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Copper(II) complexes of the antitumour-related ligand salicylaldehyde acetylhydrazone (H_2L) and the single-crystal X-ray structures of $[\{Cu(HL)H_2O\}_2]\cdot 2(NO_3)$ and $[\{Cu(HL)(pyridine)(NO_3)\}_2]$

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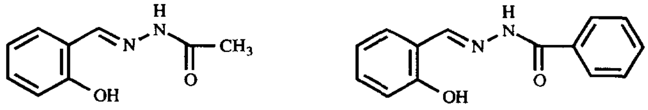
Abstract

Binary and ternary copper(II) complexes of the ligand salicylaldehyde acetylhydrazone (H_2L) have been prepared. In acid or neutral media monoanionic HL complexes separate. Addition of the Lewis bases pyridine (py) and thiourea (tu) to $[\{Cu(HL)H_2O\}_2]\cdot 2(NO_3)$ results in the monoanionic ternary ligand adducts $[\{Cu(HL)(py)(NO_3)\}_2]$ and $[Cu(HL)(tu)(NO_3)]$, respectively. With base, the less soluble dianionic complex $[\{CuL\}_2]$ was isolated. Addition of py to $[\{CuL\}_2]$ afforded the dianionic ternary complex $[CuL(py)]\cdot \frac{1}{2}H_2O$. The complexes have been characterized by a range of physicochemical techniques and the crystal and molecular structures of $[\{Cu(HL)H_2O\}_2]\cdot 2(NO_3)$ and $[\{Cu(HL)(py)(NO_3)\}_2]$ determined. Crystals of $[\{Cu(HL)H_2O\}_2]\cdot 2(NO_3)$, $C_{18}H_{22}Cu_2N_6O_{12}$, are monoclinic, with space group $P2_1/c$, $a=7.217(4)$, $b=11.758(8)$, $c=13.764(8)$ Å, $\beta=95.47(4)°$ and $Z=4$. $[\{Cu(HL)H_2O\}_2]\cdot 2(NO_3)$ is a centrosymmetric (planar) dimer, the monomeric units being bridged through the phenoxy oxygen. The copper atom has a square-pyramidal geometry with the basal donor atoms coming from the tridentate ligand (ONO) and the symmetry-related phenolate (O). The more weakly bound apical donor oxygen is supplied by a coordinated water molecule. The nitrate is not bound. Crystals of $[\{Cu(HL)(py)(NO_3)\}_2]$, $C_{28}H_{28}Cu_2N_8O_{10}$, are monoclinic, with space group $P2_1/c$, $a=10.642(3)$, $b=11.796(3)$, $c=13.137(2)$ Å, $\beta=111.03(2)°$ and $Z=4$. $[\{Cu(HL)(py)(NO_3)\}_2]$ is a weakly interacting centrosymmetric (stacked) dimer, the monomeric units being bridged axially through the phenoxy oxygen. The copper atom has a tetragonal geometry with the equatorial donor atoms coming from the tridentate ligand (ONO) and the pyridine (N). The more weakly bound nitrato anion provides the other axial donor (O). Several of the complexes exhibit interesting magnetic properties.

Keywords: Crystal structures; Dimers; Copper complexes; Antitumour; Schiff bases; Salicylaldehyde acetylhydrazone complexes; Magnetic couplings

1. Introduction

Transition metal complexes with potential biological activity are being investigated more frequently now than ever before. Most of the first-row transition metals are biologically essential, with a number of the complexes demonstrating a range of bioactivities. One example is the tridentate ligand salicylaldehyde benzoylhydrazone (H_2sb, Scheme 1), where the Cu(II) complex $[Cu(Hsb)Cl]\cdot H_2O$ was shown to be a potent inhibitor of DNA synthesis and cell growth and to be more potent than the unbound moiety [1,2]. It was therefore suggested that the metal complex is the biologically active form. This ligand also has mild bacteriostatic activity [3] and a range of analogues has been investigated as potential oral iron-chelating drugs for genetic disorders such as thalassemia [4]. Related to this system is salicylaldehyde acetylhydrazone (H_2L, Scheme 1). This has potential biological activity and has been shown to display radiation protective properties [5]. Interest is not focused solely on the biological properties of related ligands and their complexes. Such systems have also been studied for the anomalous magnetic



H_2L H_2sb

Scheme 1. Structure of salicylaldehyde acetylhydrazone (H_2L) indicating the ionizable protons and the related antitumour ligand salicylaldehyde benzoylhydrazone (H_2sb).

Abbreviations: $[\{Cu(HL)H_2O\}_2]\cdot 2(NO_3)$ = bis[(μ-*O*(salicylaldehyde-κO-acetylhydrazonato-$\kappa^2 N,O'$)-aqua-κO-copper(II))] bisnitrate; $[\{Cu(HL)(py)(NO_3)\}_2]$ = bis[pyridine-κN-(salicylaldehyde-κO-acetylhydrazonato-$\kappa^2 N,O'$)-nitrato-κO-copper(II)].

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properties of transition metal complexes [6] and salicylaldehyde n-alkanohydrazones were employed for the extraction of trivalent lanthanides [7].

In this paper we have developed the Cu(II) chemistry of H_2L and we report the preparation and characterization of mono- and dianionic complexes. Binary and ternary adducts have been isolated and the single-crystal X-ray structures of the dimeric complexes $[\{Cu(HL)(py)(NO_3)\}_2]$ and $[\{Cu(HL)H_2O\}_2]\cdot 2NO_3$ have been determined. The atypical magnetic properties are discussed in relation to the dimeric structures adopted. Comparisons between the Cu(II)–H_2L system and the analogous antitumour ligand H_2sb are made.

