

Synthesis and structure of cyclen hydroxylamine ligands and their zinc(II) complexes

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The synthesis of two new zinc(II) complexes with 1,4,7,10-tetraazacyclododecan-1-ol and 1,4,7,10-tetraazacyclododecan-1,7-diol as ligands is described. One of these complexes is characterized by X-ray structure analysis. By coordination to the metal cation the acidity of the hydroxylamine groups of the ligands is significantly increased as confirmed by potentiometric pH titrations.

Introduction

Metal complexes with substituted 1,4,7,10-tetraazacyclododecane (cyclen) derivatives as ligands are widely used in molecular recognition and catalysis.¹ Kimura *et al.*^{2,3} and others have investigated the coordination of imides and phosphates to Zn(II)-cyclen complexes in great detail. Hereby a deprotonated imide moiety or phosphate anion binds reversibly to the Lewis-acidic metal center in Zn(II)-cyclen. This binding motif, like other reversible metal–ligand interactions, offers some advantages over weaker non-covalent interactions such as hydrogen bonds, salt bridges or hydrophobic interactions. It provides sufficient binding strength to allow formation of reversible aggregates in water under physiological conditions and at high dilution. Moreover, the interaction is kinetically labile which is important for applications in catalysis.

Hydroxylamine complexes of transition metals⁴ show some interesting aspects regarding the acidity of the ligand. By coordination of the hydroxylamine nitrogen atom to a metal cation the pK_a value of the hydroxy group is changed markedly. While hydroxylamine itself is almost not acidic ($pK_a = 13.7^5$), the acidity increases significantly by coordination to transition metals as outlined in Scheme 1.

The intention of our work presented here is to combine the known excellent binding properties of Lewis-acidic Zn(II)-cyclen with the interesting features of hydroxylamine ligands.

Results and discussion

Design and synthesis

In their synthesis of macrobicyclic Co(III) hydroxylamine complexes Sargeson coworkers⁶ reacted the Co(III) azamacrobicyclic complex with H_2O_2 to obtain a mixture of complexes with one to three hydroxylamine ligands. These complexes were difficult to separate and purify. Therefore we chose a different synthetic strategy starting with the selective preparation of the free ligand followed by complexation with the metal.

The synthesis starts with the selective protection of cyclen as 1,4,7-tris-*tert*-butoxycarbonyl-1,4,7,10-tetraazacyclododecane **1**⁷ and 1,7-bis(benzyloxycarbonyl)-1,4,7,10-tetraazacyclododecane **4** (Scheme 2).⁸ These protected azamacrocycles were then reacted with dimethyldioxirane^{9,10} to obtain the corresponding hydroxylamines. The carbamates were cleaved with

Table 1 Selected bond distances (Å) and angles (°) for complex **3**

Br(1)–Zn(1)	2.3501(5)	Br(1)–Zn(1)–N(1)	108.73(7)
Zn(1)–N(1)	2.192(2)	Br(1)–Zn(1)–N(2)	115.50(8)
Zn(1)–N(2)	2.148(3)	Br(1)–Zn(1)–N(3)	115.76(7)
Zn(1)–N(3)	2.122(3)	Br(1)–Zn(1)–N(4)	110.12(8)
Zn(1)–N(4)	2.127(3)	Zn(1)–N(1)–O(1)	115.50(17)
O(1)–N(1)	1.447(4)	O(1)–N(1)–C(1)	107.2(2)
		O(1)–N(1)–C(8)	106.8(2)

hydrobromic acid and after elution over a basic anion exchange column the zinc(II) complexes were synthesized by reaction with $Zn(ClO_4)_2 \cdot 6H_2O$.

X-Ray structure of **3**

Colourless crystals of complex **3** suitable for X-ray diffraction were obtained by slow evaporation of a methanolic solution of **3**. The structure of **3** in the crystal is shown in Fig. 1 and selected bond distances and angles are listed in Table 1.

