Zn(II) coordination to tren-based tris-macrocycles. Activity of their trinuclear Zn(II) complexes in carboxy- and phosphate-ester hydrolysis†

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Zn(II) binding by two tren-based tris-macrocycles has been analysed by means of potentiometric measurements in aqueous solutions. Both ligands form stable trinuclear Zn(II) complexes. Deprotonation of Zn(II)-coordinated water molecules gives mono-, di- and tri-hydroxo complexes. The ability of these trinuclear complexes as hydrolytic agents has been tested by using *p*-nitrophenyl acetate and bis(*p*-nitrophenyl) phosphate (BNPP) as substrates. BNPP cleavage takes place through a bridging interaction of the substrate with at least two metals and simultaneous nucleophilic attack of a Zn–OH function at phosphorus. A significant increase of the hydrolysis rate with respect to the mononuclear Zn(II) complex with [12]aneN₄ is observed.

In recent years, a variety of polyamine ligands able to bind two or more metal ions in close proximity have appeared in the literature. Special attention has been devoted to macrocyclic ligands, because of their ability to impose a high degree of reorganisation on metal coordination.[1–15] In particular, polyamine macrocycles with a large number of donors and cavities of appropriate shape and dimension may be able to hold two or more metal centers at short distances, mimicking the multinuclear metal arrays at the active sites of several metalloenzymes. Examples include P1 nuclease which uses three metal ions to catalyse the cleavage of phosphate ester bonds in nucleotides, such as RNA and DNA.[16] Among hydrolytic enzymes, the metal ions are often Zn(II). To this purpose, several dinuclear Zn(II) complexes with macrocyclic ligands have been used as simple structural or functional models for hydrolytic metallo-enzymes.[17–36] Trinuclear synthetic Zn(II) complexes used in biomimetic studies are more rare.[37–40] In one of the approaches, multiple macrocyclic rings, separated by a rigid benzene spacer, have been used to hold, at short distance, up to three metal centers.[38,41]

We have recently described the synthesis of a new series of tren-based tris-macrocycles (tren = tris(2-aminoethyl)amine).[42] Two of the simplest contain respectively three 1,4,7,10-tetrazacyclododecane ([12]aneN₄) and three 1,5,9,12-tetraazacyclotetradecane (herein indicated as [14]aneN₄) macrocyclic moieties appended to a "tren" unit (**L1** and **L2** in Scheme 1).

The simple Zn(II) complex with the macrocyclic ligand [12]aneN₄ has been largely investigated as a potential model for

hydrolytic enzymes.[20,43,44] In this complex, in fact, the metal displays a coordination environment not saturated by the ligand donors. At the same time, facile deprotonation of a Zn(II)-bound water molecule gives a monohydroxo [Zn[12]aneN₄-(OH)]⁺ species, able to promote the hydrolysis of several substrates, such as acetate and phosphate esters.[20,43] With the purpose of developing new and more efficient models for polynuclear Zn(II) hydrolytic enzymes, we decided to investigate Zn(II) coordination by ligands **L1** and **L2**. We hoped, in fact, that these ligands could form stable trinuclear Zn(II) complexes in aqueous solution. At the same time, in the **L1** and **L2** complexes the metals should display a coordination sphere not fulfilled by the ligand donors, offering free binding sites for substrate coordination and activation. To test the effective hydrolytic properties of the **L1** and **L2** complexes, we have analysed their reactivity toward an acetate ester, *p*-nitrophenyl acetate, and a phosphate one, bis(*p*-nitrophenyl) phosphate.

Results and discussion

Crystal structure of [Zn₃L1Cl₃](ClO₄)₃·H₂O

The molecular structure consists of [Zn₃L1Cl₃]³⁺ trinuclear complex cations, perchlorate anions and water molecules. An ORTEP drawing of the [Zn₃L1Cl₃]³⁺ cation is shown in Fig. 1, and Table 1 reports selected distances and angles for the metal coordination environments. The coordination sphere is almost equal for the three Zn(II) ions. Each metal ion, in fact, is five-coordinated by the four nitrogens of a cyclic [12]aneN₄ moiety
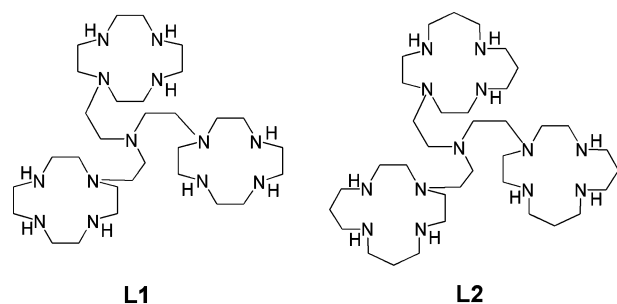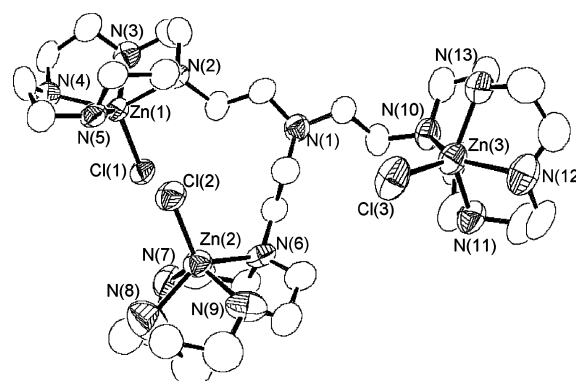

Scheme 1

Fig. 1 ORTEP[52] drawing of the [Zn₃LCl₃]³⁺ cation.

† Electronic supplementary information (ESI) available: ligand protonation constants determined in 0.1 mol dm⁻³ NMe₄NO₃ solutions at 298.1 K and 308.1 K. See http://www.rsc.org/suppdata/dt/b3/b306577d/

Table 1 Bond lengths [Å] and angles [°] for the metal coordination environments in the [Zn₃**L1**Cl₃]³⁺ cation

Zn(1)–Cl(1)	2.220(3)	Zn(1)–N(2)	2.26(1)
Zn(1)–N(3)	2.11(1)	Zn(1)–N(4)	2.14(1)
Zn(1)–N(5)	2.11(1)	Zn(2)–Cl(2)	2.230(3)
Zn(2)–N(6)	2.24(1)	Zn(2)–N(7)	2.06(1)
Zn(2)–N(8)	2.23(2)	Zn(2)–N(9)	2.11(1)
Zn(3)–Cl(3)	2.211(5)	Zn(3)–N(10)	2.22(1)
Zn(3)–N(11)	2.08(1)	Zn(3)–N(12)	2.17(1)
Zn(3)–N(13)	2.11(1)		
Cl(1)–Zn(1)–N(2)	107.4(2)	Cl(1)–Zn(1)–N(3)	111.8(3)
Cl(1)–Zn(1)–N(4)	115.8(3)	Cl(1)–Zn(1)–N(5)	115.1(3)
N(2)–Zn(1)–N(3)	81.2(4)	N(2)–Zn(1)–N(4)	136.7(4)
N(2)–Zn(1)–N(5)	80.7(4)	N(3)–Zn(1)–N(4)	82.0(4)
N(3)–Zn(1)–N(5)	132.8(4)	N(4)–Zn(1)–N(5)	82.2(4)
Cl(2)–Zn(2)–N(6)	115.8(3)	Cl(2)–Zn(2)–N(7)	116.2(3)
Cl(2)–Zn(2)–N(8)	103.4(5)	Cl(2)–Zn(2)–N(9)	116.4(3)
N(6)–Zn(2)–N(7)	83.4(4)	N(6)–Zn(2)–N(8)	140.8(6)
N(6)–Zn(2)–N(9)	80.9(5)	N(7)–Zn(2)–N(8)	81.8(6)
N(7)–Zn(2)–N(9)	126.9(5)	N(9)–Zn(2)–N(8)	79.6(6)
Cl(3)–Zn(3)–N(10)	114.0(3)	Cl(3)–Zn(3)–N(11)	110.2(3)
Cl(3)–Zn(3)–N(12)	109.3(4)	Cl(3)–Zn(3)–N(13)	117.4(1)
N(10)–Zn(3)–N(11)	81.6(4)	N(10)–Zn(3)–N(12)	136.6(5)
N(10)–Zn(3)–N(13)	80.8(4)	N(11)–Zn(3)–N(12)	81.4(5)
N(11)–Zn(3)–N(13)	132.3(5)	N(12)–Zn(3)–N(13)	81.8(5)

