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pH-Dependent Imidazolato Bridge Formation in Dicopper Complexes: Magnetic, Electrochemical, and Catalytic Repercussions

Pages: 12

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The dicopper complexes of two dinucleating ligands derived from 2-methylimidazole and 2 equiv. of an L-amino acid are presented (H₃bphenim derived from L-phenylalanine and H₃bleuim derived from L-leucine). For each ligand L, three different protonation states for the complex, Cu_2HL^{2+} , Cu_2L^+ , and Cu_2LOH , have been characterized in solution by potentiometric, spectrophotometric, and electrochemical techniques. X-ray diffraction studies enabled the characterization, in the solid state, of the $[Cu_2(bphenim)]^+$ and $[Cu_2Hbleuim]^{2+}$ cations. Magnetic measurements showed that while only a very slight coupling could be detected in

 $[Cu_2Hbleuim]^{2+}$, $[Cu_2(bphenim)]^+$ is strongly antiferromagnetically coupled. The extent of this coupling can also be appreciated from room temperature, pH-dependent EPR spectroscopic studies, where the signal is quenched at pH values where the imidazolato-bridged species is predominant. These observations are consistent with the cyclic voltammetric studies. The catecholase activity of the complexes in the form $[Cu_2L]^+$ is low, however, an important increase in activity is observed above pH = 8.5 where the concentration of the species $[Cu_2LOH]$ starts to become significant.

Introduction

Imidazole is a ubiquitous ligand in biological systems as it occurs in proteins as part of the side chain of the amino acid histidine found coordinated to the metal centers in most copper proteins. However, imidazolate is comparatively scarce because of the very weak acid character of the imidazole moiety ($pK_a = 14.4$).^[1] It is known that metal coordination of the pyridinic nitrogen dramatically increases the acidity of the pyrrolic site, which encourages its coordination to a second metal ion.^[2] Imidazolato-bridged transition-metal complexes have been known since the early 1960s,^[3] and attracted a lot of interest when the X-ray crystal structure of the enzyme bovine erythrocyte superoxide dismutase (SOD) showed that the active site consisted of a Zn–Cu bimetallic pair bridged by the imidazolato group of a deprotonated histidine residue.^[4]

Many dinuclear imidazolato-bridged complexes have been prepared with the aim of modeling the active site of

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SOD. Lippard and coworkers prepared a series of imidazolato-bridged complexes and studied their solution equilibriums, their SOD activity, and their magnetic behavior. They observed that in complexes where imidazolato is a discrete unit, the bridge is quite prone to dissociating in solution, but that if this moiety was incorporated in the ligand framework a much more robust bridged structure is produced.^[5] More recent reports have corroborated this observation.^[6]

The antiferromagnetic coupling observed among paramagnetic metal ions when bridged by the imidazolato moiety has encouraged numerous studies that have focused on elucidating the factors determining the extent of this coupling,^[7] which may gain relevancy since there is current interest in the potential applications of this bridging moiety in supramolecular chemistry.^[8]

In our group, we have been studying the dicopper complexes of a series of imidazole-derived ligands and their catecholase activity. The ligands presented in this paper (Scheme 1) contain one imidazole unit condensed with two amino acid equivalents (phenylalanine or leucine) by means of a Mannich reaction. Since these ligands promote the formation of imidazolato-bridged dinuclear complexes, we have investigated the spectroscopic and electrochemical evidence of the formation of the bridge as a function of pH, as well as their magnetic behavior. The potentiometric and spectrophotometric speciation of the system allowed the identification of the catalytically active form of the complexes in the oxidation of di-*tert*-butylcatechol.



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Date: 2

Pages: 12

FULL PAPER



Scheme 1. General formula for the ligands and ¹H NMR spectroscopic identification.

Results and Discussion

Synthesis of the Ligands and Complexes

We have previously described the dicopper complexes of a series of related, but significantly different ligands obtained from the same type of Mannich reaction. When the amine employed is a primary amine^[9] or a nonchiral amino acid (glycine^[10] or β -alanine^[11]) the product is a 10-membered cyclic diazecine, incorporating two imidazole and two amine moieties. However, when an L-amino acid^[12] is used as the amine source, a ligand comprising only one imidazole moiety, similar to the ones described here, is obtained. The ligands used in the present work are H₃bphenim (derived from 2-methylimidazole and L-phenylalanine) and H₃bleuim (derived from 2-methylimidazole and L-leucine).

In principle, at least two forms of each one of the two dinuclear complexes can be isolated depending on the pH of the medium. When 1 equiv. of the ligand is combined with an aqueous solution containing 2 equiv. of $Cu(NO_3)_2$ or $Cu(ClO_4)_2$, without the addition of a base, the pH drops to approximately 1.5 and a complex with a cation of the acidic form $[Cu_2HL]^{2+}$ is formed. If the pH is increased to above 6, the complex cation is of the deprotonated form $[Cu_2L]^+$. Crystals suitable for X-ray determination of the structure could be obtained for the acidic form $- [Cu_2-HL]^{2+}$ – only for the leucine derivative and for the basic form $- [Cu_2L]^+$ – only for the phenylalanine derivative.

Crystal Structures

$[Cu_2(bphenim)(H_2O)_4]ClO_4 \cdot 2.86(H_2O)$

The complex cation $[Cu_2(bphenim)(H_2O)_4]^+$ in compound **1** is build up of the H₃bphenim molecule, after deprotonation of both ammonium and imidazole functionalities, allowing the coordination of two Cu^{II} ions. The main ligand lies on a twofold axis, resulting in an asymmetric unit limited to a half-cation. The metal center coordinates three heteroatoms in the ligand, and the coordination sphere is completed by two water molecules (Figure 1). The [CuN₂O₃] coordination geometry may be described as distorted square pyramidal, as reflected by the τ index^[13] computed for this center, τ (Cu1) = 0.27, with the apical position occupied by the water molecule O18. A MOGUL analysis^[14] shows that this molecule is found at the expected distance, Cu1–O18 2.161(13) Å, while the basal bond lengths are rather short. For example, Cu1-N2 1.938(8) Å, while the basal water molecule O19 is bonded at a distance 1.944(11) Å shorter than Cu-OH₂(basal) distances in related complexes with a [CuN₂O₃] core.^[10,15] This strong coordination, and the angle restrictions imposed by the two five-membered chelate rings formed upon coordination, ensure that the Cu^{II} center is displaced by 0.33 Å from the basal plane. The bridging aromatic imidazolate ring (Im), although having a low C_2 crystallographic symmetry, is almost perfectly planar, and CuII ions are placed 0.06 Å above and below the Im mean plane. Such planar Cu^{II}-(µ-Im)-Cu^{II} fragments have been described in other polymetallic complexes with various imidazole derivatives, forming either monomeric,^[16] cyclic-oligomeric,^[17] or polymeric^[18] systems. The Cu-Cu separation is found in the rough range 5.6–6.2 Å in the complexes bearing a Cu^{II} –(µ-Im)– Cu^{II} fragment. The distance observed in the cation [Cu₂(bphenim)(H₂O)₄]⁺ is Cu···Cu 6.056(3) Å, which is within the expected range. Actually, the shortest metal-metal separation in the crystal is 5.180(3) Å, which involves two neighboring cations related through a 2_1 screw axis.



Figure 1. ORTEP-like view^[20] of the cation $[Cu_2(bphenim)-(H_2O)_4]^+$ in compound 1, with ellipsoid displacements at the 20% probability level. H atoms have been omitted for clarity. Atoms belonging to the asymmetric unit are labeled.

