

Zinc(II) complexes of tripodal ligands providing phenolate and pyridine donors: formation, structure and hydrolytic activity

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A group of zinc(II) complexes derived from tri- and tetra-dentate proligands bearing pyridyl and phenolic arms have been prepared and characterised. Potentiometric titrations suggested that a stepwise complexation initially to the pendant OH, and then to pendant O⁻ occurred. The crystal structures of [Zn₂L³]₂[ClO₄]₂ (L³ = 2-{bis[2-(2-pyridyl)ethyl]aminomethyl}phenolate) and [Zn₂L⁶]₂[Zn(NCS)₄].0.5H₂O (L⁶ = 2-{bis[2-(2-pyridyl)ethyl]aminomethyl}-4-nitrophenolate) reveal that both complexes are dimers in the solid state; the co-ordination geometries around zinc(II) can be best described as distorted square pyramidal with one pyridyl nitrogen atom, one tertiary nitrogen atom and two phenolic oxygen atoms forming the basal plane and a pyridyl nitrogen atom in the axial position. The interzinc separations are 3.284 Å and 3.274 Å respectively. The crystal structure of [Zn L⁷]₂ (L⁷ = 4-nitro-2-{[2-(2-pyridyl)ethyl]aminomethyl}phenolate) reveals an octahedral complex with the zinc atom on a symmetry centre. The complexes [Zn₂L³]₂[ClO₄]₂ and [Zn₂L⁶]₂[BPh₄]₂, promote the hydrolysis of tris(4-nitrophenyl) phosphate; the former also has a small activity in the hydrolysis of bis(4-nitrophenyl) phosphate.

Three zinc motifs have been recognised in zinc enzymes, structural, catalytic, and co-catalytic zinc.¹ The role of zinc in the former is to maintain the structural integrity of the protein in the immediate vicinity of the metal. The critical feature of the catalytic site is the presence of a molecule of water which can be ionised, polarised or displaced. A co-catalytic site contains two, or more, zinc atoms in close proximity which together can act as a catalytic unit.

In *Escherichia coli* alkaline phosphatase (AP), a non-specific phosphomonoesterase,² there are three metal atoms, two zinc and one magnesium, so constituting a co-catalytic site (Fig. 1). In this trinuclear constellation the two zinc atoms are separated by 3.94 Å. One zinc atom (Zn¹) occupies a catalytic site and is five-co-ordinated to His-331 and His-412, to both carboxylate oxygens of Asp-327 and to a water molecule.^{2,3} The second non-catalytic zinc (Zn²) is tetrahedrally co-ordinated by His-370, one oxygen atom from Asp-369, the hydroxyl group from Ser-102 and the carboxyl group of Asp-51. This group serves as a bridge to the magnesium. An amino acid bridge between the two non-catalytic metal sites is a feature of co-catalytic sites and helps hold the three metals in close proximity.

In order to investigate the mechanism of phosphate ester hydrolysis and the relationship between structure and reactivity, small-molecule zinc(II) model complexes have been studied.⁴⁻¹⁵ In a number of these studies relatively rigid ligands, homoleptic macrocyclic ligands such as 1,4,7-triazacyclononane¹⁰ and 1,5,9-triazacyclododecane¹¹⁻¹⁴ or homoleptic tripodal ligands derived from the hydrotris(pyrazolylborate) anion,¹⁵ capable of capping one face of a tetrahedron were used to co-ordinate to three sites on the metal and so leave zinc(II) co-ordinatively unsaturated enabling the co-ordination of water. The aquazinc complexes formed can then generate the L-Zn^{II}-OH species proposed as present at the catalytic site during the hydrolytic action of zinc-containing enzymes.¹⁶ As the metalloproteins in question are often heteroleptically co-ordinated we have initiated a programme to develop heteroleptic tripodal ligands which will facilitate five-co-ordination of zinc, as in AP, and from which we aim to gain insight into the roles played by chelate ring size, geometric constraints and electronic effects on the reactivity of the metal centre. Recently we reported a five-co-ordinate zinc(II) complex, derived from a tripodal ligand bearing two phenolate

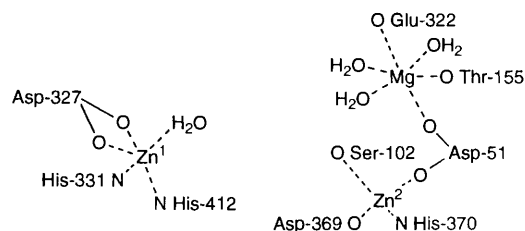


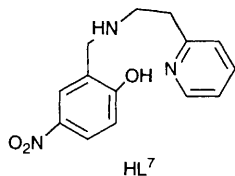
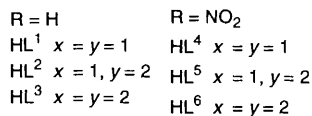
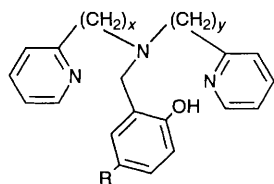
Fig. 1 Schematic representation of the trinuclear metal constellation in *Escherichia coli* AP

donors, which showed hydrolytic activity towards bis- and tris-nitrophenyl phosphates.¹⁷ In the present report we describe the synthesis of a series of zinc(II) complexes derived from tripodal ligands providing a single phenolate donor together with the structures of three of the complexes. Initial results on the abilities of two of the complexes to promote hydrolysis of phosphates are also presented.

Experimental

Reagents and solvents used were of commercial reagent quality. Purification of the proligands HL¹–HL⁶ was effected by using flash chromatography with silica gel (40–63 µm).¹⁸ Elemental analyses were carried out by the University of Sheffield Microanalytical Service. Infrared spectra were recorded as KBr discs using a Perkin-Elmer 1600 IR Fourier-transform spectrophotometer (4000–400 cm⁻¹), electronic absorption spectra using a Philips PU8720 UV/VIS scanning spectrophotometer operating in the range 220–500 nm, ¹H NMR spectra at 220 MHz on a Perkin-Elmer R34 spectrometer, ¹³C NMR spectra (62.9 MHz) using a Bruker AM-250 spectrometer and positive-ion fast atom bombardment (FAB) mass spectra on a Kratos MS 80 spectrometer (matrix 3-nitrobenzyl alcohol).

CAUTION: although no problems were encountered during the preparation of the perchlorate salts and the use of perchloric acid in the titrations described below, suitable care and precautions should be taken when handling such potentially hazardous compounds.



Syntheses

The proligands (HL¹–HL⁶) were prepared according to the methods described previously.^{19,20}

HL⁷. To a cold tetrahydrofuran (thf) solution (80 cm³) containing 2-(2-aminoethyl)pyridine (10 mmol, 1.22 g) and triethylamine (20 mmol, 2.02 g), was added dropwise 2-chloromethyl-4-nitrophenol (10 mmol, 1.88 g) in thf (20 cm³) with rapid stirring. The mixture was allowed to warm to room temperature and then heated to reflux for 2 h. On cooling the resultant suspension was filtered to remove the solid. After evaporation of the filtrate to dryness, MeOH (60 cm³) was added to the residue and the mixture was heated to reflux. After cooling the suspension was filtered to obtain a yellow solid which was recrystallised from methanol to generate yellow crystals (2.05 g, 74.8%) (Found: C, 61.35; H, 5.60; N, 15.55. Calc. for C₁₄H₁₅N₃O₃: C, 61.55; H, 5.55; N, 15.40%). ¹H NMR (Me₂SO): δ 3.10 (t, 2 H), 3.25 (t, 2 H), 4.00 (s, 2 H), 6.45–8.00 (m, 6 H, aromatic), and 8.50 (d, 1 H, pyridine). Mass spectrum: *m/z* = 274 (*M* + H⁺, 100), 123 (50), 106 (10) and 94 (35%).

