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Di- and poly-nuclear zinc(II) Schiff base complexes: synthesis, structural studies and reaction with an α-amino acid ester †

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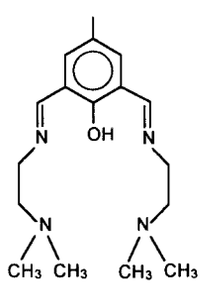
In order to model peptide hydrolysis by dimetallic aminopeptidases, the dinuclear zinc(II) Schiff base complex $[Zn_2L^1(CH_3CO_2)_2]ClO_4$ **1a** [HL^1 = 2,6-bis{*N*-[2-(dimethylamino)ethyl]iminomethyl}-4-methylphenol] has been prepared and characterised by X-ray crystallography. The zinc ions are bridged by the deprotonated phenolic oxygen of L^1 and two acetate groups, the Zn · · · Zn distance being 3.234(1) Å. Complex **1a** was shown to promote hydrolysis of glycine ethyl ester under mild conditions. Reaction of the hydrolysis product glycine with **1a** led to the conversion of the ligand into L^2 (H_3L^2 = corresponding Schiff base derived from glycine). The X-ray analysis of the resulting zinc complex **2** revealed the novel pentanuclear complex $[\{Zn_2L^2(CH_3CO_2)_2\}_2Zn(H_2O)_4]\cdot 4.5H_2O$, and the crystal structure of polymeric $\{[Zn(HL^2)]\cdot 3H_2O\}_\infty$ was determined. Complex **2** is built up of two dinuclear acetate-bridged Zn_2/ligand moieties that are linked through bridging carboxylate functions of the ligand to the fifth Zn atom. In the polymer one co-ordination site of the binucleating ligand is occupied by a Zn, while the second one is protonated.

Introduction

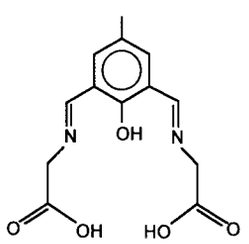
Zinc-containing, carboxylate-bridged dimetallic centres are a widespread structural motif in hydrolytic metalloenzymes, such as phosphatases and aminopeptidases.[1] The catalytic role of Zn comprises Lewis acid activation of the substrate, generation of a reactive nucleophile (Zn–OH) and stabilisation of the leaving group. Small-molecule metal complexes that can serve as structural and functional models for these enzymes receive continuous interest. Over the years, numerous mononuclear model complexes have been designed and studied in order to investigate the mechanism of phosphate ester, carboxy ester and amide hydrolysis and the relationship between structure and reactivity.[2] More recent studies on dinuclear model systems have manifested the importance of polynuclear centres and of co-operativity between the metal ions in phosphate diester hydrolysis.[3] In contrast, dinuclear aminopeptidase models are rare.[4] Aminopeptidases catalyse the hydrolysis of the amino-terminal peptide bond in polypeptides. Bovine lens leucine aminopeptidase (blLAP) and aminopeptidase from *Aeromonas proteolytica* (AAP) which have been structurally characterised contain μ-hydroxo-bis(μ-carboxylato)-dizinc(II) and μ-hydroxo-μ-carboxylato-dizinc(II) cores.[5,6] Two alternative mechanisms have been proposed for blLAP, both including co-operativity between the metal centres. On the basis of the crystal structure of a transition-state analogue complex of blLAP, bidentate co-ordination of the peptide through the terminal amino group to Zn(1) and through the carbonyl oxygen to Zn(2) and nucleophilic attack by the bridging hydroxide at the carbonyl carbon has been suggested by Sträter and Lipscomb.[7] Alternatively, monodentate co-ordination *via* the carbonyl oxygen and nucleophilic attack by terminally bound hydroxide has also been discussed.[5]

One type of ligand often used to model dinuclear biosites are phenol-based compartmental ligands of 'end-off' type.[8] Que and co-workers[9] have studied diiron and dimanganese active sites utilising 2,6-bis[bis(2-pyridylmethyl)aminomethyl]-4-methylphenol which was first described by Suzuki *et al.*[10] Zinc complexes of related ligands have been reported by Krebs, Sakiyama and Wang.[4,11] Okawa and co-workers[12] used 2,6-bis{*N*-[2-(dimethylamino)ethyl]iminomethyl}-4-methylphenol (HL^1) to mimic the dinickel site of urease as well as dimanganese sites.

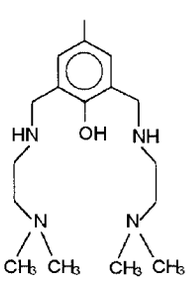
Here we report on the synthesis and structural characterisation of the dinuclear zinc(II) Schiff base complex $[Zn_2L^1(CH_3CO_2)_2]X$ **1** and its reaction with an α-amino acid ester. In the course of our attempt to model peptide hydrolysis by a dimetallic site we obtained the novel pentanuclear complex $[\{Zn_2L^2(CH_3CO_2)_2\}_2Zn(H_2O)_4]\cdot 4.5H_2O$ **2**. The crystal structure of **2** is presented along with that of polymeric $\{[Zn(HL^2)]\cdot 3H_2O\}_\infty$ **4**.



HL^1



H_3L^2



HL^4

Experimental

Syntheses

2,6-Diformyl-4-methylphenol was prepared according to ref. 13, HL^1 by reaction of 2,6-diformyl-4-methylphenol and *N*,*N*-dimethylethylenediamine in $CHCl_3$ and subsequent evap-

† Electronic supplementary information (ESI) available: crystal packing diagrams. See http://www.rsc.org/suppdata/dt/a9/a907839h/

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oration of the solvent and HL[4] [2,6-bis{*N*-[2-(dimethylamino)-ethyl]aminomethyl}-4-methylphenol] was prepared by reduction of HL[1] by $NaBH_4$ in methanol according to standard literature procedures.[14] Glycine and glycine ethyl ester hydrochloride were obtained from Fluka. All chemicals and solvents were reagent grade used without further purification.