2. Experimental

The electronic transmittance spectra were recorded on a Shimadzu UV-240 spectrophotometer using Nujol mulls. Room-temperature magnetic susceptibility measurements were carried out on a Johnson Matthey magnetic susceptibility balance with $Hg[Co(SCN)_4]$ as the calibrator. Corrections for diamagnetism were made using Pascal's constants [8]. Microanalyses (Table 1) were performed by the Microanalysis Laboratory at the National University of Singapore. Conductance measurements were made using a Kyoto Electronics CM-115 conductivity meter with a Kyoto Electronics conductivity cell on about 1 mmol dm^{-3} solutions. IR spectra were recorded on a Shimadzu IR-470 spectrophotometer as KBr discs in the range 4000–400 cm^{-1}. All chemicals were of Analar grade and used as supplied. Solvents were distilled prior to use.

Table 1
Colours, analytical and magnetic data

Complex	Colour	Analyses [a] (%)			$\mu_{eff}{}^{b}/\mu_B$
		C	H	N	
1 $[\{CuL\}_2]$	green	44.7 (45.1)	3.1 (2.9)	11.8 (11.7)	2.60
2 $[\{CuL\}_2]\cdot 2H_2O$	green	41.9 (41.9)	3.4 (3.9)	10.7 (10.9)	2.60
3 $[CuL(py)]\cdot \frac{1}{2}H_2$	dark green	51.4 (51.3)	3.9 (4.3)	12.8 (12.8)	1.92
4 $[\{Cu(HL)H_2O\}_2]\cdot 2NO_3$	dark green	33.7 (33.7)	3.5 (3.5)	12.9 (13.1)	1.28
5 $[Cu(HL)Cl(H_2O)]\cdot H_2O$	green	34.4 (34.6)	4.3 (4.2)	8.8 (9.0)	1.78
6 $[Cu(HL)Br(H_2O)]$	green	31.9 (31.9)	3.2 (3.3)	8.1 (8.3)	1.93
7 $[\{Cu(HL)ClO_4\}_2]$	green	31.9 (31.8)	2.8 (2.7)	8.2 [c] (8.2)	1.49
8 $[Cu(HL)CF_3SO_3]$	pale green	30.8 (30.8)	2.3 (2.3)	7.0 [d] (7.2)	2.18
9 $[Cu(HL)SCN]\cdot H_2O$	dark green	37.9 (37.9)	3.6 (3.5)	13.2 (13.3)	2.05
10 $[\{Cu(HL)(py)NO_3\}_2]$	green	44.5 (44.0)	3.7 (3.7)	14.5 (14.7)	2.15
11 $[Cu(HL)tu]\cdot NO_3$	green	31.8 (31.7)	3.5 (3.5)	18.3 (18.5)	2.01

[a] Calculated values are given in parentheses.

[b] At 298 K per metal ion.

[c] % Cl 10.8 (10.4).

[d] % F 14.1 (14.6).

2.1. Ligand preparation

To a solution of acetic hydrazide (synthesized following a published procedure [7]: 6.00 g, 81.0 mmol) in 50% ethanol (40 cm^3) was added salicylaldehyde (8.45 cm^3, 81.0 mmol) dropwise with gentle warming. The white product which separated was filtered, washed with 50% ethanol and ice cold ethanol, recrystallized from ethanol and then dried in vacuo. Yield: 11.55 g (80%).

2.2. Complex preparation

$[\{CuL\}_2]$ (1)

To a hot solution of H_2L (356 mg, 2.00 mmol) in 20% ethanol (25 cm^3) was added LiOH (100 mg, 4.18 mmol). To the resulting yellow solution, $Cu(NO_3)_2\cdot 3H_2O$ (449 mg, 2.04 mmol) in water (5 cm^3) was added. The green precipitate which formed was filtered and washed successively with water, ethanol and diethyl ether, and then dried in vacuo. Yield: 340 mg (71%).

$[\{CuL\}_2]\cdot 2H_2O$ (2)

In an attempt to prepare a 2,2′-bipyridyl adduct of $Cu(HL)^+$ the title compound was isolated. To a filtered solution of $[\{Cu(HL)H_2O\}_2]\cdot 2NO_3$ (303 mg, 0.50 mmol) in hot 20% ethanol (50 cm^3) was added 2,2′-bipyridyl (156 mg, 1.00 mmol) in hot water (10 cm^3). Dimethylformamide (5 cm^3) was added and the solution filtered. The dark green complex which separated on cooling was filtered off and washed with water, ethanol and then diethyl ether before drying in vacuo. Yield: 49 mg (19%).

$[CuL(py)]\cdot \frac{1}{2}H_2O$ (3)

To a suspension of $[\{CuL\}_2]$ (100 mg, 0.21 mmol) in hot ethanol (2 cm^3) was added excess pyridine (py, 1 cm^3, 12.4 mmol) to give an emerald green solution. The solution was left to go to dryness, then the crystalline material was filtered and washed with diethyl ether before drying in vacuo. Yield: 71 mg (52%).

$[\{Cu(HL)H_2O\}_2]\cdot 2NO_3$ (4)

To H_2L (3.564 g, 20.0 mmol) in hot ethanol (230 cm^3) was added $Cu(NO_3)_2\cdot 3H_2O$ (4.838 g, 20.0 mmol) in the same solvent (30 cm^3). The intense green solution was concentrated by heated with stirring (to about 100 cm^3). After 2 days the crystals which had formed were filtered and washed with ethanol, then diethyl ether, followed by drying in vacuo. Yield: 5.494 g (86%). IR (–NO_3, cm^{-1}): $\nu(NO_3)$ 1375–1440s, 1270–1300m.

