New metal-binding modes for 5-aminoorotic acid: preparation, characterization and crystal structures of zinc(II) complexes

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Treatment of ZnCl$_2$ with 2 equivalents of 5-aminoorotic acid (5-amino-2,6-dioxo-1,2,3,6-tetrahydropyrimidine-4-carboxylic acid, H$_4$L) and 2 equivalents of NaOH in water–methanol yielded a mixture of crystals and powder of complexes [{Zn(H$_2$L)(H$_2$O)$_2$}$_n$] 1 and [Zn(H$_3$L)$_2$(H$_2$O)$_4$] 2, respectively. A good yield (ca. 70%) of pure 2 can be obtained by the reaction of Zn(O$_2$CMe)$_2$·2H$_2$O and 2 equivalents of H$_4$L in refluxing water. The crystal structure of 1 consists of neutral octahedral [Zn(H$_2$L)(H$_2$O)$_2$] units which form polymer chains along the b axis; H$_2$L^{2-} behaves as a bis(bidentate) bridging ligand co-ordinating to two zinc atoms via the amino nitrogen, the oxygen of the neutral carboxamide group, the deprotonated carboxamide nitrogen and one of the carboxylate oxygens and forming two five-membered chelate rings. The ^{1}H NMR spectra of 1 in (CD$_3$)$_2$SO at 290 and 310 K suggest that its solid-state structure is not retained in solution. Slow crystallization of 1 or 2 from dmso solutions yielded crystals of the monomeric octahedral complex [Zn(H$_3$L)$_2$(dmso)$_2$(H$_2$O)$_2$] 3 the structure of which was solved by single-crystal X-ray crystallography. The monoanion H$_3$L$^-$ utilizes only one carboxylate oxygen for metal binding in the centrosymmetric complex 3. The difference in anionic charge and co-ordination mode between H$_2$L^{2-} and H$_3$L$^-$ leads to different hydrogen-bonded supramolecular structures for 1 and 3. The IR and ^{1}H NMR spectra of the prepared complexes are discussed.

The co-ordination chemistry of orotic acid (2,6-dioxo-1,2,3,6-tetrahydropyrimidine-4-carboxylic acid, vitamin B$_{13}$, H$_3$L′) has been an area of great activity,[1–19] research in this area ranging from bioinorganic to pharmaceutical and materials chemistry. Orotic acid occupies a unique position in biology by being the only effective precursor in the biosynthesis of pyrimidine bases of nucleic acids in living organisms.[20,21] It has been established that during these processes the presence of metal ions, especially Mg^{2+}, is necessary, particularly during the phosphoribosylation of orotic acid.[22] One of the roles played by the metal is making H$_3$L′ available in the form of its reactive N^{3}H dianion, thus contributing to the phosphoribosylation at the N^1 site.[23] Of particular interest is dihydroorotase (DHOase), the enzyme that catalyses the conversion of N-carbamyl-L-aspartate to L-dihydroorotate, the third reaction in the de novo biosynthesis of pyrimidine nucleotides.[24] The active site of DHOase contains a Zn^{2+} ion co-ordinated by three histidine groups, and the mechanism of action involves co-ordination of N-carbamyl-L-aspartate to the zinc ion, ring closure and deco-ordination of L-dihydroorotate;[24,25] the latter is converted into the pyrimidine orotate in the fourth reaction in the biosynthesis of pyrimidines.

|	R
H$_3$L′	H
H$_4$L	NH$_2$
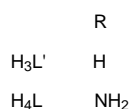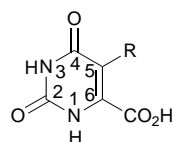
Metal orotates are also widely applied in medicine.[26] For example, they have been used as uricosurica (for enhanced excretion of uric acid) and for electrolyte substitution (in heart and liver protection). Platinum, palladium and nickel orotate complexes have been screened as therapeutic agents for cancer.[28,29] More recent interest has focused on the proposed biological carrier function of orotic acid and the corresponding anionic species for metal ions, which is held responsible for the successful application of orotate complexes in curing syndromes associated with a deficiency of a variety of metals such as calcium, magnesium, zinc or iron.[6–8,26]

Recently Mingos, Williams and co-workers[3,30] have given a new dimension to the chemistry of orotate metal complexes demonstrating that the in-built triple hydrogen-bonding functionality of the co-ordinated dianion of H$_3$L′ is able to recognize at a molecular level organic molecules, which have complementary hydrogen-bonding groups; such interactions have potential implications for metallo-drug design and for materials chemistry. Besides the above described importance, H$_3$L′ and its derivatives are also interesting ligands since they are potentially polydentate;[4] especially above the deprotonation pH values, co-ordination may occur through the carboxylate group, the heterocyclic N atoms of the pyrimidine ring and the two exocyclic carbonyl O atoms.

