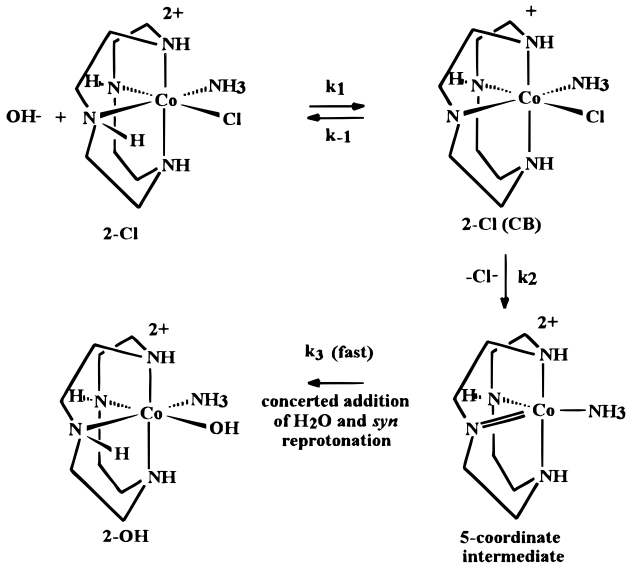
Scheme 1. Suggested Mechanism for Base Hydrolysis of **2**-Cl



that the enhanced reactivity lies solely with the OH^--catalyzed reaction and is not a property of the complex as a whole. Direct measurement of the acidity constant, K_a, was not possible because of the extreme reactivity of these complexes at high OH^- concentrations ($t_{1/2} \approx 2$ μs for **1**-Cl in 1.0 M NaOH). However, for the more stable $[Co(cyclen)(en)]^{3+}$ and $[Co(cyclen)(S\text{-}AlaO)]^{2+}$ systems, rapid spectrophotometric measurement is possible, giving pK_a values of 13.2 and 13.7, respectively (I = 1.0 M, $NaClO_4$).[13] The lower charged $[Co(cyclen)(O_2CO)]^+$ ion also gives immediate and substantial absorbance changes in strong alkali, and the doubly deprotonated $[Co(cyclen\text{-}2H)(O_2CO)(OH)]^{2-}$ species has been suggested as a major contributor to release of CO_3^{2-} under these conditions.[25] The H-exchange rates reported here (and elsewhere[18]) concur with these findings, with the rate for the 3+ ion (X = OH_2) being at, or close to, the diffusion limit ($k_H = 7 \times 10^9$ M^{-1} s^{-1}, I = 0.2 M $NaClO_4$, 25 °C), and only slightly less for the most acidic proton in the 2+ ions ($k_H = (1-2) \times 10^9$ M^{-1} s^{-1} for X = Cl, N_3; $(1.5-6.4) \times 10^9$ M^{-1} s^{-1} for the $[Co(cyclen)(S\text{-}AlaO)]^{2+}$ isomers[18]). Only for the 1+ ions $[Co(cyclen)(O_2CO)]^+$ [25] and $[Co(Mecyclen)(O_2C_2O_2)]^+$,[26] is k_H significantly reduced ($(2-5) \times 10^7$ and 3×10^8 M^{-1} s^{-1}, respectively). We therefore predict K_a values of ca. 6×10^{-14} M for the 3+ ion (X = OH_2) and ca. 2×10^{-14} M for the most acidic proton in the 2+ ions (*trans* to X = Cl, N_3).[27] Such k_H measurements, because they refer to specific sites, also tell us that strain about the meridional NH centers plays a role since the *ap*-NH sites, which bridge facial chelates but which are otherwise identical, are some $10-10^2$ less acidic (cf. X = Cl, Table 1; also for $[Co(cyclen)(S\text{-}AlaO)]^{2+}$ [18]). Clearly, deprotonation of a meridional N*H* center is preferred. However, there is little difference between the labilities (acidities) of *syn*- and *anti*-N*H* protons, i.e., their orientation with respect to X is unimportant. Thus, for X = NH_3, k_H is the same for both (7×10^9 M^{-1} s^{-1}),[26] and a similar situation is found with $[Co(cyclen)(O_2CO)]^+$ (k_H = 2 and 5×10^7 M^{-1} s^{-1})[25] and $Co(Mecyclen)(O_2C_2O_2)]^+$ (k_H = 2.7 and 3.4×10^8 M^{-1} s^{-1}).[26] However, as is found with other Co(III) complexes,[5,24] electronegative X (e.g., Cl^-, N_3^-, RCO_2^-) increases the lability (acidity) of a *trans*-NH center. Thus, for **1**-Cl N*H*-(*syn*(NH_3)) is some 40 times more labile than N*H*-(*anti*(Cl)), $k_H = 2 \times 10^9$ vs 5×10^7 M^{-1} s^{-1}; whereas for **2**-Cl, the difference is even larger, $k_H = 2 \times 10^9$ M^{-1} s^{-1} for N*H*-(*anti*(NH_3)) vs 4×10^6 M^{-1} s^{-1} for N*H*-(*syn*(Cl)). Similar differences are found with the $[Co(cyclen)(S\text{-}AlaO)]^{2+}$ isomers where the donor atom in the *trans* ligand is carboxylate-O.[18] Also, in these unsymmetrical systems, there does seem to be a difference between the *syn* and *anti* protons with the k_H values indicating that it is easier to remove a proton *anti* to electronegative X than one *syn* to it. Overall, these comparisons give a good appreciation of the *trans* electronegative effect on proton acidity since the reference amine is the same in each case, a situation not often realized in Co(III) chemistry.