CAUTION: perchlorate salts of metal complexes are potentially explosive and should be handled with care.

$[Zn_2L^1(CH_3CO_2)_2]X$ (X = ClO_4 1a or PF_6 1b). 2,6-Diformyl-4-methylphenol (100 mg, 0.61 mmol) and $Zn(CH_3CO_2)_2{\cdot}2H_2O$ (335 mg, 1.53 mmol) were dissolved in ethanol (25 cm^3). After addition of *N*,*N*-dimethylethylenediamine (108 mg, 1.23 mmol) dissolved in water (5 cm^3) the reaction mixture was stirred overnight at room temperature. Treatment with $NaClO_4{\cdot}H_2O$ (343 mg, 2.44 mmol) or KPF_6 (336 mg, 1.83 mmol) gave complex **1a** as yellow cubes (303 mg, 76%) and **1b** as a pale yellow powder (312 mg, 73%). Found: C, 38.3; H, 5.3; N, 8.4. $C_{21}H_{33}ClN_4O_9Zn_2$ requires C, 38.7; H, 5.1; N, 8.6. Found: C, 36.0; H, 4.6; N, 8.0. $C_{21}H_{33}F_6N_4O_5PZn_2$ requires C, 36.2; H, 4.8; N, 8.0%. ^{1}H NMR (CD_3OD): δ 8.54 (s, 2 H, H_{im}), 7.39 (s, 2 H, H_{ar}), 3.81 (t, 4 H, CH_2), 2.81 (t, 4 H, CH_2), 2.47 (s, 12 H, NCH_3), 2.29 (s, 3 H, CH_3) and 2.02 (s, 6 H, $CH_3CO_2^-$). IR (cm^{-1}): $[Zn_2L^1(CH_3CO_2)_2]^+$ 3005m, 2973m, 2926m, 2890m, 2872m, 2843m, 2795w, 1655s, 1647s, 1597s, 1549s, 1448s, 1374m, 1334m, 1276w, 1239m, 1196w, 1025m, 990m, 947m, 893m, 818m, 783m, 548m, 500w, 483w and 450m; ClO_4^- (**1a**) 1094s and 622m; PF_6^- (**1b**) 840s and 668m.

$[\{Zn_2L^2(CH_3CO_2)_2\}_2Zn(H_2O)_4]{\cdot}4.5H_2O$ 2 and $\{[Zn(HL^2)]{\cdot}3H_2O\}_\infty$ 4. Glycine (304 mg, 4.05 mmol) was dissolved in water (15 cm^3) and added to a solution of 2,6-diformyl-4-methylphenol (330 mg, 2.01 mmol) and $Zn(CH_3CO_2)_2{\cdot}2H_2O$ (1.097 mg, 5.00 mmol) in ethanol (75 cm^3). After stirring overnight at room temperature a yellow precipitate was filtered off. Recrystallisation from water afforded small yellow needles of complex **2** in 52% yield. Found: C, 32.5; H, 3.8; N, 4.4. $C_{34}H_{51}N_4O_{26.5}Zn_5$ requires C, 32.2; H, 4.1; N, 4.4%. ^{1}H NMR (CD_3OD): δ 8.45 (s, 2 H, H_{im}), 7.35 (s, 2 H, H_{ar}), 4.16 (s, 4 H, CH_2), 2.28 (s, 3 H, CH_3) and 1.96 (s, 6 H, $CH_3CO_2^-$). IR (cm^{-1}): 3399vs, br, 1645s, br, 1578s, br, 1448s, 1399s, 1333m, 1298m, 1239m, 1195w, 1079m, 1050m, 1007w, 935w, 877w, 822m, 762m, 699w, 669m, 620m, 575m and 488m. Slow evaporation of the filtrate at room temperature gave yellow cubes of **4** (240 mg, 30%). Found: C, 38.9; H, 4.5; N, 6.5. $C_{13}H_{18}N_2O_8Zn$ requires C, 39.4; H, 4.6; N, 7.0%. ^{1}H NMR (D_2O, pD 6.9): δ 8.40 (s, 1 H, H_{im}), 8.33 (s, 1 H, H_{im}), 7.59 (s, 1 H, H_{ar}), 7.44 (s, 1 H, H_{ar}), 4.38 (s, 2 H, CH_2), 4.25 (s, 2 H, CH_2) and 2.24 (s, 3 H, CH_3). IR (cm^{-1}): 3426s, br, 1653s, 1631s, 1594s, 1541s, 1489w, 1456w, 1384s, 1305w, 1274m, 1223m, 1068m, 996m, 960w, 878w, 823w, 760w, 707w, 668w, 585m, 491w and 419w.

$[Zn_2L^4Cl_3]{\cdot}1.5H_2O$ 3. Zinc chloride (552 mg, 4.05 mmol), HL[4] (500 mg, 1.62 mmol) and $NaOCH_3$ (89 mg, 1.65 mmol) were allowed to react in ethanol–water (5 : 1, 24 cm^3) overnight at room temperature. Slow evaporation of the solvent yielded a white, microcrystalline precipitate of complex **3** (156 mg, 17%). Found: C, 35.5; H, 5.6; N, 9.8. $C_{17}H_{34}Cl_3N_4O_{2.5}Zn_2$ requires C, 35.7; H, 6.0; N, 9.8%. ^{1}H NMR (D_2O, pD 7.2): δ 7.03 (s, 2 H, H_{ar}), 3.96 (s, br, 4 H, $C_{ar}CH_2$), 3.02 (s, br, 4 H, NCH_2), 2.66 (s, br, 4 H, NCH_2), 2.21 (s, 12 H, NCH_3) and 2.10 (s, 3 H, CH_3). IR (cm^{-1}): 3503br, 3196m, 3001m, 2971m, 2916br, s, 1477s, 1312m, 1267m, 1165m, 1089m, 1030m, 964w, 937m, 886w, 860m, 803m, 780m, 668w, 592w, 556w, 501m, 462w and 401w.

