

NMR and Electronic Relaxation in Paramagnetic Dicopper(II) Compounds

Narasimha N. Murthy,^{†,‡} Kenneth D. Karlin,^{*,†} Ivano Bertini,^{*,§} and Claudio Luchinat[‡]

Contribution from the Department of Chemistry, Johns Hopkins University, Baltimore, Maryland 21218, Department of Chemistry, University of Florence, 50121 Florence, Italy, and Department of Soil Science & Plant Nutrition, University of Florence, 50144 Florence, Italy

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Abstract: ¹H-NMR spectral properties of two paramagnetic binuclear copper(II) complexes **1** and **2**, which are weakly antiferro- and ferromagnetically coupled, respectively, in the solid state, have been studied in solution; corresponding parameters are compared to a mononuclear copper(II) analogue **1a**. Compound **1** exhibits unusually sharp and hyperfine shifted ligand signals (+230 to −14 ppm) that are about 100 times sharper than corresponding signals that could be detected for **1a** (+20.4 to −13 ppm). Complex **2** also displays moderately sharp signals, shifted even to a greater magnitude (+272 to 0 ppm). These observations are in contrast with other moderately antiferromagnetically coupled binuclear copper(II) systems where much broader signals are observed in addition to reduced hyperfine chemical shifts. A complete assignment of signals for **1** and **2** was accomplished by a combination of proton relaxation data and two-dimensional correlated spectroscopy (COSY) measurements, while for **1a** only partial analysis could be performed because of broadness of its signals. An analysis of the relaxation data and a quantitative comparison among **1a**, **1**, and **2** show that the unusual spectral features observed for the weakly coupled binuclear copper(II) ($S = 1/2$) centers is caused by a two orders of magnitude decrease in the electron relaxation ($\tau_s = 10^{-11}$ s) as compared to $\tau_s = 10^{-9}$ s for the mononuclear copper(II) species, **1a**. Shortening of τ_s for homobinuclear compounds is not otherwise predicted, and possible mechanisms for the results are discussed. The present findings are significant with respect to the factors determining electronic relaxation in magnetically coupled systems and to the understanding of proton NMR when applicable to binuclear copper(II) metalloproteins.

Introduction

Proton nuclear magnetic resonance spectroscopic studies of paramagnetic compounds have become increasingly useful in applications such as probing metalloprotein active site structure and mechanism,¹ and in the development of contrast agents for magnetic resonance imaging (MRI).² Paramagnetism induces hyperfine shifts (δ) of NMR signals and shortening of nuclear longitudinal (T_1) and transverse (T_2) relaxation times. Both shifts and relaxation time shortening are a source of information, making high resolution NMR of paramagnetic compounds the subject of increasing research interest.³

A drawback in the investigation of paramagnetic compounds is that when nuclear relaxation is too fast, signal line widths

are large, resolution may become poor and, most important, coherence and magnetization transfer may be below detection. When the electronic relaxation time, τ_s , is short enough (e.g., 10^{-11} s), for instance low spin Fe(III), high-spin Co(II), lanthanides(III) and, in general, all electronic configurations possessing low-lying excited states, high resolution NMR nowadays can be performed with success^{1c–e} and the solution structures of paramagnetic proteins⁴ or insights into electronic structure of synthetic compounds can be obtained.³ However, for mononuclear copper(II) ($S = 1/2$) the ground state is well isolated from the excited states, not providing efficient electronic relaxations, generally leads to long τ_s values and broad ¹H-NMR resonances.⁵ Estimates of τ_s range from 10^{-8} – 10^{-9} for tetragonal copper(II) centers to 10^{-10} s for blue copper proteins.⁶

The situation is different when more than one paramagnetic center is present in the same molecule. When copper(II) is

[†] Johns Hopkins University.

[‡] Current address: Department of Chemistry, IIT Madras, Madras 600 036, India.

[§] University of Florence, Department of Chemistry.

[⊗] University of Florence, Department of Soil Science & Plant Nutrition.