[Zn₂L₂][BPh₄]₂·H₂O 1. A methanolic solution (40 cm³) containing proligand HL¹ (1 mmol, 0.31 g), Zn(ClO₄)₂·6H₂O (1 mmol, 0.37 g) and triethylamine (1 mmol, 0.10 g) was heated to reflux for 1 h. The salt NaBPh₄ (1 mmol, 0.37 g in 5 cm³ MeOH) was added and a white precipitate emerged immediately. The mixture was refluxed for another hour. On cooling the resulting crystalline solid was filtered off and recrystallised from MeCN–MeOH (1:1) to give small crystals of the product (0.56 g, 81%) (Found: C, 74.25; H, 5.35; N, 6.25. Calc. for C₈₆H₇₈B₂N₆O₃Zn₂: C, 74.10; H, 5.65; N, 6.05%). IR (KBr disc): 3053, 1609, 1577, 1483, 1446, 1426, 1265, 1025, 753, 734 and 706 cm⁻¹. Mass spectrum: *m/z* = 371 (74) and 369 ([ZnL¹]⁺, 20%).

[Zn₂L₂][BPh₄]₂·2MeCN 2. The compound was prepared by the same procedure as 1. Recrystallisation of the resultant solid from acetonitrile–methanol (1:1) generated small crystals (0.36 g, 52%) (Found: C, 73.75; H, 5.75; N, 7.20. Calc. for C₉₂H₈₆B₂N₈O₂Zn₂: C, 74.35; H, 5.85; N, 7.55%). IR (KBr disc): 3054, 1609, 1577, 1482, 1446, 1266, 1024, 752, 734 and 706 cm⁻¹. Mass spectrum: *m/z* = 1087 (*M*⁺, 21) and 382 (100%).

[Zn₂L₂][ZnCl₄]₂ 3. Proligand HL³ (1 mmol, 0.33 g), ZnCl₂ (2 mmol, 0.27 g) and NEt₃ (1 mmol, 0.10 g) were dissolved in methanol (50 cm³); the mixture was heated to reflux for 2 h. The resulting solution was filtered whilst still warm to remove any residual solid. The filtrate was allowed to stand at room temperature for a few days and a microcrystalline solid deposited (0.32 g, 64%) (Found: C, 50.45; H, 4.55; N, 8.60. Calc. for C₄₂H₄₄Cl₄N₆O₂Zn₃: C, 50.30; H, 4.40; N, 8.40%). IR (KBr disc): 1608, 1567, 1485, 1446, 1269, 1105, 1024 and 769 cm⁻¹. Mass spectrum: *m/z* = 793 ([Zn₂L₂]⁺, 12), 396 ([ZnL³]⁺, 100) and 290 (35%).

[Zn₂L₂][ClO₄]₂ 4. Proligand HL³ (1 mmol, 0.33 g) and triethylamine (1 mmol, 0.10 g) were dissolved in methanol (30 cm³). To the warm solution an equimolar amount of Zn(ClO₄)₂·4Me₂SO (0.77 g in 5 cm³ hot methanol) was added. The mixture was refluxed for 4 h. On cooling a white solid emerged and was filtered off (0.36 g, 72%). Recrystallisation of this powder from acetonitrile–methanol (1:9) solution gave suitable crystals for X-ray analysis (Found: C, 50.50; H, 4.40; N, 8.50. Calc. for C₄₂H₄₄Cl₂N₆O₁₀Zn₂: C, 50.70; H, 4.45; N, 8.45%). IR (KBr disc): 1609, 1571, 1482, 1448, 1387, 1314, 1263, 1088, 1026, 764 and 623 cm⁻¹. Mass spectrum: *m/z* = 894 (*M*⁺, 20) and 396 (100%).

[Zn₂L₂][BPh₄]₂·H₂O 5. Equimolar amounts (1 mmol) of proligand HL⁴ (0.35 g) and Zn(ClO₄)₂·6H₂O (0.37 g) were dissolved in MeOH (50 cm³), triethylamine was added and a yellow precipitate emerged immediately. The mixture was heated to reflux for 1 h. The yellow powder was filtered off and dissolved in acetonitrile–methanol (1:2); NaBPh₄ (1 mmol, 0.37 g in 5 cm³ MeOH) was added dropwise. The solution was refluxed for another hour and a yellow-white solid emerged. This was recrystallised from MeCN (0.37 g, 48%) (Found: C, 69.20; H, 4.85; N, 7.85. Calc. for C₈₆H₇₆B₂N₈O₇Zn₂: C, 69.50; H, 5.15; N, 7.55%). IR (KBr disc): 3053, 1608, 1577, 1508, 1482, 1438, 1339, 1302, 1267, 1095, 735 and 707 cm⁻¹. Mass spectrum: *m/z* = 413 ([ZnL]⁺, 86) and 391 (100%).

[ZnL⁴(4-O₂NC₆H₄CO₂)] 6. The compound Zn(4-O₂NC₆H₄CO₂)₂ was prepared by replacement reaction with Zn(NO₃)₂ and sodium 4-nitrobenzoate in aqueous solution. The blue-green solid generated was filtered off and washed three times with 50% ethanol–water, dried in vacuum and used quickly without further purification.

The compound Zn(4-O₂NC₆H₄CO₂)₂ (1 mmol, 0.40 g) was dissolved in warm MeOH (40 cm³) and then the proligand HL⁴ (0.5 mmol, 0.18 g in 10 cm³ MeOH) and triethylamine (0.5 mmol, 0.06 g) were added. The mixture was heated to reflux for 2 h. After cooling the resultant solution was filtered to remove any residual solid. The filtrate was allowed to stand at room temperature overnight; needle-like crystals were deposited. Recrystallisation from acetonitrile–methanol (1:1) produced yellow block-like crystals (0.12 g, 56%) (Found: C, 53.45; H, 3.40; N, 11.90. Calc. for C₂₆H₂₁N₅O₇Zn: C, 53.90; H, 3.65; N, 12.10%). IR (KBr disc): 1624, 1595, 1517, 1488, 1438, 1342, 1377, 1305, 1183, 1093, 826, 772, 727 and 671 cm⁻¹. Mass spectrum: *m/z* = 413 (*M*⁺, 100%).

[Zn₂L₂][BPh₄]₂ 7. The compound was prepared using the same procedure as for 5. Yield = 0.43 g, 83% (Found: C, 70.70; H, 5.60; N, 7.45. Calc. for C₈₈H₇₈B₂N₈O₆Zn₂: C, 70.75; H, 5.25; N, 7.50%). IR (KBr disc): 1609, 1576, 1512, 1448, 1286, 1093 and 661 cm⁻¹. Mass spectrum: *m/z* = 427 ([ZnL]⁺, 100%).

[Zn₂L₂][BPh₄]₂ 8. To a methanolic solution (25 cm³) containing HL⁶ (1 mmol, 0.38 g) and an equimolar amount of triethylamine (0.10 g) was added Zn(ClO₄)₂·6H₂O (1 mmol, 0.37 g) in methanol (5 cm³). The mixture was heated to reflux for 2 h. On cooling, NaBPh₄ (1 mmol, 0.34 g in 5 cm³ methanol) was added to the clear solution. The resulting solution was heated again to reflux; a yellow-white precipitate emerged after a few minutes. This yellow-white powder (0.55 g, 91.2%) was recrystallised from acetonitrile–methanol (1:1) (Found: C, 70.95; H, 5.25; N, 7.05. Calc. for C₉₀H₈₂B₂N₈O₆Zn₂: C, 70.95; H, 5.40; N, 7.35%). Mass spectrum: *m/z* = 1204 (*M*⁺, 12) and 441 (100%).

[Zn₂L₂][Zn(NCS)₄] 9. A methanolic solution (40 cm³) containing proligand HL⁶ (1 mmol, 0.38 g), Zn(BF₄)₂·H₂O (1 mmol, 0.24 g) and triethylamine (1 mmol, 0.10 g) was heated to reflux for 1 h and then cooled. The compound NaSCN (1.5

mmol, 0.12 g) in MeOH (5 cm³) was added. After stirring at reflux temperature for another hour the resulting solution was left to stand at room temperature for a few days. The solvent was removed from the solution, the residue was crystallised with MeOH-ethyl acetate (1:3), and straw yellow block crystals were deposited (0.25 g, 43%) (Found: C, 46.50; H, 3.45; N, 14.10; S, 10.50. Calc. for C₄₆H₄₄N₁₂O₆S₄Zn₃: C, 46.00; H, 3.70; N, 14.00; S, 10.65%). IR (KBr disc): 2075 (SCN), 1610, 1577, 1510, 1483, 1447, 1336, 1305, 1284 (NO₂), 1265, 1092 and 661 cm⁻¹. Mass spectrum *m/z* = 441 ([ZnL]⁺, 100%). Crystals suitable for X-ray analysis were grown from ethanol; the analysis showed the complex was hemihydrated, [Zn₂L₆]⁺·[Zn(NCS)₄]⁻·0.5H₂O **9a**.