[Cu(HL)Br(H$_2$O)] (6) and [{Cu(HL)ClO$_4$}$_2$] (7)

To a solution of H_2L (356 mg, 2.00 mmol) in hot ethanol (30 cm^3) was added either $CuBr_2$ (450 mg, 2.02 mmol) or $Cu(ClO_4)_2 \cdot 6H_2O$ (750 mg, 2.02 mmol) in ethanol (5 cm^3) and the resultant solutions were left for 5 h and 2 days, respectively. The product which separated was filtered and given a cursory wash in ethanol, washed several times in ethyl acetate, then diethyl ether before drying in vacuo. Yields: 226 mg (33%) **6**; 160 mg (24%) **7**. IR (–ClO_4, cm^{-1}): ν_3 1170–1040vs. **Caution**: perchlorate salts are potentially explosive.

[Cu(HL)CF$_3$SO$_3$] (8)

When a solution of H_2L (0.713 g, 4.00 mmol) in hot ethyl acetate (120 cm^3) was added to $Cu(CF_3SO_3)_2$ (1.447 g, 4.00 mmol) in ethyl acetate (20 cm^3) a pale green powder separated. After boiling for 5 min the mixture was filtered hot and the product washed with ethyl acetate, then diethyl ether prior to drying in vacuo. Yield: 1.465 g (94%). IR (–CF_3SO_3, cm^{-1}): $\nu_{as}(SO_3)$ 1249–1286s; $\nu_{as}(CF_3)$ 1155m; $\nu_s(SO_3)$ 1037m; $\delta_s(SO_3)$ 649m.

[Cu(HL)SCN]·H$_2$O (9)

To the filtered solution of $[\{Cu(HL)H_2O\}_2] \cdot 2NO_3$ (321 mg, 0.50 mmol) in hot ethanol (30 cm^3) was added KSCN (94 mg, 0.97 mmol) in water (2 cm^3) upon which a green precipitate separated. The suspension was cooled, then stirred for 5 min prior to filtering and washing with water, ethanol and diethyl ether. Yield: 142 mg (45%). IR (–SCN, cm^{-1}): ν(CN) 2080s; δ(NCS) 749m.

[{Cu(HL)(py)(NO$_3$)}$_2$] (10)

To a solution of $[\{Cu(HL)H_2O\}_2] \cdot 2NO_3$ (321 mg, 0.50 mmol) in hot ethanol (20 cm^3) was added excess pyridine (1.7 cm^3, 20.9 mmol). The solution was heated under mild reflux for 1 h, after which the resulting complex was filtered and washed with ethyl acetate, then dried in vacuo. Yield: 102 mg (27%). On standing for 3 days, the filtrate deposited crystals (about 17 mg) suitable for single crystal X-ray analysis. IR (–NO_3, cm^{-1}): $\nu(NO_3)$ 1412s, 1300m, sh.

[Cu(HL)(tu)(NO$_3$)] (11)

To a filtered solution of $[\{Cu(HL)H_2O\}_2] \cdot 2NO_3$ (321 mg, 1.00 mmol) in hot ethanol (20 cm^3) was added dropwise thiourea (tu, 152 mg, 2.00 mmol) in hot water (5 cm^3). The green precipitate which separated was filtered off and washed with water, ethanol and diethyl ether before being dried in vacuo. Yield: 143 mg (38%). IR (–NO_3, cm^{-1}): $\nu(NO_3)$ 1412s, sh, 1300m, sh.

[Cu(HL)Cl(H$_2$O)]·H$_2$O (5)

To a hot solution of H_2sa (356 mg, 2.00 mmol) in ethanol (30 cm^3) was added $CuCl_2 \cdot 2H_2O$ (341 mg, 2.00 mmol) in ethanol (5 cm^3) and 2 M HCl (1 cm^3, 2 mmol). The crystals which formed were filtered and washed with dichloromethane to remove a small amount of an organic compound which had co-separated, then dried in vacuo. Yield: 226 mg (36%).

2.3. Crystal structure of [{Cu(HL)H$_2$O}$_2$]·2(NO$_3$)

Crystal data

$C_{18}H_{22}Cu_2N_6O_{12}$, $M = 641.4$, monoclinic, space group $P2_1/c$, $a = 7.217(4)$, $b = 11.758(8)$, $c = 13.764(8)$ Å, $\beta = 95.47(4)°$, $U = 1162.6(12)$ Å^3 (by least-squares refinement on the setting angles of 25 automatically centred reflections), $\lambda = 0.710\,73$ Å, $Z = 4$, $D_c = 1.832$ g cm^{-3}. Dark green prism, dimensions 0.45 × 0.35 × 0.30 mm mounted in a capillary; μ(Mo Kα) = 19.1 cm^{-1}.

Data collection and processing

Siemens R3m/V diffractometer, ω scan, with scan range (ω) 1.40°, scan speed 3.00–26.04° min^{-1}, temperature 298 K, Mo Kα radiation, 2279 reflections measured ($0 \leq h \leq 7$, $0 \leq k \leq 14$, $-16 \leq l \leq 16$), 1938 unique (maximum and minimum transmission factors 0.351 and 0.229, respectively) giving 1125 with $F > 6\sigma(F)$. Crystal decomposition at the end of the data collection meant that azimuthal absorption corrections could not be applied.