and a chloride anion. The coordination geometry of the three Zn(II) cations can be described as distorted square pyramidal; the basal planes are defined by the four amine groups of the [12]aneN₄ units, the maximum deviations from the mean planes being 0.02 (1) Å for N(4) (Zn(1)), 0.18(2) Å for N(8) (Zn(2)) and 0.02(1) Å for N(13) (Zn(3)). The axial positions are occupied by a chloride anion, with angles of 4.0(2)°, 4.5 (2)° and 4.41(2)° between the Zn(1)–Cl(1), Zn(2)–Cl(2) and Zn(3)–Cl(3) bonds and the normal to the corresponding basal planes. Finally, the three metal cations Zn(1), Zn(2) and Zn(3) lie respectively 0.828(1), 0.852(2) and 0.83(2) above the basal plane, shifted towards the apical position. Similar coordination geometries have been already observed in several Zn(II) complexes with [12]aneN₄ or [12]aneN₄-derivatives, the apical position being occupied by a nitrogen- or oxygen-donor of a substrate molecule or anion.[38,44,45]

Considering the overall conformation of the complex, the "tren" nitrogens N(1) N(2), N(6) and N(10) lie on the same plane (maximum deviation 0.02 Å for N(1)), giving rise to a rather open conformation of the ligand. Two of the macrocyclic units (N(6)–N(9) and N(10)–N(13)) are located above this plane. In consequence Zn(2) and Zn(3) lie 1.38(2) and 1.94(2) Å above the plane defined by the "tren" nitrogens. The third macrocyclic unit (N(2)–N(5)), instead, is bisected by the plane defined by the "tren" nitrogens and the Zn(1) ion lies 0.985(1) Å below this plane. Interestingly, the planes defined by the N(2)–N(5) and N(6)–N(9) macrocycles are almost parallel (dihedral angle of 5.76°). The two corresponding Zn(1)–Cl(1) and Zn(2)–Cl(2) units display a face to face disposition, with the two Zn(II) ions located 5.835(2) Å apart from one another. Longer distances separate the Zn(1) · · · Zn(3) (10.303(2) Å) and Zn(2) · · · Zn(3) (7.722(2) Å) couples.

Zn(II) coordination in aqueous solution

Table 2 collects the stability constants for the complexes of **L1** and **L2** with Zn(II), potentiometrically determined in 0.1 mol dm⁻³ NMe₄NO₃ aqueous solution at 298.1 and 308.1 K, while Fig. 2 displays the distribution diagrams for the **L1** and **L2** complexes with a metal to ligand 3 : 1 molar ratio at 298.1 K. Both ligands can form stable mono-, di- and tri-nuclear complexes in aqueous solutions. The most relevant difference between the Zn(II)**L** systems (**L** = **L1** and **L2**) at 298.1 K and at 308.1 K is the lower stability of the [Zn**L**]²⁺ and [Zn₂**L**]⁴⁺ complexes at the highest temperature, due to the exothermic process of metal coordination. In the case of the **L2**, the trinuclear

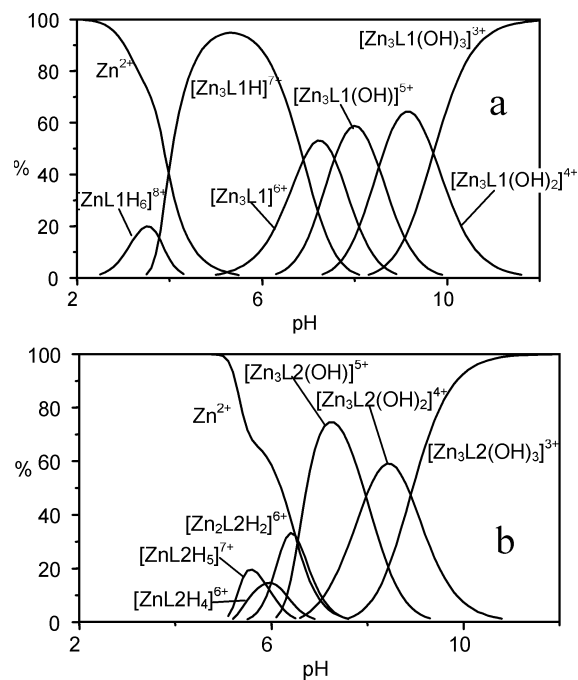**Fig. 2** Distribution diagrams for the systems **L1**/Zn²⁺ (a) and **L2**/Zn²⁺ (b) with a ligand to metal 1 : 3 molar ratio ([Zn²⁺] = 3 × 10⁻³ M; [**L1**] = [**L2**] = 1 × 10⁻³ M).

[Zn₃**L2**]⁶⁺ species was not detected by potentiometry. The trinuclear [Zn₃**L1**]⁶⁺ complex, however, still displays a lower stability at 308.1 K. On the contrary, the pK_a values of the coordinated water generally decrease at the highest temperature (for example, considering the formation of the [Zn₃**L1**(OH)₂]⁴⁺ species, pK_a values of 8.21 at 308.1 K and 8.57 at 298.1 K can be calculated from the formation constants in Table 2). This is likely due to the endothermic process of acidic dissociation of coordinated water molecules. These two effects reduce the percentages of the [Zn**L**]²⁺, [Zn₂**L**]⁴⁺ and [Zn₃**L**]⁶⁺ complexes formed at 308.1 K.

Considering the mononuclear complexes, the stability of the [Zn**L1**]²⁺ and [Zn**L2**]²⁺ complexes are somewhat lower than those of the corresponding complex with [12]aneN₄ and [14]aneN₄, respectively (log K = 19.91 and 23.5 for the equilibrium Zn²⁺ + **L** = Zn**L**²⁺ at 298.1 K, for **L** = **L1** and [12]aneN₄,[46] respectively, and log K = 13.95 and 15.44 at 298 K for **L** = **L2** and [14]aneN₄[47] respectively). Most likely, in both the [Zn**L**]²⁺ complexes the metal is coordinated by an N₄ donor set belonging to a single macrocyclic unit. The presence of a tertiary nitrogen, a weaker σ-donor than a secondary one, in the metal coordination sphere in the mononuclear complexes with **L1** and **L2** would account for the lower stability of [Zn**L1**]²⁺ and [Zn**L2**]²⁺ with respect to the corresponding complexes with [12]aneN₄ and [14]aneN₄. The other two cyclic units are probably not involved in metal coordination and facile protonation occurs on their nitrogen atoms. Actually, both the [Zn**L**]²⁺ complexes present a high tendency to bear protonation and several protonated [Zn**L**H$_n$]$^{(n + 2)}$ species are formed in aqueous solution (Table 2). At the same time, the first five protonation constants are only 0.5–2 logarithmic units lower than the corresponding basicity constants of the corresponding free amines, indicating that protonation occurs on nitrogen atoms not bound to the metal.