[ZnL₇]⁺ **10**. A suspension containing methanol (60 cm³) and HL⁷ (1 mmol, 0.27 g) was heated to reflux until the proligand dissolved. To the warm solution, triethylamine (1 mmol, 0.10 g) was added and then ZnCl₂ (1 mmol, 0.14 g in 5 cm³ methanol). The mixture was refluxed for 4–5 h. After cooling the resulting suspension was filtered to obtain a yellow powder (0.16 g, 52.3%), which was recrystallised from acetonitrile-methanol (1:4) solution at room temperature to generate crystals suitable for X-ray analysis (Found: C, 54.90; H, 4.75; N, 13.65. Calc. for C₂₈H₂₈N₆O₆Zn: C, 55.15; H, 4.65; N, 13.80%). IR (KBr disc): 3265, 1593, 1559, 1497, 1481, 1439, 1368, 1291, 1170, 1085 and 663 cm⁻¹. Mass spectrum: *m/z* = 611 (*M*⁺, 23) and 274 (41%).

Potentiometric pH titration^{21,22}

Titration were carried out under N₂ in a cell thermostatted at 25 °C by means of a water-circulating bath. The electrode system was standardised with appropriate buffers immediately before use and checked by the theoretical titration curves of 3.00 and 4.00 mmol dm⁻³ HClO₄ with a 0.100 mol dm⁻³ NaOH solution at 25 °C and *I* = 0.10 mol dm⁻³ (NaClO₄) in high- and low-pH regions. The pH value in 33 and 52% ethanol aqueous solution at 25 °C ± 0.1 °C was determined by subtracting 0.09 and 0.22 units respectively from the pH-meter reading according to the method of Bates *et al.*²³ Titrant was delivered by means of a micrometer-driven syringe. A typical pH-metric determination was carried out as follows: an aqueous EtOH solution (40 cm³) of the proligand (1.00 mmol dm⁻³) with 3 equivalents HClO₄ (3.00 mmol dm⁻³) in the absence [for determination of ligand ionisation constants (p*K*_a)] or presence of zinc(II) ion [for determination of deprotonation constants of zinc(II)-bound H₂O in the zinc(II) complex] was titrated with 0.10 mol dm⁻³ NaOH aqueous solution; NaClO₄ was used as supporting electrolyte (*I* = 0.10 mol dm⁻³). The titration data were treated by using the ULTRAFIT 881 program (Biosoft, Cambridge) (p*K*_a determination). At least two independent pairs of titrations were always made for the determination of these constants.

Kinetics of hydrolysis

Tris(4-nitrophenyl) phosphate. The hydrolysis rate in 33 (for complex **4**) and 52% (for **8**) EtOH solution was measured by following the increase in UV absorption at 405 nm at 25.0 ± 0.2 °C and *I* = 0.10 mol dm⁻³ (NaClO₄) according to the method of Koike and Kimura.¹¹ A series of buffered solutions containing 10 mmol dm⁻³ buffer {piperazine-*N,N'*-bis(ethane-2-sulfonate) (pipes) (pH 6.5–7.5), *N'*-(2-hydroxyethyl)piperazine-*N*-ethanesulfonate (hepes) (pH 7.5–8.0), 3-[tris(hydroxymethyl)methylamino]propanesulfonate (taps) (pH 8.0–9.0), 2-(cyclohexylamino)ethanesulfonate (ches) (pH 8.6–10.0)} were used. The initial solution containing 33 μmol dm⁻³ phosphate and 1.0–2.0 mmol dm⁻³ complex was prepared from stock solution (5.0 mmol dm⁻³ phosphate in dry thf, 60 mmol dm⁻³ complex **4** in 1:1 MeCN–MeOH and 30 mmol dm⁻³ complex **8** in MeCN). A typical procedure was as

follows: immediately after rapid injection of 20 μl of 5.0 mmol dm⁻³ phosphate in dry thf into the appropriate pH buffer solution (10 mmol dm⁻³, total 3.0 cm³) containing 1.0 mmol dm⁻³ zinc(II) complex [the reference experiment did not contain the zinc(II) complex], the absorption increase was recorded until 3 half-lives were complete. The pseudo-first-order rate constants *k*_{obs}/s⁻¹ were obtained by fitting the absorbance *versus* time data by the first-order reaction exponential model *A_t* = *a*(1 – e^{-*kt*}) + *b*, where *a* = *A_∞* – *A₀*, *b* = *A₀* using the MACCURVEFIT 1.0.7 program. A plot of *k*_{obs} vs. the zinc(II) complex concentration (1.0–2 mmol dm⁻³) at a given pH gave a straight line (ULTRAFIT 881 linear), the slope of which was the second-order rate constant *k*₂/dm³ mol⁻¹ s⁻¹ and the intercept *k*₀/s⁻¹. Subsequent hydrolysis of the bis(4-nitrophenyl) phosphate produced was too slow to be detected under the above conditions, thus another experimental procedure was employed.

Bis(4-nitrophenyl)phosphate. The hydrolysis of the phosphate in 33% ethanol aqueous solution was measured by following the increase in UV absorption at 405 nm of the released 4-nitrophenolate at *I* = 0.20 mol dm⁻³ (NaClO₄). In this case the temperature was 35 °C and 4 mmol dm⁻³ phosphate were employed otherwise the reaction conditions used for the tris derivative were maintained. The absorption increase giving a straight line was recorded until 1% hydrolysis had occurred. The reported rate constants (*k*_{obs}) are averages of duplicate or triplicate measurements.

Crystallography

[Zn₂L₂][ClO₄]₂ **4**. *Crystal data.* C₄₂H₄₄Cl₂N₆O₁₀Zn₂, *M* = 994.52, crystallises from ethanol-methanol as clear blocks, crystal dimensions 0.55 × 0.25 × 0.175 mm, orthorhombic, space group *Pbca* (*D*_{2h}¹⁵, no. 61), *a* = 13.079(18), *b* = 15.320(6), *c* = 21.862(8) Å, *U* = 4381(6) Å³, *Z* = 4, *D_c* = 1.508 g cm⁻³, Mo-Kα radiation (λ = 0.710 69 Å), μ(Mo-Kα) = 13.06 cm⁻¹, *F*(000) = 2047.59.

Three-dimensional, room-temperature X-ray data were collected in the range 3.5 < 2θ < 50° on a Nicolet R3 diffractometer by the ω-scan method. Of the 4557 reflections measured, all of which were corrected for Lorentz-polarisation effects, and for absorption by analysis of six azimuthal scans (minimum and maximum transmission coefficients 0.244 and 0.331), 2021 independent reflections exceeded the significance level |*F*|/σ(|*F*|) > 3.0. The structure was solved by direct methods and refined by blocked-cascade least-squares on *F*. The perchlorate anion was refined with constrained *T_d* symmetry, but no significant disorder was detected. Hydrogen atoms were detected and refined in riding mode. Refinement converged at a final *R* = 0.0966 (*R'* = 0.1040, 282 parameters, mean and maximum δ/σ 0.015, 0.091), with allowance for the thermal anisotropy of all non-hydrogen atoms. Minimum and maximum final electron density –0.34 and 0.75 e Å⁻³. A weighting scheme *w*⁻¹ = σ²(*F*) + 0.003 06*F*² was used in the latter stages of refinement. Complex scattering factors were taken from the program package SHELXTL^{24a} as implemented on a Data General DG30 computer.

[Zn₂L₂][Zn(NCS)₄]-0.5H₂O **9a**. *Crystal data.* C₄₆H₄₃N₁₂O_{6.5}S₄Zn₃, *M* = 1192.27, crystallises from ethanol as yellow oblong blocks, crystal dimensions 0.82 × 0.47 × 0.32 mm, triclinic, space group *P* $\bar{1}$ (*C*₁, no. 2), *a* = 10.867(2), *b* = 14.450(2), *c* = 17.609(7) Å, α = 84.43(2), β = 73.48(2), γ = 82.490(10)°, *U* = 2623.0(12) Å³, *Z* = 2, *D_c* = 1.510 Mg m⁻³, Mo-Kα radiation (λ = 0.710 73 Å), μ(Mo-Kα) = 1.579 mm⁻¹, *F*(000) = 1218.