Hydrolysis of glycine ethyl ester

A 25 µl 0.2 M stock solution of glycine ethyl ester in D_2O and 25 µl 0.2 M stock solution of complex **1** or **3** in $(CD_3)_2SO$ were mixed in 0.5 cm^3 buffer (50 mM EPPS [4-(2-hydroxyethyl)-1-piperazinepropanesulfonic acid] in D_2O, pD 7.4). The reaction was monitored by ^{1}H NMR spectroscopy at 20 °C. The hydrolysis was complete after *ca*. 2 d in the case of **1** and after *ca*. 12 h in the case of **3**. As a control experiment glycine ethyl ester was treated with 2 equivalents $Zn(CH_3CO_2)_2$ under the same conditions (25 µl 0.2 M stock solution of glycine ethyl ester in D_2O, 50 mM EPPS in D_2O, pD 7.4). 54% ester cleavage was observed after 69 h. Treatment of glycine ethyl ester with $Zn(CH_3CO_2)_2$ (2 equivalents) in the presence of *N*,*N*,*N*′,*N*′-tetramethylethylenediamine (2 equivalents) resulted in 66% substrate conversion within 62 h.

Instrumentation

The ^{1}H NMR spectra were recorded on a Bruker AC200 spectrometer. Spectra were run in D_2O, $(CD_3)_2SO$ or CD_3OD solutions using sodium 3-trimethylsilylpropanesulfonate as internal reference. The pD values of D_2O solutions were obtained by use of a glass electrode and addition of 0.4 to the pH meter reading. Infrared spectra of KBr pellets were taken on a Bruker IFS 28 FT-spectrometer.

Crystal structure analyses

Crystal data for compounds **1a**, **2** and **4** were measured at room temperature on an Enraf-Nonius-KappaCCD diffractometer[15] using graphite-monochromated Mo-Kα radiation (λ = 0.71069 Å). For data reduction and cell refinement the programs DENZO and SCALEPACK were applied.[16] The structures were solved by conventional Patterson (**1a** and **2**) or direct (**4**) methods and subsequent Fourier syntheses and refined by full-matrix least squares on F^2 using the SHELXTL PLUS, SHELXL 93 and SHELXL 97 programs.[17] All non-hydrogen atoms were refined anisotropically [with the following exceptions: C(11), C(16), C(17), O(3), O(11) in **1a** and O(2W), O(3W), O(4W), O(5W), O(6W), O(7W) and O(8W) in **4**]. In **1a** and **2** hydrogen atoms except for those of the water molecules were generated geometrically and given isotropic thermal parameters equivalent to 1.2 times those of the atom to which they were attached. In **4** the hydrogen atoms (except for those of the water molecules) were located in the Fourier-difference map and refined isotropically. The perchlorate oxygens in **1a** are disordered. The Fourier-difference syntheses revealed eight oxygens to which occupancy factors of 0.6 [O(10), O(11), O(12) and O(13)] and 0.4 [O(20), O(21), O(22) and O(23)] were assigned. On the basis of the peak height in the Fourier map site occupancy factors of 0.5 were assigned to O(5W) in **2** and to O(4W) in **4** as well as of 0.25 to O(3W), O(5W), O(6W), O(7W) and O(8W) in **4**.

Crystallographic data and details of refinement are reported in Table 1. Selected bond lengths and angles are listed in Tables 2–4.

CCDC reference number 186/1775.

See http://www.rsc.org/suppdata/dt/a9/a907839h/ for crystallographic files in .cif format.

Results and discussion

Synthesis and characterisation of $[Zn_2L^1(CH_3CO_2)_2]X$

Schiff base complexes are generally easily accessible by condensation of an aldehyde with an amine in the presence of the metal ion.[18] Reaction of 2,6-diformyl-4-methylphenol with *N*,*N*-dimethylethylenediamine in the presence of $Zn(CH_3CO_2)_2$ leads to the dinuclear zinc complex $[Zn_2L^1(CH_3CO_2)_2]X$ (X = ClO_4 **1a** or PF_6 **1b**). For **1a** crystals suitable for X-ray analysis were obtained, and the crystal structure was determined.

A view of the cation of complex **1a** is depicted in Fig. 1 and selected bond lengths and angles are presented in Table 2. The Zn atoms, which are 3.234(1) Å apart, are bridged by the deprotonated phenolic oxygen of L^1 and two acetate groups.

Table 1 Crystal data for $[Zn_2L^1(CH_3CO_2)_2]ClO_4$ **1a**, $[\{Zn_2L^2(CH_3CO_2)_2\}_2Zn(H_2O)_4]\cdot 4.5H_2O$ **2** and $\{[Zn(HL^2)]\cdot 3H_2O\}_\infty$ **4**

	1a	**2**	**4**
Empirical formula	$C_{21}H_{33}ClN_4O_9Zn_2$	$C_{34}H_{51}N_4O_{26.5}Zn_5$	$C_{13}H_{18}N_2O_8Zn$
Formula weight	651.70	1266.64	395.66
Crystal system	Triclinic	Triclinic	Monoclinic
Space group	$P\bar{1}$	$P\bar{1}$	$C2/c$
a/Å	8.717(1)	8.192(2)	20.290(4)
b/Å	11.285(1)	11.841(2)	8.514(2)
c/Å	15.057(1)	14.520(3)	19.488(4)
α/°	99.37(1)	100.61(3)	
β/°	94.00(3)	91.98(3)	108.13(3)
γ/°	104.04(3)	102.71(3)	
V/Å^3	1408.5(2)	1346.3(5)	3199.4(12)
Z	2	1	8
μ(Mo-Kα)/mm^{-1}	1.850	2.278	1.580
T/K	293	293	293
No. measured reflections	4573	4087	5372
No. independent reflections	4573	4064	2920
No. observed reflections [$I > 2\sigma(I)$]	3164	2213	1864
Final $R1$, $wR2$ indices [$I > 2\sigma(I)$]	0.048, 0.128	0.087, 0.206	0.043, 0.088
(all data)	0.080, 0.158	0.149, 0.218	0.087, 0.119

