Inorganica Chimica Acta, *218* (1994) 53–58

Substituent effect on the coordination ability of the amide group of N-protected amino acids

Gigliola Lusvardi, Ledi Menabue* and Monica Saladini
Dipartimento di Chimica, Università di Modena, via Campi 183, 41100 Modena (Italy)

(Received September 8, 1993; revised October 25, 1993)

Abstract

The binary system Cu(II)–hydantoic acid (hydaH) and the corresponding ternary systems with 2,2′-bipyridine(bpy) and 1,10-phenanthroline (ophen) were investigated both in the solid state and solution. The crystal and molecular structure of the complex $[Cu(ophen)(hyda)_2]\cdot H_2O$ was also determined. The crystal of the compound $C_{18}H_{20}CuN_6O_7$ is monoclinic, space group $P2_1/c$, $a = 7.601(5)$, $b = 14.647(2)$, $c = 19.714(3)$ Å, $\beta = 96.57(3)$, $Z = 4$, $R = 0.049$, $R_w = 0.053$. The structure consists of discrete $[Cu(ophen)(hyda)_2]$ units and lattice water molecules. The Cu(II) atom is coordinated in the equatorial plane by two nitrogens from the ophen molecule and two oxygens from two hydantoate anions; the nitrogen atom of the neutral NH group of a hydantoate anion occupies the more distant fifth position (Cu–N(1) = 2.541(5) Å) giving rise to elongated square-pyramidal geometry. In solution the carboxylate species $[CuL_2]$ is formed in the binary system and the species $[CuAL_2]$, $[CuAL(OH)]$ in the ternary systems with bpy and ophen. Spectroscopic data indicate that any possibility of the NH group being coordinated in solution can be excluded.

Key words: Crystal structures; Copper complexes; Amino acid complexes

Introduction

The substitution of one or both of the hydrogen atoms of the amino group frequently modifies the coordination behavior and reactivity of an amino acid molecule, depending mainly on the electrophilic character and steric hindrance of the substituent. Substituent groups such as CH_3– [1], C_2H_5– [2], $(C_6H_5)_3C$– [3], $(HOC_2H_4)_3C$– [4], in binary systems, do not alter the reactivity and coordination behavior of the amino acid, which coordinates through the amino nitrogen and one carboxylate oxygen forming complexes with stability similar to that of the parent amino acids. In the ternary complex with 2,2′-bipyridine, tritylglycine [3] acts only as carboxylate ligand, probably because of the cooperative effect of the steric hindrance of the trityl group $[(C_6H_5)_3C–]$ and the selectivity of bpy towards oxygen donor ligands.

With weakly electrophilic substituent groups, such as R–CO– and Ar–CO–, the basicity of nitrogen strongly diminishes and the only active binding site on the amino acid is the carboxyl, which is a weak coordinating group. In a few cases, in anhydrous complexes, a second metal binding site is found to be the carbonyl oxygen, which is more basic than the amide nitrogen [5]. In such N-protected amino acids the substitution of the NH hydrogen for a metal ion (Cu(II), Cd(II), Co(II), Ni(II) and Zn(II)) [6] is never possible, because the high pH value required for the reaction (for the free ligand $pK_{NH} \sim 15$) favors more the precipitation of metal hydroxide.

With an amino nitrogen substituent such as Ar–SO_2, the amino acid acts as a simple carboxylate ligand at low pH, and in some conditions the sulfonyl oxygens can also interact with the metal. Because of the great electrophilic power of this group, the pK_{NH} decreases to ~ 11.5; with metal ions it decreases further to ~ 8 with Cd(II) and ~ 7.5 with Cu(II), forming a five- or six-membered NO–chelate ring which gives rise to complexes whose stability is greater than that of the parent amino acids [6].

It is reasonable to suppose that the amino acid N-protected by the carbamyl group NH_2–CO– should present the behavior typical of R–CO–N-protected amino acids [6] which give rise to simple carboxylate complexes. Nevertheless, the involvement of carbonylic oxygen in the metal coordination, as found in *catena*-poly-{[μ-(*N*-acetyl-DL-valinato)-O^1:O^3]-copper(II) [5], cannot be excluded.

---

*Author to whom correspondence should be addressed.