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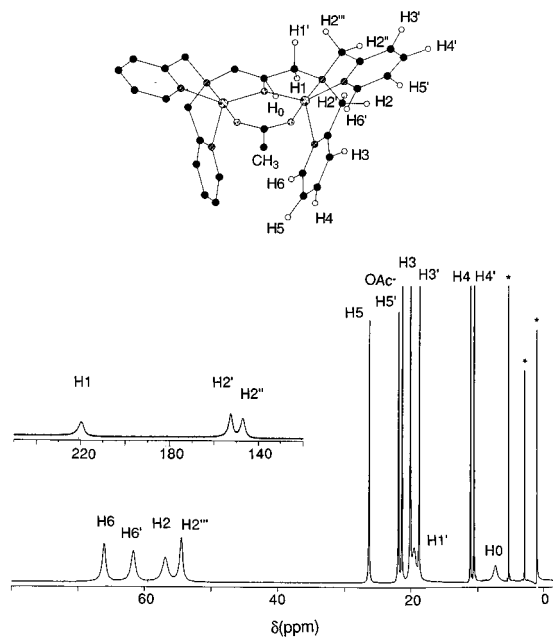


Figure 2. Chem3D representation of the crystal structure and ^1H NMR of **2** in CD_3NO_2 at 75°C at 300 MHz; an asterisk represents peaks due to solvent impurities.

copper(II) $S = 1/2$ centers is weakly antiferromagnetic ($J = -22.3\text{ cm}^{-1}$) for **1**, while weakly ferromagnetic ($J = +44.2\text{ cm}^{-1}$) for the other, **2**, resulting in $S = 0$ and 1 ground and excited states, or vice versa. Such weak magnetic interactions (with variable sign of J) are typical of carboxylate bridged binuclear copper(II) complexes.^{12,13} The solution magnetic moments of **1** and **2**, as determined by the Evans method, are $1.9 \pm 0.1\ \mu_{\text{B}}/\text{Cu}$ at 25°C for both complexes, consistent with weak magnetic interactions between the two copper(II) ions in solution, as well. The solution susceptibility measurements by this method do not confirm the sign of J except its being small, and experimental limitations preclude an accurate determination. We believe that the solid-state structures of **1** and **2** are preserved in solution, as supported by their ^1H -NMR data (vide infra). The mononuclear complex **1a**, in DMF, also shows a spin-only moment of $1.9 \pm 0.1\ \mu_{\text{B}}/\text{Cu}$, confirming the presence of a mononuclear Cu(II) ($S = 1/2$) species in the solution.

The Spectra and Paramagnetic Shift. Representative proton spectra of **1a**, **1**, and **2** are shown in Figures 1 and 2. The binuclear complex **1** exhibits unusually sharp and hyperfine shifted signals spanning from +230 to -14 ppm with most line widths less than ~ 100 Hz. Complex **2** also exhibits moderately sharp signals, shifted an even greater magnitude, +272 to 0 ppm. For **1a**, a spectrum quite similar to that observed for analogue **1** would be predicted, but fewer and broad signals (+20.4 to -13 ppm) are seen, typical of mononuclear copper(II). The spectral features of **1** are in striking contrast with observations for other moderately coupled binuclear copper(II) systems (e.g., $J = -100$ to -250 cm^{-1}), where broader signals with reduced hyperfine shifts are observed.^{9,15} The peak positions for **1** and **2** are essentially insensitive to a change of solvent (e.g., CH_3CN , CH_2Cl_2 , CH_3NO_2 , or DMF). In DMF, **1a** is mononuclear, but in the other solvents it displays quite different (sharper and less shifted) spectral features, ascribed to formation of a dimeric phenoxide-bridged species (with smaller magnetic moment $1.2\ \mu_{\text{B}}/\text{Cu}$), as has been previously observed.¹⁶

Spectra of **1** and **2** were monitored by variable-temperature measurements (-40 to 75°C , **1**; -22 to 75°C , **2**; Supporting