Three-dimensional, room-temperature X-ray data were collected in the range 3.5 < 2θ < 45° on a Siemens P4 diffractometer by the ω-scan method. Of the 8073 reflections

measured, all of which were corrected for Lorentz-polarisation effects (but not for absorption), 5611 independent reflections exceeded the significance level $|F|/\sigma(|F|) > 4.0$. The structure was solved by direct methods and refined by full-matrix blocked least squares on F^2 . Hydrogen atoms were included in calculated positions (and, in the case of the solvent water in optimised hydrogen-bonding positions) and refined in riding mode. Refinement converged at a final $R = 0.0443$ ($wR2 = 0.1202$ for all 6796 unique data, 647 parameters, mean and maximum δ/σ 0.000), with allowance for the thermal anisotropy of all non-hydrogen atoms. Minimum and maximum final electron density -0.58 and $0.44 \text{ e } \text{\AA}^{-3}$. A weighting scheme $w = 1/[\sigma^2(F_o^2) + (0.0631P)^2 + 1.8856P]$ where $P = (F_o^2 + 2F_c^2)/3$ was used in the latter stages of refinement. Complex scattering factors were taken from the program package SHELXL 93^{24b} as implemented on a Viglen 486dx computer.

[ZnL₂]⁷ 10. *Crystal data.* C₂₈H₂₈N₆O₆Zn, $M = 609.93$, crystallises as colourless oblong blocks, crystal dimensions $0.55 \times 0.40 \times 0.24 \text{ mm}$, monoclinic, space group $C2/c$, $a = 13.852(3)$, $b = 11.2780(13)$, $c = 17.7050(14) \text{ \AA}$, $\beta = 99.53(4)^\circ$, $U = 2727.8(7) \text{ \AA}^3$, $Z = 4$, $D_c = 1.485 \text{ Mg m}^{-3}$, Mo-K α radiation ($\lambda = 0.71073 \text{ \AA}$), $\mu(\text{Mo-K}\alpha) = 0.955 \text{ mm}^{-1}$, $F(000) = 1264$.

Three-dimensional, low-temperature X-ray data were collected in the range $2.33 < \theta < 25.03$ on an Enraf-Nonius FAST area detector. Of the 5633 reflections measured, all of which were corrected for Lorentz-polarisation effects (but not for absorption), 1709 independent reflections exceeded the significance level $|F|/\sigma(|F|) > 4.0$. The structure was solved by direct methods and refined by blocked-cascade least squares on F^2 . Hydrogen atoms were included in calculated positions and refined in riding mode. Refinement converged at a final $R = 0.0407$ ($wR2 = 0.1087$ for all 2041 unique data, 187 parameters, mean and maximum δ/σ 0.000), with allowance for the thermal anisotropy of all non-hydrogen atoms. Minimum and maximum final electron density -0.507 and $0.603 \text{ e } \text{\AA}^{-3}$. A weighting scheme $w = 1/[\sigma^2(F_o^2) + (0.0618P)^2]$ where $P = (F_o^2 + 2F_c^2)/3$ was used in the latter stages of refinement. Complex scattering factors were taken from the program package SHELXL 93^{24b} as implemented on a Viglen 486dx computer.

Atomic coordinates, thermal parameters, and bond lengths and angles have been deposited at the Cambridge Crystallographic Data Centre (CCDC). See Instructions for Authors, *J. Chem. Soc., Dalton Trans.*, 1996, Issue 1. Any request to the CCDC for this material should quote the full literature citation and the reference number 186/60.

Results and Discussion

Synthesis and characterisation of complexes

Zinc(II) complexes of the tripodal ligands were synthesised using similar procedures to those used in the preparation of the copper(II) analogues.¹⁹ Most require the presence of a bulky anion, tetraphenylborate, to enable the products to be precipitated. The precipitates can be then recrystallised from either methanol, acetonitrile or their mixed solvent to yield crystalline materials. The reaction between proligand HL³ and Zn(ClO₄)₂ however yielded a white solid directly from the cold reaction mixture single crystals of which complex, **4**, were generated by recrystallisation of the solid from MeCN–MeOH. The crystal structure showed that the complex molecule is a dimeric species. In contrast when the complexation reaction was conducted with zinc chloride, bearing the strongly coordinating chloride anion, or by addition of NaSCN in order to cleave the dimer and to provide an exogenous donor, yellow-block crystalline products were formed. Microanalytical data

suggested that there is an extra molecule of ZnCl₂ or Zn(NCS)₂ present in the zinc(II) complexes **3** and **9** respectively. This unexpected result has been shown, by the X-ray crystallographic study of **9**, to stem from the presence of a [Zn(NCS)₄]²⁻ anion. Complex **3** is therefore expected to contain a [ZnCl₄]²⁻ anion.

The IR spectra of the zinc(II) complexes have similar patterns to those of the copper(II) analogues.¹⁹ Three sets of peaks at around 1600, 1450 and 1300 cm⁻¹ can be assigned to stretches from the ligand frameworks. The characteristic bands for the anions are identified as peaks at 1088 and 623 cm⁻¹ for perchlorate and 3050, 735 and 707 cm⁻¹ for tetraphenylborate. The band for the NO₂ group from the ligands and from nitrobenzoate can be observed at around 1280 cm⁻¹; this often overlays with the band of the ligand framework at 1300 cm⁻¹. A very strong absorption band at 2075 cm⁻¹, for SCN⁻, is found in the spectrum of complex **9**.

The positive-ion FAB mass spectra of all the zinc(II) complexes exhibit strong parent peaks. In the spectra of the dimers, peaks, generally weak, corresponding to [Zn₂L₂X]⁺, can be found. The elemental analysis data are consistent with the proposed formulation of the complexes.

For comparison, a further zinc(II) complex **10** was synthesised from the reaction of linear tridentate HL⁷ carrying pyridyl and phenolic moieties. The complexation reaction was performed in a similar manner to the procedure for the tripodal zinc(II) complexes. Equimolar amounts of the proligand and ZnCl₂ in methanol solution containing triethylamine were heated to reflux for a few hours. The resultant yellow powder was recrystallised from an acetonitrile–methanol solvent mixture to generate suitable single crystals for X-ray crystallography. The product was shown to be a mononuclear six-co-ordinated complex in which two equivalent ligands share a zinc(II) ion even though an excess amount of zinc(II) was used in the complexation. The positive-ion FAB mass spectrum shows a molecular peak at $m/z = 611$ confirming the formation of the complex.

Crystal structures of complexes

[ZnL₃][ClO₄]₂ 4. The X-ray single-crystal study of complex **4** confirmed that it is a dimer (Fig. 2, Table 1) similar to the copper(II) complex derived from the same ligand.^{19,25} The molecular structure illustrates that two pyridyl nitrogen atoms, an amine nitrogen atom, and a phenoxo oxygen atom from the tetradentate ligand form the co-ordination sphere of zinc(II). Five-co-ordination is achieved through the phenolate oxygen