Is it the meridional N*H* proton *cis* or *trans* to X which leads to the most reactive conjugate base? It is now generally agreed that a *cis*-N*H* proton does lead to enhanced reactivity.[5,24,28,29] This has been proven with α,β-$[Co(trien)(GlyO)Cl]^+$,[30] α,β-$[Co(tetraen)(ONO_2)]^{2+}$,[31] and $[Co(dien)(dapo)Cl]^{2+}$,[32] where more acidic *trans*-NH_2 protons exist, but where inversion about a cis meridional NH center during hydrolysis requires this center to be responsible. It has also been proven with *t*-$[Co(tren)(NH_3)Cl]^{2+}$,[33] *t*-$[Co(trenen)Cl]^{2+}$,[34] *asym*-$[Co(datn)Cl]^{2+}$,[35] and all-*trans*-$[Co(N)_4Cl_2]^+$ systems where no *trans*-NH center exists. The certain reactivity of a *trans*-deprotonated center now seems unlikely, even if it is far more acidic (cf. *s*(*R*)-$[Co(trenen)X]^{2+}$, X = NO_3, Cl, where retention of the *s*(*R*) center is found in the first formed product,[31,36] k_{OH} (X = Cl) = 518 M^{-1} s^{-1},[36] with *s*(*R*)-$[Co(Metrenen)Cl]^{2+}$, $k_{OH} = 1.2 \times 10^4$ M^{-1} s^{-1},[36], where a *cis*-NH_2 proton must be involved). It seems that in the present complexes, a *cis*(X) meridional center is responsible for hydrolysis, even though it does not contain the most acidic N*H* proton.

We believe that the orientation of the *cis*-N*H* proton is most important, with repulsive overlap between the *syn* lone pair of the CB and the filled bonding and nonbonding π-lobes of X assisting in its departure, cf. Scheme 1. An *anti* lone pair cannot do this. It is this lowering in energy of the transition state leading to the 5-coordinate intermediate which controls the reaction rate (k_2) rather than the energy of the 5-coordinate intermediate itself. This aspect does not seem to have received sufficient attention in the past, possibly because a *trans* amine center was believed to be responsible.[37] Experimental verification of *syn*(X) overlap is difficult to prove largely because, while a *cis* lone pair often points in the general direction of X, its exact location (and often designation) remains uncertain due to conformational or rotational flexibility.