Information). Most of the signals, except those in the diamagnetic region, are temperature dependent, with the most up- or downfield signals being the most sensitive. Plots of observed chemical shifts (δ) vs reciprocal temperatures (T^{-1}) follow Curie-like behavior, i.e. their shifts decrease with an increase in temperature. The intercepts at infinite temperature for most of the signals are within or close to the diamagnetic region, consistent with the small value of J and shifts being predominantly contact in origin. The δ intercepts of some of the signals deviate appreciably from zero (Supporting Information). They are positive for signals H1' of **1** and H2 and H2''' of **2**, and negative for signals H1 of **1** and H1, H1', H2', and H2'' for **2**. Up- and downfield intercepts may indicate either occurrence of magnetic coupling or an appreciable pseudocontact contribution to the isotropic shifts. While it is well known that the magnetic anisotropy giving rise to the pseudocontact contribution is usually very small for Cu(II) systems,¹⁷ it may not be negligible for CH groups that are very close to Cu(II). However, all of these signals belong to methylene proton pairs, and three out of four methylenes show up- and downfield shifts within the same pair. This suggests that more plausible sources of deviation from Curie behavior may be temperature dependent conformational changes, affecting Cu-N-C-H dihedral angles within each pair, and thus contact shifts.

Interpretation of T_1 and T_2 Values and Signal Assignment.

Signal assignment for cases like **1**, **1a**, and **2** is a challenge because of the large hyperfine shifts caused by the paramagnetic Cu(II). However, unambiguous assignments for **1** and **2** were accomplished using a combination of measurements: proton longitudinal relaxation times (T_1) that correlate with proximity of H's to copper ion, line widths that correlate with through-bond electron delocalization, and two-dimensional correlation spectroscopy (COSY) that provides spin patterns. The results of these measurements, using protocols developed for paramagnetic metal centers^{1c} and recently applied to other binuclear copper(II) systems,^{13b} are collected in Table 1. Several conclusions can be drawn upon inspection of these data. The majority of the protons that are close to copper have very short T_1 s, in the narrow range 1–2 ms with broader line widths (shorter T_2 values), while those in the periphery have longer T_1 s (27–84 ms) and narrower line widths. This is expected because the protons closer to the copper center(s) experience stronger paramagnetic effect and hence shorter T_1 s and larger shifts. Another observation is that there is a good correlation between the solution-determined Cu-H distances, using relative T_1 values, and the range found in the crystal structure (Table 1). In fact, based on these data signal assignment of protons that are closer to copper was possible, as they are not accessible to other 2D techniques because of their very short relaxation times.

The spectrum of **1**, in solution, is quite simple (Figure 1), indicating an highly symmetric environment, making all pyridylethyl ligand arms equivalent. The proton pair on each methylene is diastereotopic, thus all hydrogens are inequivalent. The pair on the methylene bound to the arylamine nitrogen (H1 and H1') are closest to copper (3.0 and 3.8 Å) and are assigned to the most downfield shifted signals, δ 229.4 and 84.5, respectively. The proton, ortho to pyridine nitrogen, (H6) is also close to the copper ion (3.1 Å), and is assigned to the next most downfield signal. For the rest of the signals, a conclusive assignment was not possible solely based on the relative T_1 , line widths, and Cu-H proximity data. However, a complete assignment was accomplished in combination with two-

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Table 1. Peak Positions, T_1 and T_2 values, Proximity of H's to Cu, and Assignments for **1a**, **1**, and **2** at 25 °C