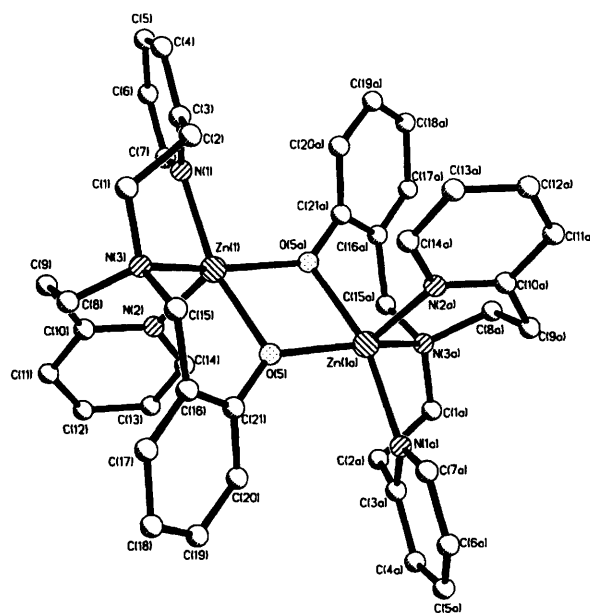


Fig. 2 The molecular geometry of the cation of complex **4**

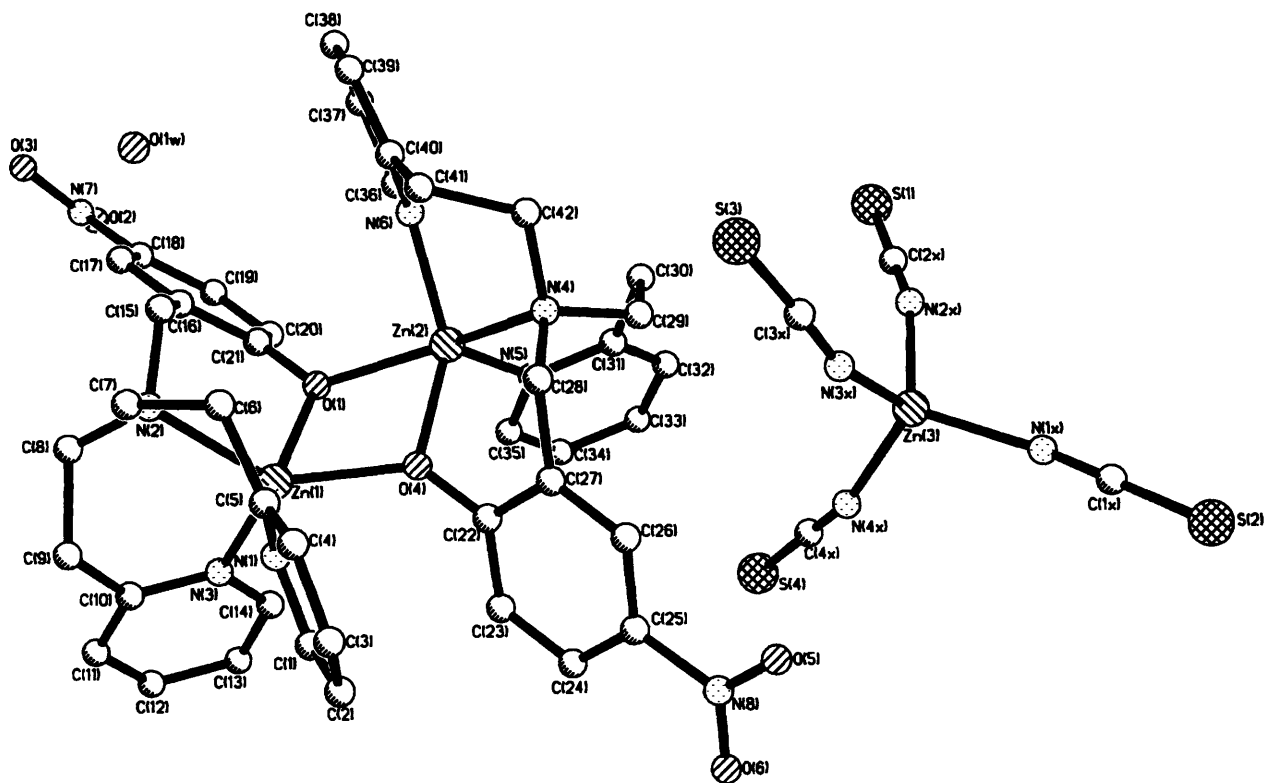


Fig. 3 The molecular geometry of complex **9a**

acting as a bridging atom linking the two parts of the dimer. The zinc(II) co-ordination geometry is best described as distorted square pyramidal. One pyridyl nitrogen atom, one tertiary amine nitrogen atom and two phenolate oxygen atoms lie approximately in the basal plane, in which, N(1) is *trans* to O(5) [$N(1)-Zn(1)-O(5)$ 163.0°] and N(3) is *trans* to O(5a) [$N(3)-Zn(1)-O(5a)$ 150.0°]. Another pyridyl nitrogen atom occupies the axial position of the square pyramid. The two halves of the dimer are *trans* to each other. The two zinc atoms are separated by 3.284 Å; this is shorter than the separation between the two zinc atoms of the active site in alkaline phosphatase. The bridge is asymmetric and the Zn(1)–O(5) bond [2.088(6) Å] is longer than Zn(1)–O(5a) [2.054(7) Å]. The two pyridyl arms, which are equivalent in the proligand, have different co-ordination features in the complex. One provides an equatorial bond and the other arm provides an axial bond to the zinc(II): the former [Zn(1)–N(1) 2.114(8) Å] is longer than the latter [Zn(1)–N(2) 2.081(8) Å].

[Zn₂L₆][Zn(NCS)₄] \cdot 0.5H₂O **9a**. The crystal structure of complex **9a** displays an interesting combination of co-ordination environments for the zinc atom (Fig. 3). Besides the tripodal dimeric cation, the structure contains a tetrathiocyanatozincate(2[−]) anion. Surprisingly the addition of thiocyanate to the reaction mixture did not result in cleavage of the dimer. This result contrasts with that observed for the copper analogue in which added thiocyanate caused cleavage of the dimer such that a mononuclear complex was formed.¹⁸ The dimeric cation in the present complex has a very similar geometric structure to that of complex **4**. Its two parts share nitrophenolate oxygen atoms which are opposite each other. The co-ordination geometry around the zinc atoms can be described as trigonal bipyramidal with a large distortion. Four thiocyanate anions equivalently surround the third zinc atom, co-ordinating through the nitrogen atoms such that an almost perfect tetrahedral geometry occurs. A solvent water molecule is disordered between two symmetry-equivalent sites near to an inversion centre. It forms a pair of almost identical length

hydrogen bonds to a symmetry-related nitro group O(2) atom (O \cdots O 2.886 and 2.923 Å).

[ZnL₂]**10**. The co-ordination geometry about the zinc(II) of complex **10** (Fig. 4) is very close to octahedral. The zinc atom, which is on a symmetry centre, is bonded to the phenolic oxygen atoms, the secondary amine and pyridyl nitrogen atoms of two ligands, giving an all-*trans* octahedral adduct. The two secondary amine nitrogen atoms (Zn–N 2.161 Å) and the two phenolic oxygen atoms (Zn–O 2.052 Å) make up a square plane with the two pyridyl nitrogen atoms occupying the apical positions at longer distances (Zn–N 2.282 Å). The two phenol rings [root mean square (r.m.s.) deviation 0.009 Å] lie parallel to each other and the two pyridyl rings are also planar (r.m.s. deviation 0.092 Å). The co-ordination bond angles involving the equivalent *trans* ligands are 180° by symmetry; the other angles range from 86.16(9) to 93.84(9)°. The inter-zinc distance of 3.274 Å is slightly lower than that determined for complex **4**. The Zn–N distances [2.161(2) and 2.282(3) Å] are normal and lie slightly beyond the range for similar compounds.²⁶ The Zn–O bond length [2.052(2) Å] is similar to that found in complex **4**.

The formation of complexes

The mode of formation for the dinuclear complexes can be demonstrated by pH-metric titration of the proligands in the presence of 1 equivalent of Zn(ClO₄)₂ under an argon atmosphere. Fig. 5 shows typical titration curves for the formation of zinc(II) complexes in EtOH–water solution at 25 °C together with proligand ionisation trends at $I = 0.1$ mol dm^{−3} (NaClO₄). The deprotonation constants for the phenol groups of tripodal proligands in this EtOH–water solution can be determined by means of this pH-metric titration aided by spectroscopic titrations.