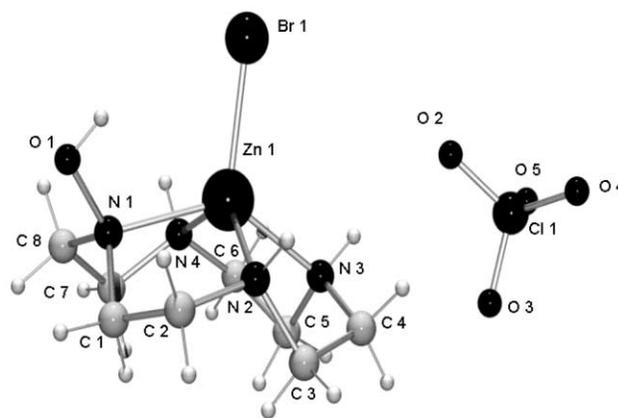
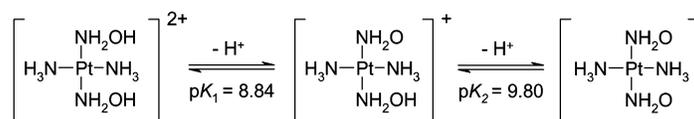


Fig. 1 Structure of complex **3** and the perchlorate counter ion in the crystal.

In complex **3** the water molecule which is usually coordinated to the axial position in aqueous solution is replaced by a bromide anion. The unit cell contains a perchlorate anion as the counter anion. The geometry of the complex is more distorted if compared to Zn(II)-cyclen² which is illustrated by the somewhat longer bond length of Zn(1)–N(1).

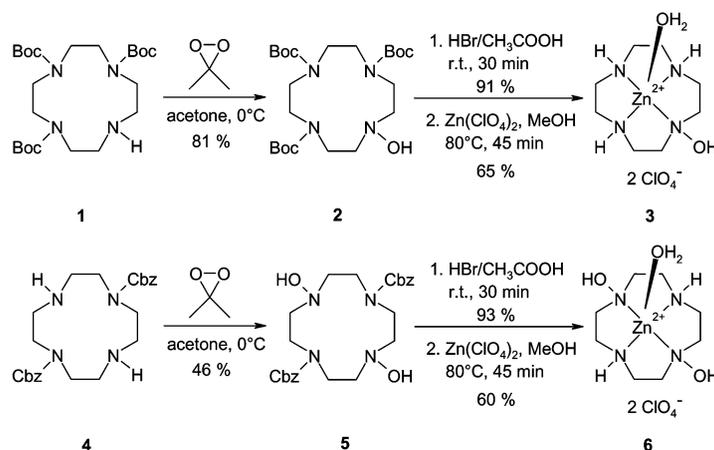


Scheme 1 pK_a values of the hydroxylamine ligands in $\text{trans}[\text{Pt}(\text{NH}_3)_2(\text{NH}_2\text{OH})_2]^{2+}$.

Table 2 Stability constants of ligands L7H₄, L8H₄ and cyclen

The following equilibria were considered for L7H ₄ :	The following equilibria were considered for L8H ₄ :	The following equilibria for cyclen are given for comparison:
$\beta_2^1: L7H_3 + H^+ = L7H_4$ $\beta_2^2: L7H_2 + H^+ = L7H_3$ $\beta_2^3: L7H + H^+ = L7H_2$ $K_2^1: Zn(ClO_4)_2 + L7H = L7H-Zn(OH_2)(ClO_4)_2$ $\beta_2^4: L7H-Zn(OH)(ClO_4^-)_2 + H^+ = L7H-Zn(OH_2)(ClO_4^-)_2$ $\beta_2^5: L7-Zn(OH)(ClO_4^-) + H^+ = L7H-Zn(OH)(ClO_4^-)$	$\beta_2^6: L8H_3 + H^+ = L8H_4$ $\beta_2^7: L8H_2 + H^+ = L8H_3$ $K_2^2: Zn(ClO_4)_2 + L8H_2 = L8H_2-Zn(OH_2)(ClO_4)_2$ $\beta_2^8: L8H-Zn(OH_2)(ClO_4^-)_2 + H^+ = L8H_2-Zn(OH_2)(ClO_4^-)_2$ $\beta_2^9: L8-Zn(OH_2)ClO_4^- + H^+ = L8H-Zn(OH_2)ClO_4^-$	$\beta_2^{10}: cyclen-H_3 + H^+ = cyclen-H_4$ $\beta_2^{11}: cyclen-H_2 + H^+ = cyclen-H_3$ $\beta_2^{12}: cyclen-H + H^+ = cyclen-H_2$ $\beta_2^{13}: cyclen + H^+ = cyclen-H$ $K_2^3: Zn(ClO_4)_2 + cyclen = cyclen-Zn(OH_2)(ClO_4)_2$ $\beta_2^{14}: cyclen-Zn(OH)(ClO_4^-)_2 + H^+ = cyclen-Zn(OH_2)(ClO_4^-)_2$
L7H ₄ ^a	L8H ₄ ^a	Cyclen ^b
—	—	log $\beta_2^{10} < 2$
log $\beta_2^1 = 8.5 (\pm 0.05)^c$	log $\beta_2^6 = 2.4 (\pm 0.04)$	log $\beta_2^{11} < 2$
log $\beta_2^2 = 10.2 (\pm 0.03)$	log $\beta_2^7 = 8.9 (\pm 0.02)$	log $\beta_2^{12} = 9.9^a$
log $\beta_2^3 = 11.6 (\pm 0.02)$	—	log $\beta_2^{13} = 11.0^a$
log $K_2^1 = 14.4 (\pm 0.02)$	log $K_2^2 = 6.0 (\pm 0.1)$	log $K_2^3 = 15.3^a$
log $\beta_2^4 = 8.0 (\pm 0.04)$	log $\beta_2^8 = 7.8 (\pm 0.04)$	log $\beta_2^{14} = 7.9^{16}$
log $\beta_2^5 = 8.4 (\pm 0.01)$	log $\beta_2^9 = 11.4 (\pm 0.04)$	—