Despite the interest in orotate metal complexes, the co-ordination chemistry of the derivatives of orotic acid has received rather scant attention.[1,4,14–16,31–38] One of these derivatives is 5-aminoorotic acid (5-amino-2,6-dioxo-1,2,3,6-tetrahydropyrimidine-4-carboxylic acid, H$_4$L) which has relatively unknown co-ordination chemistry.[36,39–41] X-Ray analyses of three platinum(II) complexes have established the binding modes shown in Scheme 1.[41] The co-ordination mode of H$_2$L^{2-} and HL^{3-} was shown to have a direct effect on the impressive,
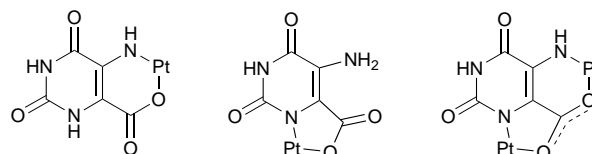
Scheme 1 Representation of the co-ordination modes of H$_2$L^{2-} and HL^{3-} established previously by X-ray crystallography
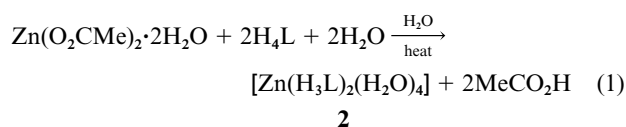
hydrogen-bonded supramolecular structures adopted by the complexes in the solid state. We have developed [34,36] an interest in the co-ordination chemistry of derivatives of orotic acid, and report herein the preparation and characterisation of three zinc(II) complexes which exhibit new metal-binding modes for H_2L^{2-} and H_3L^-.

Results and Discussion

Synthesis

Treatment of 2 equivalents of H_4L with 2 equivalents of NaOH in refluxing water followed by addition of $ZnCl_2$ (1 equivalent) in water–methanol yielded a yellow solution that slowly deposited a mixture of pale yellow crystals and a dark yellow powder. The difference in crystallinity allowed ready manual separation of the two materials. The crystals proved to be the complex $[\{Zn(H_2L)(H_2O)_2\}_n]$ **1** by single-crystal X-ray crystallography. Analytical data consistently indicated the formulation $Zn(H_3L)_2\cdot4H_2O$ **2** for the powder.

With the identities of complexes **1** and **2** established, preparative routes to pure materials were subsequently sought. Complex **2** was isolated in pure form from the reaction of $Zn(O_2CMe)_2\cdot2H_2O$ and 2 equivalents of H_4L in refluxing water [equation (1)]. All efforts to develop a clean route to **1** led to a

$$Zn(O_2CMe)_2\cdot2H_2O + 2H_4L + 2H_2O \xrightarrow[\text{heat}]{H_2O}$$

$$[Zn(H_3L)_2(H_2O)_4] + 2MeCO_2H \quad (1)$$
$$\mathbf{2}$$

slightly contaminated product. For example, the 1:1 reaction of $Zn(O_2CMe)_2\cdot2H_2O$ and H_4L in water, methanol or water–methanol led to precipitation in almost quantitative yield (typically >85%) of *almost* pure pale yellow **1**. However, very careful examination of yellow powders from this reaction revealed trace amount of dark yellow specks which were shown to be complex **2** by IR spectroscopy. Thus, the manual separation of pale yellow crystals from their above-mentioned mixture with **2** remains the only source of complex **1** to date for further measurements.

To our surprise, the ^1H NMR spectrum of complex **1** in $(CD_3)_2SO$ showed the presence of one carboxamido, one imido and two amino protons, although its solid-state structure (see below) reveals that the carboxamido group is deprotonated. Moreover, the spectra of **1** and **2** in this solvent are very similar in the regions of the resonances due to NH and NH_2 protons. The spectral behaviour of **1** strongly suggests that its polymeric solid-state structure is not retained in solution and that the aminoorotate is monoanionic (H_3L^-) following protonation at the carboxamido nitrogen by the water present in the solvent. In accordance with our suggestions, very slow crystallization of dimethyl sulfoxide (dmso) solutions of either **1** or **2** yielded bright yellow crystals of the complex $[Zn(H_3L)_2(dmso)_2(H_2O)_2]$ **3** [equations (2) and (3)], the ^1H NMR spectrum of which in $(CD_3)_2SO$ is superimposable with that of **2**.

$$2[\{Zn(H_2L)(H_2O)_2\}_n] + 2n\,dmso \xrightarrow{dmso}$$
$$\mathbf{1}$$

$$n[Zn(H_3L)_2(dmso)_2(H_2O)_2] + n\text{'}Zn(OH)_2\text{'} \quad (2)$$
$$\mathbf{3}$$

$$[Zn(H_3L)_2(H_2O)_4] + 2\,dmso \xrightarrow{dmso}$$
$$\mathbf{2}$$

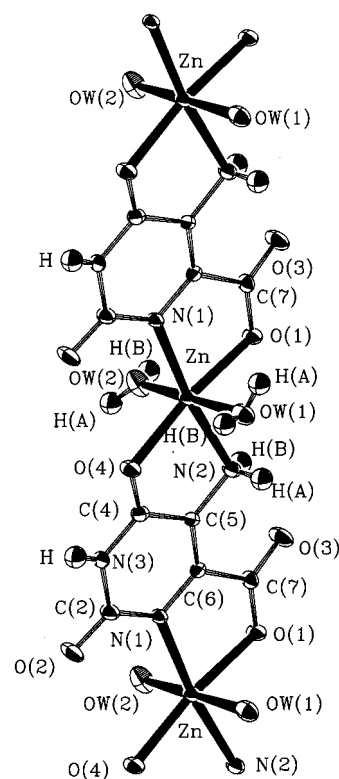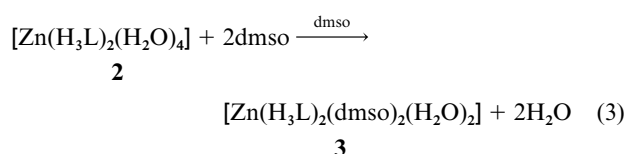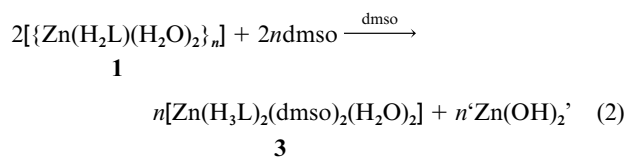$$[Zn(H_3L)_2(dmso)_2(H_2O)_2] + 2H_2O \quad (3)$$
$$\mathbf{3}$$