However, in **1**- and **2**-Cl the lone pair is constrained to quite rigid *syn* and *anti* orientations, and crystal structures[3,13,14] show

(25) Clark, C. R.; Buckingham, D. A. *Inorg. Chim. Acta* **1997**, *254*, 339.
(26) Rogers, A. J. Ph.D. Thesis, University of Otago, 1995.
(27) At the diffusion controlled limit, k_H does not give a good appreciation of K_a since reprotonation (k_{-1}) is now rate limiting.
(28) Jackson, W. G. *Inorg. Chem.* **1991**, *30*, 4813.
(29) Rotzinger, F. P.; Weber, J.; Daul, C. *Helv. Chim. Acta* **1991**, *74*, 1247.
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(34) k_{OH} = 60 M^{-1} s^{-1} reported by Cresswell, P. J. Ph.D. Thesis, Australian National University, 1974.
(35) Gahan, L. R.; Lawrance, G. A.; Sargeson, A. M. *Aust. J. Chem.* **1982**, *35*, 1119.
(36) Cresswell, P. J. Ph.D. Thesis, Australian National University, 1974.
(37) Pearson, R. G.; Basolo, F. M. *J. Am. Chem. Soc.* **1956**, *78*, 4878. *Mechanisms of Inorganic Reactions*, 2nd ed.; Wiley: New York, 1967.

Table 4. Rate Constants (k_{OH}) for Loss of X in Some [Co(cyclen)(A)X]$^{3+/2+/+}$ Complexes (I = 1.0 M, NaClO$_4$, 25 °C)

A	X	k_{OH}/M^{-1} s^{-1}
NH_3	NH_3	2×10^4 [a]
	N_3	4×10^4
	Cl(*syn*(NH_3),*anti*(Cl)	3×10^5
	Cl(*syn*(Cl),*anti*(NH_3)	4×10^6
	OH_2	4.5×10^8
	OH	4×10^4 [b]
OH_2	OH_2	1.1×10^9 [c]
Cl	Cl	2×10^7 [d]
OH	NH_3	1.0[a]

[a] Buckingham, D. A.; Clark, C. R.; Rogers, A. J., to be published. [b] Assuming k'_I (cf. text) corresponds to base hydrolysis of X = OH. [c] Compare ref 13. [d] Compare ref 4.

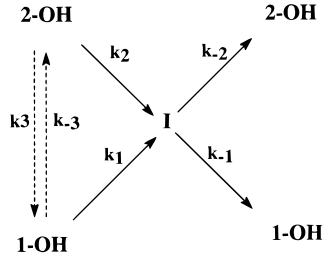
that the N−H bonds are aligned almost exactly antiparallel and parallel, respectively, to the Co−X axis. The conjugate base formed from **2**-Cl is particularly reactive, with loss of Cl$^-$ being similar in rate to reprotonation, $k_2 \approx k_{-1}$ (Scheme 1; general base catalysis was not investigated). A similar situation is possible with [Co(dien)(dapo)Cl]$^{2+}$,[32] where the conjugate base formed from the *mer*(*syn*) isomer is some 10 times more reactive than that from the *mer*(*anti*) isomer when k_H rate data are taken into account. For the slower reacting **1**-Cl isomer, while no **2**-Cl was found during hydrolysis (this would have required two inversions), it is possible that the observed rate constant corresponds to prior inversion in the 6-coordinate system to give the unstable (and never detected) *syn*(NH_3),*syn*(Cl)-isomer (**3**-Cl) which subsequently rapidly hydrolyses via its associated *syn*-N*H* proton. The observed hydrolysis rate constant of 3×10^5 M^{-1} s^{-1} is very similar to that found for isomerization **1** → **2** in [Co(cyclen)(NH_3)N_3]$^{2+}$ (k_I(**1**) = 1.5×10^5 M^{-1} s^{-1}), a process which certainly occurs in the 6-coordinate system (vide infra). It is hard to imagine that isomerization in **1**-Cl is not at least competitive with direct hydrolysis.

The immediate product on hydrolyzing both **1**- and **2**-Cl is indistinguishable from **2**-OH; certainly little **1**-OH is formed (<10%). For **2**-Cl this is easily accounted for (cf. Scheme 1) with *syn*(Cl) deprotonation leading to a 5-coordinate intermediate which adds H_2O and reprotonates on the same face in a concerted manner ($k_3 \gg k_2$, k_{-1}). For **1**-Cl, hydrolysis could occur via **3**-Cl with *syn*(Cl) deprotonation and loss of Cl$^-$ producing the 5-coordinate intermediate. This, then, could either add H_2O on the same face to give **3**-OH (preferred mechanism) or add H_2O and separately reprotonate at an opposite face to give **2**-OH directly. We will see below that **3**-OH is likely to be very unstable, and that it is more likely to isomerize largely to **2**-OH rather than to **1**-OH, although **1**-OH is (finally) the thermodynamically favored product; K_{OH}([**1**]/[**2**]) = 3.0. Alternatively **3**-OH might be indistinguishable from **2**-OH (vis−UV spectrum) and may indeed have been the immediately observed product from **1**-Cl.