Perchlorate and lattice water molecules are distributed within the crystal between the cations. As mentioned in the Exp. Section, they present very high thermal motion parameters and are prone to disorder, which indicates that they interact poorly with the cations. Hence, it may be anticipated that the dominant magnetic interaction for **1** should be sought in the planar Cu^{II} –(µ-Im)– Cu^{II} moiety of the cation, rather than in the inter-cation contacts.

Interestingly, the same cation could be crystallized with nitrate counterions in place of perchlorate, affording the compound $[Cu_2(bphenim)(H_2O)_4]NO_3\cdot 3.6(H_2O)$. This was performed with the hope of getting better single crystals than those of **1**. Unfortunately, the opposite result was obtained. The crystals belong to the same cubic space group,

 $P4_132$, but only the position of the cation was determined. The nitrate anions, which have a C_3 axis in common with a perchlorate (tetrahedral point group), are probably located on the same sites as CIO_4^- in compound **1**, but disordered by rotation. Moreover, lattice water is systematically disordered, lowering the scattering power of these crystals. The above quoted formula, including 3.6 H₂O per complex, was obtained from a SQUEEZE refinement,^[19] and should be seen as a rough estimation of the actual water content.

$[Cu_2(Hbleuim)(H_2O)_3(NO_3)]NO_3 \cdot H_2O$

Complex 2 is a polymeric compound, build up of the H₃bleuim molecule, after deprotonation of only the ammonium groups. The asymmetric unit contains one [Cu₂-(Hbleuim) $(H_2O)_3(NO_3)$]⁺ cation, one uncoordinated nitrate, and one lattice water molecule, all placed in general positions and ordered in the crystal. Metal center Cu1 (see Figure 2) has a [CuN₂O₃] coordination sphere close to that described in 1. Distortion from the square-pyramidal geometry is, however, less pronounced, and indeed very close to an ideal geometry, with τ (Cu1) = 0.02.^[13b] The apical position is occupied by the water molecule O27, with a long bond length, Cu1–O27 2.330(6) Å, and basal bond lengths are short, in the range 1.937(3)-1.997(4) Å. The metal is displaced by 0.15 Å from the basal plane. The nitrate counterion is located in the position trans to the apical water molecule O27, with a large nonbonding separation, Cu1···O37 2.721(8) Å. The Cu1 can thus alternatively be seen as an octahedral Cu^{II} ion with a huge Jahn-Teller distortion.



The most important difference between 2 and 1 is that the organic ligand in 2 features an imidazole, ImH, ring rather than an imidazolate, Im. As a consequence, ImH coordinates a single Cu^{II} ion in 2. The independent coordination site Cu2 is bonded to the amine group N8, the nitrate O atom O31, one water molecule O29, and two carboxylate O atoms (O11 and O12) belonging to two symmetry-related Hbleuim ligands. The bridging μ -carboxylate- κ^2 O:O' functionality of Hbleuim gives rise to zigzag chains of Cu2based monomers, running along the 2_1 screw axis parallel to [100], while Cu1-based groups are arms placed along the Cu2-polymer backbone (Figure 2, inset). The five-coordinate Cu2 center is strongly distorted from an ideal squarepyramidal geometry, with $\tau(Cu2) = 0.38$. The apical position is occupied by the nitrate O atom, with a long bond length Cu2–O31 2.333(5) Å, and the metal is placed 0.21 Å out of the basal mean plane. However, in contrast to the Cu1 metal center, nothing is found *trans* to the apical position, ruling out the interference of a Jahn-Teller effect in this case. It should be noted that few occurrences of bimetallic copper-bridged complexes with such different coordination geometries are found in the CSD.^[21] Such asymmetry seems to be generally a consequence of π - π interactions^[22] ($\tau = 0.07$ and 0.53) or restrictions from a polychel-

ated connectivity^[23] ($\tau = 0.07$ and 0.25). With regard to the metal–metal distances along the polymer, the Cu2 centers are separated by 4.5986(9) Å, and Cu1 ions in the arms are separated by 7.3647(16) Å (Cu2 and Cu1 stacks in the inset of Figure 2). All other Cu···Cu separations within each chain are more than 8 Å long. Finally, interchain contacts are intermediate: the shortest Cu···Cu separation involving two neighboring chains in the crystal is Cu1···Cu2^{*i*} 5.4230(8) Å (symmetry code *i*: 1/2 - x, -y, 1/2 + z).

Both X-ray structures show that H_3 bphenim and H_3 bleuim are comparable ligands, and that coordination behavior is strongly related to two factors: the pH at which the coordination is realized and the ability of the carboxylate functionality to bridge metal centers. In the case of 1, bphenim behaves as a bis-tridentate ligand, and coordinates two Cu^{II} ions in a symmetric arrangement. Once six coordination sites are used, there is no chance of forming a polymeric structure. In contrast, Hbleuim is a less symmetric ligand because the imidazole ring is protonated and thus provides a single coordination site (assuming that no tautomeric equilibrium is reached in solution). In that case, one carboxylate O atom is available to bridge two metal centers, and a 1D polymeric structure is stabilized.

Figure 2. ORTEP-like view^[34] of cation $[Cu_2(Hbleuim)(H_2O)_3(NO_3)]^+$ in compound **2**, with ellipsoid displacements for non-hydrogen atoms at the 40% probability level. C-bonded H atoms have been omitted, and the asymmetric unit is labeled. Nonlabeled atoms are connected through the 2_1 axis parallel to [100], to form the 1D polymer. Part of this chain is represented in the inset. Both coordinated and uncoordinated nitrate ions are displayed, while lattice water molecules are omitted.

Magnetic Studies

Solid-state, variable-temperature (2.0-300.0 K) dc magnetic susceptibility data using a 0.05 T field from 2 to 30 K and a 1.0 T field from 30 to 300 K were collected from a polycrystalline sample of **1**. The resulting data are plotted

FULL PAPER

as $\chi_{\rm M}T$ vs. T and $\chi_{\rm M}$ vs. T (inset) in Figure 3. The $\chi_{\rm M}T$ values found for 1 match well with that of a dinuclear complex with a strong antiferromagnetic interaction. The magnetic data were measured using two fields, 0.05 T (from 2 K to 30 K) and 1.0 T (from 30 K to 300 K). The $\chi_{\rm M}T$ value at 300.0 K is $0.65 \text{ cm}^3 \text{mol}^{-1} \text{K}$ smaller than that expected for two independent Cu^{II} centers $(0.75 \text{ cm}^3 \text{ mol}^{-1} \text{ K}$ when g = 2.0), implying that a strong coupling is already evident at high temperatures. The magnetic susceptibility decreases abruptly upon cooling to ca. 0.02 cm mol⁻¹K at 40 K and then reaches a plateau that smoothly drops close to zero at 2 K. The best-fit parameters using the Hamiltonian in the form $H = -JS_1S_2$, are: $J = -158 \pm 2 \text{ cm}^{-1}$ and g = 2.04 ± 0.01 (TIP = 120×10^{-6} cm³ mol⁻¹ and R = 7.6×10^{-4}). The J value corroborates the shape of the graph, indicating antiferromagnetic coupling and the $\chi_{\rm M}$ vs. T data exhibits a maximum at approximately 140 K, characteristic of strong AF coupled systems.^[24] This J value is similar to the most negative J value reported in the literature for imidazolato-bridged dicopper complexes, which is $J = -163 \text{ cm}^{-1}$.^[7c]



Figure 3. Fitting of the $\chi_{\rm M}T$ vs. *T* and $\chi_{\rm M}$ vs. *T* (inset) of 1 between 2.0 and 300.0 K. The experimental data are shown as black circles and the red line corresponds to the theoretical values.