Fig. 1 An ORTEP[42] representation of a part of complex **1** with the atom numbering scheme
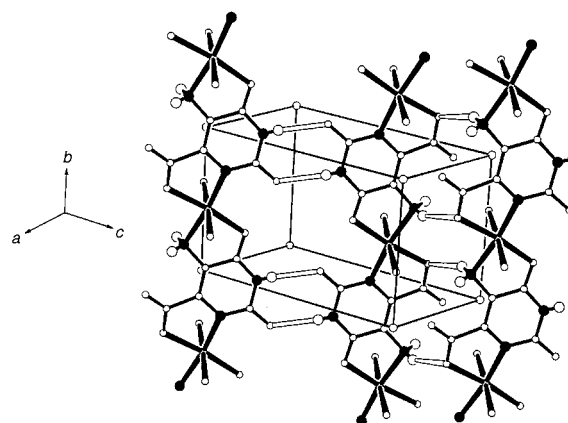

Fig. 2 Packing diagram of complex **1** showing the polymeric chains along the *b* axis and the hydrogen bonds (open bonds) forming the corrugated layers directed along the *ac* diagonal. Large circles represent H (empty) and N (filled) atoms. Hydrogen bonds involving water molecules and resulting in the three-dimensional structure are not shown for clarity

Crystal structures

Selected interatomic distances and angles for complexes **1** and **3** are listed in Tables 1 and 2, respectively. Plots of the molecular structures and crystal packing diagrams of the complexes are shown in Figs. 1–4.

The molecular structure of complex **1** shows that the aminoorotate is acting as a bis(bidentate) bridging ligand following deprotonation at the carboxylic and carboxamido groups. The complex consists of neutral $[Zn(H_2L)(H_2O)_2]$ units which are bonded to each other to form linear polymer chains by translation along the *b* axis. The donor atoms of H_2L^{2-} are the amino nitrogen, the oxygen of the neutral carboxamide group [O(4)], the deprotonated carboxamido nitrogen [N(1)] and one of the carboxylate oxygens [O(1)], thus giving two five-membered chelate rings. Two *trans* aqua ligands complete six-co-ordination at each metal.The geometry around Zn^{II} is

Table 1 Selected interatomic distances (Å), angles (°) and hydrogen-bonding interactions for complex **1**[a]

Zn···Zn	7.124(1)	N(1)–C(2)	1.346(4)
Zn–N(1)	2.070(2)	C(2)–O(2)	1.240(4)
Zn–O(1)	2.096(2)	C(2)–N(3)	1.381(4)
Zn–N(2^i)	2.121(2)	N(3)–C(4)	1.356(4)
Zn–O(4^i)	2.129(2)	C(4)–O(4)	1.256(3)
Zn–OW(1)	2.213(2)	C(4)–C(5)	1.433(4)
Zn–OW(2)	2.128(2)	C(5)–N(2)	1.442(4)
C(7)–O(1)	1.268(3)	C(5)–C(6)	1.365(4)
C(7)–O(3)	1.232(3)	C(6)–C(7)	1.534(4)
		C(6)–N(1)	1.357(4)
N(1)–Zn–O(1)	79.4(1)	N(2^i)–Zn–O(4^i)	79.8(1)
N(1)–Zn–N(2^i)	171.9(1)	N(2^i)–Zn–OW(1)	88.7(1)
N(1)–Zn–O(4^i)	108.4(1)	N(2^i)–Zn–OW(2)	88.5(1)
N(1)–Zn–OW(1)	90.7(1)	O(4^i)–Zn–OW(1)	89.8(1)
N(1)–Zn–OW(2)	91.9(1)	O(4^i)–Zn–OW(2)	90.9(1)
O(1)–Zn–N(2^i)	92.4(1)	OW(1)–Zn–OW(2)	176.9(1)
O(1)–Zn–O(4^i)	172.1(1)	O(1)–C(7)–O(3)	125.1(3)
O(1)–Zn–OW(1)	88.6(1)	O(1)–C(7)–C(6)	116.0(2)
O(1)–Zn–OW(2)	90.3(1)	O(3)–C(7)–C(6)	118.9(2)

D[b]	H	A[c]	D···A	H···A	D–H···A
OW(1)	H(A)W(1)	O(3^{ii})	2.819(1)	2.018(1)	157.9(1)
OW(1)	H(B)W(1)	O(1^{iii})	2.837(1)	2.143(1)	168.2(1)
OW(2)	H(A)W(2)	O(2^{iv})	2.797(1)	2.033(1)	154.0(1)
OW(2)	H(B)W(2)	O(4^v)	2.908(1)	2.481(1)	147.3(1)
N(2)	H(A)N(2)	O(1^{ii})	3.070(1)	2.248(1)	156.2(1)
N(3)	H	O(2^{vi})	2.841(1)	2.164(1)	173.4(1)