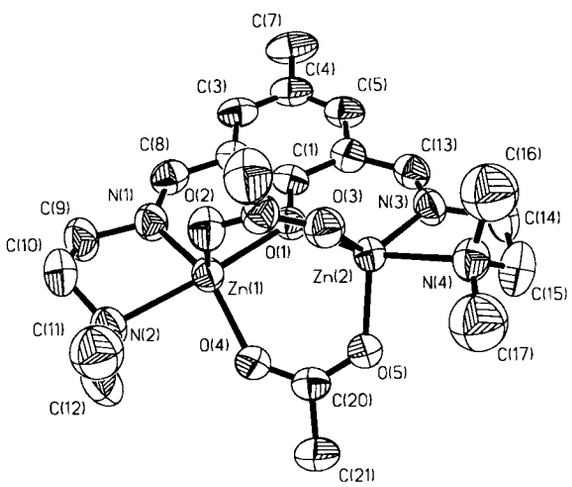

Fig. 1 View of the cation of $[Zn_2L^1(CH_3CO_2)_2]ClO_4$ **1a** with the atom numbering scheme.

Table 2 Selected bond distances (Å) and angles (°) for $[Zn_2L^1(CH_3CO_2)_2]ClO_4$ **1a**

Zn(1)–N(1)	2.013(3)	Zn(2)–N(3)	2.031(3)
Zn(1)–N(2)	2.216(3)	Zn(2)–N(4)	2.204(3)
Zn(1)–O(1)	2.093(2)	Zn(2)–O(1)	2.101(2)
Zn(1)–O(2)	1.991(2)	Zn(2)–O(3)	1.969(2)
Zn(1)–O(4)	1.966(2)	Zn(2)–O(5)	1.976(2)
N(1)–C(8)	1.282(5)	N(3)–C(13)	1.271(5)
O(2)–C(18)	1.247(4)	O(3)–C(18)	1.266(4)
O(4)–C(20)	1.246(4)	O(5)–C(20)	1.260(4)
N(1)–Zn(1)–N(2)	80.9(1)	N(1)–Zn(1)–O(2)	108.5(1)
N(1)–Zn(1)–O(4)	139.1(1)	N(2)–Zn(1)–O(1)	167.7(1)
O(1)–Zn(1)–O(4)	95.41(9)	O(2)–Zn(1)–O(4)	111.4(1)
O(1)–Zn(2)–N(4)	163.9(1)	O(1)–Zn(2)–O(3)	94.6(1)
O(3)–Zn(2)–O(5)	115.3(1)	O(3)–Zn(2)–N(3)	134.0(1)
O(5)–Zn(2)–N(3)	110.0(1)	N(3)–Zn(2)–N(4)	80.4(1)
C(8)–N(1)–Zn(1)	127.2(2)	C(10)–N(2)–Zn(1)	101.8(2)
C(13)–N(3)–Zn(2)	128.1(2)	C(15)–N(4)–Zn(2)	100.6(2)
C(1)–O(1)–Zn(1)	129.4(2)	C(1)–O(1)–Zn(2)	129.2(2)
Zn(1)–O(1)–Zn(2)	100.92(9)	O(2)–C(18)–O(3)	124.4(3)
O(4)–C(20)–O(5)	125.4(3)		

Each metal centre is five-co-ordinate through the imine nitrogen, the amine nitrogen and the phenolate and acetate oxygens. The co-ordination geometry of the Zn atoms is best described as distorted trigonal bipyramidal with the phenolic oxygen and amine nitrogen occupying the apical positions. The acetate groups form an angle of 49.9(2)° with each other. The Zn–N and Zn–O distances range from 1.966 to 2.216 Å, with the Zn–N (imine) bonds [2.013(3) and 2.031(3) Å] being significantly shorter than the Zn–N (amine) bonds [2.216(3) and 2.204(3) Å].

In the IR spectrum of complexes **1a** and **1b** the ν(C=N) vibration is observed at 1647 cm^{-1}. The asymmetric and symmetric stretching vibrations of the acetate groups appear at 1597 and 1448 cm^{-1}, respectively.‡ The difference between ν_{asym}(COO) and ν_{sym}(COO) (149 cm^{-1}), which is smaller than 164 cm^{-1} observed in ionic acetate, reflects the bidentate bridging co-ordination mode.[19] The proton NMR spectrum of **1** in CD_3OD shows two singlets in the aromatic region corresponding to the azomethine (δ 8.54) and phenolic ring (δ 7.39) protons. Compared to the "free" ligand HL^1 these resonances are shifted to higher field by 0.04 and 0.16 ppm. The methylene protons give two broad triplets at δ 3.81 and 2.81, and the signals of the N–CH_3 and Ph–CH_3 methyl groups occur at δ 2.47 and 2.29. A mixture of complex **1** and HL^1 in CD_3OD shows two distinct sets of resonances indicating that the complex is non-labile on the NMR timescale. The 0.14 ppm downfield shift of the acetate resonance (δ 2.02) compared with that of ionic acetate (CH_3CO_2Na, δ 1.88) in CD_3OD suggests interaction of the acetate with the metal centres in solution.