Structure analysis and refinement

The structure was solved by direct methods and refined by the full-matrix least-squares technique. Hydrogen atoms were included at calculated positions riding on the atom to which they were attached with one overall isotropic thermal parameter ($U = 0.080$ Å^2). Final R values of 0.0771 and wR of 0.0888 were calculated for the 173 variables refined; $F(000) = 652$. Atomic coordinates are given in Table 2 and selected bond lengths and angles in Tables 3 and 4, respectively. The numbering system used is shown in Fig. 1. Least-

Table 2
Atomic coordinates (×10^4) for $[\{Cu(HL)H_2O\}_2] \cdot 2NO_3$ with standard deviations in parentheses

Atom	x	y	z
Cu	9201(2)	−1117(1)	9632(1)
O(1)	10541(10)	−1230(7)	8214(5)
O(2)	8601(8)	504(6)	9609(5)
O(8)	9324(8)	−2793(6)	9780(5)
O(1N)	7795(16)	−81(10)	6852(8)
O(2N)	7074(12)	1661(11)	6572(8)
O(3N)	9576(11)	1268(9)	7340(7)
N(1)	6706(11)	−1478(8)	9072(6)
N(2)	6501(11)	−2671(8)	8996(6)
N(3)	8114(14)	947(10)	6917(7)
C(1)	5424(12)	358(10)	8832(7)
C(2)	6966(13)	1013(10)	9226(7)
C(3)	6821(14)	2193(11)	9226(9)
C(4)	5198(14)	2719(11)	8847(8)
C(5)	3678(14)	2086(12)	8456(8)
C(6)	3784(12)	944(9)	8459(7)
C(7)	5349(12)	−859(9)	8785(7)
C(8)	7895(14)	−3313(10)	9407(8)
C(9)	7673(14)	−4553(9)	9373(9)

Table 3
Selected distances (Å) for [{Cu(HL)H_2O}$_2$]·2NO_3 and [{Cu(HL)-(py)NO_3}$_2$] with standard deviations in parentheses

[{Cu(HL)H_2O}$_2$]·2NO_3		[{Cu(HL)(py)NO_3}$_2$]	
Cu–O(2)	1.955(8)		1.905(3)
Cu–N(1)	1.937(8)		1.936(3)
Cu–O(8)	1.982(7)		1.998(3)
Cu–O(2A)	1.952(6)		2.828(4)
Cu–O(1)	2.263(8)	Cu–O(3N)	2.529(4)
Cu–N(3)			1.998(4)
O(2)–C(2)	1.382(12)		1.311(5)
C(1)–C(7)	1.433(16)		1.428(6)
C(7)–N(1)	1.253(12)		1.278(6)
N(1)–N(2)	1.413(13)		1.380(5)
N(2)–C(8)	1.339(13)		1.318(6)
C(8)–C(9)	1.468(16)		1.486(7)
C(8)–O(8)	1.265(12)		1.250(5)
Cu···Cu(A)	3.006(3)		3.610(2)
NO_3^-			
N(3)–O(1N)	1.231(17)	N(4)–O(1N)	1.215(5)
N(3)–O(2N)	1.195(16)	N(4)–O(2N)	1.227(7)
N(3)–O(3N)	1.215(13)	N(4)–O(3N)	1.257(6)

Table 4
Selected angles (°) for [{Cu(HL)H_2O}$_2$]·2NO_3 and [{Cu(HL)(py)-NO_3}$_2$] with standard deviations in parentheses

[{Cu(HL)H_2O}$_2$]·2NO_3		[{Cu(HL)(py)NO_3}$_2$]	
O(2)–Cu–N(1)	90.6(3)		91.4(1)
N(1)–Cu–O(8)	81.6(3)		80.4(1)
O(8)–Cu–O(2A)	106.6(3)	O(8)–Cu–N(3)	94.8(1)
O(2)–Cu–O(2A)	79.4(3)	O(2)–Cu–N(3)	94.0(1)
O(2)–Cu–O(8)	168.2(3)		166.7(1)
N(1)–Cu–O(2A)	166.1(3)	N(1)–Cu–N(3)	173.9(2)
O(2)–Cu–O(1)	98.9(3)	O(2)–Cu–O(3N)	92.7(1)
N(1)–Cu–O(1)	95.8(3)	N(1)–Cu–O(3N)	91.0(1)
O(8)–Cu–O(1)	90.7(3)	O(8)–Cu–O(3N)	97.9(1)
O(2A)–Cu–O(1)	95.2(3)	N(3)–Cu–O(3N)	85.9(1)
O(2)–Cu–O(2A)			82.5(1)
N(1)–Cu–O(2A)			98.8(1)
O(8)–Cu–O(2A)			88.4(1)
N(3)–Cu–O(2A)			84.8(1)
O(3N)–Cu–O(2A)			169.1(1)
Cu–O(2)–C(2)	127.5(6)		126.9(3)
O(2)–C(2)–C(3)	119.5(9)		119.1(4)
O(2)–C(2)–C(1)	121.4(10)		124.2(4)
C(2)–C(1)–C(7)	125.8(9)		122.5(4)
C(6)–C(1)–C(7)	116.2(9)		117.9(4)
C(1)–C(7)–N(1)	122.7(9)		123.9(4)
C(7)–N(1)–Cu	131.8(8)		128.4(3)
C(7)–N(1)–N(2)	118.7(8)		119.7(3)
Cu–N(1)–N(2)	109.5(6)		111.8(3)
N(1)–N(2)–C(8)	117.3(9)		115.2(3)
N(2)–C(8)–O(8)	116.8(10)		120.1(4)
N(2)–C(8)–C(9)	118.1(9)		118.0(4)
O(8)–C(8)–C(9)	125.1(9)		121.9(4)
Cu–O(8)–C(8)	114.3(7)		112.4(3)
C(11)–N(3)–Cu			121.7(3)
C(15)–N(3)–Cu			120.5(3)
Cu–O(2A)–Cu(A)	100.6(3)		97.5(1)
O(1N)–N(3)–O(2N)	123.7(11)	O(1N)–N(4)–O(2N)	121.1(5)
O(1N)–N(3)–O(3N)	119.2(11)	O(1N)–N(4)–O(3N)	121.5(3)
O(2N)–N(3)–O(3N)	117.1(12)	O(2N)–N(4)–O(3N)	117.4(4)