A summary of k_{OH} values is given in Table 4, but in the absence of known K_a values for formation of the reactive conjugate base (*cis*(Cl)), first-order rate constants for loss of X cannot be evaluated. However, NH_3 appears to be only a slightly poorer leaving group than N_3^- but is stabilized in the [Co(cyclen)(NH_3)OH]$^{2+}$ ion, possibly because OH$^-$ is the preferred leaving group in this case, and the fully deprotonated conjugate base is never fully realized. Complexes with X = N_3, OH have similar k_{OH} values, but the very large value for X = OH_2 has an alternative explanation as we will see below.

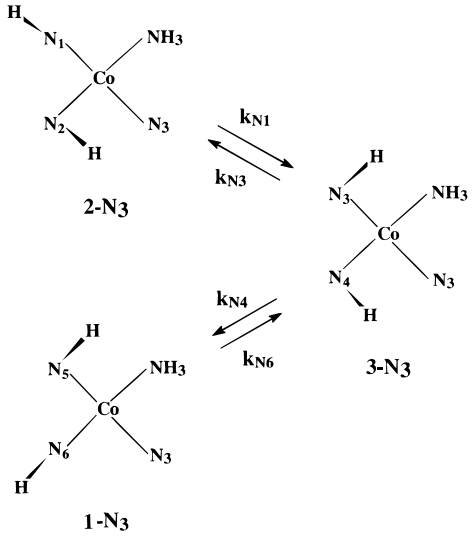
Isomerization and H_2O Exchange in the X = OH_2/OH Ions. As was pointed out in the results section, the rate data for these reactions may be interpreted in two ways: either as the OH$^-$ catalyzed reaction of the X = OH_2 complex or as an acid-independent (i.e., spontaneous) reaction of the X = OH complex. The former gives very large rate constants, k_{OH} = 4.5×10^8 M^{-1} s^{-1}, k_I = 1.4×10^8 M^{-1} s^{-1}, and these seem just too large when compared to rate constants for similar processes in other Co(III)-cyclen complexes (cf. Table 4 for k_{OH}, k_I(**1** ⇌ **2**) = 2.9×10^5 M^{-1} s^{-1} for X = N_3 and k_I(**1** ⇌ **2**) = 1.8×10^5 M^{-1} s^{-1} for [Co(cyclen)(S-AlaO)]$^{2+}$ [18]). We therefore support the alternative interpretation, whereby concerted deprotonation of N*H* and protonation of X = OH in the transition state avoids the higher energy intermediates implied by the OH$^-$-catalyzed dissociation of H_2O and by the unassisted dissociation of the poor OH$^-$ leaving group. This mechanism would seem to be restricted to cases where poor leaving groups would prefer to leave the Co(III) center as their conjugate acids, and X = OH provides possibly the best example of this. Furthermore, its concerted nature would seem to require utilization of a *syn*-N*H* proton. This aspect has not received attention previously[31,38−40] but appears to be a stereochemical requirement. Indeed, in retrospect, we now believe that it was only the *syn*(OH),*anti*(NH_3)-[Co(cyclen)(NH_3)^{17}O-H]$^{2+}$ isomer which underwent exchange in these experiments. This is suggested from our observations that less than the stoichiometric amount of $^{17}OH_2$ label was released during exchange (only ca. one-half that expected) and that a good time-independent infinity was never reached. If, as this implies, k_{ex}(**2**-OH) ≫ k_{ex}(**1**-OH), then microscopic reversibility would require the resulting 5-coordinate intermediate to re-form largely **2**-OH on water re-entry, and this is in excellent agreement with that observed on base hydrolyzing both the **1**-Cl and **2**-Cl isomers (vide supra). We therefore picture both H_2O exchange and isomerization as occurring via the same 5-coordinate intermediate (**I** in Scheme 2) with $k_2 > k_1$. The re-entry step need not be exclusive, however, with several acts of water exchange eventually leading to equilibration with **1**-OH. In this scheme, $k_2 = k_{ex}$ (=8 s^{-1}), $k_1 = k_I$(**1**) (=0.63 s^{-1}), $k_2k_{-1}/k_{-2} = k_I$(**2**) (=1.9 s^{-1}), and $k_2k_{-1}/k_1k_{-2} = K_{OH}$ (=3.0), giving k_2/k_1 = 13 and $k_{-2}/k_{-1} = 4$. Thus, loss of OH$^-$ is indeed much faster in the *syn*(OH)-isomer, and the 5-coordinate intermediate does prefer to reprotonate on this same face. Under more alkaline conditions, an OH$^-$-dependent pathway for isomerization in the X = OH ions was found (k'_I = 4×10^4 M^{-1} s^{-1}), and this could represent either rate-determining S_N1CB-catalyzed loss of OH$^-$ to form the 5-coordinate intermediate or direct OH$^-$-catalyzed isomerization in the 6-coordinate system ($k'_I = k_3 + k_{-3}$; Scheme 2).