1a^a						1						2					
signal (δ)	T_1 (ms)	T_2^b (ms)	$R_{\text{Cu-H}}(\text{\AA})$			signal (δ)	T_1 (ms)	T_2^b (ms)	$R_{\text{Cu-H}}(\text{\AA})$			signal (δ)	T_1 (ms)	T_2^b (ms)	$R_{\text{Cu-H}}(\text{\AA})$		
			X-ray	soln ^c	assign				X-ray	soln ^c	assign				X-ray	soln ^c	assign
						229.4	0.9	0.8	3.0	3.2	H1	271.9	1.0	0.22	3.3	3.1	H1
						84.5	2.8	1.0	3.8	3.5	H1'	196.9	1.7	0.26	3.2	3.4	H2', 2''
						61.6	2.8	1.9	3.1	3.5	H6	73.5	2.2	1.2	3.3	3.5	H6
						41.1	83.7*	11.7	6.1*		H _p	68.6	2.3	1.3	3.3	3.6	H6'
						25.1	17.3	9.6	4.7		OAc ⁻	65.0	2.7	1.3	3.8	3.7	H2
20.5	<i>d</i>	0.07	5.2		H3	24.1	36.0	12.2	5.1	5.3	H3	60.9	2.0	0.7	3.8	3.5	H2'''
18.7		0.09	6.0		H5	22.8	41.0	14.5	5.1	5.4	H5	28.2	19	10.6	5.0	5.1	H5
14.4	15*	0.6	6.1*		H _{m,p}	16.3	93.7	17.6	5.8	6.2	H4	26.1	18	7.0	4.9	5.1	H5'
8.9	6	0.5	4.5	5.2	H _{o,m'}	13.4	26.7	12.0	4.8	5.1	H _m	23.3	13	6.3	4.7	4.8	OAc ⁻
-9.4		0.03	3.1		H2	-9.0	3.9	3.0	3.1	3.7	H2	23.0	20	9.0	5.3	5.2	H3
-13.1		0.04	4.1		H2'	-14.0	11.5	6.9	4.2	4.4	H2'	22.8	<i>d</i>	~1	3.8	<i>d</i>	H1'
												21.8	23	10.6	5.1	5.3	H3'
												11.4	45*	13.2	5.9*		H4
												10.8	49	10.6	5.9	6.0	H4'
												7.8	<1.0	1.1	3.0	<3.0	H ₀

^a Assignment is partial, peak positions due to DMF (dimethylformamide) are not shown. ^b $T_2 = 1/\pi(\text{fwh})$, fwh is full width at half-height. ^c In solution, calculated $R_{\text{Cu-H}} = R_{\text{ref}}(T_1/T_{\text{ref}})^{1/6}$, where R_{ref} and T_{ref} are reference (*) values. ^d Not measured because of broadness or overlap.

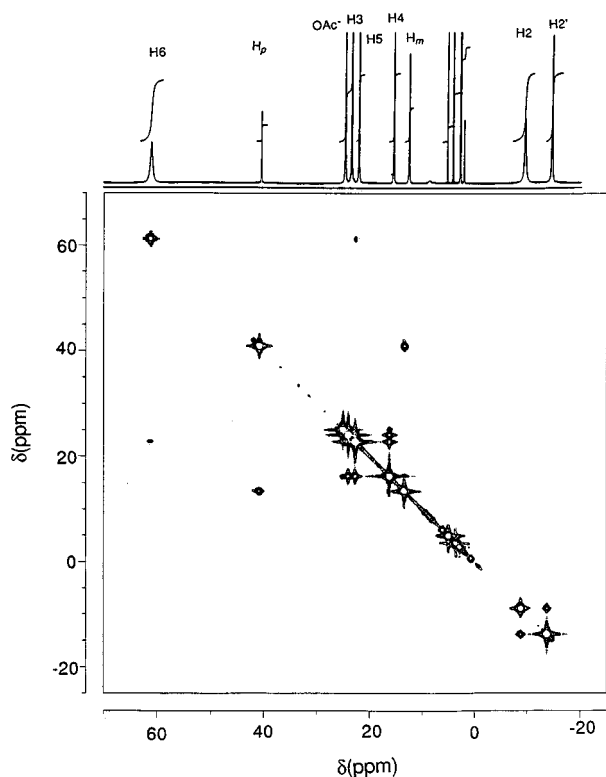


Figure 3. Representative COSY spectrum of **1** (in $\text{CD}_3\text{NO}_2/\text{CDCl}_3$ (5:1) at 300 MHz), showing correlation among the pyridine and the phenyl protons.