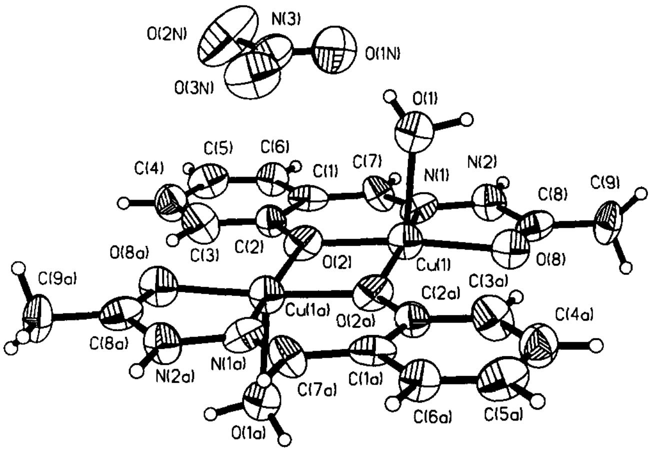

Fig. 1. Structure of the [{Cu(HL)H_2O}$_2$]$^{2+}$ cation showing the numbering scheme used. The position of one non-bonded NO_3^- is indicated.

squares refinement was by means of the Siemens SHELXTL PLUS package (PC version).

2.4. Crystal structure of [{Cu(HL)(py)(NO_3)}$_2$]

Crystal data

$C_{28}H_{28}Cu_2N_8O_{10}$, $M=763.6$, monoclinic, space group $P2_1/c$, $a=10.642(3)$, $b=11.796(3)$, $c=13.137(2)$ Å, $\beta=111.03(2)°$, $U=1539.2(6)$ Å^3 (by least-squares refinement on the setting angles of 25 automatically centred reflections), $\lambda=0.71073$ Å, $Z=4$, $D_c=1.648$ g cm^{-3}. Green prism, dimensions 0.30×0.30×0.25 mm; μ(Mo Kα) = 14.5 cm^{-1}.

Data collection and processing

Instrument and settings as for previous structure, 2878 reflections measured ($0\leq h\leq 12$, $-14\leq k\leq 0$, $-15\leq l\leq 14$), 2723 unique (maximum and minimum transmission factors 0.851 and 0.744, respectively) giving 1665 with $F>4\sigma(F)$, semi-empirical absorption corrections.

Structure analysis and refinement

The structure was solved by direct methods and refined by the full-matrix least-squares technique. Hydrogen atoms were included at calculated positions riding on the atom to which they were attached with one overall isotropic thermal parameter ($U=0.080$ Å^2). Final R values of 0.0376 and wR of 0.0413 were calculated for the 218 variables refined; $F(000)=780$. Atomic coordinates are given in Table 5 and selected bond lengths and angles in Tables 3 and 4, respectively. The numbering system used is shown in Fig. 2. Programs used are as indicated for the previous structure.

3. Results and discussion

Cu(II) complexes of the tridentate ligand H_2L have been isolated in monodeprotonated (HL) and dideprotonated (L)

Table 5
Atomic coordinates ($\times 10^4$) for $[\{Cu(HL)(py)NO_3\}_2]$ with standard deviations in parentheses

Atom	*x*	*y*	*z*
Cu	4407(1)	432(1)	6067(1)
O(2)	5979(3)	−408(2)	6178(3)
O(8)	2902(3)	1549(2)	5733(3)
O(1N)	3539(4)	1382(3)	8400(4)
O(2N)	3264(4)	−337(3)	8761(4)
O(3N)	4700(3)	51(3)	8034(3)
N(1)	5437(4)	1820(3)	6476(3)
N(2)	4616(4)	2758(3)	6332(3)
N(3)	3209(4)	−929(3)	5715(3)
N(4)	3833(4)	386(4)	8410(3)
C(1)	7648(4)	1025(4)	7062(4)
C(2)	7233(5)	−104(4)	6695(4)
C(3)	8263(5)	−914(4)	6868(4)
C(4)	9597(5)	−637(5)	7373(4)
C(5)	9992(5)	460(5)	7731(4)
C(6)	9019(5)	1266(4)	7575(4)
C(7)	6715(5)	1938(3)	6896(4)
C(8)	3313(5)	2548(4)	5922(4)
C(9)	2372(5)	3525(4)	5688(5)
C(11)	1874(5)	−835(4)	5400(4)
C(12)	1029(5)	−1757(4)	5113(4)
C(13)	1565(5)	−2814(4)	5143(4)
C(14)	2934(5)	−2923(4)	5482(4)
C(15)	3732(5)	−1974(4)	5764(4)