Scheme 2. Common Mechanism for H_2O Exchange (k_{ex}) and Isomerization (k_I) in the [Co(cyclen)(NH_3)OH]$^{2+}$ Isomers



(38) Ahmed, E.; Chatterjee, C.; Cooksey, C. J.; Tobe, M. L.; Williams, G. *J. Chem. Soc., Dalton Trans.* **1989**, 645.
(39) Kruse, W.; Tobe, M. L. *J. Am. Chem. Soc.* **1961**, *83*, 1280. Poon, C. K.; Tobe, M. L. *Inorg. Chem.* **1968**, *7*, 2398; **1971**, *10*, 225.
(40) Jackson, W. G.; Sargeson, A. M. In *Rearrangements in Ground and Excited States*; de Mayo, P., Ed., Academic Press: NY, 1980; p 273.

Scheme 3. Diagramatic Representation for Isomerization between **1**-N_3 and **2**-N_3 Isomers via (Unobserved) **3**-N_3



Anation by N_3^-. The above analysis fits in nicely with the rate data for N_3^- anation (Figure 3). This shows **2**-OH to be more reactive than **1**-OH, with the anation rate for the latter being largely [N_3^-] independent, consistent with loss of OH^- being rate determining for this species and with the resulting 5-coordinate intermediate forming **2**−OH in preference to azido products. Such a process should not display first-order kinetics, but good first-order fits were obtained. Clearly, some immediate entry of N_3^- into the first formed intermediate (**I** in Scheme 2) occurs. On the other hand, anation of **2**-OH is seen to agree with the H_2O exchange rate at high [N_3^-] ($k_{N_3} = k_2 = 8 \pm 2$ s^{-1}), suggesting exclusive entry of N_3^- under this condition. Unlike entry of H_2O, however, entry of N_3^- gives the **1**- and **2**-isomers in similar amounts, $k_2(N_3)/k_1(N_3) = 1.5$, suggesting a separate, subsequent, reprotonation step in this case.

Isomerization in the X = N_3^- System. This reaction takes place in the 6-coordinate system. Since two inversions must occur and since the process is demonstrably first-order in OH^- ($k_I = 2.9 \times 10^5$ M^{-1} s^{-1}), a *syn*,*syn* or *anti*,*anti* intermediate must be involved, with either its formation or decay being rate determining. In the [Co(cyclen)(S-AlaO)]$^{2+}$ system, isomerization ($k_I = 1.8 \times 10^5$ M^{-1} s^{-1}) via a *syn*,*syn* intermediate was proven,[18] and the similarity in rate constants and the anticipated higher energy of an *anti*,*anti* isomer make it likely that the *syn*,*syn* isomer is also involved here. Scheme 3 sets out the details with $k_I = k_{N1}k_{N4}/(k_{N1} + k_{N3}) + k_{N6} = 2.9 \times 10^5$ M^{-1} s^{-1} and $K_{eq} = k_{N1}k_{N4}/k_{N3}k_{N6} = 0.92$. However, in the absence of known properties for **3**-N_3, further analysis is not possible. If the system follows [Co(cyclen)(S-AlaO)]$^{2+}$, then the similar amounts of **1**- and **2**-N_3 found in the equilibrium mixture result from differences in both N−H acidity and inversion barriers, **1** ↔ **3** ↔ **2**.