dimensional COSY; a representative spectrum for **1** is shown in Figure 3. Clear proton cross-signals are observed within the pyridine and the phenyl, which enabled us to determine their connectivity. The signal at δ , 25.1, which has intensity 3, was assigned to acetate, CH_3CO_2^- . It showed no correlation with any other peak, as expected; in **2**, it appears around the same region, substantiating its assignment. The *para* proton of the phenyl ring (H_p), although farther from the copper, is quite downfield shifted, due to large spin delocalization through a π -bonding effect. The two upfield shifted signals at δ -9.0 and -14.0 are due to methylene protons bound to the pyridine ring. They display COSY cross peaks. It is not uncommon for a methylene pair bound to a pyridine ring to have a chemical shift similar in magnitude but opposite in sign to the aromatic proton bound in the same position.¹⁸

In **2**, unlike **1**, there are two different kinds of pyridines and methylene groups bound to them, plus the methylene on the hydroxypropane backbone (Figure 2). The proton pairs on all methylene groups are diastereotopic and inequivalent to one another. All together, along with a methine and acetate, 16 signals are anticipated, which are indeed observed either below or above room temperature. The proton pairs on methylenes are assigned based on T_1 values, line widths, and Cu-H distance-dependent arguments already described for **1**. The signals at δ 271.9 and δ 20.0 are due to the proton pair on the hydroxypropane backbone (H-1, H-1'), while those at δ 196.9, 65.0, and 60.9 are assigned to H-2', H-2'' and H-2, H-2''', respectively, on the methylenes bound to pyridines. They showed no cross peaks in the COSY, probably due to their relatively large line widths; however, by selective deuteration (of all methylene protons), the corresponding signals in the ^1H -spectrum disappeared or showed diminished intensity, confirming their assignments. The single methine resonance at δ 7.8 is assigned based on its line width and relative intensity. The signal at δ 23.3 is assigned to CH_3CO_2^- (OAc^-), which disappears upon substitution with CD_3CO_2^- . It showed no cross peak in the COSY (not shown), as expected. The order of pyridine ring proton connectivities is assigned by COSY, as described similarly for **1**.

Signal assignment for **1a** is only partial, since many possible resonances do not appear and most of the observed signals are still too broad, and precluded a similar analysis. Signals H-3, H-5, H-2, and H-2' can be assigned with confidence since they arise from the pyridine ring protons whose hyperfine coupling constants (and hence hyperfine shifts) are not expected to change on passing from mononuclear to its binuclear copper(II) analogue, **1**.

Discussion

The present binuclear copper(II) complexes show relatively sharp NMR line widths which are two orders of magnitude sharper than the mononuclear analog and about one order of magnitude sharper than other moderately antiferromagnetically coupled binuclear copper(II) complexes previously reported.⁹ We can immediately discard the possibility that the signals are narrower because of strong antiferromagnetic coupling ($J \geq kT$) which causes the paramagnetism to be strongly reduced due to depopulation of the excited $S = 1$ state (and hence long proton

relaxation times). Hyperfine shifts under these conditions are also strongly reduced. On the other hand, the magnetic coupling in the present complexes is so weakly antiferromagnetic in one case, and weakly ferromagnetic in the other case, that at room temperature the three $S = 1$ plus one $S = 0$ states must be almost equally populated. Consistently, the hyperfine shifts are very large (as large as expected for mononuclear analogue **1a**) and display an essentially normal Curie temperature dependence (Supporting Information). *Therefore, the line sharpening must be due to a decrease in the electronic relaxation time, τ_s .* Shorter τ_s values for copper(II) have been predicted, and observed, in heterobinuclear compounds where copper(II) is coupled to a fast relaxing metal ion (see Introduction). However, shortening of τ_s is not predicted in homobinuclear compounds. In the case of the fully copper-substituted copper–zinc SOD there is magnetic coupling between the two copper(II) ions, and a thorough NMR investigation has shown that the electronic relaxation time in the binuclear species is equal to that of the native copper–zinc molecule.⁷ Experimental data and analyses on binuclear coordination compounds up to now have not addressed the problem of alterations of τ_s upon coupling. In order to investigate this possibility, a quantitative analysis of τ_s in the present complexes has been carried out.