Several attempts have been made^[7a,7b,7d] to correlate the magnitude of the coupling constant with diverse structural factors such as the Cu–N bond length and two angles: *a*, the Cu–N–N angle and θ , the dihedral angle between the imidazolate plane and the copper coordination plane, considering a square or square-pyramidal coordination geometry. A stronger coupling is expected when *a* approaches 180° since this maximizes a σ interaction, while θ is expected to be relevant only in the hypothesis of a π Cu–imidazolate interaction; in which case a value of 90° would be optimal.

Table 1 shows these structural parameters for several imidazolato-bridged dicopper complexes described in the literature, with their corresponding *J* value. The large negative value found for 1 is in agreement with previous analyses,^[7b,7d] which have proposed that the *a* angles are the most important of these parameters; the closer these angles are to 180°, the stronger the coupling. This correlation suggests that σ bonding is the main path for the coupling.

Table 1. Coupling constants and selected geometrical parameters for imidazolato-bridged complexes.

Compound	$J [\mathrm{cm}^{-1}]$	<i>a</i> ₁ [°]	θ_1 [°]	Ref.
$Cu_3(iz-)_2(iz)_8(ClO_4)_4$	-117	162.9	70.0	[7b,25]
$Cu_2(TMDT)(iz)(ClO_4)_2$	-52	161.9	91.8	
Cu(macro) ²⁺	-41	158.9	68.8	[5a]
Cu ₂ (Gly–GlyO) ₂ (iz) ⁻	-38	157.5	5.8	[26]
$Cu_2(bpim)^{3+}$	-163	176.2	4.7	[7c,28]
$Cu_2(phen)_4(im)^{3+}$	-48	159.4	86.5	[7d]
$Cu(L')Cu(tfacac)_2$	-112	176.5	0.7	[29]
$[Cu(L')Cu(tebima)]PF_6$	-140	176.9	0.7	[29]
Cu ₂ (bphenim) ⁺	-158	176.6	26.5	this work

Even though 2 exhibits a complicated structural composition (a chain of Cu²⁺ ions where each metal center is connected, at the same time, to a terminal Cu²⁺ system), the magnetic data shows a straightforward behavior characteristic of a very weakly coupled Cu²⁺ species. Taking only the two crystallographically different Cu2+ centers into account, the $\chi_M T$ value at 300 K was found to be $1.03 \text{ cm}^3 \text{mol}^{-1} \text{K}$ higher than that expected for two uncoupled S = 1/2 spins assuming $g = 2.00 (0.75 \text{ cm}^3 \text{mol}^{-1} \text{ K})$. The $\chi_{\rm M}T$ value varies slightly from the highest temperatures until approximately 50 K ($0.98 \text{ cm}^3 \text{mol}^{-1}\text{K}$), then drops faster to 0.33 cm³mol⁻¹K at 2 K. Because of the complexity of the structure, fitting of the data was not feasible. Still, the disposition of the magnetic orbitals in the structure corroborates the almost nonexistent coupling between the Cu centers. This way, in the chain, the Cu centers are connected to each other through the O atoms from the carboxylate group of the ligand in a syn-anti conformation. In general, weak interactions are typical in carboxylatebridged Cu^{II} arrays where the carboxylate groups adopt *syn-anti* conformations. Here, the $d_{x^2-y^2}$ orbital of one Cu atom related with the d_{z^2} orbitals of the neighbors (equatorial-axial interactions) making the coupling almost inexistent.^[30] Furthermore, each Cu²⁺ in the chain coordinates to a terminal mononuclear Cu²⁺ system through the ligand. This time, the orbitals relating through L are both $d_{x^2-\nu^2}$ in nature, however, the ligand lies in such a way that a relevant angle forms (113.45°) between the two planes containing the magnetic orbitals and as a result the magnetic communication is very poor. Overall, this unique 1D structure depicts a very weak magnetic behavior, which in nature seems to appear antiferromagnetic.

Solution Speciation Studies

Potentiometry, UV/Vis, and EPR Spectrophotometry

Since in our group there is interest in the effect of the solvent on catecholase activity, we pursued the pH-dependent speciation of our catalysts in the two solvent mixtures in which the catalytic studies were performed, MeOH/H₂O and MeCN/H₂O (1:1 v/v).

The determination of the equilibrium constants was achieved through potentiometric titrations and treatment of the data with the program Hyperquad.^[31] Four pK_a values

Imidazolato Bridge Formation in Dicopper Complexes

were obtained for both ligands in MeOH/H₂O corresponding to the two aliphatic amine groups, the imidazole, and two equivalent carboxylate groups. For H₃bphenim these values are 9.64, 6.89, 3.95, and 2.64, while for H₃bleuim the values are 10.0, 7.71, 4.47, and 3.5, respectively. For MeCN/ H₂O, only three pK_a values could be refined for the two ligands. The values obtained for H₃bphenim are 9.37, 6.73, and 3.56, and for H₃bleuim they are 9.97, 7.53, and 3.74.

The overall formation constants for the dicopper complexes of these ligands in their different protonation states in the two mentioned media are shown on Table 2. From these values it is possible to estimate the value of the constants of two chemically relevant equilibriums. The first one corresponds to the formation of the bridged species with the deprotonation of the pyrrolic nitrogen:



$$K_{\rm eq.}^{(1)} = \frac{[{\rm Cu}_2 L^+][{\rm H}^+]}{[{\rm Cu}_2 {\rm LH}^{2+}]} \log K_{\rm eq}^{(1)} = \log \beta_{211} - \log \beta_{210}$$

While the second one corresponds to the hydrolysis of one of the metal ions in the complex:



From the values obtained for $K_{eq}^{(1)}$, it is evident that the formation of the bridged $[Cu_2L]^+$ species is strongly favored over the nonbridged $[Cu_2LH]^{2+}$ one, for both of the ligands

in both of the solvent mixtures explored. The bridged species predominates over the nonbridged one above pH = $\log K_{eq}^{(1)}$, as can be appreciated from the species predomination diagrams in Figure 4. In the four cases, this bridged species is predominant through a wide pH range, roughly from pH 5–9, the point from where the monohydrolized form [Cu₂LOH] becomes the most abundant. The corresponding p K_a value for the deprotonation of a coordinated water molecule can be estimated from $\log \beta_{201} - \log \beta_{2-11}$ (Table 2).

The formation of the imidazolato bridge can account for the significant changes observed in the UV/Vis spectra of both dinuclear complexes upon base addition. Very similar behavior was observed for both complexes, both in MeOH/ H₂O and in MeCN/H₂O. Figure 5 shows the results obtained for Cu₂bleuim in MeCN/H₂O. Consistent with what was found through the potentiometric studies, the mixing of one ligand equivalent with two Cu²⁺ equivalents causes a marked decrease in pH because of the coordination of both the carboxylate and the aliphatic amine groups.