^a All data were measured at $I = 0.1 \text{ mol L}^{-1}$ (tetraethylammonium perchlorate) and $25 \pm 0.5^\circ \text{C}$. ^b Data were measured at $I = 0.1 \text{ mol L}^{-1}$ (NaClO₄) and 25°C . ^c Standard deviation.

**Scheme 2** Synthesis of the complexes **3** and **6**.

Potentiometric studies

The properties of complexes **3** and **6** and of the free ligands were studied by potentiometric pH titration in aqueous solution. All considered equilibria and the derived stability constants are summarised in Table 2. The data for the parent compound cyclen are added for comparison.

Three equilibrium constants ($\log \beta_2^1$, $\log \beta_2^2$, $\log \beta_2^3$) were derived from the pH profile for ligand L7H₄ (see Table 2 and Scheme 3). The values at 10.2 and 11.6 most likely correspond to the protonation of secondary amines of the azamacrocycle. Deprotonation of **2** with hydrobromic acid to give L7H₄ should protonate the nitrogen of hydroxylamine, too, if its basicity remains similar to reported values of *N,N*-diethylhydroxylamine ($pK_a = 5.6$ in H₂O at 30°C and $I \approx 0.02 \text{ mol L}^{-1}$)¹¹ or *N,N*-dimethylhydroxylamine ($pK_a = 5.3$ in H₂O at 25°C and $I = 0.06 \text{ mol L}^{-1}$).¹² However, we could not determine a constant corresponding to this value. Incorporation of the hydroxylamine into the azamacrocycle therefore changes its nitrogen basicity significantly.¹³ Deprotonation of the hydroxylamine OH-group can be excluded because the elemental analysis of L7H₄ requires the trihydrobromide salt and only three equilibrium constants were observed in the titration. Moreover, comparison with literature data of *N,N*-diethylhydroxylamine

($pK_a = 12.88$ in H₂O at 25°C)¹⁴ also does not support a deprotonation of the hydroxy group.

With a $\log K_2^1$ of 14.4 the zinc(II) cation is nearly as strongly bound in the azamacrocycle as in Zn(II)-cyclen ($\log K_2^3 = 15.3$ in H₂O at 25°C and $I = 0.1 \text{ mol L}^{-1}$).¹⁵

In the titration of complex **3** [L7H-Zn(OH₂)] two equilibria were observed (see Table 2 and Scheme 4). These values differ only slightly making an exact discrimination impossible. So the assignment in Scheme 4 is arbitrary. The Lewis acidity of the metal center is preserved and it is in the range of the value measured for Zn(II)-cyclen ($\log \beta_2^{14} = 7.9$ in H₂O at 25°C and $I = 0.1 \text{ mol L}^{-1}$).¹⁶ In addition, the acidity of the hydroxylamine is, as expected, significantly enhanced by the coordination to the zinc(II) cation. The species distribution plot calculated from the potentiometric pH titration is shown in Fig. 2.

The two equilibrium constants ($\log \beta_2^6$, $\log \beta_2^7$) observed in the titration of ligand L8H₄ were assigned to the protonation of the secondary amines (see Table 2 and Scheme 5). The zinc(II) cation is bound in a significantly weaker fashion by ligand L8H₂ ($\log K_2^2 = 6.0$) if compared with L7H.