[a] Symmetry operations: i. x, $y + 1$, z; ii $1 - x$, $-y$, $-z$; iii $x - 1$, y, z; iv $1 - x$, $1 - y$, $1 - z$; v $1 + x$, $1 + y$, z; vi $-x$, $-y$, $1 - z$. [b] D = Donor. [c] A = Acceptor.
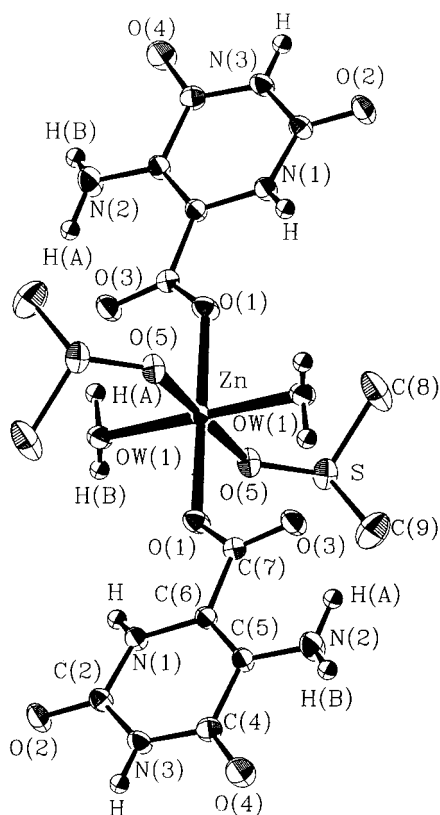
Fig. 3 An ORTEP[42] representation of complex **3** with the atom numbering scheme

moderately distorted octahedral with angles in the ranges 79.4(1)–108.3(1) and 171.9(1)–176.9(1)°. The Zn···Zn distance in the chain is 7.124(1) Å. The two C–O bond lengths at the carboxylate group are different, 1.268(3) and 1.232(3) Å, with that bonded to Zn being the longer.

The 5-aminoorotate ligand, being well endowed with hydrogen-bond donors and acceptors, has the potential to adopt several modes of interligand hydrogen bonding.[41] The polymeric chains of complex **1** are formed by translation of the monomeric [Zn(H$_2$L)(H$_2$O)$_2$] units and as a result the co-ordinated carboxylate and amino moieties are on one side of the chain and the unco-ordinated carbonyl and imido NH groups on the other (Fig. 1). Therefore, each chain is hydrogen bonded to two neighbouring chains with two different types of hydrogen bonds leading to the formation of corrugated layers which are directed along the *ac* diagonal of the unit cell (Fig. 2). These two types of hydrogen bonds form centrosymmetric pairs of the AD=DA type, involving the co-ordinated carboxylate oxygen O(1) and one of the protons of the co-ordinated amino group on one side and the pyrimidine carbonyl oxygen O(2) and the imido N(3)–H group on the other (Table 1). Such hydrogen-bond pairs have been observed in the crystal structure of one isomer of [Pt(H$_2$L)(PPh$_3$)$_2$], resulting in the formation of tetramers;[41] double hydrogen bonds are found in nature occurring in guanine tetrads (or G quarters)[43] which are stabilized by a central sodium ion. Hydrogen bonds between the co-ordinated water molecules [OW(1), OW(2)] and the oxygen atoms O(1), O(2), O(3) and O(4) of H$_2$L^{2-} hold the corrugated layers together in a three-dimensional network.
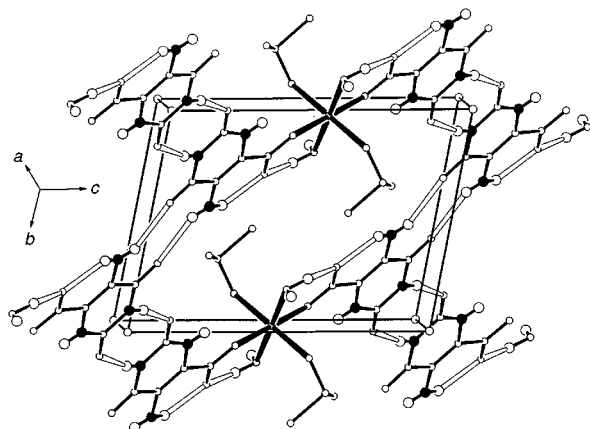
The structural analysis of complex **3** found the zinc in a slightly distorted octahedral environment (Fig. 3). This represents the first crystallographically characterized complex containing the monoanion of 5-aminoorotic acid. The molecule has a crystallographically imposed centre of symmetry, *i.e.* the metal is co-ordinated by pairs of *trans*-related H$_3$L$^-$ ions, O-bonded dmso molecules and aqua ligands. Thus, the amino-orotate(1−) ion utilizes only one of its carboxylate oxygens for metal binding. The Zn–O distances are unexceptional;[7,9,12,33,44] the Zn–O$_{carboxylate}$ [2.100(2) Å] distance is very similar to that in **1**.