SSDI 0020-1693(93)03793-A

In order to complete the investigation of the effect of the carbamyl group on the coordination behavior of glycine, we report here the results obtained for the binary Cu(II)–hydantoic acid (hydaH) and corresponding ternary 2,2′-bipyridine (bpy) and 1,10-phenanthroline (ophen) containing systems with Cu(II), both in the solid state and solution.

Experimental

Preparation of the complexes

Cu(hyda)$_2$·4H$_2$O

A methanolic solution (0.05 dm^3) of copper(II) acetate monohydrate (0.01 mol dm^{-3}) was added to a methanolic solution (0.05 dm^3) of hydantoic acid (0.02 mol dm^{-3}). A green compound separated out instantaneously but analysis did not give interpretable results; from a series of recrystallizations from H_2O a pale blue microcrystalline compound was obtained. *Anal.* Found: C, 19.60; N, 15.25; H, 5.00; H_2O, 19.30. Calc. for $C_6H_{18}CuN_4O_{10}$: C, 19.50; N, 15.15; H, 4.90; H_2O 19.50%.

Cu(bpy)(hyda)$_2$

An aqueous solution (0.02 dm^{-3}) of the pale blue binary Cu(hyda)$_2$·4H$_2$O complex (0.002 mol dm^{-3}) was mixed with an equimolar methanolic solution of bpy (0.01 mol dm^{-3}). After slow evaporation at room temperature a blue crystalline compound separated out. *Anal.* Found: C, 41.75; N, 17.90; H, 4.00. Calc. for $C_{16}H_{18}CuN_6O_6$: C, 42.32; N, 18.54; H, 4.00%.

Cu(ophen)(hyda)$_2$·H$_2$O

This compound was prepared as the bpy adduct, but crystallization required the addition of isopropanol. *Anal.* Found: C, 43.80; N, 17.10; H, 4.05; H_2O, 4.10. Calc. for $C_{18}H_{20}CuN_6O_7$: C, 43.80; N, 16.95; H, 4.10; H_2O, 3.65%.

Potentiometry

Hydantoic acid was recrystallized from a 1:1 methanolic–water solution and the concentration of the solution used throughout was tested potentiometrically. Copper(II) nitrate trihydrate was from C. Erba and the concentration of the stock solution was determined with ethylenediaminetetraacetic acid. Solutions of 2,2′-bipyridine and 1,10-phenanthroline (C. Erba) were standardized potentiometrically with strong acid.

Potentiometric measurements were performed at 25 ± 0.1 °C using a fully automatic Orion 960 Autochemistry system, Ingold 104023414 combined glass electrode and a Centronics GLPII printer for recording e.m.f. measurements, pH readings and titration curves. Sodium hydroxide (carbonate-free) (C. Erba) standardized against phthalate (N.B.S.) was used as titrant. The standard electrode potential $E°$ was determined before and after each experiment by titration of a known amount of HNO_3 (0.1 mol dm^{-3}) with NaOH.

The ionic product K_w (13.66) was calculated in the alkaline region of each calibration curve. The liquid-junction potentials were found to be reproducible and rather small as compared to the potential of the cell (about 2%); consequently, they were disregarded in the calculations. All experiments were carried out in a nitrogen atmosphere at ionic strength of 0.1 mol dm^{-3} (adjusted with solid $NaNO_3$); the equivalent point was determined by the first derivative technique with constant cm^3 increments. The starting solutions for each titration of the binary system were prepared by the successive addition of known volumes of $Cu(NO_3)_2$ and hydantoic acid solutions to the titration vessel in order to obtain 1:2, 1:4, 1:6 and 1:8 metal-to-ligand molar ratios. The metal concentration ranged from 1.0×10^{-3} to 3.0×10^{-3} mol dm^{-3}. In the ternary systems, known volumes of 2,2′-bipyridine and 1,10-phenanthroline were added, maintaining a 1:1 molar ratio with Cu^{2+} ion.

The stability constants (β_{pqrs}), which are defined by eqns. (1) and (2):

$$pM+qA+rL+sH \longleftrightarrow M_pA_qL_rH_s \qquad (1)$$

$$\beta_{pqrs}=[M_pA_qL_rH_s]/[M]^p[A]^q[L]^r[H]^s \qquad (2)$$

were refined by least-squares calculation using the computer program SUPERQUAD [7], with $\sigma_e=0.3$ mV (e.m.f. error) and $\sigma_v=0.01$ cm^3 (volume error).