Supporting Information Available: Experimental information detailing the synthesis of [Co(cyclen)Cl_2]Cl from cyclen·4HCl; the syntheses of *syn*(NH_3),*anti*(Cl)-[Co(cyclen)(NH_3)Cl](ClO_4)$_2$ and *syn*(Cl),*anti*(NH_3)-[Co(cyclen)(NH_3)Cl](ClO_4)$_2$·H_2O, *syn*(NH_3),*anti*-(OH_2)- and *syn*(OH_2),*anti*(NH_3)-[Co(cyclen)(NH_3)OH_2](ClO_4)$_2NO_3$, *syn*(NH_3),*anti*(N_3)- and *syn*(N_3),*anti*(NH_3)-[Co(cyclen)(NH_3)N_3](ClO_4)$_2$; the determination of equilibrium isomer ratios ([**1**]/[**2**]) for the [Co(cyclen)(NH_3)X]$^{2+/3+}$ complexes (X = Cl, N_3, OH, OH_2) in aqueous solution; the preparation of ^{17}O-labeled [Co(cyclen)(NH_3)OH_2](ClO_4)$_3$ (isomeric mixture); the estimation of the pK_a of [Co(cyclen)(NH_3)-OH_2](ClO_4)$_3$ (isomeric mixture); the determination of the immediate product distribution on base hydrolysis of [Co(cyclen)(NH_3)Cl](ClO_4)$_2$ (isomers **1** and **2**); descriptions of reversed phase HPLC methods, NMR and visible spectral measurements, and crystallographic measurements on *syn*(NH_3),*anti*(N_3)-[Co(cyclen)(NH_3)N_3]$Cl_{0.5}$(ClO_4)$_{1.5}$·H_2O; details of pH and pD measurements with calculations of [OH^-] and [OD^-]; Tables S1−S3 giving, respectively, rate constants for isomerization in *syn*(OH_2),*anti*(NH_3)-[Co(cyclen)(NH_3)OH_2/OH]$^{3+/2+}$, ^{17}O exchange in [Co(cyclen)(NH_3)$^{17}OH_2$]$^{3+}$, and anation by N_3^- of *syn*(NH_3),*anti*(OH)- and *syn*(OH),*anti*(NH_3)-[Co(cyclen)(NH_3)OH]$^{2+}$; Tables S4−S8 giving for [Co(cyclen)(NH_3)N_3]$Cl_{0.5}$(ClO_4)$_{1.5}$·H_2O: crystallographic data, bond lengths, and angles, atomic coordinates and equivalent isotropic displacement parameters, anisotropic displacement parameters, and hydrogen coordinates and isotropic displacement parameters, respectively; Tables S9 and S10 giving rate data for isomerization in *syn*(NH_3),*anti*(N_3)- and *syn*(N_3),*anti*(NH_3)-[Co(cyclen)(NH_3)N_3]$^{2+}$ and OH^--catalyzed hydrolysis of *syn*(NH_3),*anti*(N_3)- and *syn*(N_3),*anti*(NH_3)-[Co(cyclen)(NH_3)N_3]$^{2+}$, respectively; Figures S1−S3, giving respectively N*H* regions of the ^1H NMR spectra of *syn*(NH_3),*anti*(Cl)-[Co(cyclen)(NH_3)Cl]$^{2+}$ in 0.1 M DCl, *syn*(Cl),*anti*(NH_3)-[Co(cyclen)-(NH_3)Cl]$^{2+}$ recorded in d_6-DMSO solution (containing DCl) following isolation after various times at pD 4.3 (D_2O solution), and *syn*(NH_3),*anti*(OH_2)- and *syn*(OH_2),*anti*(NH_3)-[Co(cyclen)(NH_3)OH_2]$^{3+}$ in d_6-DMSO (containing 8 μL of concentrated HCl); Figures S4 and S5 giving respectively a structural diagram of the *syn*(NH_3),*anti*(N_3)-[Co(cyclen)(NH_3)N_3]$^{2+}$ cation and view of the unit cell contents for *syn*(NH_3),*anti*(N_3)-[Co(cyclen)(NH_3)N_3]$Cl_{0.5}$(ClO_4)$_{1.5}$·H_2O (30 pages). Ordering information is given on any current masthead page.

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