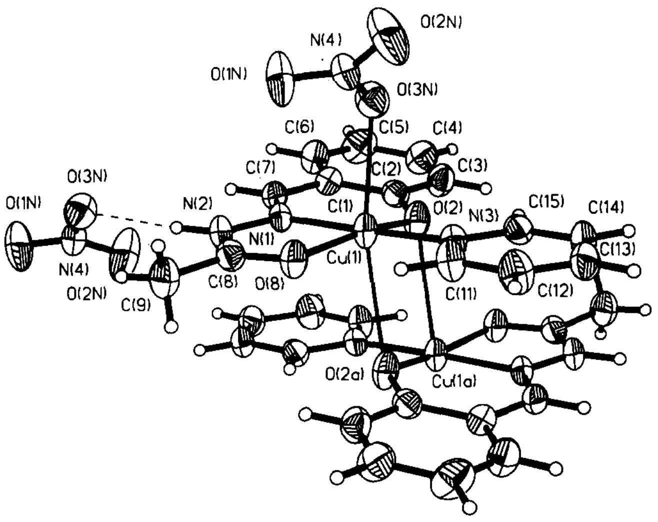

Fig. 2. Structure of $[\{Cu(HL)(py)(NO_3)\}_2]$ showing the numbering scheme used. One bonded and a symmetry-related hydrogen-bonded nitrate are shown.

forms (Table 1). With non-basic Cu(II)X_2 salts or in the presence of acid, complexes of Cu(HL)X separate where the phenolate is deprotonated. With base the amide proton is also removed to give highly insoluble $[\{CuL\}_2]\cdot xH_2O$ ($x=0$ (**1**), 2 (**2**)). Dissolution of **1** in the minimum of hot (150 °C) dimethyl sulfoxide (dmso) resulted on cooling in near quantitative precipitation of the complex with the same analytical figures. Attempts to form ternary adducts of phenolates, thiolates, phosphates and imidazolates as models for interactions with biological species all resulted in **1** or **2**. Heating $[\{Cu(HL)H_2O\}_2]\cdot 2(NO_3)$ (**4**) in aqueous or ethanolic solution results in the partial precipitation of **1** or **2**. Presumably, as the dianionic ligand complex precipitates, the released protons increase the importance of the back reaction:

$$[\{Cu(HL)\}_2]\cdot 2(NO_3)] \rightleftharpoons [\{CuL\}_2] + 2H^+ + 2NO_3^- \qquad (1)$$

stopping it going to completion. This is consistent with the observation that, besides coordinating media such as pyridine, concentrated aqueous ammonia and hot dmso, **1** and **2** are soluble in ethanolic mineral acids, but not acetic acid. The pK_a value of the amide proton in the Cu(II) complex is therefore assumed to be less than that for acetic acid (4.75) [9] but greater than for mineral acids. The complexed dianionic L moiety may be stabilized by conjugation and charge delocalization as well as by the formation of highly insoluble **1**.

Surprisingly, when $[\{Cu(HL)H_2O\}_2]\cdot 2(NO_3)$ (**4**) is treated with excess pyridine, ligand deprotonation is not observed and the ternary adduct $[\{Cu(HL)(py)(NO_3)\}_2]$ (**10**) crystallizes from the reaction mixture in high yield. Addition of the non-basic thiourea (tu) to **4** also results in a ternary complex, $[Cu(HL)(tu)(NO_3)]$ (**11**). As noted, **1** is soluble in some coordinating systems and an adduct of pyridine has been prepared. Dissolution of **1** also occurs in aqueous ammonia, although it is insoluble in water, also indicating adduct formation. A similar observation has been made for the related ligand complexes of H_2sb, where complexes formulated as [Cu(Xsb)py] and [Cu(XHsb)Cl(py)] ($X=OCH_3$, NO_2, OH in the 4 position of the benzoyl ring) were isolated [10].

Attempts to form neutral ligand complexes of the type $[Cu(H_2L)X_2]$ (X = Cl, Br) from highly acidic (HX) media resulted in the formation of the HL ligand compounds **5** and **6**, respectively. In contrast, the analogous H_2sb complexes $[Cu(H_2sb)Cl_2(H_2O)]$, $[Cu(H_2sb)Br_2]_2\cdot H_2O$ and $[\{Cu(H_2sb)(CCl_3CO_2)_2\}_2]$ have been isolated and the X-ray crystal structure of the latter determined [11]. Although there is not a significant difference in the bonding data for Cu(II) complexes of the two ligands, the change in inductive effect and conjugation between the methyl group of H_2L and the phenyl of H_2sb may play a role in the altered chemical and physical properties seen for these compounds.

3.1. *Crystal structure of $[\{Cu(HL)H_2O\}_2]\cdot 2NO_3$ (4)*

A thermal ellipsoid diagram of the structure is shown in Fig. 1. Selected bond length and angle data are given in Tables 3 and 4, respectively. The complex is a centrosymmetric dimer with the monoanionic HL ligand coordinated as a tridentate moiety. The bound phenolate, O(2), bridges the two Cu(II) centres giving a Cu···Cu separation of 3.006(3) Å. The structures of $[\{Cu(H_2sb)(CCl_3CO_2)_2\}_2]$ and

$[\{Cu(Hsb)(ClO_4)(C_2H_5OH)\}_2]$ [11] also have such a dimeric side-by-side arrangement, resulting in Cu···Cu distances of 2.968(1) and 2.999(4) Å, respectively. This structure appears to be favourable due to the donor powers and bridging ability of the phenolate, and packing resulting from the planar complexes. The Cu(II) ion is coordinated in the plane by the ligand phenolate (Cu–O(2) 1.955(8) Å), imine nitrogen (Cu–N(1) 1.937(8) Å), carbonyl (Cu–O(8) 1.982(7) Å) and bridging phenolate (Cu–O(2A) 1.952(6) Å). These four donors and the Cu are approximately planar with the biggest deviation from the plane being 0.14 Å for Cu. The Cu ion sits out of this plane towards a more weakly bound water molecule, O(1) (2.263(8) Å) which completes the coordination sphere in an axial site. The water does not sit directly over the Cu in the plane of the coordinated ligand but is tilted 4° from the normal with the Cu ion. As there is no close sixth approach to the Cu, its geometry can be described as an approximate square pyramid. The in-plane and ligand bonding data for **4** agree with the equivalent values of those for $[Cu(HL)Cl(H_2O)]\cdot H_2O$ [11].