Crystallography

A sample measuring 0.12×0.15×0.4 mm was mounted in a random orientation on a Nonius CAD4 single-crystal diffractometer, using Mo Kα radiation. Cell dimensions were determined by least-squares refinement of diffractometer angles for 25 automatically-centered reflections.

Crystal data: $C_{18}H_{20}CuN_6O_7$, $M=495.9$, monoclinic, space group $P2_1/c$, $a=7.601(5)$, $b=14.647(2)$, $c=19.714(3)$ Å, $\beta=96.57(3)°$, $V=2180(1)$ Å^3, $D_m=1.48$ g cm^{-3}, $Z=4$, $D_c=1.51$ g cm^{-3}, $F(000)=1020$, $\lambda=0.71069$ Å, μ(Mo Kα) = 10.6 cm^{-1}. A total of 3614 reflections was collected using the ω–2θ scan technique with $2.5\leqslant\theta\leqslant24°$; $-8\leqslant h\leqslant8$, $0\leqslant k\leqslant16$, $0\leqslant l\leqslant22$, scan width $1.0+0.35\tan\theta°$, and scan speed 1.64–8.42° min^{-1}. 2250 reflections had $I>2\sigma(I)$ and were considered observed and were corrected for Lorentz and polarization effects. Absorption correction was applied following Walker and Stuart [8] (absorption correction min. (max.) 0.97 (1.05)).

The structure was solved by conventional Patterson and Fourier techniques, and refined through full-matrix least-squares calculation with $\Sigma w(|F_o|-|F_c|)^2$ minimized. Hydrogen atoms, except those of the water molecule, were located on a Fourier difference map; the N(2) bonded H atoms were regularized to sp^2 hybridization; then were all treated as fixed contributors. Final refinement of this model led to $R = 0.049$, $R_w = 0.053$ using the weighting scheme $w = 2.0996/(\sigma^2(F_o) + 0.001F_o^2)$.

Complex neutral-atom scattering factors were taken from International Tables [9]. All calculations were performed on a VAX-6310 computer using SHELX76 [10], PARST [11] and ORTEP [12] programs. Final fractional coordinates for non-hydrogen atoms are given in Table 1.

Spectrophotometric measurements

Electronic spectra were recorded with a Varian Cary 2300 spectrophotometer on solutions containing 2×10^{-3} mol dm^{-3} of Cu^{2+} (cell length = 1 cm). Titrations were performed by adding small volumes of concentrated NaOH.

IR spectra were recorded with a Bruker 113v-FT instrument as KBr pellets in the spectral range 4000–400 cm^{-1}. ESR spectra were recorded with a Bruker ER 200-SRC spectrometer. Thermogravimetric analyses were performed at a rate of 5 °C/min with a Mettler TA 3000 instrument.

TABLE 1 Final positional parameters[a]

Atom	*x/a*	*y/b*	*z/c*
Cu	0.0854(1)	0.12509(5)	0.15261(4)
O(1)	−0.0532(6)	0.2359(3)	0.1409(2)
O(2)	−0.0950(7)	0.3816(3)	0.1640(3)
C(1)	−0.0069(8)	0.3101(5)	0.1723(3)
C(2)	0.1597(9)	0.3096(4)	0 2244(3)
N(1)	0.2983(7)	0.2439(4)	0.2087(3)
C(3)	0 4158(9)	0.2710(5)	0.1635(3)
N(2)	0 5621(7)	0.2153(4)	0.1632(3)
O(3)	0.3851(6)	0.3376(3)	0 1264(3)
O(4)	0.0490(6)	0.1089(3)	0.2486(2)
O(5)	−0.2134(7)	0.0394(3)	0.2165(2)
C(4)	−0.1036(9)	0 0731(4)	0 2599(3)
C(5)	−0.1338(8)	0.0751(5)	0.3355(3)
N(3)	−0.3001(7)	0.0325(4)	0.3499(3)
C(6)	−0.4609(9)	0 0732(5)	0.3314(3)
N(4)	−0.6090(8)	0.0245(5)	0 3418(4)
O(6)	−0 4716(6)	0.1515(3)	0.3075(3)
N(5)	0.1405(7)	0.1343(4)	0.0540(3)
N(6)	0.1862(7)	−0.0011(3)	0.1432(3)
C(7)	0.119(1)	0.2042(5)	0.0121(4)
C(8)	0 158(1)	0.1968(5)	−0.0566(4)
C(9)	0.2158(9)	0 1165(5)	−0.0799(4)
C(10)	0.2422(8)	0.0413(5)	−0.0356(3)
C(11)	0.2037(8)	0.0545(5)	0.0312(3)
C(12)	0.2292(8)	−0 0175(4)	0 0794(3)
C(13)	0.2976(9)	−0.1022(4)	0.0604(4)
C(14)	0 334(1)	−0 1139(5)	−0.0097(4)
C(15)	0 3104(9)	−0.0452(5)	−0.0546(3)
C(16)	0.322(1)	−0.1683(5)	0.1111(4)
C(17)	0.277(1)	−0.1520(5)	0.1743(4)
C(18)	0.208(1)	−0 0658(5)	0.1890(4)
Ow(1)*	−0.516(2)	0.3546(9)	−0.0082(8)
Ow(2)*	−0.147(2)	0.419(1)	0.020(1)