Most likely, addition of the second and the third metal ion to the [Zn**L**]²⁺ complexes to give the dinuclear and trinuclear Zn(II) species takes place on separated [12]aneN₄ or [14]aneN₄ units, to give dinuclear and trinuclear complexes where each metal is hosted, almost independently, in a single macrocyclic N₄ moiety, as actually shown by the crystal structure of the [Zn₃Cl₃**L1**]³⁺ trinuclear complex. The equilibrium constants for the addition of a second Zn(II) ion to the [Zn**L**]²⁺ complexes

Table 2 Stability constants (log K) of the Zn(II) complexes with **L1** and **L2** (0.1 M NMe$_4$NO$_3$ aqueous solution) at 298.1 and 308.1 K

Reaction	L1	L2	L1	L2
	298.1 K		308.1 K	
$Zn^{2+} + L = ZnL^{2+}$	19.91(5)	13.95(7)	18.40(5)	13.00(7)
$ZnL^{2+} + H^+ = ZnLH^{3+}$	9.77(5)	10.43(5)	9.62(5)	10.65(5)
$ZnLH^{3+} + H^+ = ZnLH_2^{4+}$	9.43(5)	9.55(6)	9.34(5)	9.62(6)
$ZnLH_2^{4+} + H^+ = ZnLH_3^{5+}$	8.38(5)	8.57(7)	8.32(6)	8.76(7)
$ZnLH_3^{5+} + H^+ = ZnLH_4^{6+}$	8.27(5)	7.55(7)	8.20(6)	7.76(7)
$ZnLH_4^{6+} + H^+ = ZnLH_5^{7+}$	4.33(5)	6.87(5)	5.11(6)	7.07(5)
$ZnLH_5^{7+} + H^+ = ZnLH_6^{8+}$	3.65(7)	–	4.06(7)	–
$ZnL^{2+} + Zn^{2+} = Zn_2L^{4+}$	15.52 (6)	10.69(9)	12.92 (6)	9.81(9)
$Zn_2L^{4+} + H^+ = Zn_2LH^{5+}$	8.52	8.78(6)	–	9.02(6)
$Zn_2LH^{5+} + H^+ = Zn_2LH_2^{6+}$	–	7.59(5)	–	7.75(5)
$Zn_2L^{4+} + Zn^{2+} = Zn_3L^{6+}$	10.18(7)	–	9.23(7)	–
$Zn_3L^{6+} + H^+ = Zn_3LH^{7+}$	6.89(9)	–	5.55(9)	–
$3Zn^{2+} + L + OH^- = Zn_3L(OH)^{5+}$	52.51(7)	38.57(5)	–	37.05(5)
$Zn_3L^{6+} + OH^- = Zn_3L(OH)^{5+}$	6.41(5)	–	6.00(5)	–
$Zn_3L(OH)^{5+} + OH^- = Zn_3L(OH)_2^{4+}$	5.26(5)	5.78(7)	5.19(5)	5.50(7)
$Zn_3L(OH)_2^{4+} + OH^- = Zn_3L(OH)_3^{3+}$	4.13(6)	4.93(4)	3.80(6)	4.57(4)
	pK_a (298.1 K)		pK_a (308.1 K)	
$Zn_3L^{6+} + H_2O = Zn_3L(OH)^{5+} + H^+$	7.42	–	7.4	–
$Zn_3L(OH)^{5+} + H_2O = Zn_3L(OH)_2^{4+} + H^+$	8.57	8.05	8.21	7.90
$Zn_3L(OH)_2^{4+} + H_2O = Zn_3L(OH)_3^{3+} + H^+$	9.70	8.90	9.6	8.83

(**L** = **L1** and **L2**) is obviously lower than the formation constant of [ZnL]$^{2+}$ (Table 2), due to the electrostatic repulsions between the metal ions, and, to a lesser extent, to statistical effects. A further decrease is observed for the addition of the third metal ion to the [Zn$_2$**L1**]$^{4+}$ complex, while in the case of **L2**, the [Zn$_3$**L2**]$^{6+}$ complex is not detected by potentiometry. As shown in Fig. 2, trinuclear metal complexes, however, are largely prevalent in aqueous solution with a metal to ligand 3 : 1 molar ratio.

Interestingly, ligand **L1** gives rise also to the formation of a stable protonated trinuclear complex, [Zn$_3$**L1**H]$^{7+}$. As shown in Fig. 2a, the [Zn$_3$**L1**H]$^{7+}$ complex is prevalent over a wide pH range and deprotonation to give [Zn$_3$**L1**]$^{6+}$ occurs only at neutral pH values. The observed high value of the constant for proton addition to the [Zn$_3$**L1**]$^{6+}$ complex may be ascribed to protonation of a nitrogen not bound to the metal, most likely the bridgehead nitrogen of the "tren" unit.

Comparing the binding ability of **L1** and **L2** toward Zn(II), the data in Table 2 point out that the formation constants of complexes with **L1** are generally higher than the corresponding complexes with **L2** (compare, for instance, the constants for the equilibria $Zn^{2+} + L = ZnL^{2+}$ and $ZnL^{2+} + Zn^{2+} = Zn_2L^{4+}$ with L = **L1** and **L2**), due to replacement of two ethylenic chains in **L1** with propylenic ones in **L2**. The larger bite of the propylenic chains, in fact, generally increases the N–Zn–N bond angle and reduces the interaction between the metal and the nitrogen donors. Actually, a similar decrease in stability is also observed passing from the [Zn[12]aneN$_4$]$^{2+}$ complex (log K = 23.5)[46] to the [Zn[14]aneN$_4$]$^{2+}$ one (log K = 15.44).[47]

The most interesting finding, however, is the formation of stable mono-, di- and tri-hydroxo trinuclear complexes, which are present in solution from slightly acidic to alkaline pH values (Fig. 2). High tendencies to form hydroxo complexes are generally related to a metal coordination sphere not saturated by the ligand donors, which leads to facile deprotonation of the coordinated water molecules. Actually, the crystal structure of the trinuclear Zn(II) complex with **L1** shows each metal coordinated by a [12]aneN$_4$ unit and a chloride anion. Most likely, the chloride anions are replaced by water molecules in aqueous solution. The mono-, di- and tri-hydroxo complexes would be therefore generated by successive deprotonation of the coordinated water molecules. The pK_a value for deprotonation of the first water molecule in the [Zn$_3$**L1**]$^{6+}$ trinuclear complex, however, is lower than that found for the mononuclear [Zn[12]aneN$_4$]$^{2+}$ one (pK_a = 7.42 and 8.02[43] at 298.1 K for the equilibria [Zn$_3$**L1**]$^{6+}$ + H$_2$O = [Zn$_3$**L1**(OH)]$^{5+}$ + H$^+$ and [Zn[12]aneN$_4$]$^{2+}$ + H$_2$O = [Zn[12]aneN$_4$](OH)]$^+$ + H$^+$, respect-

ively). This behaviour indicates a strong binding of the hydroxide ion in [Zn$_3$**L1**(OH)]$^{5+}$ and is generally ascribed to a bridging coordination mode of OH$^-$ between two metal centers.[27] In consequence of this low pK_a value, the [Zn$_3$**L1**(OH)]$^{5+}$ species is already present in aqueous solution at neutral pH. The formation of both a dihydroxo [Zn$_3$**L1**(OH)$_2$]$^{4+}$ and a trihydroxo [Zn$_3$**L1**(OH)$_3$]$^{3+}$ complex is observed at alkaline pH with pK_a values respectively of 8.57 and 9.7 at 298 K. These pK_a values are higher than those usually found for bridging hydroxide groups and are generally related to the formation of hydroxide functions bound to a single metal ion.[20,27] In the case of **L2**, the [Zn$_3$**L2**]$^{6+}$ species is not formed under our experimental conditions and the pK_a value for the formation of [Zn$_3$**L2**(OH)]$^{5+}$ cannot be calculated. Fig. 2b, however, clearly shows that this species is largely prevalent in aqueous solution at neutral pH, still suggesting strong hydroxide binding in the [Zn$_3$**L2**(OH)]$^{5+}$ complex, probably due, once again, to a bridging coordination of this anion. It is also to be noted that the pK_a values for the formation of the [Zn$_3$**L2**(OH)$_2$]$^{4+}$ and [Zn$_3$**L2**(OH)$_3$]$^{3+}$ complexes are somewhat lower than those found for the corresponding **L1** species (Table 2). The enhanced acidity of the coordinated water molecules in the trinuclear **L2** complex can be related to the weaker interaction between each metal ion and a single N$_4$ donor set in the [Zn$_3$**L2**]$^{6+}$ complex, which increases the positive charge on the metal and favours the dissociation of the metal-bound water molecules.