The p*K*_a values, for the ionisation of the phenols, of 5.80 (HL¹), 6.11 (HL²) and 7.41 (HL³) at 25 °C and $I = 0.1$ mol dm^{−3} (NaClO₄) are smaller than that of 10.0 for phenol itself

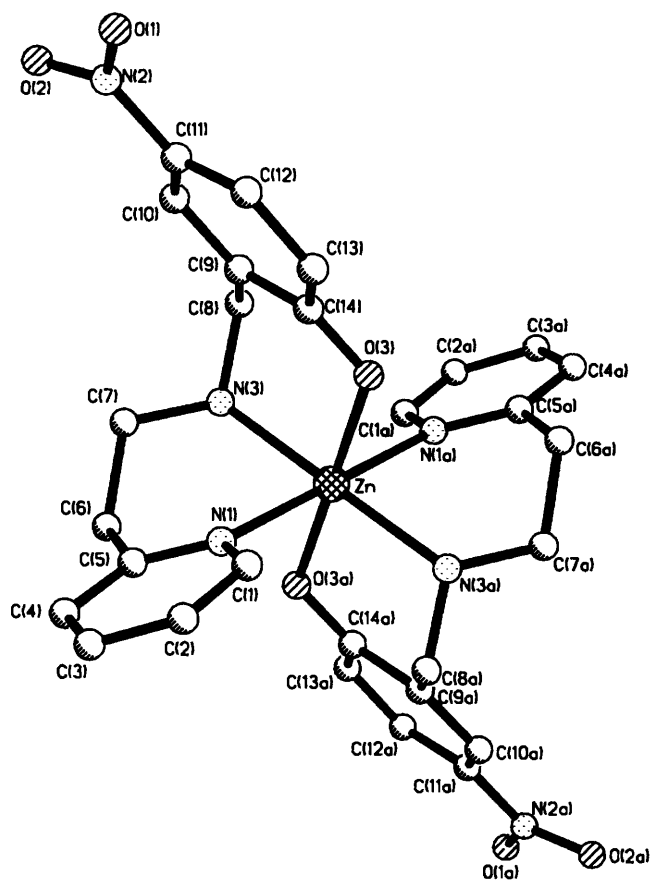


Fig. 4 The molecular geometry of complex 10

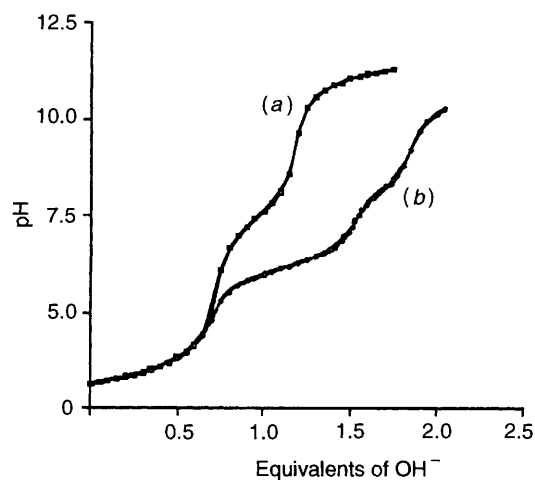


Fig. 5 Experimental titration curves at 25 °C and $I = 0.10 \text{ mol dm}^{-3}$ (NaClO_4) for (a) $1.00 \text{ mmol dm}^{-3} \text{ HL}^3 \cdot 3\text{HClO}_4$, (b) (a) in the presence of $1.00 \text{ mmol dm}^{-3} \text{ Zn}^{II}$

(Table 2). These compare favourably with the values found by Kimura *et al.*¹² for a series of macrocyclic tetraamines bearing pendant phenolic arms. The presence of a nitro-group at the *para* position of phenol leads to even lower pK_a values [4.29 (L^4), 5.24 (L^5), 5.97 (L^6) and 5.53 (L^7)]. The observed trend for the pK_a values to increase in the sequences $\text{L}^1 < \text{L}^2 < \text{L}^3$ and $\text{L}^4 < \text{L}^5 < \text{L}^6$ suggests an increase in stability due to the availability of more six-membered chelate rings in the co-ordination sphere.

The UV spectra of the proligands also provide information concerning the ionisation of the phenols. The absorption maxima (Table 2) for the phenol and phenolate forms occur discretely at 262 and 296 nm respectively, compared with 269 and 287 nm for simple phenol itself; a similar pattern occurs for

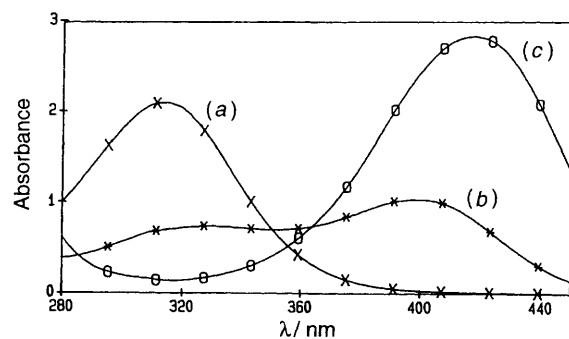
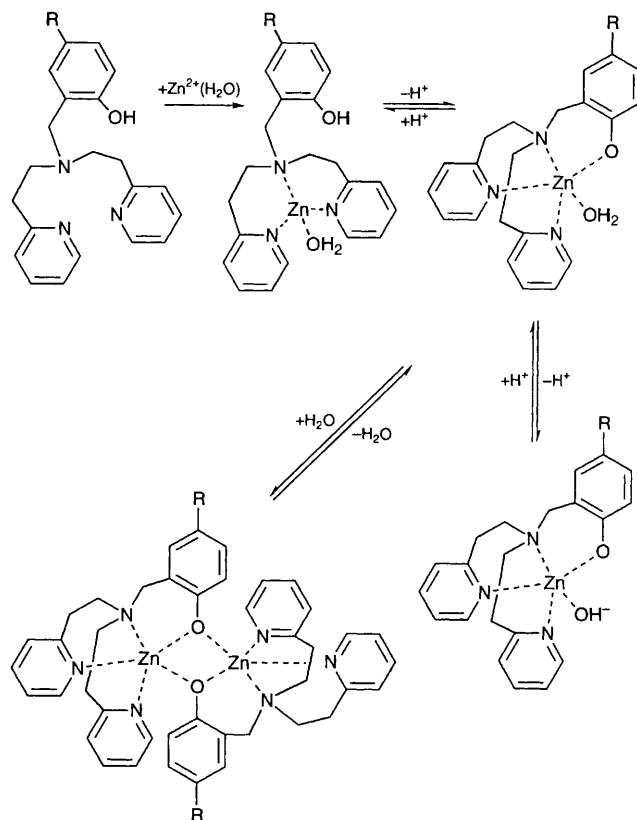


Fig. 6 The UV absorption curves of HL^6 at different pH values and $I = 0.1 \text{ mol dm}^{-3}$ (NaClO_4), pH 4.0 (a), 6.5 (b) and 10.5 (c)



Scheme 1 The stepwise formation of the zinc(II) complexes

the proligands bearing a 4-nitrophenol group. Typical UV absorption curves for HL^6 at three pH values are shown in Fig. 6. At low pH [(a)] the absorption maximum, assigned to the phenol form, occurs at 314 nm. At pH 6.5 [(b)] the deprotonation of the phenol is incomplete and two absorption bands, due to the presence of the two forms, are found in the spectrum. At high pH [(c)] the phenolate emerges as the dominant form in the spectrum with the absorption maximum occurring at 417 nm.

When the pH-metric titrations were carried out in the presence of $1.00 \text{ mmol dm}^{-3}$ zinc(II) the resultant data showed the mode of formation for the complexes. A representative titration curve for the formation of complex 4 is shown in Fig. 5(b). It reveals three points of inflection, which suggest a stepwise complexation proceeding via $[\text{Zn}(\text{HL}^3)]^{2+}$ and $[\text{ZnL}^3]^+$. The occurrence of phenol dissociation below the pK_a value of the free proligands (buffer region at $[\text{OH}] = 0.8\text{--}1.5 \text{ mol dm}^{-3}$) implies the strong tendency of phenolate co-ordination to help capture zinc(II) in complexes. The inflection point at pH 8.27 is assigned to the deprotonation constant of the co-ordinated water in the complex (Scheme 1). Similar situations occurred in the formation of the metal complexes

Table 1 Selected bond lengths (Å) and angles (°)