The titration of complex **6** [L8H₂-Zn(OH₂)] reveals two acidic protons (Table 2). We assign the two equilibria to the subsequent deprotonation of the hydroxylamine hydroxy groups (see Table 2 and Scheme 6).¹⁷ The first $\log \beta_2^8$ of 7.8 is in

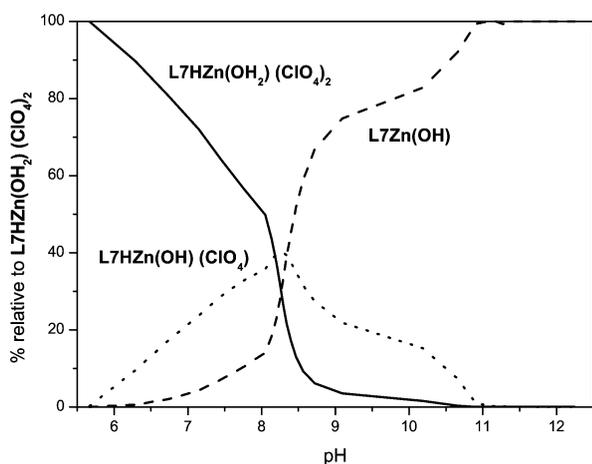
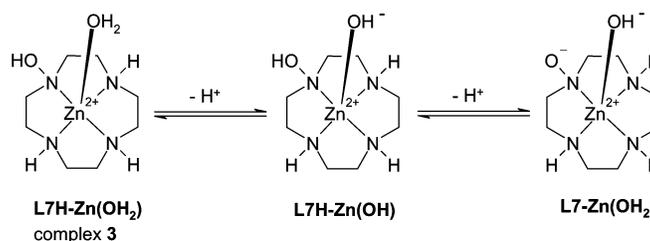
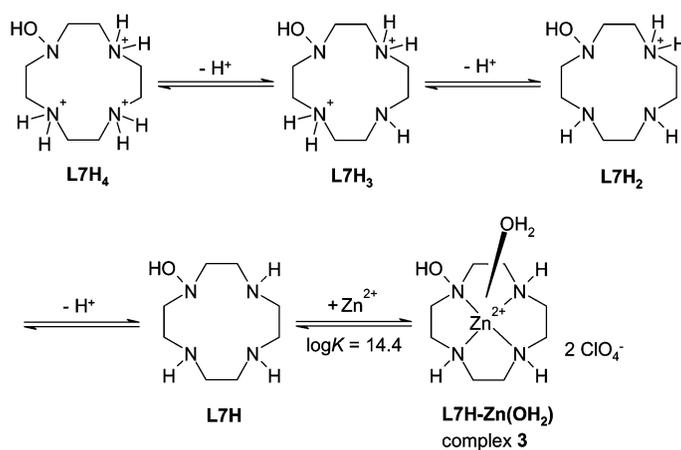
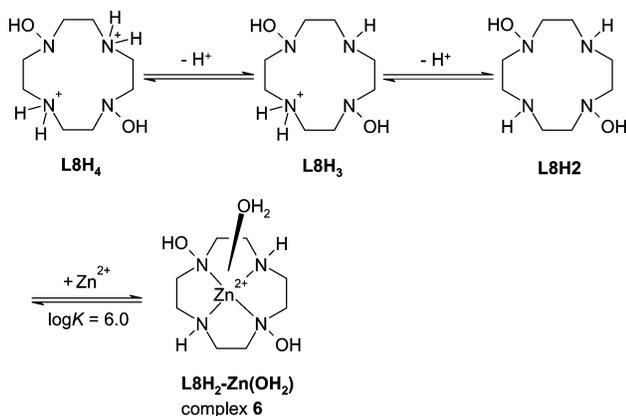
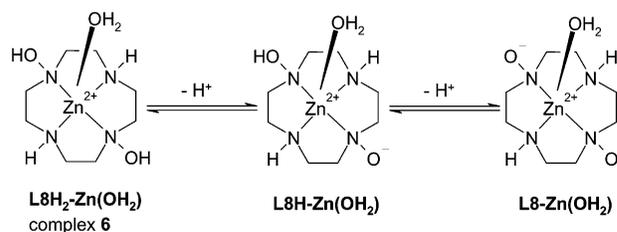


Fig. 2 Species distribution plot of complex 3. Stoichiometry of equilibria: $L7H-Zn(OH)(ClO_4)_2 + 2H^+ = L7H-Zn(OH)(ClO_4)_2 + H^+ = L7H-Zn(OH_2)(ClO_4)_2$.