The pattern of hydrogen bonding in complex **3** differs markedly from that of **1**. The unco-ordinated carboxylate oxygen atom [O(3)] is doubly hydrogen bonded to the unco-ordinated amino group and to the co-ordinated water molecule giving rise to intramolecular hydrogen bonds, the latter being particularly strong [OW(1)···O(3) 2.652(1) Å]. In addition, an extensive network of intermolecular hydrogen bonds results in a three-dimensional polymeric structure. The monomers of **3** are linked through centrosymmetric pairs of O(2)···H–N(3) hydrogen bonds of the AD=DA type, also observed in **1**, and form chains along the *ac* diagonal of the unit cell. Another centrosymmetric pair of hydrogen bonds of the AD=DA type involving the pyrimidine oxygen O(4) and the unco-ordinated amino group results in the formation of layers directed along the body diagonal of the unit cell (Fig. 4). Finally, hydrogen bonds involving co-ordinated solvent molecules and atoms N(1) and O(1) of the ligand result in the three-dimensional polymeric arrangement of the structure (Table 2).

Complexes **1** and **3** represent the fourth and fifth, respectively, structurally characterized examples of 5-aminoorotate complexes. The other examples are the two isomers of [Pt(H$_2$L)-(PPh$_3$)$_2$] and [Pt$_2$(HL)(PPh$_3$)$_4$]BF$_4$; their structures have revealed the co-ordination modes for H$_2$L^{2-} and HL^{3-} shown in Scheme 1. None of the ligation modes of H$_2$L^{2-} in [Pt(H$_2$L)-(PPh$_3$)$_2$] is similar to that observed in **1**.

Complexes **1** and **3** join a small family of structurally characterized zinc(II) complexes with orotate-type ligands. Since most of these were reported only recently, we felt it timely to collect these in Table 3, together with selected structural data for convenient comparison. We have also included the remarkable complex [Zn(H$_2$O)$_6$][H$_2$L′·H$_2$O]$_2$, the crystal lattice of which features [Zn(H$_2$O)$_6$]$^{2+}$ cations associated with two mono-hydrated orotate(1−) ions only through hydrogen bonds. Two comments are evident from Table 3. (i) In the three complexes with the dianion of orotic acid as ligand, bidentate co-

ordination *via* one of the carboxylate oxygen and deprotonated N(1) atoms is observed. The $O_{carboxylate}$, N(1)/O(4), N_{amino} bis-(bidentate) bridging behaviour of the 5-aminoorotate(2−) ligand in **1** can be attributed to extra stabilization provided by the formation of another five-membered chelate ring [ZnO(4)-C(4)C(5)N(2)]. (ii) The monoanions of orotic acid and its derivatives show a preference for monodentate $O_{carboxylate}$ co-ordination to Zn^{II}, an exception being the second L-dihydro-orotate ion (H_2dhor^-) in [{$Zn(H_2dhor)_2(H_2O)_2$}$_n$] which links adjacent metal ions *via* the two different oxygens of the carboxylate group forming a Zn–O–C–O–Zn bridge.[33] The $O_{carboxylate}$, O(4) bidentate behaviour of the isoorotate(1−) ligand in [$Zn(H_2isor)_2(H_2O)_2$] is favoured due to the closure of a stable six-membered chelate ring, a consequence of the presence of the carboxylate group in position 5 of the pyrimidine ring.[34,36]

Spectroscopic characterization of complexes 1, 2 and 3

Tentative assignments of selected IR bands of complexes **1**, **2** and **3** are given in the Experimental section. The assignments have been given by performing deuterium isotopic substitution experiments, studying literature reports[36,41] and comparing the spectra of H_4L and NaH_3L with those of the complexes. As a general remark we must emphasize that some stretching and deformation modes are coupled, so that the proposed assignments should be regarded as approximate descriptions of the vibrations.

In the $\nu(OH)_{water}$ region the spectrum of complex **1** shows one medium band at 3436 cm^{-1} attributed to the presence of co-ordinated water.[45] For **2** and **3** this band overlaps with the $\nu_{asym}(NH_2)$ band. In the spectrum of NaH_3L the bands due to the $\nu_{asym}(NH_2)$, $\nu_{sym}(NH_2)$, $\nu(C^2O)$ and $\nu(C^4O)$ vibrations appear[36] at 3430, 3340, 1726 and 1678 cm^{-1}, respectively. The absence of large systematic shifts of these bands in the spectra of **2** and **3** implies that there is no interaction between the amino nitrogen or the carbonyl oxygens and the zinc ion, in accord with the crystal structure of **3**. The lower frequencies of the $\nu_{asym}(NH_2)$ and $\nu_{sym}(NH_2)$ vibrations in complex **1** (3386 and 3264 cm^{-1}) reflect the co-ordination of the amino group. It was not possible to differentiate clearly the spectroscopic behaviour of the different carbonyl groups of this complex.

For the monodentate carboxylate co-ordination observed in the structure of complex **3** (and proposed for **2**) we would expect the relationship $\Delta_{complex} > \Delta_{NaH_3L}$ to apply,[46] where $\Delta = \nu_{asym}(CO_2) - \nu_{sym}(CO_2)$. The fact that for **2** and **3** $\Delta_{complex}$ (214 cm^{-1}) < Δ_{NaH_3L} (227 cm^{-1}) is presumably due to the involvement of the unco-ordinated carboxylate oxygen in hydrogen-bonding linkages.[46,47] The $\nu_{asym}(CO_2)$ and $\nu_{sym}(CO_2)$ bands of **1** are at 1632 and 1430 cm^{-1}, respectively; the participation of the monodentate carboxylate group of H_2L^{2-} in hydrogen bonds or/and the dianionic character of the amino-orotate ligand may be responsible for the observed low Δ value (202 cm^{-1}).