The nitrate ion is not coordinated to the Cu(II) centre in **4**, but is involved in a hydrogen-bonding network. The bound water molecule, O(1), forms three contacts (O(1N) 2.926; X, Y, Z: O(2N) 3.017; $2-X, 0.5-Y, 1.5-Z$: O(3N) 3.039 Å; $2-X, 0.5-Y, 1.5-Z$) and the protonated amide nitrogen, N(2), one contact (O(2N) 2.739 Å; $1-X, 0.5+Y, 1.5-Z$). This links dimeric units in chains through the water, with chains held together via the hydrogen-bonded amide functionality.

3.2. *Crystal structure of $[\{Cu(HL)(py)(NO_3)\}_2]$ (10)*

A thermal ellipsoid diagram of the structure is shown in Fig. 2. Selected bond length and angle data are given in Tables 3 and 4, respectively. The geometry adopted by the Cu(II) atom may be described as square-planar with weaker axial interactions giving a (4+1+1) coordination sphere. The monoanionic tridentate, ONO, ligand HL coordinates in three of the basal positions through the phenolic oxygen (Cu–O(2) 1.905(3) Å), the imine nitrogen (Cu–N(1) 1.936(3) Å) and the carbonyl oxygen (Cu–O(8) 1.998(3) Å), the fourth being occupied by the pyridine moiety (Cu–N(3) 1.998(4) Å). The nitrato anion binds weakly (Cu–O(3N) 2.529(4) Å) in one axial position. Completing the coordination sphere in the apical position is the phenolic oxygen of a symmetry-related molecule (Cu–O(2A) 2.828(4) Å; $1-X, 0-Y, 1-Z$), resulting in weakly interacting pairs of molecules. The resulting dimers have a Cu···Cu separation of 3.610(2) Å.

In the complex $[Cu(HL)Cl(H_2O)]\cdot H_2O$ [11], the fourth in-plane position is occupied by the anionic chloro moiety, whereas for the title compound this site has the neutral pyridine bound. A comparison of the bond lengths around the Cu centres for these complexes and **4** shows the Cu–ligand distances not to be significantly different; therefore, changes in the coordination sphere and geometry do not appear to alter the bonding significantly. The best-fit least-squares plane through the four basal and Cu atoms in **10** shows a small tetrahedral distortion with an average distance from the plane of 0.12 Å. The Cu atom lies 0.05 Å out of the plane on the side of N(1) and N(3), towards the nitrato ion.

The equatorial tridentate coordination mode of HL creates a five- and a six-membered chelate ring. The plane of best fit through the complexed ligand, including the Cu atom, shows the molecule to be approximately planar with the biggest deviation from the plane being 0.18 Å for Cu. A comparison of the equivalent ligand bond data with $[Cu(HL)Cl(H_2O)]\cdot H_2O$ shows that there are no significant differences.

As with the hydrogen-bonding schemes for **4**, $[Cu(HL)Cl(H_2O)]\cdot H_2O$ and Cu(II) complexes of H_2sb [11–13], the amide nitrogen is involved in a hydrogen-bonding contact. In **10** this is to the bound nitrato group (O(3N)···N(2) 2.846 Å; $1-X, -0.5+Y, 1.5-Z$). The dimeric arrangement of the complex results in an average separation between the symmetry-related halves of the dimer of 2.9 to 3.4 Å. This may result in a weak π overlap between chelate and aromatic rings adding stability to the dimer.

3.3. *Physicochemical studies*

Electronic spectral data for the complexes in the solid state are given in Table 6. The mull transmittance charge transfer (CT) maxima are at about 380 nm, often being poorly resolved shoulders. The band position is very similar to that seen for the related $Cu(Hsb)^+$ complexes [11] which was assigned to an O→Cu CT transition. For **5** and **6** this band may also contain a Cl→Cu or Br→Cu ligand-to-metal CT component, respectively. The d–d absorption maxima range from about 600 to 720 nm, and tend to be indicative of tetragonal geometries [14], as seen in the crystal structures of **4** and **10**. This has also been observed in the

Table 6
Electronic spectral and molar conductivity data for the complexes

Complex	Absorption maxima [a] (nm)		Λ [b] (S cm^2 mol^{-1})
	CT [c]	d–d	
1 $[\{CuL\}_2]$	400	600	1 [d]
2 $[\{CuL\}_2]\cdot 2H_2O$	400	600	2 [d]
3 $[CuL(py)]\cdot \frac{1}{2}H_2O$	380	560(br,sh)	3
4 $[\{Cu(HL)H_2O\}_2]\cdot 2(NO_3)$	370	720(br)	185
5 $[Cu(HL)Cl(H_2O)]\cdot H_2O$	400(sh)	680(br)	19
6 $[Cu(HL)Br]\cdot H_2O$	370	570(br) 670(br)	51
7 $[\{Cu(HL)ClO_4\}_2]$	380(sh)	660	49
8 $[Cu(HL)CF_3SO_3]$	380(sh)	690(br)	87
9 $[Cu(HL)SCN]\cdot H_2O$	400(sh)	695	40
10 $[\{Cu(HL)(py)NO_3\}_2]$	380	660(br)	87
11 $[Cu(HL)tu]\cdot NO_3$	350(sh)	640(br)	155 [e]

[a] Nujol-mull transmittance spectra.
[b] In Me_2NCHO, values given per monomeric unit.
[c] All spectra have a broad shoulder at about 480 nm.
[d] Me_2SO.
[e] H_2O.

crystal structures of [{Cu(Hsb)H_2O}$_2$SiF_6]·2H_2O [13], [{Cu(H_2sb)(CCl_3CO_2)$_2$}$_2$] and [{Cu(Hsb)ClO_4-(C_2H_5OH)}$_2$] [11]. The difference in the band positions between [Cu(HL)Cl(H_2O)]·H_2O **5** (CT 400, d–d 680 nm) and [Cu(HL)Cl(H_2O)] (CT 390, d–d 760 nm) indicates that the coordination geometries of these complexes may differ. For **5** the crystal structure analysis shows this to be square pyramidal.