Despite the well known susceptibility of imine bonds to hydrolysis, metal complexes of Schiff bases are generally resistant towards hydrolysis.[18] This is also the case for **1**: no dissociation to aldehyde and amine could be detected in a solution of **1** in D_2O (pD 7.4) after 1 week.

Hydrolysis of α-amino acid ester

Reaction of complex **1** with 1 equivalent glycine ethyl ester in D_2O at pD 7.4 and room temperature was monitored by NMR spectroscopy (Fig. 2). The ^{1}H NMR spectra clearly indicate release of ethanol which is complete in about 2 d. In contrast, in the absence of any metallocatalyst the half-life for the hydrolysis of carboxy esters at neutral pH is in the order of years.[21] Besides NMR resonances corresponding to the hydrolysis products ethanol and glycine, new signals appear in the aromatic region (δ 8.29, 7.73 and 7.36) (Fig. 2, right). By comparison with a genuine sample (see below) the singlets at δ 8.29 and 7.36 can be assigned to the zinc complex of the ligand H_3L^2 (**2**) that is formed by exchange of the ligand side arms with glycine. Fig. 3 shows the NMR spectra of **1** in D_2O after addi-

‡ The IR resonances of the acetate groups have been assigned by comparison with the IR spectrum of the analogous complex $[Zn_2L^1Cl_3]$, the X-ray analysis of which revealed one bridging and two terminally bound chlorides.[20]

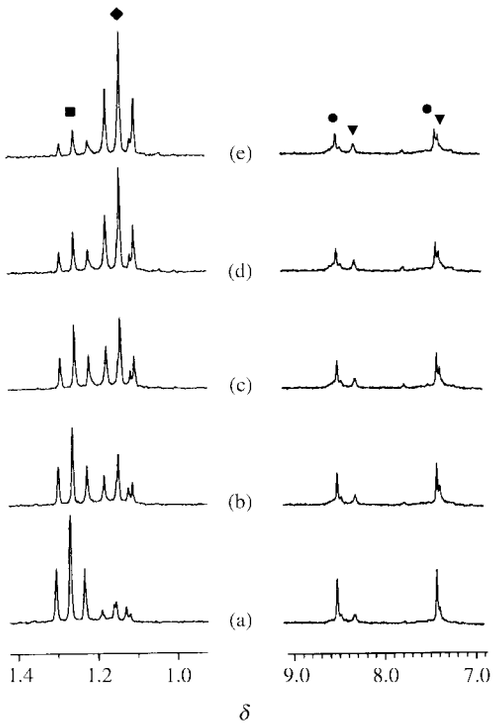

Fig. 2 Hydrolysis of glycine ethyl ester by complex **1a** at pD 7.4. Proton NMR spectra were taken after (*a*) 1, (*b*) 5, (*c*) 11, (*d*) 24 and (*e*) 39 h at 20 °C. Resonances are assigned as follows: (■) CH_3 of glycine ethyl ester, (◆) CH_3 of EtOH, (●) H_{im} and H_{ar} of **1a** and (▼) H_{im} and H_{ar} of **2**.

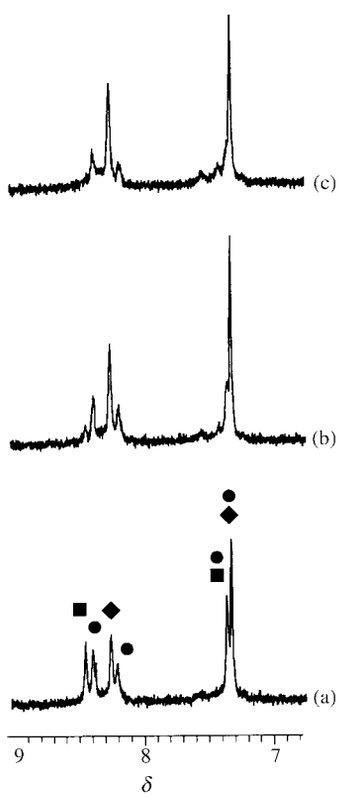

Fig. 3 Reaction of complex **1a** with glycine in D_2O (pD 7.3). Proton NMR spectra were taken after addition of (*a*) 1, (*b*) 2 and (*c*) 5 equivalents of glycine. Resonances (H_{im} and H_{ar}) are assigned as follows: (■) Zn_2L^1, (◆) Zn_2L^2 and (●) Zn_2L^3.

tion of 1, 2 and 5 equivalents glycine. Treating **1** with 1 equivalent glycine in D_2O results in a mixture of **1** (δ 8.49 and 7.40), $[Zn_2L^2]^+$ **2** (δ 8.29 and 7.36) and $[Zn_2L^3]^{2+}$ (δ 8.43, 8.23, 7.40 and 7.36; H_2L^3 = ligand containing one amine and one carboxylate side arm). After addition of 5 equivalents glycine, conversion into **2** is almost complete. Possible pathways for the hydrolysis reaction are (i) replacement of the ligand side arms by glycine ethyl ester followed by hydrolysis of the ester group in Zn_2L^1 and (ii) **1** promoted ester cleavage and subsequent reaction of the hydrolysis product glycine with **1**. In order to distinguish (i) and (ii), the imine ligand was reduced to the corresponding amine HL^4 that is incompatible with mechanism (i). The complex $[Zn_2L^4Cl_3]$ **3**‡ hydrolyses glycine ethyl ester, and the reaction is complete within 12 h. The lower cleavage rate observed with **1** is due to formation of **2** during the reaction. Generally, the reactivity of a metal catalyst for hydrolysis reactions is decreased by negatively charged donor atoms. The conversion of **1** into **2** does not allow further clarification of the hydrolytic mechanism, *e.g.* possible co-operativity between the two metal ions. Detailed kinetic studies on **3** promoted amino acid ester hydrolysis are in progress.