For complex **3** a medium peak at 1018 cm^{-1} is ascribed to the S=O stretching mode of dmso. The shift of this band to lower frequency compared with that of free liquid dmso (1055 cm^{-1}) is consistent with O-co-ordinated dmso.[48]

Fig. 4 Packing diagram of complex **3** showing intra- and inter-molecular hydrogen bonds (open bonds) resulting in the formation of layers along the body diagonal of the unit cell. Large circles represent H (empty) and N (filled) atoms. Hydrogen bonds taking part in the construction of the three-dimensional network are not shown for clarity

Table 2 Selected bond lengths (Å), angles (°) and hydrogen-bonding interactions for complex **3**[a]

Zn–O(1)	2.100(2)	C(2)–N(3)	1.378(3)
Zn–O(5)	2.122(2)	N(3)–C(4)	1.371(4)
Zn–OW(1)	2.117(2)	C(4)–O(4)	1.217(3)
C(7)–O(1)	1.275(3)	C(4)–C(5)	1.477(3)
C(7)–O(3)	1.253(3)	C(5)–N(2)	1.363(3)
O(5)–S	1.517(2)	C(5)–C(6)	1.364(4)
N(1)–C(2)	1.346(3)	C(6)–C(7)	1.485(3)
C(2)–O(2)	1.232(3)	C(6)–N(1)	1.395(3)
O(1)–Zn–O(5)	91.5(1)	O(1)–C(7)–O(3)	125.7(2)
O(1)–Zn–OW(1)	88.9(1)	O(1)–C(7)–C(6)	115.8(2)
O(5)–Zn–OW(1)	95.0(1)	O(3)–C(7)–C(6)	118.5(2)

D[b]	H	A[c]	D···A	H···A	D–H···A
OW(1)	H(A)W(1)	O(3^i)	2.652(1)	1.673(1)	160.4(1)
OW(1)	H(B)W(1)	O(1^{ii})	2.957(1)	2.281(1)	163.6(1)
N(1)	HN(1)	O(5^{iii})	2.982(1)	2.223(1)	158.5(1)
N(2)	H(A)N(2)	O(3^{iv})	2.750(1)	2.016(1)	127.3(1)
N(2)	H(B)N(2)	O(4^v)	3.033(1)	2.320(1)	153.0(1)
N(3)	HN(3)	O(2^{vi})	2.854(1)	1.991(1)	167.1(1)

[a] Symmetry operations: i $1 - x, -y, 1 - z$; ii $-x, -y, 1 - z$; iii $x - 1, y, z$; iv x, y, z; v $-x, -1 - y, 2 - z$; vi $1 - x, -y, 2 - z$. [b] D = Donor. [c] A = Acceptor.

Table 3 Literature data for the structurally characterized zinc(II) complexes with orotate-type ligands

Complex *	Ligation mode	Zn–$O_{carboxylate}$/Å	Zn–N(1)/Å	Co-ordination geometry	Ref.
[Zn(HL′)(H$_2$O)$_4$]·H$_2$O	$O_{carboxylate}$, N(1) chelating	2.073(2)	2.089(2)	Octahedral	12
[Zn(HL′)(NH$_3$)$_3$]·H$_2$O	$O_{carboxylate}$, N(1) chelating	2.213(3)	2.060(4)	Trigonal bipyramidal	9
[Zn(HL′)(H$_2$O)$_4$]·1.5H$_2$O	$O_{carboxylate}$, N(1) chelating	2.079(5)	2.088(5)	Octahedral	7
[Zn(H$_2$O)$_6$][H$_2$L′·H$_2$O]$_2$	Counter ion			Octahedral	6
[Zn(H$_2$isor)$_2$(H$_2$O)$_2$]	$O_{carboxylate}$, O(4) chelating	2.033(4)		Octahedral	44
[{Zn(H$_2$dhor)$_2$(H$_2$O)$_2$}$_n$]	$O_{carboxylate}$ monodentate and $O_{carboxylate}$, $O'_{carboxylate}$ bidentate bridging	2.041(7), 1.986(7), 2.086(6)		Square pyramidal	33
[Zn(L″)(H$_2$dhor)]·C$_6$H$_6$	$O_{carboxylate}$ monodentate	1.894(4)		Tetrahedral	1
[{Zn(H$_2$L)(H$_2$O)$_2$}$_n$] **1**	$O_{carboxylate}$, N(1)/O(4), N_{amino} bis(bidentate) bridging	2.096(2)	2.070(2)	Octahedral	This work
[Zn(H$_3$L)$_2$(dmso)$_2$(H$_2$O)$_2$] **3**	$O_{carboxylate}$ monodentate	2.100(2)		Octahedral	This work

* Abbreviations: H$_3$isor = isoorotic acid; H$_3$dhor = L-dihydroorotic acid; HL″ = tris(3-cumenyl-5-methylpyrazolyl)hydroborate.