(a) $[\text{Zn}_2\text{L}^3_2][(\text{ClO}_4)_2]$ 4			
Zn(1)–O(5)	2.088(6)	Zn(1)–N(1)	2.114(8)
Zn(1)–N(2)	2.081(8)	Zn(1)–N(3)	2.192(8)
Zn(1a)–O(5)	2.054(7)	Zn(1)–O(5a)	2.054(7)
Zn(1)···Zn(1a)	3.284(3)		
O(5)–Zn(1)–N(1)	163.0(3)	O(5)–Zn(1)–N(2)	95.9(3)
N(1)–Zn(1)–N(2)	100.6(3)	O(5)–Zn(1)–N(3)	91.0(3)
N(1)–Zn(1)–N(3)	90.7(3)	N(2)–Zn(1)–N(3)	99.2(3)
O(5)–Zn(1)–Zn(1a)	37.2(2)	N(1)–Zn(1)–Zn(1a)	131.8(2)
N(2)–Zn(1)–Zn(1a)	105.3(2)	N(3)–Zn(1)–Zn(1a)	123.6(2)
O(5)–Zn(1)–O(5a)	75.1(3)	N(1)–Zn(1)–O(5a)	95.3(3)
N(2)–Zn(1)–O(5a)	108.5(3)	N(3)–Zn(1)–O(5a)	150.0(3)
(b) $[\text{Zn}_2\text{L}^6_2][\text{Zn}(\text{NCS})_4]\cdot 0.5\text{H}_2\text{O}$ 9a			
Zn(2)–O(4)	2.015(3)	Zn(2)–N(5)	2.016(3)
Zn(2)–N(6)	2.047(4)	Zn(2)–O(1)	2.147(3)
Zn(2)–N(4)	2.168(3)	Zn(1)–O(1)	2.027(3)
Zn(1)–N(3)	2.043(4)	Zn(1)–O(4)	2.087(3)
Zn(1)–N(1)	2.101(4)	Zn(1)–N(2)	2.132(4)
Zn(3)–N(3x)	1.939(5)	Zn(3)–N(1x)	1.951(5)
Zn(3)–N(4x)	1.950(6)	Zn(3)–N(2x)	1.965(5)
Zn(1)–O(1)–Zn(2)	103.30(12)	Zn(1)–O(4)–Zn(2)	105.93(13)
O(4)–Zn(2)–N(5)	104.57(14)	O(4)–Zn(2)–N(6)	146.07(14)
N(5)–Zn(2)–N(6)	108.07(14)	O(4)–Zn(2)–O(1)	72.24(11)
N(5)–Zn(2)–O(1)	106.66(13)	N(6)–Zn(2)–O(1)	89.61(13)
O(4)–Zn(2)–N(4)	90.62(12)	N(5)–Zn(2)–N(4)	99.76(14)
N(6)–Zn(2)–N(4)	92.74(13)	O(1)–Zn(2)–N(4)	151.30(12)
O(1)–Zn(1)–N(3)	101.57(14)	O(1)–Zn(1)–O(4)	73.29(11)
N(3)–Zn(1)–O(4)	124.46(14)	O(1)–Zn(1)–N(1)	153.5(2)
N(3)–Zn(1)–N(1)	103.3(2)	O(4)–Zn(1)–N(1)	85.03(14)
O(1)–Zn(1)–N(2)	92.63(14)	N(3)–Zn(1)–N(2)	98.7(2)
O(4)–Zn(1)–N(2)	136.2(2)	N(1)–Zn(1)–N(2)	92.7(2)
N(3x)–Zn(3)–N(1x)	110.0(2)	N(3x)–Zn(3)–N(4x)	113.0(2)
N(1x)–Zn(3)–N(4x)	111.2(2)	N(3x)–Zn(3)–N(2x)	106.9(2)
N(1x)–Zn(3)–N(2x)	112.5(2)	N(4x)–Zn(3)–N(2x)	103.1(2)
(c) $[\text{ZnL}^7_2]$ 10			
Zn–O(3)	2.052(2)	Zn–N(1)	2.282(3)
Zn–N(3)	2.161(2)		
O(3)–Zn–N(1)	90.63(9)	O(3)–Zn–N(3)	90.88(9)
N(3)–Zn–N(1)	86.16(9)		

derived from macrocyclic polyamines bearing a phenol arm¹² and pendant alcohol.¹³ A possible mechanism for the dinuclear complexes is shown in Scheme 1.

Hydrolysis of phosphates enhanced by complexes

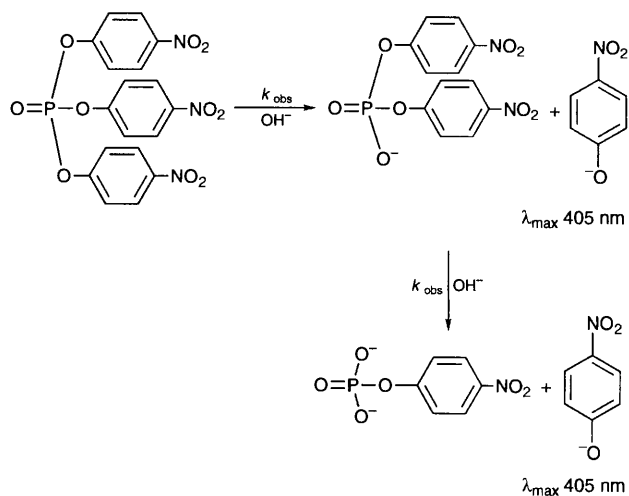
The hydrolysis of the bis- and tris-(4-nitrophenyl) phosphate esters enhanced by two representative zinc(II) complexes **4** and **8** was investigated. Since the tris phosphate and zinc(II) complexes are insoluble in pure water, EtOH was selected as a cosolvent (33% for **4** and 52% for **8**). In 33 and 52% ethanol aqueous solutions, thermodynamic deprotonation constants of zinc(II)-bound H₂O (pK_a), 8.27 for **4** and 9.86 for **8**, were determined by potentiometric pH titration at $I = 0.10$ mol dm⁻³ (NaClO₄) and 25 °C. The values are comparable with the pK_a value of 9.0 for free (solvated) zinc(II) ion in aqueous solution.²⁸

Complexes **4** and **8** promote the hydrolysis of OP(OC₆H₄NO₂-4)₃ to produce an equimolar amount of 4-nitrophenolate and ⁻O₂P(OC₆H₄NO₂-4)₂ in aqueous EtOH solution at 25 °C; **4** promotes further hydrolysis to leave an equimolar amount of ²⁻O₃P(OC₆H₄NO₂-4) at the higher temperature of 35 °C (Scheme 2). The hydrolysis of the bis phosphate promoted by complex **8** was too slow to be detected in this experiment. The reaction was monitored by following the increase in UV absorption at 405 nm (assigned to the 4-

Table 2 pK_a Values^a and UV data at $I = 0.1$ mol dm⁻³ (NaClO₄) and 25 °C

Proligand	pK_a for phenol	λ/nm ($\epsilon/\text{dm}^{-3} \text{mol}^{-1} \text{cm}^{-1}$)	
		Phenol form	Phenolate form
HL ¹	5.80	261 (6280) (pH 4.0)	296 (2060) (pH 9.5)
HL ²	6.11	262 (6300) (pH 3.5)	295 (2570) (pH 9.8)
HL ³	7.41	262 (7110) (pH 5.0)	296 (2990) (pH 10.0)
Phenol ^b	10.0	269	287
HL ⁴	4.29	319 (8910) (pH 3.5)	416 (14 990) (pH 7.0)
HL ⁵	5.24	317 (7780) (pH 3.5)	416 (14 300) (pH 7.0)
HL ⁶	5.97	314 (14 890) (pH 4.0)	399 (7790) (pH 6.5)
HL ⁷	5.53	311 (8780) (pH 3.8)	413 (8660) (pH 8.0)
4-Nitrophenol ^b	7.1	317	400 (pH 10.0)

^a Determined potentiometrically. ^b Ref. 27.