[a]Starred atoms have population 0.5.

Results and discussion

Solid state

The pale blue $Cu(hyda)_2 \cdot 4H_2O$ compound shows a d–d band maximum and ESR parameters consistent with an elongated octahedral geometry with O_6 atoms donor set (Table 2). DTG analysis displays a weight loss corresponding to dehydration with a maximum centered at 120 °C; the anhydrous compound decomposes at 200 °C. The binary complex reacts with bpy and ophen giving rise to the corresponding [Cu(bpy)(hyda)$_2$] and [Cu(ophen)(hyda)$_2$]$\cdot H_2O$ compounds; the crystals of the latter were suitable for X-ray analysis.

Description of the structure of [Cu(ophen)(hyda)$_2$]$\cdot H_2O$

The ORTEP view of the complex with the numbering scheme is reported in Fig. 1; bond distances and angles are listed in Table 3. The unit cell contains a monomeric [Cu(ophen)(hyda)$_2$] moiety and lattice water molecules. In the complex, the Cu(II) atom is coordinated in a nearly square-planar arrangement by the ophen nitrogens and two carboxylate oxygens of two hydantoate anions. The amidic nitrogen N(1) forms a long contact (2.541(5) Å) with the copper atom; the angle formed by the line Cu–N(1) with the normal to the plane of equatorial ligands is 21.5(1)°, indicating an effective overlap between metal and nitrogen orbitals. The coordination geometry of the Cu(II) atom can therefore be described as elongated square-pyramidal with N_2O_2N' atoms donor set.

Amide oxygen is not involved in metal coordination, as it is in [Zn(hyda)$_2$]$_n$ [13], where it represents the second binding site on hydantoic acid. The different binding mode between Cu(II) and Zn(II) complexes can be explained by the greater affinity of Cu(II) for nitrogen donors with respect to the Zn(II) ion.

Our complex represents an unusual binding mode of neutral amide nitrogen toward the copper(II) atom. To our knowledge the metal binding of neutral amide nitrogen concerns metal atoms which possess a peculiar affinity for nitrogen atoms, i.e. platinum [14]. It is thought that the neutral amide nitrogen cannot be coordinated to a metal ion because its lone pair is engaged in the resonance with the C=O group, as shown by the typical N–C distance of 1.325 Å, which is markedly shorter than the N–C single bond (1.45 Å) [15]. In our complex, HN–C and H_2N–C distances are comparable (range 1.368–1.389 Å) and shifted to-

TABLE 2. Room temperature electronic (cm^{-1}), IR (cm^{-1}) spectra, ESR parameters, weight-loss temperature range (°C) and decomposition temperature (°C) for the complexes

	hydaH	hydaNa	$Cu(hyda)_2 \cdot 4H_2O$	$[Cu(ophen)(hyda)_2]$ H_2O	$Cu(bpy)(hyda)_2$
d–d (max)			12970	16490, 14460	15170
$g_\parallel$			2 385	$g_1 = 2.204$, $g_2 = 2.071$, $g_3 = 2.053$	$g_{iso} = 2.138$
$g_\perp$			2.115		
Weight loss $\Delta T°$ range			30–130	70–120	
Decomposition temperature			200	200	200
ν(OH)			3540ms	3489sb	
$\nu(NH_2) + \nu(NH)$	3405vs, 3389vs, 3227s, 3370s	3420s, 3383s, 3280s, 3318s, 3163ms	3410vs, 3194vs, 3324vs	3412s, 3373s, 3230sh, 3331s	3439s, 3422s, 3225s, 3326s
Amide II (δNH_2)	1669s	1661s	1652vs	1660s	1675s
Amide I (νCO)	1645vs	1633ms	1622sh	1645vs	1641vs
$\nu(OCO)_{as}$	1717vs	1591vs	1572s	1597vs	1603vs
Amide II ($\nu C{=}N + \delta NH_2$)	1577s, 1547s	1554m	1552s	1562s, 1536ms	1550ms, 1535ms
$\nu(OCO)_s$	1313s	1417vs	1400s	1393vs	1420s