These features make the trinuclear Zn(II) complexes with **L1** and **L2** promising hydrolytic agents. They contain three metal centers as potential binding sites for substrate molecules or anions. In these complexes, in fact, the metal coordination spheres are not fulfilled by the ligand donors and the Zn(II) ions may be used for substrate binding and activation. At the same time, facile deprotonation of metal-bound water molecules occurs from neutral to alkaline pH, giving Zn–OH functions as potential nucleophiles in hydrolytic reactions. Therefore, we decided to test the potential hydrolytic activity of these complexes by using as substrates an activated acetate ester, p-nitrophenyl acetate (NA), and an activated phosphate ester, bis(p-nitrophenyl) phosphate (BNPP).

Kinetics of p-nitrophenyl acetate (NA) hydrolysis

NA hydrolysis promoted by the trinuclear Zn(II) complexes with **L1** and **L2** at different pH was followed by the appearance of the p-nitrophenate anion at 403 nm (298.1 K, I = 0.1 mol dm^{-3} NMe$_4$NO$_3$). For both ligands significant enhancement of the hydrolysis rate is observed only above pH 7 and second

Table 3 Second order rate constants k'_{NA} (M^{-1} s^{-1}) for the hydrolysis of *p*-nitrophenyl acetate and pK_a values for the corresponding hydroxo complexes at 298.1 K

Nucleophile	k'_{NA}/M^{-1} s^{-1}	pK_a	Nucleophile	k'_{NA}/M^{-1} s^{-1}	pK_a
$[Zn_3L1(OH)]^{5+}$	< 0.03	7.42	$[Zn_3L2(OH)]^{5+}$	< 0.03	–
$[Zn_3L1(OH)_2]^{4+}$	0.56 ± 0.06	8.57	$[Zn_3L2(OH)_2]^{4+}$	0.34 ± 0.04	8.05
$[Zn_3L1(OH)_3]^{3+}$	4.2 ± 0.4	9.7	$[Zn_3L2(OH)_3]^{3+}$	3.7 ± 0.4	8.9
$[Zn[12]aneN_4(OH)]^{+a}$	0.11 [a]	8.02			

[a] From reference 43a, I = 0.15 M NaClO$_4$.
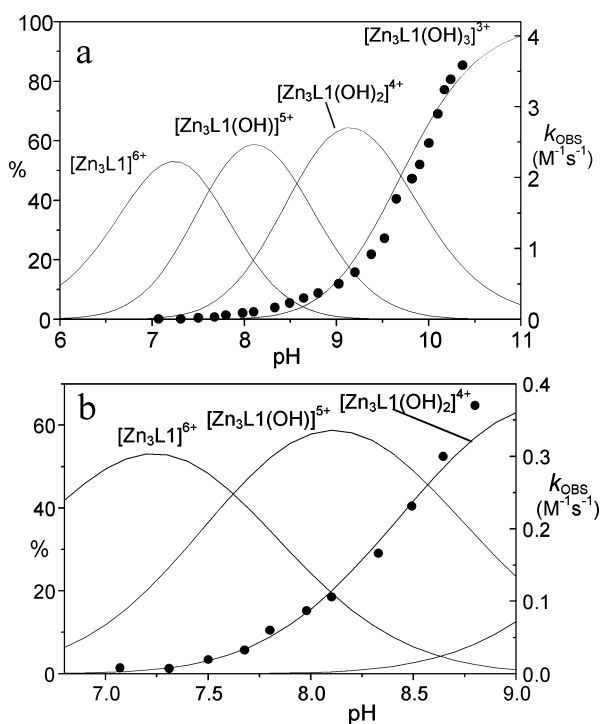
Fig. 3 (a) Plot of the distribution curves of the **L1** trinuclear hydroxo complexes (solid line, left *y* axis) and k_{obs} values for NA hydrolysis (●, right *y* axis) as a function of pH (0.1 mol dm^{-3} NMe$_4$NO$_3$, 298.1 K). (b) Expansion of the 6.6–9 pH region, evidencing the hydrolytic effect of the $[Zn_3L1(OH)_2]^{4+}$ complex.

order kinetics is followed. Fig. 3 reports the measured k_{obs} values at different pH for the **L1** trinuclear complexes, together with their distribution curves. From these data the single contributions to the k_{obs} values of each trinuclear species can be calculated (see Experimental section). The trinuclear $[Zn_3L1]^{6+}$ complex does not show any hydrolytic activity, while the monohydroxo complex $[Zn_3L1(OH)]^{5+}$ displays a very low enhancement of the hydrolysis rate (k_{NA} < 0.03). An equal behaviour is found for the trinuclear complexes with **L2**. The low activity of the $[Zn_3L(OH)]^{5+}$ species (L = **L1** or **L2**) is in accord with the generally observed low hydrolytic ability of Zn$_2$(μ-OH) functions;[27] simultaneous binding to two electrophilic metal centers, in fact, reduces the nucleophilicity of the hydroxide anion. The $[Zn_3L(OH)_2]^{4+}$ and $[Zn_3L(OH)_3]^{3+}$ (L = **L1** or **L2**) complexes, instead, give a significant promotion of the NA hydrolysis rate. These complexes, however, are formed in at most 80–90% in the pH ranges used in the kinetic measurements. Therefore, in order to quantify the different activity in NA hydrolysis of the present complexes, we determined the second order rate constants k'_{NA} at 100% formation of the $[Zn_3L(OH)_2]^{4+}$ and $[Zn_3L(OH)_3]^{3+}$ species (see Experimental section). The calculated k'_{NA} values for the present complexes are listed in Table 3, together with the corresponding pK_a values. The data in Table 3 clearly show that the rate constants for the $[Zn_3L(OH)_3]^{3+}$ complexes (L = **L1** or **L2**) are much higher than those found for the corresponding $[Zn_3L(OH)_2]^{4+}$ species. At the same time, the di-hydroxo and tri-hydroxo **L1** complexes are more active in NA cleavage than the corresponding **L2** ones. In other words, among the different

complexes, the rate constants increase with the pK_a values, *i.e.*, with the nucleophilicity of the Zn–OH functions. This result is in accord with a mechanism for NA hydrolysis involving a merely nucleophilic attack of the metal-bound hydroxide at the carbonyl group of the ester and release of *p*-nitrophenate.[20,27] The three Zn(II) ions do not play any cooperative role in substrate activation and a simple bimolecular mechanism is predominant.