Table 3 Selected bond distances (Å), angles (°) and possible hydrogen-bonding interactions for $[\{Zn_2L^2(CH_3CO_2)_2\}_2Zn(H_2O)_4]\cdot 4.5H_2O$ **2**

Zn(1)–N(1)	1.998(11)	Zn(2)–N(2)	2.009(10)
Zn(1)–O(1)	2.088(8)	Zn(2)–O(1)	2.060(8)
Zn(1)–O(3)	2.080(8)	Zn(2)–O(4)	2.092(8)
Zn(1)–O(6)	1.965(8)	Zn(2)–O(7)	1.962(9)
Zn(1)–O(8)	1.971(9)	Zn(2)–O(9)	1.966(9)
Zn(3)–O(5)	2.17(1)	Zn(3)–O(10)	2.070(8)
Zn(3)–O(11)	2.073(7)	N(1)–C(8)	1.29(2)
N(2)–C(11)	1.30(2)	O(3)–C(10)	1.25(2)
O(4)–C(13)	1.28(2)	O(5)–C(13)	1.22(1)
O(6)–C(14)	1.27(2)	O(7)–C(14)	1.26(2)
O(9)–C(16)	1.25(1)	C(10)–O(2)	1.24(2)
N(1)–Zn(1)–O(1)	89.9(4)	N(1)–Zn(1)–O(3)	81.2(4)
N(1)–Zn(1)–O(6)	121.1(4)	N(1)–Zn(1)–O(8)	119.1(4)
O(1)–Zn(1)–O(3)	170.0(3)	O(3)–Zn(1)–O(6)	87.4(3)
O(6)–Zn(1)–O(8)	119.0(4)	N(2)–Zn(2)–O(1)	88.2(3)
N(2)–Zn(2)–O(4)	79.6(4)	N(2)–Zn(2)–O(9)	112.9(4)
O(1)–Zn(2)–O(4)	167.4(3)	O(7)–Zn(2)–O(4)	87.0(4)
O(7)–Zn(2)–O(9)	113.6(4)	O(7)–Zn(2)–N(2)	132.0(4)
O(5)–Zn(3)–O(10)	93.0(3)	O(5)–Zn(3)–O(11)	86.9(3)
O(10)–Zn(3)–O(11)	88.6(3)	Zn(2)–O(1)–Zn(1)	99.9(3)
C(8)–N(1)–Zn(1)	127.5(9)	C(11)–N(2)–Zn(2)	127.6(8)
C(16)–O(9)–Zn(2)	126.6(9)	C(13)–O(5)–Zn(3)	124.7(9)
O(2)–C(10)–O(3)	125(1)	O(4)–C(13)–O(5)	126(1)
O(6)–C(14)–O(7)	125(1)	O(8)–C(16)–O(9)	126(1)
$O(2)\cdots O(10)^a$	2.78(1)	$O(3)\cdots O(11)^b$	2.76(1)
$O(4)\cdots O(11)^c$	2.68(1)	$O(5)\cdots O(3W)^d$	2.88(1)
$O(5)\cdots O(11)$	2.92(1)	$O(6)\cdots O(3W)^c$	2.87(1)
$O(10)\cdots O(2W)^e$	2.84(1)	$O(1W)\cdots O(2W)^b$	2.75(2)
$O(1W)\cdots O(3W)^f$	2.88(2)	$O(1W)\cdots O(4W)^g$	2.76(2)
$O(2W)\cdots O(9)^c$	2.76(1)	$O(3W)\cdots O(5W)^h$	2.84(2)
$O(4W)\cdots O(4W)^i$	2.83(3)	$O(4W)\cdots O(5W)$	2.75(2)
$O(5W)\cdots O(5W)^j$	2.84(4)		

Symmetry operations: [a] $-x, -y+1, -z$; [b] $x, y+1, z$; [c] $-x, -y, -z$; [d] $-x, -y-1, -z$; [e] $-x+1, -y, -z$; [f] $x+1, y, z$; [g] $x, y-1, z$; [h] $-x, -y-1, -z-1$; [i] $-x+1, -y, -z-1$; [j] $-x, -y, -z-1$.

Zinc complexes of H_3L^2

Complex **2** was prepared on a preparative scale by treating 2,6-diformyl-4-methylphenol with 2 equivalents glycine in the presence of $Zn(CH_3CO_2)_2$. The complex precipitated from ethanol–water and recrystallisation yielded small yellow needles of composition $[\{Zn_2L^2(CH_3CO_2)_2\}_2Zn(H_2O)_4]\cdot 4.5H_2O$ **2**. Slow evaporation of the filtrate gave a second product of composition $[Zn(HL^2)]\cdot 3H_2O$ **4**. The structures of both compounds were determined by X-ray analysis.

Crystal structure of complex 2. Fig. 4 gives a view of complex **2**, selected bond lengths, angles and possible hydrogen-bonding interactions are listed in Table 3. The pentanuclear compound is built up of two dinuclear acetate-bridged Zn_2/ligand moieties linked through bridging carboxylate functions of the ligand side arm to the fifth Zn atom that is located on a crystallo-