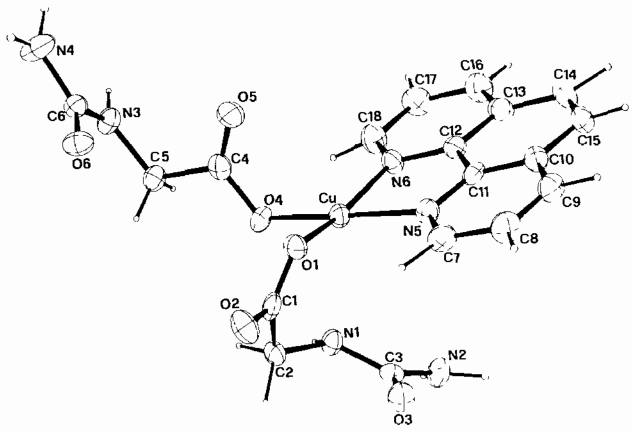

Fig. 1 ORTEP view of the $[Cu(ophen)(hyda)_2]$ complex showing the atom numbering and the thermal ellipsoids (40%) for non-hydrogen atoms. The H atoms are represented as spheres of arbitrary radius.

wards the value for a single bond, so the lone pair on the HN group can effectively interact with the metal atom.

The equatorial bond distances at the metal are normal and fall within the range observed for $Cu{-}O_{carbox}$ [6] and $Cu{-}N_{ophen}$ [16] bond lengths, while the deviations of the atoms from their mean plane are in the range ±0.149 Å, with the Cu atom 0.092 Å shifted towards the N(1) atom. The carboxylate groups are exactly planar in both hydantoate residues, while the C(5), N(3), O(6), C(6), N(4) atoms of the O-bonded hydantoate anion are nearly coplanar with deviations in the range ±0.042 Å. The atoms C(2), N(1), C(3), O(3), N(2) in the N,O-bonded hydantoate anion are only fairly planar, in fact N(1) and C(2) deviate significantly from planarity (+0.104 and −0.121 Å, respectively); this may be due to the involvement of N(1) in metal coordination. In the monodentate hydantoate anion, the C–O distances in the carboxyl are markedly different from one another and move towards the value of protonated carboxyl; all the remaining bond distances and angles are similar in both anions.

The ophen molecule is planar and forms an angle of 9.2(1)° with the equatorial coordination plane.

The lattice water molecule forms a short contact (2.85(2) Å) with the O(3) atom, while the nitrogen atoms N(2), N(4) and N(5) form hydrogen bonds with both carbonyl oxygens and with the carboxylate oxygen O(1).

Crystal packing is determined by ring stacking interactions between ophen rings involving the molecule at $-x$, $-y$, $-z$ (range 3.58–3.99 Å) and that at $-x+1$, $-y$, $-z$ (range 3.41–3.72 Å); the terminal amide group of the N,O-bonded hydantoate moiety gives rise to intramolecular hydrophobic contacts with the ophen molecule (range 3.20–3.88 Å).

The electronic spectrum of the compound shows two well-resolved bands whose positions are in agreement with a strongly elongated square-pyramidal geometry and N_2O_2N' metal environment. The ESR spectrum is rhombic and the g values are consistent with a weak axial ligand field. The electronic spectrum of the bpy adduct presents a d–d band maximum shifted towards lower energy with respect to the ophen adduct, which suggests a more effective axial ligand field than is normally found for the bpy adduct of N-protected amino acids [17]. On the basis of the chemical formula, the involvement of the NH_2–CO–NH residue in metal coordination should be taken into account. The more relevant bands of the IR spectra of hydantoic acid, its sodium salt and copper(II) complexes are assigned by comparison with the spectra of ethylhydantoate, hydantoate amide [18] and substituted ureas [19], and

TABLE 3. Bond distances (Å) and angles (°)