The initial addition of base does not cause any change in the position of the absorption maximum and a decrease in absorbance is attributed merely to the dilution of the complex while the free H⁺ is neutralized. Starting at pH = 3.9, the maximum begins to shift to smaller wavenumber values, with a considerable increase in the intensity of the absorption, similar to what has been described by other authors.^[5d,32]

An additional confirmation of the imidazolato-bridge formation came from EPR spectroscopy. Room temperature MeOH/H₂O solution and aqueous solution spectra are shown in Figure 6. The initial spectrum may be associated with the overlap of two sets of peaks corresponding to two different copper(II) complexes in tetragonal environments, the first in which the imidazole nitrogen is coordinated to the metal together with the neighboring amino acid ligand moiety, and the second in which only the other amino acid ligand donor atoms are coordinated. As the pH rises upon the addition of base, the formation of the imidazolato bridge quenches the EPR signal because of the strong antiferromagnetic coupling. It is interesting to mention that this

$\beta = \frac{[\mathrm{Cu}_{\mathrm{x}}\mathrm{H}_{\mathrm{y}}\mathrm{L}_{\mathrm{z}}]}{[\mathrm{Cu}^{2+}]^{x}[\mathrm{H}^{+}]^{y}[\mathrm{L}]^{z}}$		$K_{a}^{(i)} = \frac{[Cu_2L(H)]}{[Cu_2L(H)]}$		
H ₃ bphenim MeOH/H ₂ O	MeCN/H ₂ O	H ₃ bleuim MeOH/H ₂ O	MeCN/H ₂ O	Related equilibrium
$log \beta_{221} =$ 24.026 ± 0.057		$\log \beta_{221} = 21.689 \pm 0.035$		$2\mathrm{Cu}^{2+} + \mathrm{L}^- + 2 \mathrm{H}^+ \to \mathrm{Cu}_2\mathrm{H}_2\mathrm{L}$
$\log \beta_{211} =$ 20.503 ± 0.051	$\log \beta_{211} =$ 18.063 ± 0.041	$\log \beta_{211} = 17.623 \pm 0.016$	$\log \beta_{211} = 17.472 \pm 0.063$	$2\mathrm{Cu}^{2+} + \mathrm{L}^- + \mathrm{H}^+ \rightarrow \mathrm{Cu}_2\mathrm{HL}$
$\log \beta_{201} =$ 15.937 ± 0.055	$\log \beta_{201} =$ 13.800 ± 0.036	$\log \beta_{201} = 12.286 \pm 0.020$	$\log \beta_{201} = 12.581 \pm 0.053$	$2Cu^{2+} + L^- \rightarrow Cu_2L$
$\log K_{\rm eq}^{(1)} = 4.56$ $\log \beta_{2-11} = 6.860 \pm 0.056$	$\log K_{\rm eq}^{(1)} = 4.26$ $\log \beta_{2-11} =$ 4.557 ± 0.037	$\log K_{\rm eq}^{(1)} 5.33 \log \beta_{2-11} = 2.855 \pm 0.027$	$\log K_{\rm eq}^{(1)} = 4.89$ $\log \beta_{2-11} = 2.822 \pm 0.061$	$\begin{array}{l} (Cu_2LH)^{2+} \rightarrow Cu_2L^+ + H^+ \\ 2Cu + L + OH \rightarrow Cu_2L(OH)^+ \end{array}$
$pK_{a}(hyd) = 9.077$	$pK_{a}(hyd) = 9.243$	$pK_{a}(hyd) = 9.431$	$pK_{a}(hyd) = 9.759$	$Cu_2L(H_2O) \rightarrow Cu_2L(OH) + H^+$

Table 2. Equilibrium constants in MeOH/H2O and MeCN/H2O.



Figure 4. Top: species distribution diagrams as a function of pH for 2Cu²⁺:H₃bleuim in MeCN/H₂O (left) and in MeOH/H₂O (right). Bottom: species distribution diagrams as a function of pH for 2Cu²⁺:H₃bphenim in MeCN/H₂O (left) and in MeOH/H₂O (right).



Figure 5. UV/Vis spectra of a solution of 2Cu2+:1H3bleuim in MeCN/H₂O, upon base additions.

quenching is more pronounced when the spectra are recorded in an aqueous solution, and also at room temperature.

Cyclic Voltammetry

The presence of two reduction signals in dinuclear copper complexes can be attributed to two different chemical environments for each copper ion, or to a strong coupling



Figure 6. Room-temperature EPR spectra of 2Cu²⁺:1H₃bphenim at variable pH. Top: in MeOH/H₂O, bottom: in H₂O.

between two metal ions in identical chemical environments.[5e,33]



Figure 7 shows the cyclic voltammograms of the MeCN/ H₂O solutions of $2Cu^{2+}:1H_3$ bphenim, at two different pH values. On top at pH = 3.8, when from the corresponding speciation diagram only scarce formation of the bridged species is expected, it can be assumed that the dominant copper species is that labeled **A** in equilibrium (1). The two observed reduction signals appear at $E_{pc}(1) = +0.05$ V and $E_{pc}(2) = -0.51$ V, $\Delta E = 0.56$ V. The first one can be assigned to the reversible reduction of the less coordinatively saturated Cu²⁺ ion, i.e. the one coordinated to only two of the three potentially available donor atoms the ligand has for each metal ion. The second signal can then be assigned to a more strongly coordinated Cu²⁺ ion bound to three donor atoms from the ligand.



Figure 7. Voltammograms of a MeCN/H₂O solution of $2Cu^{2+}$:1H₃bphenim at pH = 3.8 (top) and pH = 7.5 (bottom).

At pH = 7.5 (bottom), the two nonreversible peaks shift to lower potential values and $E_{pc}(1) = -0.50$ V and $E_{pc}(2) = -0.64$ V, and the separation becomes smaller, $\Delta E = 0.14$ V. At this pH the predominant species is **B** in equilibrium (1), the two copper ions are in identical chemical environments, bridged by the imidazolato group. The intense electronic communication between the two copper ions, evidenced by magnetic susceptibility and EPR spectroscopic measurements, causes the presence of these two reduction signals.

Catecholase Activity

In our group we have been interested in the catecholase activity of a series of dinuclear copper complexes with dinucleating ligands derived from imidazole and amines.^[9b,9c,34] These complexes have shown important catecholase activity, in spite of the steric impossibility for the two Cu ions to act concertedly on the substrate. They all exhibit a slight antiferromagnetic coupling in the solid state and their frozen-solution EPR spectra display seven hyperfine lines in the parallel region, associated with the coupling of an electron with two nuclei with S = 3/2, regardless of a separation between the two copper ions of more than 7 Å. Now, since catecholase is a type III copper enzyme – EPR silent – with two strongly coupled Cu^{II} centers and the complexes described in this paper have similar magnetic behavior, we decided to test their catecholase activity as well.

The catalytic oxidation of 3,5-di-*tert*-butylcatechol (H₂DTBC) has been widely studied as a model reaction for the catecholase activity of tyrosinase and catechol oxidase. This model substrate is oxidized to the corresponding quinone (Scheme 2), while the Cu^{II} catalyst is reduced to Cu^I and reoxidized by atmospheric oxygen. The kinetic studies on the oxidation of H₂DTBC were carried out by the method of initial rates, monitoring the increase in the characteristic quinone (DTBQ) absorption band at 400 nm as a function of time.



Scheme 2. Catechol oxidation by oxygen.

Since the dicopper complexes of the ligands described in this work undergo drastic changes as a function of pH because of the formation of the imidazolato bridge, we studied the variation in catecholase activity of the compounds Cu₂bphenim and Cu₂bleuim as a function of pH in two solvent mixtures, MeCN/H₂O and MeOH/H₂O. This is shown in Figure 8 where the effect of the buffered medium in the absence of catalyst can be appreciated.

These results led us to choose a pH of 8.5, in both solvent mixtures, to determine the kinetic parameters (Table 3) since at this value the largest increment in activity was observed compared to the activity of the medium without the catalyst. The initial rates method was used for the analysis of the kinetic profile obtained for the aerobic oxidation of DTBC, which follows the Michaelis–Menten model. As we previously reported for similar catalytic systems^[9c] the catalytic efficiency is significantly better in MeOH/H₂O than in MeCN/H₂O: This was previously explained by electrochemical studies that showed that these catalysts are easier to regenerate, being oxidized from Cu^I to Cu^{II}, in MeOH/H₂O than in MeCN/H₂O, where Cu^I is stabilized.