Table 4 Crystallographic data for complexes **1** and **3**[a]

	1	**3**
Empirical formula	$C_5H_7N_3O_6Zn$	$C_{14}H_{24}N_6O_{12}S_2Zn$
M	270.5	597.9
$a/Å$	5.230(1)	5.249(1)
$b/Å$	7.124(1)	9.074(2)
$c/Å$	10.425(1)	11.826(3)
$\alpha/°$	93.44(1)	98.90(1)
$\beta/°$	101.38(1)	91.25(1)
$\gamma/°$	94.58(1)	100.77(1)
$U/Å^3$	400.13(7)	545.9(2)
Radiation	Mo-Kα (λ 0.710 70 Å, Graphite monochromated)	Cu-Kα (λ 1.54 180 Å, Ni-filtered)
Z	2	1
D_c/Mg m^{-3}	2.245	1.819
$F(000)$	272	308
Crystal shape and colour	Pale yellow prism	Bright yellow prism
Crystal size/mm	$0.15 \times 0.25 \times 0.50$	$0.10 \times 0.25 \times 0.40$
μ/mm^{-1}	3.09	4.06
Diffractometer	Crystal Logic Dual Goniometer	Nicolet P2$_1$
Scan speed/° min^{-1}	4.0	3.0
Scan range/°	2.5 + $\alpha_1\alpha_2$ separation	2.4 + $\alpha_1\alpha_2$ separation
2θ Range/°	4.0–50.0	7.6–130.0
hkl	0 − 6, −8 to 8, −12 to 12	−6 to 6, −10 to 10, −13 to 0
Collected reflections	1576	1951
Unique reflections (R_{int})	1416 (0.0088)	1851 (0.0080)
Observed reflections [$I > 2\sigma(I)$]	1331	1776
Weighting scheme,[b] w^{-1}	$\sigma^2(F_o^2) + (0.0182P)^2 + 0.5443P$	$\sigma^2(F_c^2) + (0.0680P)^2 + 0.4254P$
No. refined parameters	164	208
$R1, wR2$[c] (observed reflections)	0.0251, 0.0698	0.0386, 0.1058
Goodness of fit	1.089	1.086
Maximum Δ/σ	0.000	0.008
Largest residuals/e Å^{-3}	0.504, −4.472	0.635, −0.994

[a] Details in common: triclinic, space group $P\bar{1}$ Lorentz, polarization and ψ-scan absorption corrections applied; θ–2θ scan method. [b] $P = \frac{1}{3}(2F_c^2 + F_o^2)$. [c] $R1 = \Sigma(|F_o| − |F_c|)/\Sigma(|F_o|)$ and $wR2 = [\Sigma w(F_o^2 − F_c^2)^2/\Sigma w(F_o^2)^2]^{\frac{1}{2}}$.

The identical ^{1}H NMR spectra of complexes **2** and **3** in $(CD_3)_2SO$ show the expected three resonances due to the NH protons. The carboxamido and imido protons give singlets at δ_H 11.30 and 8.96 and the amino protons give a broad signal at δ_H 4.73.[41] In the spectrum of **1** in the same solvent the amido and imido protons are observed at *ca.* δ_H 11.3 and 9.0. The 290 K spectrum shows two very broad peaks at *ca.* δ_H 5.6 and 3.6, which are due to the intermolecular exchange of protons between the amino group and water (contained in the solvent). The facts that we did not observe two sharp signals of the separated species or an averaged signal are attributed to the intermediate rate of the exchange.[49,50] In accord with our suggestion, increase of the temperature to 310 K results in the appearance of a broad averaged signal at *ca.* δ_H 4.0.

The fact that complexes **2** and **3** possess very similar IR spectra (except for the bands due to dmso in **3**) supports analogous structures for them in the solid state.

Conclusion

The complexes described above demonstrate once more[41] the versatility of the 5-aminoorotate ligand, which adopts two co-ordination modes involving one (**2**, **3**) or two (**1**) zinc(II) atoms. The different charge and co-ordination mode of the ligand have a major effect on the supramolecular structures adopted by the complexes. From previous results,[41] this work and recent unpublished data of our group, it is clear that the nature of 5-aminoorotic acid makes its various anionic forms versatile ligands for use with a variety of metals and for a variety of objectives/advantages, including variable co-ordination modes, high-nuclearity aggregate formation and/or linking of aggregates into polymeric arrays. Thus, we believe that H_4L has great potential as a generally useful new polyfunctional ligand in metal chemistry and it will prove attractive to a variety of co-ordination chemists.

Experimental

General

All manipulations were performed under aerobic conditions. All chemicals and solvents were of reagent grade obtained from commercial sources and used without further purification; water was distilled in-house.

Physical methods

Microanalytical data were obtained on a Perkin-Elmer 2400 elemental analyser by the University of Ioannina (Greece) Microanalytical Service. Zinc analysis was carried out by ethylenedinitrilotetraacetate titration. The IR spectra were recorded on a Perkin-Elmer 16 PC spectrometer as KBr pellets, 200 MHz ^{1}H NMR spectra on a Varian XL-200E instrument, at the Institute of Physical Chemistry, NCSR 'Demokritos', Aghia Paraskevi Attikis, Greece, using $(CD_3)_2SO$ as the solvent; the chemical shifts (δ) are given in ppm relative to the residual signal of the solvent.