Kinetics of bis(*p*-nitrophenyl) phosphate (BNPP) hydrolysis

Fig. 4 shows the pH dependence of the measured second order rate constants, k_{obs}, for BNPP hydrolysis in the presence of the **L1** and **L2** trinuclear complexes, together with the distribution curves of **L1** and **L2** trinuclear complexes. Only the di- and tri-hydroxo complexes promote BNPP hydrolysis in aqueous solution (L = **L1** and **L2**), while the monohydroxo species $[Zn_2L(OH)]^{3+}$ do not promote this process, in accord with the very low activity in NA hydrolysis found for this complex. The $[Zn_3L(OH)_2]^{4+}$ and $[Zn_3L(OH)_3]^{3+}$ complexes are the kinetically active species.
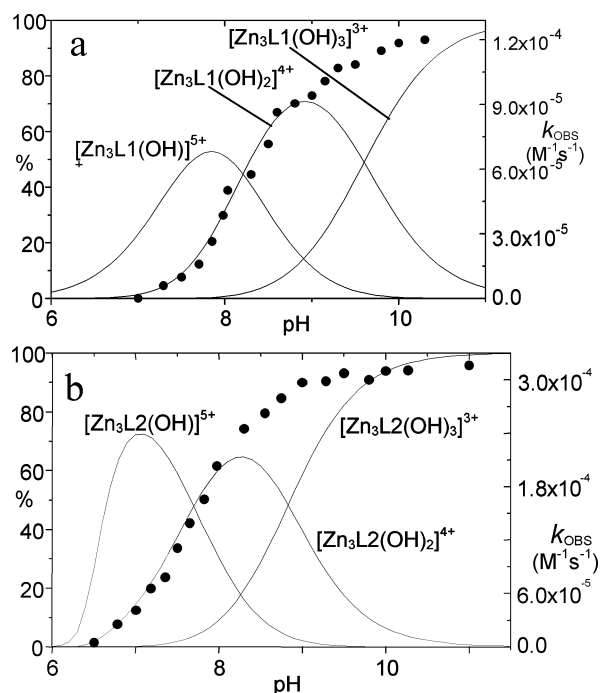

Fig. 4 (a) Plot of the distribution curves of the **L1** trinuclear hydroxo complexes (solid line, left *y* axis) and k_{obs} values for BNPP hydrolysis (●, right *y* axis) as a function of pH (0.1 mol dm^{-3} NMe$_4$NO$_3$, 308.1 K). (b) Plot of the distribution curves of the **L2** trinuclear hydroxo complexes (solid line, left *y* axis) and k_{obs} values for BNPP hydrolysis (●, right *y* axis) as a function of pH (0.1 mol dm^{-3} NMe$_4$NO$_3$, 308.1 K).

As in the case of NA hydrolysis, the rate constants k'_{BNPP} at 100% formation of the $[Zn_3L(OH)_2]^{4+}$ and $[Zn_3L(OH)_3]^{3+}$ species can be calculated from the experimental k_{obs} values, and their values are reported in Table 4, in comparison with the corresponding pK_a values. The k'_{BNPP} values reported for

Nucleophile	$k'_{BNPP} \times 10^4$/M^{-1} s^{-1}	pK_a	Nucleophile	$k'_{BNPP} \times 10^4$/M^{-1} s^{-1}	pK_a
[Zn$_3$**L1**(OH)]$^{5+}$	–	7.40	[Zn$_3$**L2**(OH)]$^{5+}$	–	–
[Zn$_3$**L1**(OH)$_2$]$^{4+}$	1.2 ± 0.06	8.21	[Zn$_3$**L2**(OH)$_2$]$^{4+}$	2.9 ± 0.15	7.90
[Zn$_3$**L1**(OH)$_3$]$^{3+}$	1.1 ± 0.05	9.6	[Zn$_3$**L2**(OH)$_3$]$^{3+}$	3.1 ± 0.2	8.83
[Zn[12]aneN$_4$(OH)]$^{+}$ ^{a}	0.21	7.9			

^{a} From reference 43a, I = 0.15 M NaClO$_4$.

the mononuclear complex with [12]aneN$_4$ are also reported for comparison.

The data in Table 4 outline that the trinuclear **L1** and **L2** complexes are remarkably more active in BNPP hydrolysis than the mononuclear Zn(II) complex with [12]aneN$_4$.[43a] In comparison with [Zn[12]aneN$_4$(OH)]$^+$, a *ca.* five-fold and fourteen-fold increase in the hydrolysis rate is observed in the presence of the trinuclear complexes [Zn$_3$**L1**(OH)$_2$]$^{4+}$ and [Zn$_3$**L2**(OH)$_2$]$^{4+}$, respectively. These complexes are also more active than the binuclear Zn(II) complex with the ligand 1,4,7,10,19,22,25,28-octaza-13,16,31,34-tetraoxacyclohexatriacontane (**L3**), which contains two Zn(II) coordinated, almost independently, by two separated tetraaza moieties (k'_{BNPP} = 5.4 × 10^{-5} M^{-1} s^{-1} for [Zn$_2$**L3**(OH)$_2$]$^{2+}$).[27c] These results suggest that the metal centers in the present complexes play a cooperative role in BNPP cleavage. For BNPP hydrolysis promoted by mononuclear Zn(II) complexes, such as [Zn[12]aneN$_4$(OH)]$^+$, an "associative" mechanism has been proposed where BNPP starts by interacting with Zn(II), an electrophilic binding site for P–O, and at the same time the Zn(II)–OH function acts as a nucleophile.[20,43] The higher activity in BNPP hydrolysis observed for our trinuclear complexes may be explained by considering that the phosphate ester would interact with at least two Zn(II) centers, and simultaneously a Zn(II)-bound hydroxide operates a nucleophilic attack at phosphorus to give mono(p-nitrophenyl) phosphate and p-nitrophenate (Fig. 5). In other words, the observed rate increase would be generated by a bridging interaction of BNPP with at least two electrophilic metal centers, *i.e.*, by a higher substrate activation.
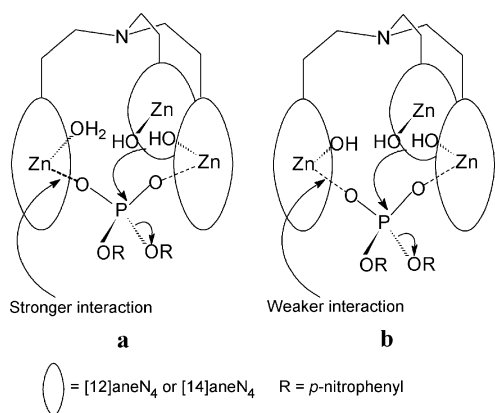

Fig. 5 Proposed mechanism for BNPP cleavage promoted by complexes [Zn$_3$**L**(OH)$_2$]$^{4+}$ (a) and [Zn$_3$**L**(OH)$_3$]$^{3+}$ (b) (**L** = **L1** or **L2**).

Comparing the hydrolytic properties of the [Zn$_3$**L1**(OH)$_2$]$^{4+}$ and [Zn$_3$**L1**(OH)$_3$]$^{3+}$ complexes with those of the corresponding **L2** ones, the activity of the complexes in BNPP hydrolysis decreases from **L2** to **L1** (k'_{BNPP} = 2.9 × 10^{-4} and 1.2 × 10^{-4} for [Zn$_3$**L2**(OH)$_2$]$^{4+}$ and [Zn$_3$**L1**(OH)$_2$]$^{4+}$, respectively; k'_{BNPP} = 3.1 × 10^{-4} and 1.1 × 10^{-4} for [Zn$_3$**L2**(OH)$_3$]$^{3+}$ and [Zn$_3$**L1**(OH)$_3$]$^{3+}$, respectively), *i.e.*, the hydrolytic ability decreases as the pK_a of the complexes increases, which is opposite to the behaviour found in NA cleavage. Thus, in BNPP cleavage the hydrolytic properties of the complexes are not only determined by the nucleophilicity of the Zn–OH functions. This behaviour can be

explained, once again, in terms of an associative cleavage mechanism.[20,27,43] Lower pK_a values, in fact, generally imply a more electrophilic Zn(II) center and, therefore, a better ability in substrate binding. The **L2** complexes, which contain the less nucleophilic Zn(II)–OH functions, would give a stronger interaction with BNPP during the hydrolytic process, leading to an enhanced substrate activation and to higher rate accelerations.