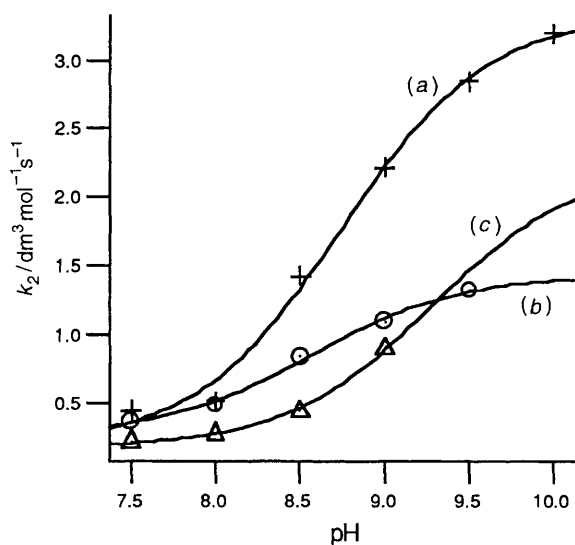
**Scheme 2** The hydrolysis of phosphate esters

nitrophenolate anion). The pseudo-first-order rate constants $k_{\text{obs}}/\text{s}^{-1}$ at various pH and zinc complex concentrations were obtained by fitting the absorbance *versus* time data by a first-order reaction model using the MACCURVEFIT 1.0.7 program. From the linear plots of k_{obs} *versus* $[\text{Zn}^{2+}]$, the second-order rate constants k_2 (slopes) were obtained. The intercepts k_0 are the conditional first-order rate constants (at $[\text{Zn}^{2+}] = 0$) for the hydrolytic processes mediated mainly by buffer and free OH⁻ ions. These preliminary kinetic data for the hydrolysis of the phosphate esters are given in Table 3. The pH dependence for OP(OC₆H₄NO₂-4)₃ and ⁻O₂P(OC₆H₄NO₂-4)₂ with **4** and **8** over the range 7.5–10.0 is shown in Fig. 7.

For complex **4**, the k_2 *vs.* pH profiles (Fig. 7) for the OP(OC₆H₄NO₂-4)₃ hydrolysis at 25 °C and ⁻O₂P(OC₆H₄NO₂-4)₂ hydrolysis at 35 °C respectively show that both series have similar profiles: activity increases with increasing pH at intermediate pH values, but levels off at low and high pH. This is consistent with both the acidic and basic forms of the complex being active. From the pH *vs.* rate profile, points of inflection at pH 8.57 for OP(OC₆H₄NO₂-4)₃ and pH 8.42 for ⁻O₂P(OC₆H₄NO₂-4)₂, which are near the $pK_a(\text{H}_2\text{O})$ value determined from the potentiometric pH titrations, are

Table 3 Second-order rate constants $k_2/\text{dm}^3 \text{mol}^{-1} \text{s}^{-1}$ and conditional rate constants k_0/s^{-1}

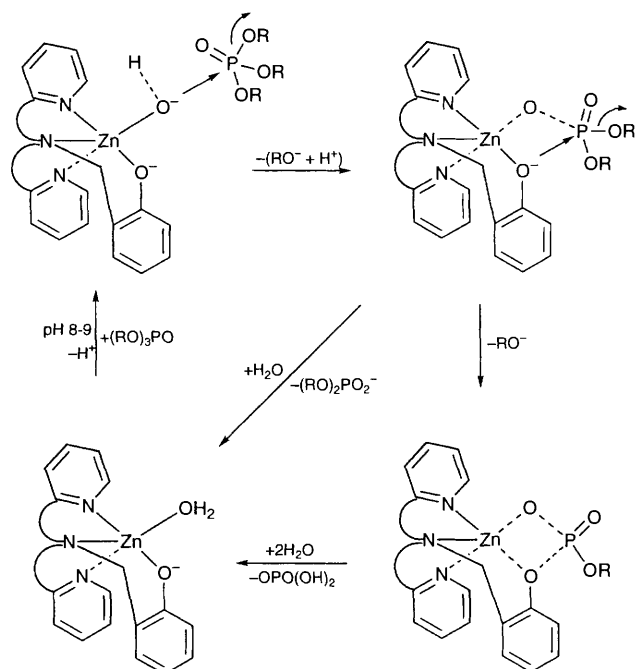
pH	4 vs. $\text{OP}(\text{OC}_6\text{H}_4\text{NO}_2-4)_3$		4 vs. $^-\text{O}_2\text{P}(\text{OC}_6\text{H}_4\text{NO}_2-4)_2$		8 vs. $\text{OP}(\text{OC}_6\text{H}_4\text{NO}_2-4)_3$	
	k_2	$10^3 k_0$	$10^3 k_2$	$10^7 k_0$	k_2	$10^3 k_0$
7.5	0.454	0.219	0.361	0.622	0.214	0.261
8.0	0.520	0.586	0.485	0.892	0.275	0.539
8.5	1.425	0.808	0.835	1.170	0.435	0.879
9.0	2.210	1.092	1.091	1.301	0.895	1.066
9.5	2.830	1.623	1.315	1.834		
10.0	3.195	1.840				

**Fig. 7** Plot of k_2 vs. pH for the hydrolysis of $\text{OP}(\text{OC}_6\text{H}_4\text{NO}_2-4)_3$ (+) and $^-\text{O}_2\text{P}(\text{OC}_6\text{H}_4\text{NO}_2-4)_2$ (O) catalysed by complex **4** in 33% EtOH-water and hydrolysis of $\text{OP}(\text{C}_6\text{H}_4\text{NO}_2-4)_3$ (Δ) catalysed by complex **8** in 52% EtOH-water respectively. The k_2 values in curve (b) have been multiplied by a factor of 10^3

obtained. This suggests that the complex functions by providing a high concentration of the nucleophilic reagent (co-ordinated hydroxide). This type of mechanism has been demonstrated for reactions accelerated by other complexed hydroxide ions,^{4,8,10,11} in which the active species in hydrolysis are proposed to be zinc(II)-bound hydroxides.

In the $\text{OP}(\text{OC}_6\text{H}_4\text{NO}_2-4)_3$ hydrolysis accelerated by complex **8** the k_2 vs. pH profile has a similar trend in that k_2 increases with increasing pH; an increase in activity became more noticeable at $\text{pH} > 8.5$. Although the k_2 values cannot be measured precisely at $\text{pH} > 9.2$, because of the emergence of a fine precipitate, the profile implies that the catalytic activity of the complex is related to co-ordinated hydroxide [$\text{p}K_a(\text{H}_2\text{O}) = 9.86$].

As shown in potentiometric titrations on solutions (33 or 52% EtOH) of proligands (1.0 mmol dm^{-3}) containing an equimolar amount of zinc perchlorate, the complexes have essentially formed by $\text{pH} 7.0$ (for **4**) and 6.5 (for **8**). Therefore at the concentrations and pH values employed in this hydrolysis study it is likely that the complexes are fully formed and so the enhancements noted can be attributed to the influence of complexes. This suggests that the five-co-ordinated zinc(II) complexes derived from tripodal ligands bearing a pendant phenol have the propensity for inducing catalytic hydrolysis of phosphate esters. A possible mechanism is that in solution a water molecule is added easily to the monomeric zinc complex, probably by substitution of a loosely held anion, leading to the formation of a $\text{LZn}(\text{OH})$ intermediate at appropriate pH, which nucleophilically attacks the phosphate ester to induce its hydrolysis. Recently, Kimura and co-workers^{13,14} found that pendant alcohol in zinc(II) complexes can be activated by the

**Scheme 3** A possible mechanism for phosphate ester hydrolysis

adjacent general base (O^-) $\text{Zn}(\text{OH})$ and so become a strong nucleophile towards nitrophenyl acetate. In the present hydrolysis of phosphate esters a similar nucleophilic attack from the pendant phenol may also occur to yield a transient intermediate, which can then hydrolyse to reproduce the monomeric zinc(II) species and complete the catalytic cycle (Scheme 3). This mechanism can be compared to the serine-activation mechanism proposed for hydrolytic zinc enzymes.²

In addition, Fig. 7 reveals that the catalysis of triester hydrolysis is far more efficient than that for the diester. Although the reaction temperature for the diester is 10°C higher than that for the triester, the apparent rate constants of triester hydrolysis are still over 10^3 times greater than that for the diester. This is possibly due to electrostatic repulsions between the attacking OH^- species and anionic substrates. The same effect is well known in the enzymatic hydrolysis of anionic phosphate esters in the presence of magnesium(II) ions.²⁹

In parallel with the above experiments, attempts were made to test the possible hydrolysis reaction of phosphate esters promoted by the six-co-ordinated zinc(II) complex **10**. Since **10** is difficult to dissolve in EtOH-water solution, acetonitrile was therefore selected as a cosolvent (60%). Following the experimental procedure employed above, no determinable enhancement of hydrolysis was found for complex **10**. This is probably because the six-co-ordinated species is stable in solution and so the zinc atom remains co-ordinatively saturated. There is therefore no available reaction pathway for the hydrolytic reaction.

Acknowledgements

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