Scheme 5 Protonation and zinc(II) ion coordination of ligand L8H₄.



Scheme 6 Protonation equilibria of complex L8H₂-Zn(OH₂) (complex 6).

the range of the value measured for the hydroxylamine in complex 3, while the second hydroxylamine is significantly less acidic (for comparison see Scheme 1).

Conclusion

We have prepared two new cyclen ligands bearing hydroxylamino moieties. The ligands are able to bind zinc(II) ions tightly. Moreover, by coordination of the metal cation the acidity of the hydroxylamines is increased markedly. Hence these complexes may find use as interesting binding sites for molecular recognition.

Experimental

General

Compounds **1**⁷ and **4**⁸ as well as dimethyldioxirane¹⁸ were prepared by known methods. Melting points were taken on a hot-plate microscope apparatus and are not corrected. UV/VIS spectra: Varian Cary 50 Bio. IR spectra: Bio-Rad FTS 3000 FT-IR. ¹H- and ¹³C-NMR spectra: Bruker AM 400 or Bruker AC 250; chemical shifts relative to SiMe₄; s = singlet, m = multiplet; the multiplicity of the ¹³C signals was determined using the DEPT technique and quoted as (+) for CH₃ or CH, (−) for CH₂, and (C_{quart}) for quaternary carbons.

10-Hydroxy-1,4,7,10-tetraazacyclododecane-1,4,7-tricarboxylic acid tri-*tert*-butyl ester (2)

1,4,7-Tris-*tert*-butoxycarbonyl-1,4,7,10-tetraazacyclododecane **1** (0.50 g, 1.06 mmol) was dissolved in 5 mL of degassed acetone. Under cooling in an ice-bath 16 mL of dimethyldioxirane in acetone (*ca.* 0.1 M) were added slowly. The reaction mixture was then stirred for 4 h at room temperature. The solvent was evaporated and the crude product was purified by column chromatography on silica (eluent: ethyl acetate, $R_f = 0.6$). The hydroxylamine **2** (0.42 g, 0.86 mmol, 81%) was obtained as a white solid. M.p. 84 °C. IR (KBr, cm^{-1}): $\nu = 775, 1174, 1249, 1366, 1420, 1466, 1694, 2933, 2977, 3428$. $^1\text{H NMR}$ (250 MHz, CDCl_3): δ 1.45 (s, 18 H, CH_3), 1.47 (s, 9 H, CH_3), 2.91 (bs, 4 H, CH_2), 3.31–3.95 (m, 12 H, CH_2), 5.85 (bs, 1 H, OH). $^{13}\text{C NMR}$ (62 MHz, CDCl_3): δ 28.47 (+), 28.69 (+), 45.27 (–), 46.14 (–), 47.81 (–), 48.15 (–), 49.57 (–), 50.14 (–), 59.07 (–), 59.69 (–), 79.41 (C_{quart}), 79.81 (C_{quart}), 79.94 (C_{quart}), 155.36 (C_{quart}), 156.07 (C_{quart}), 156.41 (C_{quart}). MS (ESI, $\text{MeOH}/\text{CH}_2\text{Cl}_2 + 1\% \text{ AcOH}$): m/z (%) = 489 (100) [MH^+]. Anal. calc. for $\text{C}_{23}\text{H}_{44}\text{N}_4\text{O}_7$: C, 56.54; H, 9.08; N, 11.47. Found: C, 56.40; H, 9.33; N, 11.12%.

1,4,7,10-Tetraazacyclododecan-1-ol tri-hydrobromide

Compound **2** (0.30 g, 0.62 mmol) was mixed with 2.0 mL of HBr in glacial acetic acid (33%, 4.1 M) and stirred for 30 min at room temperature. Then 5 mL of diethyl ether were added to the suspension. The precipitate was collected by suction filtration and washed with diethyl ether. The hydrobromide (0.24 g, 0.56 mmol, 91%) was obtained as a colourless powder. Decomp. at 210 °C. IR (KBr, cm^{-1}): $\nu = 1635, 2760, 2926, 3422$. $^1\text{H NMR}$ (250 MHz, D_2O): δ 2.84–3.52 (m, CH_2). $^{13}\text{C NMR}$ (100 MHz, D_2O): δ 42.61 (–), 43.39 (–), 44.04 (–), 54.39 (–). MS (ESI, H_2O): m/z (%) = 189 (100) [MH^+]. Anal. calc. for $\text{C}_8\text{H}_{23}\text{Br}_3\text{N}_4\text{O} \cdot 0.5\text{CH}_3\text{COOH}$: C, 23.45; H, 5.47; N, 12.15. Found: C, 23.03; H, 5.46; N, 12.53%.