Cu–O(1)	1.934(4)	Cu–O(4)	1.957(5)
Cu–N(5)	2.040(5)	Cu–N(6)	2.018(5)
Cu···N(1)	2.541(5)	O(1)–C(1)	1.281(8)
O(4)–C(4)	1.315(8)	O(2)–C(1)	1.245(8)
O(5)–C(4)	1.227(8)	C(1)–C(2)	1.537(9)
C(4)–C(5)	1.534(9)	C(2)–N(1)	1.486(8)
C(5)–N(3)	1.467(8)	N(1)–C(3)	1.389(9)
N(3)–C(6)	1.370(8)	C(3)–N(2)	1.380(9)
C(6)–N(4)	1.368(9)	C(3)–O(3)	1.226(8)
C(6)–O(6)	1.239(8)	N(5)–C(7)	1.315(9)
N(5)–C(11)	1.359(8)	N(6)–C(12)	1.356(8)
N(6)–C(18)	1.306(8)	C(7)–C(8)	1.424(10)
C(8)–C(9)	1.353(11)	C(9)–C(10)	1.405(10)
C(10)–C(11)	1.395(9)	C(10)–C(15)	1.436(10)
C(11)–C(12)	1.418(9)	C(12)–C(13)	1.412(9)
C(13)–C(14)	1.448(10)	C(13)–C(16)	1.389(10)
C(14)–C(15)	1.338(10)	C(16)–C(17)	1.350(10)
C(17)–C(18)	1.412(10)		
O(1)–Cu–O(4)	94.7(2)	O(4)–Cu–N(6)	94.3(2)
O(1)–Cu–N(5)	89.9(2)	N(5)–Cu–N(6)	81.4(2)
O(1)–Cu–N(6)	164.8(2)	O(4)–Cu–N(5)	175.1(2)
O(1)–C(1)–O(2)	122.5(6)	O(4)–C(4)–O(5)	125.8(6)
O(1)–C(1)–C(2)	118.7(6)	O(4)–C(4)–C(5)	112.9(6)
O(2)–C(1)–C(2)	118.8(6)	O(5)–C(4)–C(5)	121.2(6)
C(1)–C(2)–N(1)	114 4(5)	C(4)–C(5)–N(3)	114.1(5)
C(2)–N(1)–C(3)	118.1(5)	C(5)–N(3)–C(6)	121.7(5)
N(1)–C(3)–N(2)	114.3(6)	N(3)–C(6)–N(4)	117.2(6)
N(1)–C(3)–O(3)	121.2(6)	N(3)–C(6)–O(6)	121.4(6)
N(2)–C(3)–O(3)	124.5(6)	N(4)–C(6)–O(6)	121.2(6)
C(7)–N(5)–C(11)	119.1(6)	C(12)–N(6)–C(18)	119 2(6)
Cu–N(5)–C(11)	112.2(4)	Cu–N(6)–C(12)	112.4(4)
N(5)–C(7)–C(8)	120.8(6)	C(11)–C(12)–N(6)	117.5(6)
C(7)–C(8)–C(9)	121.1(7)	C(13)–C(12)–N(6)	122 5(6)
C(8)–C(9)–C(10)	119.9(7)	C(11)–C(12)–C(13)	120 0(6)
C(9)–C(10)–C(11)	116 6(6)	C(12)–C(13)–C(14)	118 3(6)
C(11)–C(10)–C(15)	119.3(6)	C(12)–C(13)–C(16)	116 3(6)
C(10)–C(15)–C(14)	121.1(6)	C(13)–C(14)–C(15)	121.1(7)
C(10)–C(11)–C(12)	120.2(6)	C(13)–C(16)–C(17)	121.0(7)
N(5)–C(11)–C(12)	116.3(6)	C(16)–C(17)–C(18)	119.1(7)
C(10)–C(11)–N(5)	123.4(6)	C(17)–C(18)–N(6)	121.8(6)

are reported in Table 2. The stretching vibrations assigned to NH_2, NH and CO are almost unchanged in all the samples and the spectrum of the ophen adduct is not affected by the metal coordination of the NH group. On the other hand, NH coordination to the metal does not affect the bond distances and angles within the ligand in the ophen complex.

Solution

Neutral hydantoic acid. The pH-metric titration of the amino acid shows only one equivalent point corresponding to the dissociation of the carboxylate group with a p*K* value (Table 4) of 3.67, close to the values of 3.67 [21] and 3.80 [21] reported for *N*-acetyl and *N*-benzoylglycine, respectively.