Differently from NA hydrolysis, the trihydroxo complexes [Zn$_3$**L**(OH)$_3$]$^{3+}$ (**L** = **L1** or **L2**) displays a hydrolytic ability equal, within experimental error, to that of the corresponding dihydroxo species [Zn$_3$**L**(OH)$_2$]$^{4+}$. This result is rather surprising, since the [Zn$_3$**L**(OH)$_3$]$^{3+}$ complexes display a markedly higher nucleophilic character than the [Zn$_3$**L**(OH)$_2$]$^{4+}$ ones, which would lead, in principle, to higher rate constants for BNPP cleavage in the presence of the [Zn$_3$**L**(OH)$_3$]$^{3+}$ species. A tentative explanation of this behaviour could reside in a lower BNPP activation by the [Zn$_3$**L**(OH)$_3$]$^{3+}$ species, *i.e.*, in a reduced interaction of the phosphate ester with the metal centers in these trihydroxo complexes. The dihydroxo complexes, in fact, contain two Zn–OH functions and a Zn–OH$_2$ group, which is replaced by a further Zn–OH unit in the trihydroxo species. Since hydroxide is strongly bound to Zn(II) with respect to a water molecule, the phosphate ester would give a stronger interaction with a Zn–OH$_2$ group than with a Zn–OH function, as sketched in Fig. 5. The consequent overall lower interaction of the substrate with the [Zn$_3$**L**(OH)$_3$]$^{3+}$ complexes would compensate for their higher nucleophilicity, leading to the observed almost equal activity in BNPP hydrolysis of the di- and trihydroxo complexes.

Experimental

General procedures

Ligands **L1** and **L2** were obtained as previously reported.[42] UV-vis spectra were recorded on a Shimadzu UV-2101PC spectrophotometer.

Synthesis of the complexes

[Zn$_3$L1Cl$_3$](ClO$_4$)$_3$·H$_2$O. A sample of Zn(ClO$_4$)$_2$·6H$_2$O (84 mg, 0.22 mmol) was added to a methanol solution (20 cm^3) of **L1** (46 mg, 0.075 mmol). NaCl (10 mg) was added. The resulting solution was stirred for 1 h at room temperature and butanol (20 cm^3) was then added. Colourless crystals of the title compound were obtained by slow evaporation of this solution. Yield: 73 mg (80%) Anal. Calcd. for C$_{30}$H$_{71}$N$_{13}$Cl$_6$O$_{13}$Zn$_3$: C, 29.28; H, 5.81; N, 14.79. Found: C, 29.4; H, 5.63; N, 14.9%.

[Zn$_3$L2](ClO$_4$)$_6$·3H$_2$O. This compound was obtained as a colourless powder from Zn(ClO$_4$)$_2$·6H$_2$O (94 mg, 0.25 mmol) and **L2** (58 mg, 0.08 mmol) by using the same procedure reported for the **L1** complex. Yield: 97 mg (75%). Anal. Calcd. for: C$_{36}$H$_{87}$N$_{13}$Cl$_6$O$_{27}$Zn$_3$: C, 28.02; H, 5.68; N, 11.80. Found: C, 28.1; H, 5.5; N, 12.0%.

Single crystal X-ray diffraction analysis

Formula: C$_{30}$H$_{71}$Cl$_6$Zn$_3$N$_{13}$O$_{13}$, M = 1230.81; a = 7.9390(10), b = 29.5390(10), c = 22.459(4) Å; β = 99.000(5)°; Z = 4, mono-

clinic, space group $P21/n$, $V = 5202.0(11)$ Å^3, $T = 298$ K, $F(000) = 2552$. Data collection: P4 SIEMENS X-ray diffractometer, $\lambda = 1.54178$ Å (Cu-Kα), graphite monochromated, $0.25 \times 0.2 \times 0.1$ mm. Data collection to $2\theta_{max}$ of 100.12° gave 7063 reflections collected. The structure was solved by direct methods using the Sir-97 program.[48] Refinement was performed by means of the full-matrix least squares method of the SHELX-97[49] program. Refinement included 561 parameters on 5256 unique reflections for which $I > 2.00\sigma(I)$, to give $R = 0.0909$, $R_w = 0.2763$, and GOF = 1.089.

A double position was found for the C(17) carbon atom (population parameter ratio: 0.3/0.7). As is often found in perchlorate, the Cl(6) perchlorate anion exhibits disorder with high thermal displacements. All the non-hydrogen atoms were anisotropically refined, except C(17A), C(17B), C(18), O(61), O(62), O(63) and O(64). The hydrogen atoms were introduced in calculated positions and their coordinates and thermal factors refined in agreement with those of the linked atoms.

CCDC reference number 212434.

See http://www.rsc.org/suppdata/dt/b3/b306577d/ for crystallographic data in CIF or other electronic format.

Potentiometric measurements

Equilibrium constants for complexation reactions with **L1** and **L2** were determined by means of potentiometric measurements (pH = $-\log$ [H$^+$]), carried out in 0.1 mol dm^{-3} NMe$_4$NO$_3$ at 298.1 ± 0.1 K and 308.1 ± 0.1 K, in the pH range 2.5–11, using equipment that has been already described.[27a] The reference electrode was an Ag/AgCl electrode in saturated KCl solution. The glass electrode was calibrated as a hydrogen concentration probe by titrating known amounts of HCl with CO$_2$-free NaOH solutions and determining the equivalence point by Gran's method.[50] This allows one to determine the standard potential $E°$, and the ionic product of water (p$K_w = 13.83 \pm 0.01$ and 13.40 ± 0.01 at 298.1 K and 308.1 K, respectively). Ligand concentration was about 1×10^{-3} M, while metal concentration was in the range 3×10^{-3} to 5×10^{-4} M. At least three measurements (about 100 experimental points each one) were performed for each system. The computer program HYPERQUAD[51] was used to calculate the protonation constants and the stability constants of Zn(II) complexes from emf data. Ligands protonation constants at 298.1 and 308.1 K are supplied within the ESI.† The titration curves for each system were treated either as a single set or as separate entities without significant variations in the values of the protonation or metal complexation constants.

Kinetics of p-nitrophenyl acetate (NA) hydrolysis

The hydrolysis rate of p-nitrophenyl acetate in the presence of the trizinc complexes with **L1** and **L2** was measured by an initial slope method following the increase in the 403 nm absorption of the released p-nitrophenolate at 298.1 ± 0.1 K by using the procedure reported in reference 27. The ionic strength was adjusted to 0.1 M with NMe$_4$NO$_3$. The reaction solution was maintained at 298.1 ± 0.1 K. MES (pH 5.5–6.7), MOPS (pH 6–7.8), TAPS (pH 7.8–8.9) and CAPSO (pH 8.9–10) buffers were used (50 mM). In a typical experiment, after p-nitrophenyl acetate and the trizinc complexes with **L1** or **L2** (0.1–1 mM) in 10% CH$_3$CN solutions at appropriate pH (the reference experiment does not contain the Zn(II) complex) were mixed, the UV absorption decay was recorded immediately and was followed generally until 2% decay of p-nitrophenyl acetate. For both ligands the rate increase due to the [Zn$_3$L(OH)]$^{5+}$ complex is negligible. Two species, [Zn$_3$L(OH)$_2$]$^{4+}$ and [Zn$_3$L(OH)$_3$]$^{3+}$ give significant enhancement of the hydrolysis rate. Therefore, at each pH value, the measured second order rate constants k_{obs} are given by:

$$k_{obs}[\text{total trinuclear Zn(II) complex}][\text{NA}] = k_{1NA}[\text{Zn}_3\text{L(OH)}_2{}^{4+}][\text{NA}] + k_{2NA}[\text{Zn}_3\text{L(OH)}_3{}^{3+}][\text{NA}]$$

The k_{1NA} and k_{2NA} values were calculated by least squares fitting of the k_{obs} values collected at different pH. Plots of the k_{1NA} and k_{2NA} values vs. [Zn$_3$L(OH)$_2$]$^{4+}$ and [Zn$_3$L(OH)$_3$]$^{3+}$ percentages, respectively, gave straight lines and allow one to determine the rate constants k'_{NA} at 100% formation of [Zn$_3$L(OH)$_2$]$^{4+}$ and [Zn$_3$L(OH)$_3$]$^{3+}$, given in Table 3.