1,4,7,10-Tetraazacyclododecan-1-ol-zinc(II) di-perchlorate (3)

The above hydrobromide (0.22 g, 0.51 mmol) was dissolved in 2 mL of H_2O and eluted over a basic anion exchange column. The solution was evaporated to dryness and the solid residue was dissolved in 2 mL of methanol. Then a solution of $\text{Zn}(\text{ClO}_4)_2 \cdot 6\text{H}_2\text{O}$ (0.28 g, 0.75 mmol) in 2 mL of methanol was added and the mixture was heated at 80 °C for 45 min. After removal of most of the solvent, the reaction mixture was cooled in an ice-bath and the precipitate was collected by suction filtration. Complex **3** (0.15 g, 0.33 mmol, 65%) was isolated as a white solid. Decomp. at 235 °C. IR (KBr, cm^{-1}): $\nu = 628, 1089, 1459, 2933, 3163, 3254, 3410$. $^1\text{H NMR}$ (250 MHz, CD_3CN): δ 2.60–2.79 (m, 4 H, CH_2), 2.84–3.20 (m, 12 H, CH_2), 3.36 (bs, 3 H, NH), 6.73 (bs, 1 H, OH). $^{13}\text{C NMR}$ (62 MHz, CD_3CN): δ 43.77 (–), 44.97 (–), 45.15 (–), 56.23 (–). MS (ESI, $\text{H}_2\text{O} + 1\% \text{ AcOH}$): m/z (%) = 311 (100) [$(3^{2+} + \text{CH}_3\text{COO}^-)^+$], 351 (35) [$(3^{2+} + \text{ClO}_4^-)^+$]. Anal. calc. for $\text{C}_8\text{H}_{20}\text{Cl}_2\text{N}_4\text{O}_9\text{Zn} \cdot 0.5\text{CD}_3\text{CN}$: C, 22.78; H, 4.88; N, 13.28. Found: C, 22.92; H, 4.98; N, 13.18%.

4,10-Dihydroxy-1,4,7,10-tetraazacyclododecane-1,7-dicarboxylic acid dibenzyl ester (5)

1,7-Bis(benzyloxycarbonyl)-1,4,7,10-tetraazacyclododecane **4** (0.70 g, 1.60 mmol) was dissolved in 10 mL of degassed acetone. Under cooling in an ice-bath 41 mL of dimethyldioxirane in acetone (*ca.* 0.1 M) were added. The reaction mixture was then stirred for 30 min in the ice-bath and for a further 40 min at room temperature. The solvent was evaporated and the crude product was purified by column chromatography on silica (eluent: CH_2Cl_2 – $\text{MeOH} = 10:1$, $R_f = 0.8$). The hydroxylamine **5** (0.34 g, 0.73 mmol, 46%) was isolated as a white solid. M.p. 54 °C. IR (KBr, cm^{-1}): $\nu = 772, 1020, 1167, 1260, 1361, 1412, 1479,$

1699, 2948, 3494, 3540. UV/VIS (CH_3CN): λ_{max} ($\log \epsilon$) = 206 nm (4.297). $^1\text{H NMR}$ (400 MHz, CDCl_3): δ 2.86–4.14 (m, 16 H, CH_2), 5.22 (m, 2 H, CH_2), 5.27 (m, 2 H, CH_2), 7.35 (m, 10 H, CH). $^{13}\text{C NMR}$ (100 MHz, CDCl_3): δ 47.93 (–), 48.70 (–), 48.92 (–), 49.76 (–), 60.48 (–), 61.24 (–), 61.39 (–), 67.67 (–), 67.74 (–), 127.78 (+), 127.90 (+), 127.94 (+), 128.14 (+), 128.34 (+), 128.40 (+), 128.65 (+), 128.69 (+), 128.71 (+), 128.76 (+), 156.37 (C_{quart}), 156.47 (C_{quart}), 175.26 (2 C, C_{quart}). MS (ESI, $\text{MeOH}/\text{CH}_2\text{Cl}_2 + 1\% \text{ AcOH}$): m/z (%) = 473 (100) [MH^+], 495 (2) [MNa^+]; HRMS ($\text{C}_{24}\text{H}_{33}\text{N}_4\text{O}_6^+$): calc. 473.2400, found. 473.2391 \pm 0.0006. Anal. calc. for $\text{C}_{24}\text{H}_{32}\text{N}_4\text{O}_6 \cdot 2\text{H}_2\text{O}$: C, 56.68; H, 7.13; N, 11.02. Found: C, 56.83; H, 7.13; N, 11.02%.