TABLE 4. Logarithms of overall protonation and Cu^{2+} complexes stability constants at 25 °C and $I=0.10$ mol dm^{-3} ($NaNO_3$) with e.s.d.s in parentheses

LH	log β_{0011}	3.67(1)	
$[CuL]^+$	log β_{1010}	2.5(2)	
$[CuL_2]$	log β_{1020}	4 51(3)	
		A = bpy	A = ophen
$[CuAL_2]$	log β_{1120}	12.25(5)	13.71(5)
$[CuAL(OH)]$	log β_{1111}	3.75(2)	5.29(3)
$[CuA]^{2+}$	log β_{1100}	8.00[a]	9.25[a]

[a] Values taken from ref. 20.

Binary system

Up to pH ~ 6 the pH-metric titration curves of the binary system are almost superimposable to that of the ligand for all the metal/ligand molar ratios investigated, and at pH ~ 6 one equivalent point corresponding to the dissociation of the carboxyl group, followed by the precipitation of the copper(II) hydroxide, is observed. This finding suggests only a weak interaction between amino acid and Cu(II), the only active binding site being the carboxylic group. In the data treatment the species $[CuL]^+$ and $[CuL_2]$ were taken into account, but the better convergence was reached considering only the latter species and its calculated $\log\beta = 4.51 \pm 0.01$ is close to the mean value of 4.9 ± 0.5 found for other carboxylate complexes with $R-SO_2-N-$ amino acids [6]. Nevertheless the model containing the $[CuL]^+$ complex converged with the $\log\beta$ value of 2.5 ± 0.2.

Ternary system

The pH-metric titration curves show two equivalent points, the first corresponding to the complete dissociation of the carboxylate group, while the second, which is accompanied by a color change from pale blue to deep blue, needs a number of NaOH equivalents corresponding to those of Cu(II). The precipitation of copper hydroxide does not occur even beyond pH 10.

The spectrophotometric analysis of the system Cu^{2+}/hyda/bpy in the molar ratio 1:2:1 shows a titration pattern with a displacement of the d–d band maximum from 675 nm at pH 5.5 to 615 nm at pH 10.3. The spectrophotometric titration of the system Cu(II)–*N*-acetylglycine–bpy in the molar ratio 1:2:1 shows a similar trend. It is known that, in the above system, amide nitrogen deprotonation does not take place [15]; in our ternary system, therefore, the second equivalent point could be confidently attributed to H_2O deprotonation. Similar behavior is also observed for the ophen-containing ternary system.

The treatment of data takes into account the species $[CuAL_2]$ and $[CuAL(OH)]$ and their $\log\beta$ values are reported in Table 4. We also calculated $\Delta\log K$ ($\Delta\log K = \log\beta^{Cu}{}_{[CuAL_2]} - \log\beta^{Cu}{}_{[CuA]}$), which is −0.26

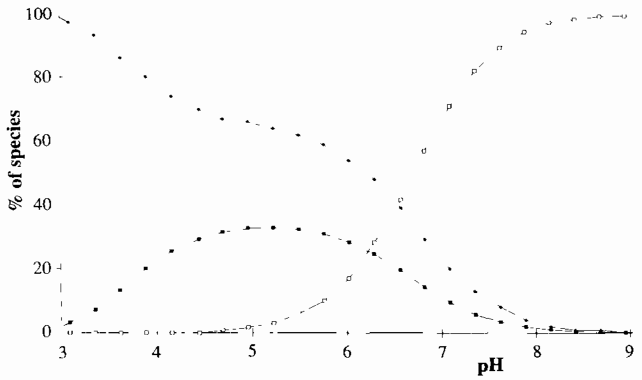

Fig. 2. Species distribution curves for the ternary system Cu^{2+}–bpy–hydaH in the 1.1:4 molar ratio. ◆ $[Cu(bpy)]^{2+}$; ■ $[Cu(bpy)(hyda)_2]$; □ $[Cu(bpy)(hyda)(OH)]$; $[Cu]^{2+} = 2\times10^{-3}$ mol dm^{-3}.

and −0.05 for bpy an ophen, respectively. These values are greater than the statistical value of −0.5 [22] and suggest that the selective effect of bpy and ophen towards carboxylate ligands is maintained. At pH ~ 6.5 the mixed hydroxo complexes are the prevailing species in both bpy- and ophen-containing systems (Fig. 2).