Preparations

Complexes 1 and 2 in a mixture. A suspension of H_4L (0.34 g, 2.0 mmol) in water (60 cm^3) was treated with a standard aqueous 0.1000 mol dm^{-3} NaOH solution (20 cm^3, 2.0 mmol) under reflux. The resulting yellow solution (pH ≈ 7.5) was stirred while a solution of $ZnCl_2$ (0.14 g, 1.0 mmol) in water (20 cm^3)–methanol (10 cm^3) was added to give a homogeneous solution of the same colour (pH 4.5–5.0). After 2 d a mixture of pale yellow crystals and a dark yellow powder was formed. The

two products were readily separated manually. The pale yellow prismatic crystals proved to be the complex $[\{Zn(H_2L)(H_2O)_2\}_n]$ **1**. The powder was identified as $Zn(H_3L)_2\cdot4H_2O$ **2** by elemental analysis. Complex **1** (Found: C, 22.4; H, 2.67; N, 15.6; Zn, 23.8. $C_5H_7N_3O_6Zn$ requires C, 22.2; H, 2.61; N, 15.5; Zn, 24.2%): $\tilde{\nu}_{max}/cm^{-1}$ 3436m [ν(OH)], 3386m [ν_{asym}(NH$_2$)], 3264m [ν_{sym}(NH$_2$)], 3208m [ν(NH)], 1702s [ν(CO)], 1650(sh) [ν(C=C)], 1632s [ν_{asym}(CO$_2$)], 1492m [ν(C−N)], 1430m [ν_{sym}(CO$_2$)] and 1382s [δ(NH)]; δ_H[(CD$_3$)$_2$SO, 290 K] 11.35 (1 H, s, NH), 9.07 (1 H, s, NH), 5.60 (2 H, br s, NH$_2$) and 3.62 (br s, H$_2$O/OH$^-$); δ_H[(CD$_3$)$_2$SO, 310 K] 11.29 (1 H, s, NH), 8.95 (1 H, s, NH) and 4.02 (br s, NH$_2$/H$_2$O/OH$^-$). Complex **2** (Found: C, 25.0; H, 3.16; N, 17.9; Zn, 13.2. $C_{10}H_{16}N_6O_{12}Zn$ requires C, 25.1; H, 3.38; N, 17.6; Zn, 13.7%): $\tilde{\nu}_{max}/cm^{-1}$ 3450m [ν(OH), ν_{asym}(NH$_2$)], 3346m [ν_{sym}(NH$_2$)], 3230 (sh) and 3202m (br) [ν(NH)], 1732m and 1680s [ν(CO)], 1653 (sh) [ν(C=C)], 1634m [ν_{asym}(CO$_2$)], 1504m and 1442w [ν(CN)], 1420m [ν_{sym}(CO$_2$)] and 1378s [δ(NH)]; δ_H[(CD$_3$)$_2$SO] 11.30 (1 H, s, NH), 8.96 (1 H, s, NH) and 4.73 (br s, H$_2$O/NH$_2$); the NH$_2$ chemical shift is concentration dependent.

[Zn(H$_3$L)$_2$(H$_2$O)$_4$] 2. Water (120 cm^3) was added to a mixture of Zn(O$_2$CMe)$_2$·2H$_2$O (0.22 g, 1.0 mmol) and H$_4$L (0.34 g, 2.0 mmol). The solids dissolved on stirring to give a yellow solution, which was refluxed for 30 min. The solution (pH $\approx$ 3.5–4.0) was allowed to stand undisturbed at room temperature for 1–2 h. The resultant dark yellow microcrystalline solid was filtered off, washed with water, ethanol and diethyl ether and dried *in vacuo* overnight. Yield 0.32 g (67%). The identity of the product was confirmed by elemental analyses; the IR and ^{1}H NMR spectra of this sample are identical with those of samples from the above-described preparation of **2**.

[Zn(H$_3$L)$_2$(dmso)$_2$(H$_2$O)$_2$] 3. Either complex **1** or **2** (10 mmol) was dissolved in hot dmso (15 cm^3). The yellow solution obtained was allowed to stand undisturbed at room temperature for 2 months, and the resulting bright yellow crystals were filtered off, washed with diethyl ether and dried in air; typical yields are in the 25–35% range (Found: C, 28.2; H, 4.14; N, 14.2; Zn, 11.2. $C_{14}H_{24}N_6O_{12}S_2Zn$ requires C, 28.1; H, 4.05; N, 14.1; Zn, 10.9%). $\tilde{\nu}_{max}/cm^{-1}$ 3458m [ν(OH), ν_{asym}(NH$_2$)], 3342m [ν_{asym}(NH$_2$)], 3246m and 3160m [ν(NH)], 1715 (sh) and 1686s [ν(CO)], 1652 (sh) [ν(C=C)], 1636s [ν_{asym}(CO$_2$)], 1485m [ν(C−N)], 1422m [ν_{sym}(CO$_2$)], 1382m [δ(NH)] and 1018m [ν(SO)]. The ^{1}H NMR spectrum in (CD$_3$)$_2$SO is identical with that of **2**.

Crystallography

A summary of the crystal data, data-collection and structure-solution and refinement parameters for complexes **1** and **3** is given in Table 4. Prismatic crystals of **1** and **3** were mounted in capillaries filled with drops of mother-liquor and in air, respectively. Unit-cell dimensions were determined and refined by using the angular settings of 25 automatically centred reflections in the ranges $11 < 2\theta < 23$ (**1**) and $24 < 2\theta < 54°$ (**3**). Intensity data were collected at 298 K with θ–2θ scan mode. Three standard reflections, monitored every 97, showed less than 3% intensity fluctuation and no decay.

The structures were solved by direct methods using SHELXS 86[51] and refined by full-matrix least-squares techniques on F^2 with SHELXL 93.[52] For both structures all hydrogen atoms were located by difference maps and their positions refined isotropically. All non-hydrogen atoms were refined anisotropically.

CCDC reference number 186/904.

See http://www.rsc.org/suppdata/dt/1998/1327/ for crystallographic files in .cif format.

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