Kinetics of bis(p-nitrophenyl) phosphate (BNPP) hydrolysis

The hydrolysis rate of BNPP to give mono(p-nitrophenyl) phosphate and p-nitrophenate was measured in aqueous solution at 308 ± 0.1 K by using a similar method and procedure to those reported for NA hydrolysis. The visible absorption increase at 403 nm was recorded immediately after mixing BNPP (1–10 mM) and the trizinc complexes (1–10 mM) aqueous solutions and was followed generally until 0.2% formation of p-nitrophenate (for each second order rate constant determination at least five experiments were followed until 5–10%). A plot of the hydrolysis rate vs. BNPP concentration (1–10 mM) at a given pH gave a straight line, and then we determined the slope/[zinc complex] as the second order rate constants k_{obs} (M^{-1} s^{-1}). Errors on k_{obs} values were about 5%. Similar to the case of NA hydrolysis, [Zn$_3$L(OH)]$^{5+}$ does not promote BNPP cleavage and, therefore:

$$k_{obs}[\text{total trinuclear Zn(II) complex}][\text{BNPP}] = k_{1BNPP}[\text{Zn}_3\text{L(OH)}_2{}^{4+}][\text{BNPP}] + k_{2BNPP}[\text{Zn}_3\text{L(OH)}_3{}^{3+}][\text{BNPP}]$$

The k_{1BNPP}, k_{2BNPP} and k'_{BNPP} values (k'_{BNPP} = rate constants at 100% formation of the [Zn$_3$L(OH)$_2$]$^{4+}$ and [Zn$_3$L(OH)$_3$]$^{3+}$ complexes) were calculated by using the method reported for the corresponding NA rate constants.

References

1 (a) J. S. Bradshaw, *Aza-crown Macrocycles*, Wiley, New York, 1993; (b) R. M. Izatt, K. Pawlak and J. S. Bradshaw, *Chem. Rev.*, 1995, **95**, 2529.

2 J. M. Lehn, *Supramolecular Chemistry* VCH, New York, 1995.

3 (a) L. F. Lindoy, *The Chemistry of Macrocyclic Ligand Complexes*, Cambridge University Press, Cambridge, UK, 1993; (b) L. F. Lindoy, *Pure Appl. Chem.*, 1997, **69**, 2179–2184.

4 (a) R. Raidt, M. Neuburger and T. A. Kaden, *Dalton Trans.*, 2003, 1292; (b) T. A. Kaden, *Coord. Chem. Rev.*, 1999, **190–192**, 371.

5 J. Nelson, V. McKee and G. Morgan, *Prog. Inorg. Chem.*, 1998, **47**, 167.

6 A. Bencini, A. Bianchi, P. Paoletti and P. Paoli, *Coord. Chem. Rev.*, 1992, **120**, 51.

7 (a) F. H. Fry, G. D. Fallon and L. Spiccia, *Inorg. Chim. Acta*, 2003, **346**, 57.

8 (a) S. D. Brooker, T. C. Davidson, S. J. Hay, R. J. Kelly, D. K. Kennepohl, P. G. Plieger, B. Moubaraki, K. S. Murray and E. Bill, *Coord. Chem. Rev.*, 2001, **216–217**, 3; (b) S. D. Brooker, *Eur. J. Inorg. Chem.*, 2002, **10**, 2535; (c) S. D. Brooker, *Coord. Chem. Rev.*, 2001, **222**, 33.

9 (a) L. Lamarque, C. Miranda, P. Navarro, F. Escartí, E. García-España, J. Latorre and J. A. Ramírez, *Chem. Commun.*, 2000, 1337; (b) L. Lamarque, P. Navarro, C. Miranda, V. J. Aran, C. Ochoa, F. Escartí, E. García-España, J. Latorre, S. V. Luis and J. F. Miravet, *J. Am. Chem. Soc.*, 2001, **123**, 10560.

10 P. Guerriero, S. Tamburini and P. A. Vigato, *Coord. Chem. Rev.*, 1995, **139**, 17.

11 (a) M. A. Hortala, L. Fabbrizzi, N. Marcotte, F. Stomeo and A. Taglietti, *J. Am. Chem. Soc.*, 2003, **125**, 20; (b) V. Amendola, E. Bastianello, L. Fabbrizzi, C. Mangano, P. Pallavicini, A. Perotti,

A. Manotti-Lanfredi and F. Ugozzoli, *Angew, Chem., Int. Ed.*, 2000, **39**, 2917.

12 (*a*) M. Formica, V. Fusi, M. Micheloni, R. Pontellini and P. Romani, *Coord. Chem. Rev.*, 1999, **184**, 347; (*b*) P. Dapporto, M. Formica, V. Fusi, L. Giorgi, M. Micheloni, P. Paoli, R. Pontellini and P. Rossi, *Inorg. Chem.*, 2001, **40**, 6186.

13 D. K. Chand, H.-J. Schneider, A. Bencini, A. Bianchi, C. Giorgi, S. Ciattini and B. Valtancoli, *Chem. Eur. J.*, 2000, **6**, 4001.

14 (*a*) H. Adams, S. Clunas, D. E. Fenton and S. E. Spey, *Dalton Trans.*, 2003, 625; (*b*) H. Okawa, H. Furutachi and D. E. Fenton, *Coord. Chem. Rev.*, 1998, **174**, 51.

15 R. M. Izatt, K. Pawlak, J. S. Bradshaw and R. L. Bruenig, *Chem. Rev.*, 1991, **91**, 1721.

16 For recent reviews, see: (*a*) W. N. Lipscomb and N. Sträter, *Chem. Rev.*, 1996, **96**, 2375; (*b*) D. E. Wilcox, *Chem. Rev.*, 1996, **96**, 2435; (*c*) N. Sträter, W. N. Lipscomb, T. Klabunde and B. Krebs, *Angew. Chem., Int. Ed. Engl.*, 1996, **35**, 2024; (*d*) H.-J. Schneider and A. Yatsimirsky, in *Metal Ions in Biological Systems*, ed. H. Sigel and A. Sigel, Marcel Dekker, New York, 2003, vol. 40, p. 369.

17 A. Blasko and T. C. Bruice, *Acc. Chem. Res.*, 1999, **32**, 475 and refs. therein.

18 (*a*) E. L. Hegg and J. N. Burstyn, *Coord. Chem. Rev.*, 1998, **173**, 133 and refs. therein.

19 (*a*) R. Krämer, *Coord. Chem. Rev.*, 1999, **182**, 243 and refs. therein; (*b*) C. Wendelstorf, S. Warzeska, E. Kovari and R. Kramer, *J. Chem. Soc., Dalton Trans.*, 1996, 3087.

20 (*a*) E. Kimura, *Acc. Chem. Res.*, 2001, 171 and refs. therein; (*b*) S. Aoki and E. Kimura, *Rev. Mol. Biotech.*, 2002, **90**, 129 and refs. therein; (*c*) E. Kimura, *Prog. Inorg. Chem.*, 1994, **41**, 443.