At the optimal pH for the catalytic reaction we can see from the species distribution diagrams (Figure 4) that in both solvent mixtures and with both ligands, the dominant species is type "B" in equilibriums (1) and (2). However, this species is predominant over a wide pH range below 8.5,



Figure 8. The pH effect on the catecholase activity of Cu_2 bphenim in MeOH/H₂O (top, left) and MeCN/H₂O (top, right). pH effect on the catecholase activity of Cu_2 bleuim in MeOH/H₂O (bottom, left) and MeCN/H₂O (bottom, right). (Concentrations in MeOH/H₂O were 10 times lower due to solubility).

Table 3. Kinetic parameters for Cu_2 by benim and Cu_2 bleuim at pH = 8.5 in MeOH/H₂O and MeCN/H₂O.

	Cu ₂ bphenim		Cu ₂ bleuim		
	MeOH/H ₂ O	MeCN/H ₂ O	MeOH/H ₂ O	MeCN/H ₂ O	
R^2	0.989	0.987	0.994	0.997	
K _M	0.00098	0.00207	0.00120	0.0032	
$V_{\rm max}$	2.92×10^{-6}	2.98×10^{-6}	1.86×10^{-6}	3.76×10^{-6}	
[Cu ₂ L] [M]	1×10^{-5}	2×10^{-5}	1×10^{-5}	2×10^{-5}	
k _{cat}	0.292	0.149	0.186	0.188	
$k_{\rm cat}/K_{\rm M}$	299	72	155	59	

at which the catalytic efficiency is not as high. Besides, it is possible to appreciate from the diagrams that at pH = 8.5, the species of type "C" is present at a lower, but definitively relevant, proportion.

It has been mentioned before that the OH⁻ group coordinated to the copper ions at the active site of catecholase^[35] has a basic role in the mechanism of catechol oxidation. In many model systems described in the literature^[36] this has proven to be the case. The model substrate, H₂DTBC is not fully deprotonated^[37] below pH = 10. We therefore propose that the catalytically active form of the complex is "C", where the imidazolato bridge is formed and one of the coordinated water molecules has been deprotonated.

The slightly higher catalytic efficiency of Cu₂bpheim compared to Cu₂bleuim must be related to the aromatic moiety in the former interaction, which can participate in a π - π interaction with the substrate and in which the aliphatic residue of the latter cannot engage.

Conclusions

The dinucleating ligands presented here promote the formation of imidazolato-bridged dicopper complexes, which are stable over a wide range of pH values. A strong antiferromagnetic coupling between the copper ions in the bridged species is observed, both in the solid state and in solution. In the solid state, magnetic susceptibility studies gave a value of $J = -158 \text{ cm}^{-1}$ for this coupling. The extent of the coupling in solution was assessed by the quenching of the EPR spectroscopic signal that accompanies the formation of the bridged species. The cyclic voltammograms of these solutions are also consistent with a strong electronic communication between the two metal centers. Important catecholase activity was found for these complexes at pH = 8.5, which led us to propose a hydrolyzed species of the type [Cu₂LOH] as being catalytically active.

Experimental Section

4,5-Bis(phenylalanyl-N-methyl)-2-methylimidazole (H₃bphenim) and 4,5-Bis(leucyl-N-methyl)-2-methylimidazole (H₃bleuim): The ligands H₃bphenim and H₃bleuim were prepared according to a procedure described previously.^[38] 2-Methylimidazole (2.05 g, 0.025 mol) was dissolved in distilled water (150 mL) together with the corresponding amino acid (0.05 mol, phenylalanine for H₃bphenim and leucine for H₃bleuim). A concentrated KOH solution was added dropwise until these reactants were completely dissolved. Formaldehyde (6 mL, 0.075 mol, 37% aqueous solution) was added dropwise to this mixture while stirring. Finally, the mixture pH was adjusted to 12 with a concentrated KOH solution and the solution was stirred



at 55 °C for 24 h. After this time, the solution was neutralized with acetic acid. The solid obtained was collected and washed a couple of times with water and ethanol.

H₃bphenim: C₂₄H₂₈N₄O₄·2H₂O: calcd. C 61.00, H 6.83, N 11.86; found C 61.24, H 7.00, N 12.06. ¹H NMR (D₂O) (see Scheme 1): δ = 2.37 [s, 3 H, -CH₃; (a)], 3.10 [o, 4 H, -CH₂-φ; (d)], 4.23 [s, 4 H, -CH₂-Im; (b)], 4.27 [t, 2 H, alpha C=O, (c)], 7.1 [m, 10 H, phenyl; (e)]; yield 28%.

H₃bleuim: C₁₈H₃₂N₄O₄·2H₂O: calcd. C 53.47, H 7.92, N 13.86; found C 53.91, H 8.07, N 14.12. ¹H NMR (D₂O): δ = 1 [q, 12 H, CH₃; (h)], 1.8 [m, 4 H, -CH₂-; (f)], 1.95 [m, 2 H, -CH<; (g)], 2.7 (s, 3 H, CH₃-Im), 4.4 [t, 2 H, alpha C, (c)], 4.7 [c, 4 H, -CH₂-Im; (b)]; yield 19%.

¹³C NMR spectroscopic data are available in the Supporting Information.

[Cu₂(bphenim)(H₂O)₂]NO₃ and [Cu₂(bphenim)(H₂O)₂]ClO₄: Crystals of the copper complex Cu₂bphenim with nitrate or perchlorate can be obtained as described previously,^[38] from a 50% mixture of an aqueous solution buffered to pH 7.5 with HEPES and acetonitrile (MeCN + H₂OpH 7.5), mixing H₃bphenim·2H₂O (0.47 g, 1 mmol) with Cu(NO₃)₂·2.5H₂O (0.464 g, 2 mmol), or Cu(ClO₄)₂·6H₂O (0.741 g, 2 mmol). The dark blue solutions obtained were allowed to stand for several days until crystallization occurred. [Cu₂(C₂₄H₂₅N₄O₄)(H₂O)₄]NO₃·4H₂O: calcd. C 37.60, H 5.34, N 9.13; found C 37.98, H 4.97, N 9.07. [Cu₂(C₂₄H₂₅N₄O₄)(H₂O)₄]-ClO₄·4H₂O: calcd. C 35.84, H 5.1, N 6.97; found C 36.1, H 4.92, N 7.08.