The position of the d–d band maximum of the solution obtained by dissolving the $[CuAL_2]$ complexes differs markedly from that in the solid state, and the possibility of the NH group being involved in metal coordination in solution may thus be discounted. In solution, the ligand behaves as a simple carboxylate, just like other N-protected amino acids in acidic media.

Conclusions

The crystal structure of $[Cu(ophen)(hyda)_2]\cdot H_2O$ throws new light on the coordination ability of the amide group. The presence of NH_2, which participates in the resonance of the amide group, enhances the basicity of NH, making it an alternative to oxygen as a second active binding site. Nevertheless, because the sp^2 hybridization of nitrogen is maintained, its ligand field is weaker than that of the oxygen atom and can form bond interactions longer than the normal value of about 2.37 Å observed in square pyramidal N,O-bonded complexes.

The affinity of the copper(II) atom for the nitrogen donor ligand causes it to prefer nitrogen coordination, whereas in the zinc(II) complex oxygen coordination is observed.

Supplementary material

Lists of anisotropic thermal parameters, hydrogen atom parameters, least-squares planes, possible hydrogen bonds, and observed and calculated structure factors (11 pp) are available from the authors on request.

Acknowledgements

The authors are grateful to the Ministero dell'Università e della Ricerca Scientifica e Tecnologica of Italy for financial support (40%), the Centro Interdipartimentale di Calcolo Automatico (C.I.C.A.I.A.) of the University of Modena for computing support, and the Centro Interdipartimentale Grandi Strumenti (C.I.G.S.) of the University of Modena which supplied the diffractometer and the ESR instrument.

References

1 T. Cameron, K. Prout, F.J.C. Rossotti and D. Steele, *J. Chem Soc, Dalton Trans*, (1973) 2626.
2 C.P. Nash and W.P. Schaefer, *J Am. Chem. Soc*, *91* (1969) 1319.
3 L Menabue and M. Saladini, *J Chem Soc, Dalton Trans*, (1990) 1581.
4 L. Menabue and M. Saladini, *J Crystallogr Spectrosc Res*, *22* (1992) 713
5 L. Menabue and M. Saladini, *Acta Crystallogr Sect C, 44* (1988) 2097, and refs therein.
6 A Bonamartini Corradi, *J Coord Chem*, *117* (1992) 45.
7 P Gans, A. Sabatini and A. Vacca, *J Chem. Soc, Dalton Trans*, (1985) 1185.
8 F. Ugozzoli, *ASSORB*, a program for Walker and Stuart's absorption correction, University of Parma, Italy, 1983
9 *International Tables for X-ray Crystallography,* Vol. 4, Kynoch, Birmingham, UK, 1974, pp 99–101.
10 G.M Sheldrick, *SHELX76,* program for crystal structure determination, University Chemical Laboratory, Cambridge, UK, 1976
11 M. Nardelli, *Comput Chem*, *7* (1983) 95.
12 C.K. Johnson, ORTEP, *Rep ORNL-3794,* Oak Ridge National Laboratory, Oak Ridge, TN, 1965
13 L. Menabue and M Saladini, *Acta Crystallogr. Sect C,* in press
14 R Cini, F P. Fanizzi, F.P Intini and G. Natile, *J Am Chem Soc*, *113* (1991) 7805
15 H. Sigel and R.B. Martin, *Chem Rev., 85* (1982) 385.
16 L. Antolini, G. Marcotrigiano, L. Menabue, G.C. Pellacani, M Saladini and M. Sola, *Inorg Chem., 24* (1985) 3621.
17 L.P. Battaglia, A Bonamartini Corradi, L. Menabue, M Saladini and M. Sola, *J Chem Soc, Dalton Trans*, (1987) 1333
18 H.M. Randall, R G. Fowler, N. Fuson and J.R. Dange, *Infrared Determination of Organic Structures,* Van Nostrand, New York, 1961.
19 C.I Jose, *Spectrochim Acta, Part A, 75* (1969) 111
20 G. Anderegg, *Helv Chim. Acta, 46* (1963) 2397.
21 *Handbook of Chemistry and Physics,* CRC, Boca Raton, FL, 56 edn., 1975–76
22 R. Malini-Balakrishanan, K.H. Scheller, U.K. Haring, R Tribolet and H Sigel, *Inorg Chem., 24* (1985) 2067