21 M. Yashiro, A. Ishikubo and M. Komiyama, *J. Chem. Soc., Chem. Commun.*, 1995, 1793.

22 (*a*) P. Rossi, F. Felluga, P. Tecilla, F. Formaggio, M. Crisma, C. Toniolo and P. Scrimin, *Biopolymers*, 2000, **55**, 496; (*b*) C. Sissi, P. Rossi, F. Felluga, F. Formaggio, M. Palumbo, P. Tecilla, C. Toniolo and P. Scrimin, *J. Am. Chem. Soc.*, 2001, **123**, 3169.

23 P. Molenveld and J. F. J. Engbersen, *Chem. Soc. Rev*, 2000, **29**, 75.

24 D. Lee, P.-L. Hung, B. Spingler and S. J. Lippard, *Inorg Chem.*, 2002, **41**, 521 and refs. therein.

25 (*a*) P. Jurek and A. E. Martell, *Inorg. Chim. Acta*, 1999, **287**, 47; (*b*) M. T. B. Luiz, B. Szpoganicz, M. Rizzoto, M. G. Basallote and A. E. Martell, *Inorg. Chim. Acta*, 1999, **287**, 134; (*c*) D. Kong, A. E. Martell and J. Reibenspies, *Inorg. Chim. Acta*, 2002, **333**, 7.

26 (*a*) W. H. Chapman, Jr. and R. Breslow, *J. Am. Chem. Soc.*, 1995, **117**, 5462.

27 (*a*) C. Bazzicalupi, A. Bencini, A. Bianchi, V. Fusi, C. Giorgi, P. Paoletti, B. Valtancoli and D. Zanchi, *Inorg. Chem.*, 1997, **36**, 2784; (*b*) C. Bazzicalupi, A. Bencini, E. Berni, A. Bianchi, V. Fedi, C. Giorgi, P. Paoletti and B. Valtancoli, *Inorg. Chem.*, 1999, **38**, 4115; (*c*) C. Bazzicalupi, A. Bencini, E. Berni, A. Bianchi, C. Giorgi, P. Paoletti and B. Valtancoli, *Inorg. Chem.*, 1999, **38**, 6323.

28 S. Kondo, K. Shinbo, T. Yamaguchi, K. Yoshida and Y. Yano, *J.Chem.Soc., Perkin Trans. 2*, 2001, 128.

29 F. Nihan, M. S. Akkaya and E. U. Akkaya, *J. Mol. Catal. A: Chem.*, 2001, **165**, 291.

30 S. Kawahara and T. Uchimaru, *Eur. J. Inorg. Chem*, 2001, 2437.

31 D. E. Fenton and H. Okawa, *Chem. Ber.*, 1997, **130**, 433.

32 S.-A. Li, D.-X. Yang, D.-F. Li, J. Huang and W.-X. Tang, *New J. Chem.*, 2002, **26**, 1831.

33 C. Vichard and T. A. Kaden, *Inorg. Chim. Acta*, 2002, **337**, 173.

34 K. Yamada, Y. Takahashi, H. Yamamura, S. Araki, K. Saito and M. Kawai, *Chem. Commun.*, 2000, 1315.

35 O. Iranzo, A. Y. Kovalevski, J. R. Morrow and J. P. Richard, *J. Am. Chem. Soc.*, 2003, **125**, 1988.

36 K. Worm, F. Chu, K. Matsumoto, M. D. Best, V. Linch and E. V. Anslyn, *Chem. Eur. J.*, 2003, **3**, 741.

37 (*a*) M. Yashiro, A. Ishikubo and M. Komiyama, *Chem. Commun.*, 1997, 83; (*b*) S. Matsuda, M. Yashiro, A. Kuzuka, A. Ishikubo and M. Komiyama, *Angew. Chem., Int. Ed.*, 1998, **37**, 3284.

38 (*a*) E. Kimura, S. Aoki, T. Koike and M. Shiro, *J. Am. Chem. Soc.*, 1997, **119**, 3068; (*b*) E. Kimura, M. Kikuchi, H. Kitamura and T. Koike, *Chem. Eur. J.*, 1999, **5**, 3113.

39 (*a*) P. Molenveld, W. M. G. Stikvoort, H. Kooijman, A. L. Spek, J. F. J. Engbersen and D. N. Reinhoudt, *J. Org. Chem.*, 1999, **64**, 3896; (*b*) P. Molenveld, J. F. J. Engbersen and D. N. Reinhoudt, *Angew. Chem., Int. Ed.*, 1999, **38**, 3189.

40 S. R. Korupoju, N. Mangayarkarasi, P. S. Zacharias, J. Mizuthani and H. Nishihara, *Inorg. Chem.*, 2002, **41**, 4099.

41 L. Spiccia, B. Graham, M. T. V. Hearn, G. Lazarev, B. Mourabaki, K. S. Murray and E. E. T. Tiekink, *J. Chem. Soc., Dalton Trans*, 1997, 4089.

42 C. Bazzicalupi, A. Bencini, A. Bianchi, E. Berni, C. Giorgi, S. Maoggi, P. Paoletti and B. Valtancoli, *J. Org. Chem.*, 2002, **67**, 9107.

43 (*a*) T. Koike and E. Kimura, *J. Am. Chem. Soc.*, 1991, **113**, 8935; (*b*) T. Koike, M. Takamura and E. Kimura, *J. Am. Chem. Soc.*, 1994, **116**, 8443; (*c*) E. Kimura, Y. Kodama, T. Koike and M. Shoro, *J. Am. Chem. Soc.*, 1995, **117**, 8304.

44 A. Schrodt, A. Neubrand and R. van Eldik, *Inorg. Chem.*, 1997, **36**, 4579.

45 (*a*) S. Aoki, M. Shiro and E. Kimura, *Chem. Eur. J.*, 2002, **8**, 929; (*b*) S. Aoki, K. Iwaida, N. Hanamoto, M. Shiro and E. Kimura, *J. Am. Chem. Soc.*, 2002, **124**, 5256; (*c*) S. Aoki, M. Shiro, T. Koiche and E. Kimura, *J. Am. Chem. Soc.*, 2000, **122**, 576; (*d*) T. Koike, M. Takashige, E. Kimura, H. Fujioka and M. Shiro, *Chem. Eur. J.*, 1996, **2**, 617; (*e*) E. Kimura, T. Ikeda, M. Shionoya and M. Shiro, *Angew. Chem., Int. Ed. Engl.*, 1995, **34**, 663; (*f*) M. Shionoya, E. Kimura and M. Shiro, *J. Am. Chem. Soc.*, 1993, **115**, 6730.

46 X. Zhang and R. van Eldik, *Inorg. Chem.*, 1995, **34**, 5606.

47 R. Luckay and R. Hancock, *J. Chem. Soc., Dalton Trans*, 1991, 1491.

48 A. Altomare, M. C. Burla, M. Camalli, G. L. Cascarano, C. Giacovazzo, A. Guagliardi, A. G. Moliterni, G. Polidori and R. Spagna, *J. Appl. Crystallogr.*, 1999, **32**, 115.

49 G. M. Sheldrick, SHELX-97, University of Göttingen, Germany, 1997.

50 (*a*) G. Gran, *Analyst (London)*, 1952, **77**, 661; (*b*) F. J. Rossotti and H. Rossotti, *J. Chem. Educ.*, 1965, **42**, 375.

51 P. Gans, A. Sabatini and A. Vacca, *Talanta*, 1996, **43**, 807.

52 M. N. Burnett and C. K. Johnson, ORTEP-III: Oak Ridge Thermal Ellipsoid Plot Program for Crystal Structure Illustrations, Report ORNL-6895, Oak Ridge National Laboratory, Oak Ridge, TN, USA, 1996.