 $\label{eq:cu2} \begin{array}{l} \label{eq:cu2} [{Cu2}({Hbleuim})({H_2O})_3({NO_3})]{NO_3}\cdot {H_2O}: \ H_3 \ bleuim\cdot 2H_2O \quad (0.404 \ g, 1 \ mmol) \ was dissolved in water (20 \ mL), which contained Cu(NO_3)_2 \cdot 2.5H_2O \quad (0.464 \ g, 2 \ mmol), \ and \ was left to stand. \ The \ pH \ of \ the \ solution \ was approximately 1.5. \ Deep \ blue \ crystals \ were \ found \ after \ 2 \ w. \ [Cu_2(C_{18}H_{30}N_4O_4)(NO_3)(H_2O)]NO_3\cdot H_2O: \ calcd. \ C \ 31.35, \ H \ 5.52, \ N \ 12.19; \ found \ C \ 31.54, \ H \ 5.63, \ N \ 11.93. \end{array}$

Crystal Structures: X-ray diffraction data for complexes [Cu₂-(bphenim)(H₂O)₄)ClO₄·2.86(H₂O) (1) and [Cu₂(Hbleuim)(H₂O)₃-(NO₃)]NO₃·H₂O (2) were collected at room temperature with a Bruker P4 diffractometer^[39] using Mo- K_{α} radiation (Table 4). Raw data were corrected for absorption effects^[40] and the structures refined with the SHELX programs.^[41]

Complex 1 only gave very poorly diffracting single crystals and resolution for data was limited to $d = 0.93 \text{ Å} (2\theta_{\text{max}} = 45^{\circ})$, since beyond this angle no diffraction was observed at all. The position of the cation was easily determined by direct methods, while other residues were difficult to locate as a consequence of their very large and anisotropic displacement parameters. The perchlorate anion is equally disordered over two sites in the asymmetric unit, both with a threefold symmetry. The geometry of the anions was regularized through suitable restraints on Cl-O bond lengths and O···O separations. Similarity restraints on ADP were applied on O atoms, and atom O31 was refined isotropically with a displacement parameter fixed to 0.4 $Å^2$. At this point, the largest peak in a difference map was assigned to a water lattice molecule (O41) with full occupancy. All C- and N-bonded H atoms were placed in idealized positions (riding refinement). Positions for water H atoms were first refined freely, although with restricted geometries, and eventually forced to ride on the O atoms in the last least-squares cycles. This model (R_1 = 10% for observed reflections) still contained solvent accessible regions and was further refined after applying the SQUEEZE procedure,^[19] which recovered 103 electrons per cell, assigned to disordered water molecules (0.858 H_2O for each cation). The final refinement converges to $R_1 = 9.38 \% [I \ge 2\sigma(I)]$, a disappointing resid-

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Table 4. Crystal data for the complexes.

	1	2	
Empirical formula	C ₂₄ H _{38,72} ClCu ₂ N ₄ O _{14,86}	C ₁₈ H ₃₈ Cu ₂ N ₆ O ₁₄	
M_r [gmol ⁻¹]	783.57	689.62	
Color, habit	green, irregular	blue, prism	
Crystal size [mm]	$0.6 \times 0.4 \times 0.2$	$0.42 \times 0.20 \times 0.18$	
Space group	P4 ₁ 32	$P2_{1}2_{1}2_{1}$	
a [Å]	21.549(2)	7.3647(16)	
b [Å]	_	19.050(2)	
c [Å]	_	21.0189(19)	
V[Å ³]	10006.6(18)	2948.9(8)	
Z, Z'	12, 1/2	4, 1	
$\rho_{\rm calcd} [\rm g cm^{-3}]$	1.560	1.553	
$\mu [\mathrm{mm}^{-1}]$	1.427	1.514	
2θ range [°]	4-45	4-52.5	
Reflections collected	9608	5643	
Independent reflections	2192 (0.058)	5057 (0.022)	
(R_{int})			
Transmission factors	0.220-0.298	0.244-0.280	
(min., max.)			
Final R indices	0.094, 0.215	0.044, 0.099	
$[I \ge 2\sigma(I)] R_1, wR_2$		*	
Final <i>R</i> indices (all data)	0.119, 0.226	0.062, 0.107	
R_1, wR_2	,	,	
Goodness-of-fit on F^2	1.84	1.06	
Data/restraints/	2192/24/210	5057/102/379	
parameters			
Largest difference peak/	0.603, -0.628	0.442, -0.375	
hole $[e Å^{-3}]$			
Residuals R_{int} , R_1 , and wR_2 are standard indices computed by			
SHELXL	-		

ual considering that d > 0.9 Å. However, a sensible geometry is obtained for the cation, which is the residue of interest.

Complex **2** was much easier to refine, since all residues are ordered, including one lattice water molecule (O38). Nitrate ions, however, present high displacement parameters, which were refined through similarity restraints and forced to approximate an isotropic behavior. C- and N-bonded H atoms were treated as in **1**, and water H atoms were found in a difference map, and refined with free coordinates and restrained geometry. In both crystals, the absolute configuration was determined by refining a Flack parameter, x = -0.03(6) for **1** and x = 0.00(2) for **2**, which accounts for *S* chiral centers in the ligands (C6 in **1** and C9/C19 in **2**).

Full details about these models may be obtained from the archived CIF file, and diffraction data are available on request. CCDC-866651 (for 1) and -866652 (for 2) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

Magnetic Measurements: Magnetic measurements were carried out in the "Unitat de Mesures Magnètiques (Universitat de Barcelona)" on polycrystalline samples with a Quantum Design SQUID MPMS-XL magnetometer working in the 2.0–300 K range. The magnetic fields were 0.05 T (from 2.0 to 30 K) and 1.0 T (from 30 to 300 K) for compounds **1** and **2**. The diamagnetic corrections were evaluated from Pascal's constants. The fit was performed by minimizing the function *R* (agreement factor defined as):^[24]

 $\Sigma[(\chi_{\rm M} T)^{\rm exp} - (\chi_{\rm M} T)^{\rm calcd}]^2 \ / \ \Sigma[(\chi_{\rm M} T)^{\rm exp}]^2$

Potentiometric Studies: For all solution studies spectrophotometric grade solvents were mixed with bidistilled water.

Potentiometric titrations were performed in two different media: $MeOH/H_2O$ (1:1 v:v) and $MeCN/H_2O$ (1:1 v:v) using a Methrom

FULL PAPER

702 Titrino set including a digital pH meter coupled to a PC, fitted with a Methrom Ag|AgCl combined electrode that was calibrated differently in each media.

In the solvent mixtures a single point calibration was made using a succinate buffer in MeOH/H₂O (pH = 4.94)^[42] and a biphthalate buffer in MeCN/H₂O (pH = 5.37)^[43] followed by a HClO₄ titration in the solvent mixture where values of pH and *E* were collected for each titration point in order to obtain the parameter of cell efficiency *E*_f by means of the equation:^[44]

$$pH_{corr} = pH_{exp} + \left[\frac{pH_{cal} - pH_{exp}}{pH_{cal}}\right]E_{f}$$

where pH_{corr} is the corrected pH, pH_{exp} the experimental pH, pH_{cal} the pH value used for the calibration of the electrode and E_{f} the cell efficiency by which all data should be corrected. E_{f} was obtained by setting the pH vs. E slope to the Nernst slope (-59.16).

Each solvent mixture's autoionization constant was determined by performing the titration of standardized HClO₄ solutions with standardized NaOH and refining the corresponding pK_i with Hyperquad. pK_i for MeOH/H₂O was 14.28 and for MeCN/H₂O was 14.74.

In all the solution studies, standardized copper perchlorate and perchloric acid solutions were used. In each medium two systems of each ligand were titrated (three times each): $L + 4H^+$ (ligand fully protonated) and $L + 2Cu^{II} + 4H^+$ (ligand protonated in the presence of copper). The ionic strength was maintained at 0.1 M with NaClO₄. Titrations were performed the usual way: 25 mL of the studied solution was contained in a 75 mL jacketed glass cell thermostated at 25.00(±0.05) °C by a circulating constant-temperature water bath and purged with a purified nitrogen stream. Additions of a standardized ca. 0.1 M carbonate free NaOH water solution were performed and the pH was determined after each addition.

UV/Vis Spectrophotometric Studies: Titrations of the L + $2Cu^{II}$ + $4H^+$ system with a carbonate free NaOH water solution in H₂O, MeOH/H₂O, and MeCN/H₂O were followed simultaneously potentiometrically and spectrophotometrically. After each NaOH addition, absorption spectra were recorded with an Agilent 8453 spectrophotometer and pH values were measured with a Metrohm Ag/AgCl combined electrode that had been previously calibrated.