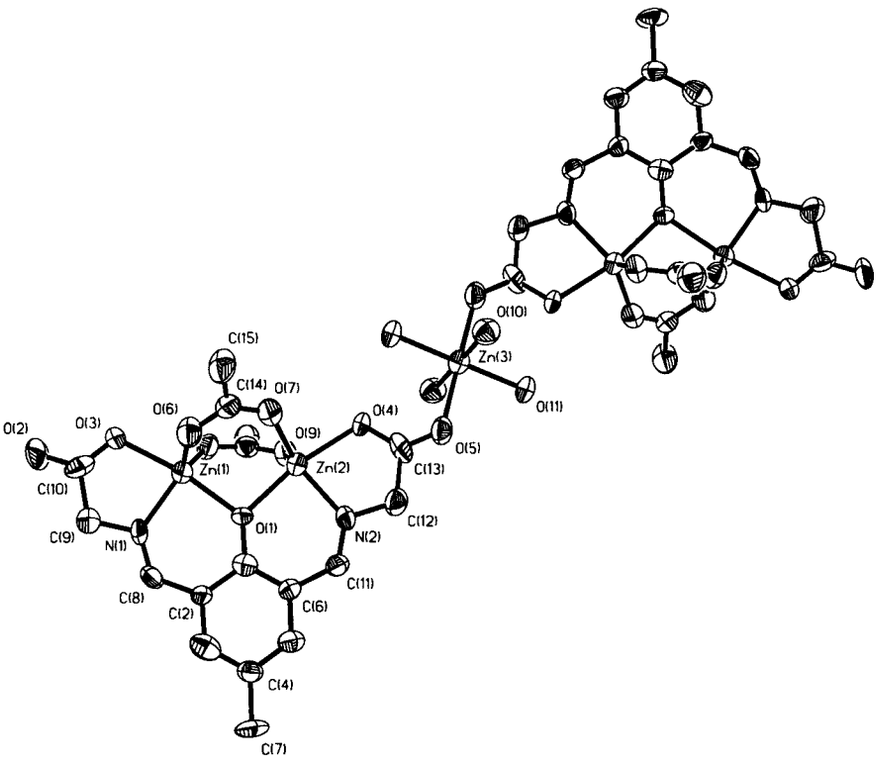

Fig. 4 View of $[\{Zn_2L^2(CH_3CO_2)_2\}_2Zn(H_2O)_4]$ **2** with the atom numbering scheme.

graphic inversion centre. The Zn atoms of the dinuclear unit [Zn(1) and Zn(2)] are five-co-ordinate through imine nitrogen, carboxylate, phenolate and two acetate oxygens. The intermetallic distance is 3.175(2) Å, slightly shorter than in **1a** [3.234(1) Å]. The co-ordination geometry of Zn(1) and Zn(2) is trigonal bipyramidal. The carboxylate and bridging phenolic oxygens occupy the apical positions, the equatorial planes are formed by the acetate oxygens and the imine nitrogens. The valence angles around Zn(1) are close to the ideal 90 and 120° angles [ranges 119.0–121.1, 81.2–96.0°], while a more distorted co-ordination sphere is observed for Zn(2) [ranges 112.9–132.0, 79.6–99.1°]. The greatest deviations from the ideal bond angles are found for O(3)–Zn(1)–N(1) [81.2(4)°] and O(4)–Zn(2)–N(2) [79.6(4)°] which may be caused by the narrow bite of the chelating side arms of the ligand. The angle between the acetate groups is 57.4(5)°. The Zn–O (acetate) bond distances [1.962(9)–1.971(9) Å] are equal within experimental error and significantly shorter than the Zn–O (carboxylate) bond distances [2.080(8)–2.17(1) Å]. In contrast to the symmetrically bridging acetate, the carboxylate bridge between Zn(2) and Zn(3) is asymmetric: the Zn(2)–O(4) bond [2.092(8) Å] is significantly shorter than the Zn(3)–O(5) bond [2.17(1) Å]. The central Zn atom is six-co-ordinate through two carboxylate functions *trans* to each other and four water ligands. The co-ordination geometry deviates only slightly from an ideal octahedron, with the valence angles around Zn(3) ranging from 86.9 to 93.1°.

In the crystal packing the neutral molecules stack along the crystallographic *x* axis. Adjacent stacks are connected *via* hydrogen bonds involving water of crystallisation. Short contacts are also found between the carboxylate oxygens O(2) and O(3) and the water ligands bound to Zn(3) (Table 3).

Crystal structure of complex 4. A section of the polymeric compound **4** is shown in Fig. 5. Selected bond lengths, angles and possible hydrogen-bonding interactions are reported in Table 4. The polymeric, three-dimensional network is built up of dimeric subunits $\{Zn(HL^2)\}_2$ interconnected through carboxylate bridges. Each ligand co-ordinates one Zn through the

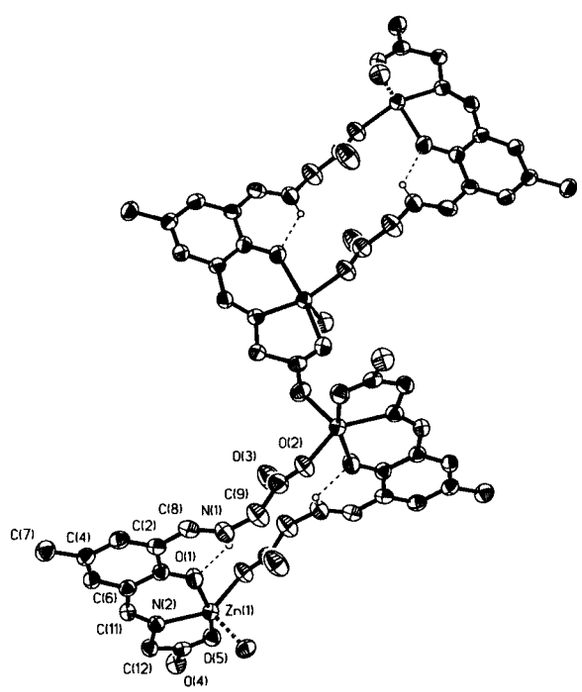

Fig. 5 Section of polymeric $[Zn(HL^2)]_\infty$ **4**. Hydrogen atoms were located in the Fourier-difference map, but for clarity only hydrogen atom H(1) is shown.

deprotonated phenolic oxygen and one chelating side arm. The other side arm binds *via* a carboxylate oxygen [O(2)] to the second Zn of the dimer, while its imine nitrogen N(1) is protonated with the proton forming a hydrogen bond to the phenolate oxygen [N(1)···O(1) 2.647(4) Å]. The corresponding hydrogen atom H(1) could be located in the Fourier-difference map. The five-co-ordination sphere of Zn is completed by the carboxylate oxygen O(4) of the adjacent dimer. As found for **1a** and **2**, the co-ordination geometry around Zn is distorted trigonal bipyramidal with the phenolic