The molar conductance values for the complexes as formulated in Table 6 show the complexes of the dianionic ligand (**1**, **2** and **3**) to be non-electrolytes, as expected. The monoanionic ligand complexes (**4** to **10**) have Λ values consistent with 1:1 electrolytes, indicating that the anion is ionized in solution, whereas partial solvolysis is seen for **11**. In contrast, a range of Cu(II) complexes of the related monodeprotonated Hsb showed that the majority were at most only partial electrolytes in dmso [11]. This shows there are subtle differences between the physicochemical properties of the Cu(HL)(anion) and Cu(Hsb)(anion) complexes.

The IR (KBr) spectra were used where possible to identify anions and differentiate between mono- and dianionic ligand complexes. The ν(C=O) and ν(C=N) peaks in H_2L (1680(vs), 1607(m) cm^{-1}) shift and split on coordination (about 1620–1610(s), 1580–1540(vs), 1530(m) cm^{-1}) indicating bonding through the carbonyl O and the imine N (as well as increased conjugation). Complexes of the dianionic ligand (**1–3**) are characterized by bands at 1619(s), 1600(m), 1538(m) and 1507(s) cm^{-1} in this region. These bands are possibly due to a conjugated diimine group (C=N–N=C) contribution [10]. The ν(N–H) (and ν(O–H)) frequencies of H_2L (3170(w), 3060(m), 2930(m), 2850(w) cm^{-1}) appear as weak, broad peaks between about 3500 and 2600 cm^{-1} for Cu(HL)$^+$. Species formulated as hydrates were confirmed by the appearance of bands in the range 3500–3200(m to s) cm^{-1}. For the dianionic ligand complexes no bands were present in this region except for ν(O–H) of water of crystallization, confirming loss of the phenolic and amide protons.

Nitrate IR bands for **4**, **10** and **11** were not well resolved but are consistent with ionic or weak monodentate binding as observed in the X-ray structures of **4** and **10** [15]. For **7**, the ClO_4^- ν_3 absorption at 1170–1040 cm^{-1} is indicative of non-bonding or weakly interacting anion. The $CF_3SO_3^-$ bands for **8** are close to those observed in non-bonding, ionic triflates [16], indicating weak bonding at most. The weak association of anions may favour the formation of dimers, vide infra. The ν(CN) (2080 cm^{-1}) and δ(NCS) (749 cm^{-1}) resonances for **9** show the presence of bound thiocyanate but cannot definitely distinguish the bonding mode.

There is continued interest in the magnetic properties of di- and oligomeric Cu(II) complexes from theoretical and biological viewpoints. The magnetic moment for the dimer [{Cu(HL)H_2O}$_2$]·2(NO_3) (**4**, Fig. 2) of 1.28 μ_B indicates antiferromagnetic coupling. The X-ray crystal structure shows a side-by-side arrangement of the metal chelates with the phenolate bridging the Cu(II) centres. Magnetic exchange may then be effected via favourable overlap of the assumed ground-state $d_{x^2-y^2}$ orbitals on the metal (tetragonally elongated) via the bridge. The low moment for [{Cu(HL)ClO_4}$_2$] (**7**) of 1.49 μ_B has, by analogy with **4**, been assumed to result from a side-by-side dimeric structure. In **10** a stacked dimeric arrangement is found (Fig. 1) and a normal moment of 2.15 μ_B. Poor overlap of the magnetic orbitals is expected from the d_{z^2} through the $d_{x^2-y^2}$ orbitals. Complexes of the dianionic ligand **1** and **2** have magnetic moments of about 2.6 μ_B. Multiple preparations of these compounds from different solvents, using different bases and recrystallization from dmso, still gave these elevated values. The reason for this is not presently known but is tentatively ascribed to ferromagnetic interactions and the complexes have accordingly been assigned dimeric structures. The related sb compound [{Cu(sb)}$_2$] has a low moment (1.16 μ_B) and is antiferromagnetically coupled [11]. All other complexes in this work have normal moments and are formulated as monomers, although the existence of weakly interacting dimers is possible in **8** and **11** by analogy with **4** (**7**) and **10**, respectively. Cytotoxicity testing is presently being conducted.

4. Conclusions

We have prepared binary and ternary Cu(II) complexes of both the mono- and dianionic forms of the ligand H_2L. Even with one metal a diverse chemistry has been displayed by this system. The formulation of many complexes as dimers is based on the magnetic exchange coupling observed as well as the planar, dimeric side-by-side arrangement for [{Cu(HL)H_2O}$_2$]·2NO_3 and the stacked dimer [{Cu(HL)(py)(NO_3)}$_2$]. The mode of biological action of related complexes is not known, but ternary adduct formation may play a role in the in vivo activity of such complexes through binding of the species to biological ligands. We have isolated Lewis-base adducts, and studied one, [{Cu(HL)(py)(NO_3)}$_2$], by crystallography, showing that such interactions are possible in vitro.

5. Supplementary material

Additional material comprising hydrogen-atom coordinates, thermal parameters and remaining bond lengths and angles is available from the authors.

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