EPR Studies: X-band EPR spectra of systems Cu/L, 2:1 in H_2O and MeOH/ H_2O with different pH values ranging from 2.5 to 9 (adjusted with NaOH and/or HNO₃) were recorded with a Bruker ER200-SRC spectrometer with a cylindrical cavity at room temperature.

Electrochemical Studies: Cyclic voltammetric studies were performed on the Cu/L, 2:1 systems with an AUTOLAB PGSTAT 100 potentiostat/galvanostat in MeCN/H₂O at pH values of 3.8 and 7.5. The experiments were carried out under a nitrogen atmosphere in a conventional three-electrode cell composed of: a reference electrode Ag/AgCl_(s)/0.1 M KCl in the corresponding solvent mixture; a platinum wire as auxiliary electrode, and a glassy carbon disk as working electrode. Cyclic voltammograms were performed over a potential range of -1.0 to 1.2 V vs. Ag/AgCl at a sweep rate of 100 mV s^{-1} and were initiated from an open circuit potential ($E_{i=0}$). The 10^{-3} M complex solutions were prepared in situ. The buffer also played the role of the supporting electrolyte.

Catecholase Activity: The catecholase activity of the complexes was evaluated by the oxidation of 3,5-di-*tert*-butylcatechol (3,5-DTBC) in MeOH/H₂O and MeCN/H₂O. The increase of the absorption band at 400 nm from the formation of the 3,5-di-*tert*-butyl-*o*-

benzoquinone (3,5-DTBQ) over time ($\varepsilon_{MeOH/H2O} = 1640 \text{ M}^{-1} \text{ cm}^{-1}$ and $\varepsilon_{MeOH/H2O} = 1630 \text{ M}^{-1} \text{ cm}^{-1}$) was monitored spectrophotometrically with an Agilent 8453 diode-array spectrophotometer with a magnetically stirred and thermostatted quartz cell with a 1 cm path length at (25 ± 0.1) °C. The catalytic activity of the complexes was determined by the method of initial rates by obtaining the slope of the A vs. *t* plot over the first 15 to 120 s of the reaction.

Three sets of experiments were performed in each medium. In the first one, aimed to observe the effect of the catalyst concentration on the initial rate of the reaction, the concentration of catalyst was varied from 1×10^{-5} to 6×10^{-5} M at a constant pH and the concentration of 3,5-DTBC was 6×10^{-3} M in MeOH/H₂O and 2×10^{-3} M in MeCN/H₂O. This series of experiments was performed at pH = 7.0, 7.5, 8.0, 8.5, 9.0, and 9.5 fixed with HEPES (pH 7.0, 7.5, 8.0) and TRIS (pH 8.5, 9.0, 9.5) buffers (0.1 M).

In the second one, the pH was varied from 6.0 to 9.5 and its influence on the initial rate of the reaction was evaluated with and without a catalyst. The concentration of 3,5-DTBC used was 2×10^{-3} M in MeOH/H₂O and 2×10^{-2} M in MeCN/H₂O, when needed, the concentration of the catalyst used was 3×10^{-5} M in MeOH/H₂O and 3×10^{-4} M in MeCN/H₂O. The pH was fixed with buffers HEPES and TRIS as stated above and values under pH = 7.0 were fixed with MES buffer, all at a 0.1 M concentration.

In the last set of experiments the concentration of substrate was varied from 1×10^{-4} M to 2.5×10^{-3} M in MeOH/H₂O and from 6×10^{-4} M in MeCN/H₂O at a constant pH = 8.5 fixed with HEPES (0.15 M) and a 1×10^{-5} M in MeOH/H₂O and 2×10^{-5} M in MeCN/H₂O concentration of catalyst in order to observe the influence of the substrate concentration on the initial rate of the reaction. This last set of experiments was fitted to a Michaelis–Menten model and the parameters V_{max} , k_{cat} , and K_{M} were determined.

Supporting Information: $\chi_M T$ vs. T and χ_M vs. T curves for 2. ¹³C NMR spectroscopic data for ligands.

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- [1] G. Yagil, Tetrahedron 1967, 23, 2855.
- [2] C. R. Johnson, W. W. Henderson, R. E. Sheperd, *Inorg. Chem.* 1984, 23, 2754.
- [3] a) R. B. Martin, J. T. Edsall, J. Am. Chem. Soc. 1960, 82, 1107;
 b) J. E. Bauman Jr., J. C. Wang, Inorg. Chem. 1964, 3, 368.
- [4] J. S. Richardson, K. A. Thomes, B. H. Rubin, D. C. Richardson, Proc. Natl. Acad. Sci. USA 1975, 72, 1349.
- [5] a) C.-L. O'Young, J. C. Dewan, H. R. Lilienthal, S. J. Lippard, J. Am. Chem. Soc. **1978**, 100, 7291; b) P. K. Coughlin, J. C. Dewan, S. J. Lippard, E.-i. Watanabe, J. M. Lehn, J. Am. Chem. Soc. **1979**, 101, 265; c) P. K. Coughlin, S. J. Lippard, A. E. Martin, J. E. Bulkowski, J. Am. Chem. Soc. **1980**, 102, 7616; d) G. Kolks, C. R. Firhart, P. K. Coughlin, S. J. Lippard, Inorg. Chem. **1981**, 20, 2933; e) P. K. Coughlin, S. J. Lippard, Inorg. Chem. **1984**, 23, 1446.
- [6] a) Q. Yuan, K. Cai, Z.-P. Qi, Z.-S. Bai, Z. Su, W.-Y. Sun, J. Inorg. Biochem. 2009, 103, 1156; b) Z.-P. Qi, K. Cai, Q. Yuan, T. Okamura, Z.-S. Bai, W.-Y. Sun, N. Ueyama, Inorg. Chem. Commun. 2010, 13, 847.