Table 4 Selected bond distances (Å), angles (°) and possible hydrogen-bonding interactions for $\{[Zn(HL^2)]\cdot 3H_2O\}_\infty$ **4**

Zn(1)–N(2)	2.036(3)	Zn(1)–O(1)	2.040(3)
Zn(1)–O(2)[a]	1.976(3)	Zn(1)–O(4)[b]	1.960(3)
Zn(1)–O(5)	2.219(3)	N(1)–C(8)	1.284(5)
O(2)–C(10)	1.258(5)	O(3)–C(10)	1.240(5)
O(4)–C(13)	1.257(4)	O(5)–C(13)	1.239(4)
N(2)–Zn(1)–O(2)[a]	133.2(1)	N(2)–Zn(1)–O(4)[b]	122.3(1)
O(1)–Zn(1)–N(2)	88.5(1)	O(1)–Zn(1)–O(4)[b]	106.4(1)
O(1)–Zn(1)–O(5)	161.1(1)	O(2)[a]–Zn(1)–O(4)[b]	102.6(1)
O(5)–Zn(1)–N(2)	77.7(1)	C(8)–N(1)–C(9)	123.0(4)
C(11)–N(2)–C(12)	117.7(3)	C(11)–N(2)–Zn(1)	126.7(3)
C(1)–O(1)–Zn(1)	130.2(2)	C(10)–O(2)–Zn(1)[a]	122.8(3)
C(13)–O(4)–Zn(1)[c]	143.5(3)	C(13)–O(5)–Zn(1)	114.3(2)
O(2)–C(10)–O(3)	126.5(4)	O(4)–C(13)–O(5)	127.2(4)
N(1)···O(1)	2.647(4)	O(3)···O(3W)[a]	2.69(3)
O(3)···O(5W)[a]	2.91(2)	O(3)···O(7W)[a]	2.73(3)
O(3)···O(8W)[a]	2.62(3)	O(5)···O(1W)[c]	2.869(6)
O(1W)···O(2W)[d]	2.740(7)	O(1W)···O(6W)[b]	2.61(2)
O(2W)··· O(3W)	2.68(3)	O(2W)···O(3W)[e]	2.68(3)
O(2W)···O(5W)	3.02 (2)	O(2W)···O(7W)[e]	2.61(2)
O(2W)···O(7W)	2.61(2)	O(2W)···O(8W)[e]	2.91(2)
O(2W)···O(8W)	2.91(2)	O(4W)···O(7W)	2.58(3)
O(4W)···O(7W)[e]	2.58(3)	O(4W)···O(8W)	2.81(2)
O(4W)···O(8W)[e]	2.81(2)	O(6W)···O(7W)[e]	2.77(3)
O(6W)···O(8W)[e]	2.88(3)		

Symmetry operations: [a] $-x+1, -y, -z+1$; [b] $-x+\frac{1}{2}, y-\frac{1}{2}, -z+\frac{1}{2}$; [c] $-x+\frac{1}{2}, y+\frac{1}{2}, -z+\frac{1}{2}$; [d] $x-\frac{1}{2}, y+\frac{1}{2}, z$; [e] $-x+1, y, -z+\frac{1}{2}$.

[O(1)] and carboxylate [O(2)] oxygens occupying the apical positions. Owing to the narrow bite of the chelating side arm the N(2)–Zn(1)–O(5) bond angle is reduced from the ideal 90° angle to 77.7(1)°. The lengthening of the Zn(1)–O(5) bond to 2.219(3) Å [compared with 1.960(3) Å for Zn(1)–O(4) and 1.976(3) Å for Zn(1)–O(2)] may also be caused by steric effects of the chelate ligand.

In the three-dimensional structure the dimeric subunits are connected in such a way that long channels are produced along the crystallographic *y* axis that are stabilised by water of crystallisation. The disordered water molecules form hydrogen bonds among each other and to the carboxylate O(3) and O(5) oxygens (Table 4). The phenolic rings are stacked along the *y* axis so that neighbouring rings overlap partly.

Spectroscopic characterisation of complexes 2 and 4. As described above, the ^{1}H NMR spectrum of complex **2** shows two singlets in the aromatic region: in CD_3OD the azomethine and phenolic ring protons are detected at δ 8.45 and 7.35. The singlets at δ 4.16 and 2.28 correspond to the methylene and methyl protons. In the IR spectrum, the ν(C=N) vibration of **2** appears at 1645 cm^{-1}. The difference of 130 cm^{-1} between ν_{asym}(COO) [1578 cm^{-1}] and ν_{sym}(COO) [1448 cm^{-1}] is consistent with the bridging co-ordination mode of the acetate groups. The IR spectrum of **4** shows two ν(C=N) vibration modes at 1653 and 1631 cm^{-1}. In the ^{1}H NMR spectrum (D_2O, pD 6.9) the non-equivalent azomethine and aromatic ring protons of the mono-co-ordinated compound are detected at δ 8.40, 8.33 (azomethine), 7.59 and 7.44 (aromatic ring).

Conclusion

This work described the hydrolysis of glycine ethyl ester promoted by a dinuclear zinc(II) Schiff base complex under mild conditions. Reaction of the Schiff base complex with the hydrolysis product glycine results in conversion of the ligand. The crystal structures of the pentanuclear complex $[\{Zn_2L^2(CH_3CO_2)_2\}_2Zn(H_2O)_4]\cdot 4.5H_2O$ and of the polymeric complex $\{[Zn(HL^2)]\cdot 3H_2O\}_\infty$ have been determined.

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