1,4,7,10-Tetraazacyclododecane-1,7-diol di-hydrobromide

Compound **5** (0.28 g, 0.60 mmol) was mixed with 3.0 mL of HBr in glacial acetic acid (33%, 4.1 M) and stirred for 30 min at room temperature. Then 5 mL of diethyl ether were added to the suspension. The precipitate was collected by suction filtration and washed with diethyl ether. The hydrobromide (0.20 g, 0.55 mmol, 93%) was obtained as a colourless powder. M.p. 151 °C. IR (KBr, cm^{-1}): $\nu = 1457, 1705, 2762, 2960, 3046, 3259, 3427$. $^1\text{H NMR}$ (250 MHz, D_2O): δ 3.04–3.48 (m, CH_2). $^{13}\text{C NMR}$ (62 MHz, D_2O): δ 42.91 (–), 45.02 (–), 53.08 (–). MS (ESI, H_2O): m/z (%) = 205 (100) [MH^+]. Anal. calc. for $\text{C}_8\text{H}_{22}\text{Br}_2\text{N}_4\text{O}_2 \cdot 0.5\text{CH}_3\text{CH}_2\text{OCH}_2\text{CH}_3$: C, 29.79; H, 6.75; N, 13.90. Found: C, 30.23; H, 6.22; N, 14.18%.

1,4,7,10-Tetraazacyclododecane-1,7-diol-zinc(II) di-perchlorate (6)

Compound **6** was synthesized from the above hydrobromide (0.20 g, 0.55 mmol) by a method similar to that of **3**. The complex **6** (0.15 g, 0.33 mmol, 60%) was obtained as a white solid. M.p. 138–140 °C. IR (KBr, cm^{-1}): $\nu = 628, 1090, 1389, 1450, 2941, 3167, 3224, 3422$. $^1\text{H NMR}$ (250 MHz, CD_3CN): δ 2.65–2.75 (m, 4 H, CH_2), 3.02–3.27 (m, 12 H, CH_2), 3.71 (bs, 2 H, NH), 7.12 (bs, 1 H, OH), 7.39 (bs, 1 H, OH). $^{13}\text{C NMR}$ (62 MHz, CD_3CN): δ 44.05 (–), 56.65 (–). MS (ESI, $\text{MeOH} + 10 \text{ mmol NH}_4\text{Ac}$): m/z (%) = 327 (100) [$(6^{2+} + \text{CH}_3\text{COO}^-)^+$].

Potentiometric titrations

Potentiometric pH titrations were performed with a computer-controlled pH-meter (pH 3000, WTW; glass pH electrode Metrohm) and automatic titration apparatus (dosimat 665, Metrohm). For all titrations 0.1 M perchloric acid (Merck, p.a.) and 0.1 M tetraethylammonium hydroxide (TEAOH) (Merck, p.a.) in water containing tetraethylammonium perchlorate to maintain an ionic strength of $I = 0.1 \text{ mol L}^{-1}$ were used. The water used is of ultrapure HPLC grade deionized with the Milli-Q185 apparatus from Millipore. Tetraethylammonium perchlorate (Fluka, purum) was recrystallized twice from acetonitrile. TEAOH solutions were calibrated with mono sodium phthalate (Merck, p.a.). A titration of perchloric acid with TEAOH solution was used for calibration and to determine $\log K_w$ and A_I by the method of Gran.¹⁹ Titrations were measured over a pH range from 2.7 to 12.6 with a minimum of 80 data points recorded. Titrations were performed in duplicate or triplicate. The stability constants given and their standard deviations are average values. All measurements were performed at 25 ± 0.5 °C. Data and error analysis was done with the computer program Hyperquad 2000.²⁰

Crystal structure determination

Suitable crystals for X-ray experiments of complex **3** were obtained by slow evaporation of a methanolic solution.

Formula: $\text{C}_8\text{H}_{20}\text{BrN}_4\text{OZn} \cdot \text{ClO}_4$, $M = 433.02$, crystal system: orthorhombic, space group $P2_12_12_1$, $a = 8.9049(5)$, $b = 12.2325(8)$, $c = 14.0969(11)$ Å, $\alpha = \beta = \gamma = 90^\circ$, $V = 1535.56(18)$ Å³, $Z = 4$, $D_c = 1.873 \text{ g cm}^{-3}$, $F(000) = 872$, $\mu = 4.398 \text{ mm}^{-1}$,

crystal size: $0.525 \times 0.454 \times 0.375$ mm, colourless, rod-like crystals.