Imidazolato Bridge Formation in Dicopper Complexes



- [7] a) A. Bencini, C. Benelli, D. Gatteschi, C. Zanchini, *Inorg. Chem.* **1986**, *25*, 398; b) C. Benelli, R. K. Bunting, D. Gatteschi, C. Zanchini, *Inorg. Chem.* **1984**, *23*, 3074; c) G. Kolks, S. J. Lippard, J. V. Waszczak, H. R. Lilienthal, *J. Am. Chem. Soc.* **1982**, *104*, 717; d) S. M. Morehouse, *Inorg. Chim. Acta* **1996**, *243*, 327.
- [8] a) R. Watanabe, N. Koyama, T. Nogami, T. Ishida, T. Kogane, *Chem. Lett.* **2009**, *38*, 30; b) N. Koyama, R. Watanabe, T. Ishida, T. Nogami, T. Kogane, *Polyhedron* **2009**, *28*, 2001.
- [9] a) G. Mendoza-Díaz, W. L. Driessen, J. Reedijk, Acta Crystallogr., Sect. C 1996, 52, 960; b) L. Gasque, V. M. Ugalde-Saldívar, I. Membrillo, J. Olguín, E. Mijangos, S. Bernes, I. González, J. Inorg. Biochem. 2008, 108, 1227; c) L. González-Sebastián, V. M. Ugalde-Saldívar, E. Mijangos, M. R. Mendoza-Quijano, L. Ortiz-Frade, L. Gasque, J. Inorg. Biochem. 2010, 104, 1112.
- [10] G. Mendoza-Díaz, W. L. Driessen, J. Reedijk, S. Gorter, L. Gasque, K. R. Thompson, *Inorg. Chim. Acta* 2002, 339, 51.
- [11] L. Gasque, unpublished results.
- [12] L. Gasque, E. Mijangos, S. Bernes, Acta Crystallogr., Sect. E 2005, 61, o284.
- [13] a) A. W. Addison, T. N. Rao, J. Reedijk, J. v. Rijn, G. C. Verschoor, J. Chem. Soc., Dalton Trans. 1984, 1349; b) E. L. Muetterties, I. J. Guggenberger, J. Am. Chem. Soc. 1974, 96, 1748.
- [14] I. J. Bruno, J. C. Cole, M. Kessler, J. Luo, W. D. S. Motherwell, L. H. Purkis, B. R. Smith, R. Taylor, R. I. Cooper, S. E. Harris, A. G. Orpen, J. Chem. Inf. Comput. Sci. 2004, 44, 2133.
- [15] B.-L. Lee, M. D. Kärkäs, E. V. Johnston, A. K. Inge, L.-H. Tran, Y. Xu, Ö. Hansson, X. Zou, B. Åkermark, *Eur. J. Inorg. Chem.* 2010, 5462.
- [16] S. Li, D. Li, D. Yang, Y. Li, J. Huang, K. Yu, W. Tang, Chem. Commun. 2003, 880.
- [17] T. Higa, M. Moriya, Y. Shimazaki, T. Yajima, F. Tani, S. Karasawa, M. Nakano, Y. Naruta, O. Yamauchi, *Inorg. Chim. Acta* 2007, 360, 3304.
- [18] J.-L. Lin, Y.-Q. Zheng, Z. Kristallogr. New Cryst. Struct. 2004, 219, 431.
- [19] a) A. L. Spek, J. Appl. Crystallogr. 2003, 36, 7; b) P. van der Sluis, A. L. Spek, Acta Crystallogr., Sect. A 1990, 46, 194.
- [20] C. F. Macrae, I. J. Bruno, J. A. Chisholm, P. R. Edgington, P. McCabe, E. Pidcock, L. Rodriguez-Monge, R. Taylor, J. van de Streek, P. A. Wood, J. Appl. Crystallogr. 2008, 41, 466.
- [21] F. H. Allen, Acta Crystallogr., Sect. B 2002, 58, 380.
- [22] P. Kopel, Z. Trávníček, J. Marek, M. Korabik, J. Mrozinski, Polyhedron 2003, 22, 411.
- [23] M. Lubben, R. Hage, A. Meetsma, K. Bÿma, B. L. Feringa, *Inorg. Chem.* 1995, 34, 2217.
- [24] O. Kahn, Molecular Magnetism, Wiley-VCH, New York, 1993.
- [25] G. Ivarson, B. K. S. Lundberg, N. Ingri, Acta Chem. Scand. 1972, 26, 3005.

- [26] M. G. B. Drew, M. McCann, S. M. Nelson, J. Chem. Soc., Dalton Trans. 1981, 1868.
- [27] K. Matsumoto, S. Ooi, Y. Nakao, W. Mori, A. Nakahara, J. Chem. Soc., Dalton Trans. 1981, 2045.
- [28] J. C. Dewan, S. J. Lippard, Inorg. Chem. 1980, 19, 2079.
- [29] N. Matsumoto, T. Akui, H. Murakami, J. Kanesaka, A. Ohyoshi, H. Ōkawa, J. Chem. Soc., Dalton Trans. 1988, 1021.
- [30] a) H. Arora, F. Lloret, R. Mukherjee, *Inorg. Chem.* 2009, 48, 1158; b) J. Cano, P. Alemany, S. Alvarez, M. Verdaguer, E. Ruiz, *Chem. Eur. J.* 1998, 4, 476.
- [31] P. Gans, A. Sabatini, A. Vacca, Talanta 1996, 43, 1739.
- [32] a) B. Verdejo, S. Blasco, E. García-España, F. Lloret, P. Gaviña, C. Soriano, S. Tatay, H. R. Jiménez, A. Domenech, J. Latorre, *Dalton Trans.* 2007, 4726; b) R. N. Patel, N. Singh, K. K. Shukla, V. L. N. Gundla, *Spectrochim. Acta Part A* 2005, 61, 1893.
- [33] a) H. Ohtsu, Y. Shimazaki, A. Odani, O. Yamauchi, W. Mori, S. Itoh, S. Fukuzumi, *J. Am. Chem. Soc.* 2000, *122*, 5733; b) G. Tabbi, W. L. Driessen, R. Reedijk, R. P. Bonomo, N. Veldman, A. L. Spek, *Inorg. Chem.* 1997, *36*, 1168.
- [34] M. R. Mendoza-Quijano, G. Ferrer-Sueta, M. Flores-Alamo, N. Aliaga-Alcalde, V. Gómez-Vidales, V. M. Ugalde-Saldívar, L. Gasque, *Dalton Trans.* 2012, DOI: 10.1039/C2DT12155G.
- [35] C. Gerderman, C. Eicken, B. Krebs, Acc. Chem. Res. 2002, 35, 183.
- [36] a) J. Kaizer, T. Csay, G. Speier, M. Giorgi, J. Mol. Catal. A 2010, 329, 71; b) A. Granata, E. Monzani, L. Casella, J. Biol. Inorg. Chem. 2004, 9, 903; c) C. Fernandes, A. Neves, A. J. Bortoluzzi, A. S. Mangrich, E. Rentschler, B. Szpoganicz, E. Schwingel, Inorg. Chim. Acta 2001, 320, 12; d) C. Belle, K. Selmeczi, S. Torelli, J.-L. Pierre, C. R. Chim. 2007, 10, 271.
- [37] S. V. Jovanovic, K. Konya, J. C. Scaiano, Can. J. Chem. 1995, 73, 1803.
- [38] A. M. Sosa, V. M. Ugalde-Saldívar, L. Gasque, I. González, J. Electroanal. Chem. 2005, 579, 103.
- [39] XSCAnS (rel. 2.21), User Manual, Siemens Analytical X-ray Instruments Inc., Madison, WI, USA, 1996.
- [40] A. C. T. North, D. C. Phillips, F. S. Mathews, Acta Crystallogr., Sect. A 1968, 24, 351.
- [41] G. M. Sheldrick, Acta Crystallogr., Sect. A 2008, 64, 112.
- [42] T. Mussini, A. K. Covington, P. Longhi, S. Rondinini, Pure Appl. Chem. 1985, 57, 865.
- [43] S. Rondinini, P. R. Mussini, T. Mussini, Pure Appl. Chem. 1987, 11, 1549.
- [44] J. M. Islas-Martínez, D. Rodríguez-Barrientos, A. Galano, E. Ángeles, L. A. Torres, F. Olvers, M. T. Ramírez-Silva, A. Rojas-Hernández, J. Phys. Chem. B 2009, 113, 11765.
- [45] I. Puigdomenech, MEDUSA (Making Equilibrium Diagrams Using Sophisticated Algorithms), http://www.kemi.kth.se/ medusa/

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Dicopper Complexes

The dicopper complexes of two dinucleating ligands undergo a strong antiferromagnetic coupling upon formation of an imidazolato bridge. UV/Vis and EPR spectroscopy as well as electrochemical studies confirmed the potentiometric solution speciation.



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pH-Dependent Imidazolato Bridge Formation in Dicopper Complexes: Magnetic, Electrochemical, and Catalytic Repercussions

Keywords: Copper / N ligands / Enzymes / Amino acids / Cyclic voltammetry / Antiferromagnetism