Data collection was carried out at 173 K on a STOE-IPDS diffractometer with graphite-monochromated Mo-K α radiation ($\lambda = 0.71073$ Å); 11 144 reflections (2904 unique reflections, $R_{\text{int}} = 0.0396$) were measured from 2.71 to 25.77°.

The structure was solved by direct methods (SIR97)²¹ and refined by full-matrix least squares on F^2 for all non-H-atoms.²² H-atoms were included in calculated positions. $\omega R(F^2)$ (all data) = 0.0843; $R(F) = 0.0308$, $S = 1.073$, max. $\Delta\rho = 1.248$ e Å⁻³.

CCDC reference number 187581.

See <http://www.rsc.org/suppdata/dt/b2/b207571g/> for crystallographic data in CIF or other electronic format.

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References and notes

- 1 R. Reichenbach-Klinke and B. König, *J. Chem. Soc., Dalton Trans.*, 2002, 121.
- 2 M. Shionoya, E. Kimura and M. Shiro, *J. Am. Chem. Soc.*, 1993, **115**, 6730.
- 3 E. Kimura, T. Ikeda and M. Shionoya, *Pure Appl. Chem.*, 1997, **69**, 2187.
- 4 K. Wieghardt, *Adv. Inorg. Bioinorg. Mech.*, 1984, **3**, 213.
- 5 A. F. Hollemann, E. Wiberg, N. Wiberg, *Lehrbuch der Anorganischen Chemie*, de Gruyter, Berlin, 1985, p. 591.
- 6 D. J. Bull, I. I. Creaser, A. M. Sargeson, B. W. Skelton and A. H. White, *Inorg. Chem.*, 1987, **26**, 3040.
- 7 S. Brandes, C. Gros, F. Denat, P. Pullumbi and R. Guillard, *Bull. Soc. Chim. Fr.*, 1996, **133**, 65.
- 8 Z. Kovacs and A. D. Sherry, *Synthesis*, 1997, 759.
- 9 R. W. Murray and R. Jeyaraman, *J. Org. Chem.*, 1985, **50**, 2847.
- 10 R. W. Murray and M. Singh, *US Pat.*, 5001233, 1991.
- 11 S. Ball and T. C. Bruice, *J. Am. Chem. Soc.*, 1980, **102**, 6498.
- 12 T. C. Bissot, R. W. Parry and D. H. Campbell, *J. Am. Chem. Soc.*, 1957, **79**, 796.
- 13 On the basis of the titration data no final assignment of the pK_a values to the protonation of a specific nitrogen atom is possible.
- 14 M. J. Colthurst, A. J. S. S. Kanagasooriam, M. S. O. Wong, C. Contini and A. Williams, *Can. J. Chem.*, 1998, **76**, 678.
- 15 T. Koike, S. Kajitani, I. Nakamura, E. Kimura and M. Shiro, *J. Am. Chem. Soc.*, 1995, **117**, 1210.
- 16 E. Kimura, T. Shiota, T. Koike, M. Shiro and M. Kodama, *J. Am. Chem. Soc.*, 1990, **112**, 5805.
- 17 Additional evidence for this interpretation comes from proton NMR investigations: the proton NMR of compound L8H₂-Zn(OH₂) in DMSO-d₆ shows two hydroxy signals, at δ 4.82 [bs, 2H, Zn(OH₂)] and δ 8.58 (bs, 2H, N-OH). Upon addition of potassium carbonate as base the signal at δ 8.58 disappears, which supports preferred deprotonation of coordinated hydroxylamine moieties.
- 18 W. Adam, Y. Chan, D. Cremer, J. Gauss, D. Scheutzow and M. Schindler, *J. Org. Chem.*, 1987, **52**, 2800.
- 19 G. Gran, *Analyst*, 1952, **77**, 661.
- 20 P. Gans, A. Sabatini and A. Vacca, *Talanta*, 1996, **43**, 1739.
- 21 A. Altomare, G. Cascarano, C. Giacovazzo and A. Guagliardi, *J. Appl. Crystallogr.*, 1993, **26**, 343.
- 22 G. M. Sheldrick, SHELXL97, Program for Refinement of Crystal Structures, University of Göttingen, Germany, 1997.