The equations for nuclear (proton) longitudinal and transverse relaxation rate enhancements due to dipolar and contact coupling to a paramagnetic center in the absence of chemical exchange are available:¹⁹

$$T_{1M}^{-1} = K_{\text{dip}} \left(\frac{7\tau_{c2}}{1 + \omega_s^2 \tau_{c2}^2} + \frac{3\tau_{c1}}{1 + \omega_1^2 \tau_{c1}^2} \right) \quad (1)$$

$$T_{2M}^{-1} = \frac{1}{2} K_{\text{dip}} \left(4\tau_{c1} + \frac{13\tau_{c2}}{1 + \omega_s^2 \tau_{c2}^2} + \frac{3\tau_{c1}}{1 + \omega_1^2 \tau_{c1}^2} \right) \quad (2)$$

$$T_{1M}^{-1} = K_{\text{con}} \frac{\tau_{s2}}{1 + \omega_s^2 \tau_{s2}^2} \quad (3)$$

$$T_{2M}^{-1} = \frac{1}{2} K_{\text{con}} \left(\frac{\tau_{s2}}{1 + \omega_s^2 \tau_{s2}^2} + \tau_{s1} \right) \quad (4)$$

where

$$K_{\text{dip}} = \frac{2}{15} \left(\frac{\mu_0}{4\pi} \right)^2 \frac{\gamma_1^2 g_e^2 \mu_B^2 S(S+1)}{r^6}$$

and

$$K_{\text{con}} = \frac{2}{3} \left(\frac{A}{\hbar} \right)^2 S(S+1)$$

The nuclear relaxation rate enhancements depend, besides on several constants, on metal ion electronic configuration (S), hyperfine coupling constant (A), and the nucleus–electron reorientational correlation times $\tau_{c1,2}$ and $\tau_{s1,2}$. The latter are the electron longitudinal (τ_{s1}) and transverse (τ_{s2}) relaxation times, and the former are given by:

$$\tau_{c1}^{-1} = \tau_{s1}^{-1} + \tau_r^{-1} \quad (5)$$

$$\tau_{c2}^{-1} = \tau_{s2}^{-1} + \tau_r^{-1} \quad (6)$$

where τ_r is the molecular reorientational time. In most cases,

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the differentiation between τ_{s1} and τ_{s2} is unnecessary, and therefore reference is made only to τ_c or τ_s unless otherwise specified. For mononuclear copper complexes τ_s is typically around $1-5 \times 10^{-9}$ s,^{20,21} while τ_r is one to two orders of magnitude shorter for aqueous solutions.²¹ Therefore, the correlation time for dipolar relaxation is essentially τ_r , whereas contact relaxation depends only on τ_s . As the rotational correlation time for the binuclear copper(II) complexes must be similar to that of the mononuclear tetragonal copper(II) species (or even slightly larger), the striking difference in proton relaxation must be indeed due to a decrease in τ_s . This is particularly true for nuclear transverse relaxation times, where the contact contribution is the dominant contribution, as can be seen by comparing eqs 2 and 4. The decrease in τ_s is due to magnetic coupling in **1** and **2**.

NMR line widths of **1** and **2** can be thus directly analyzed in terms of τ_s , using equations analogous to eqs 2 and 4, except for the incorporation of a multiplication coefficient which depends on the Boltzmann population of the electronic energy levels in the coupled binuclear copper(II) systems.²¹⁻²³ In the present case where $|J| \ll kT$, the coefficient is $1/2$.²¹⁻²³ As a result, it is theoretically predicted that the nuclear relaxation rate enhancements are all decreased by a factor of 2 in the presence of magnetic coupling between the two metal ions, independent of the relaxation mechanism.²⁴ Consistent with this conclusion, it may be appropriate to mention that the hyperfine coupling measured in EPR spectroscopy for homobinuclear copper(II) centers is just $1/2$ that of mononuclear centers.

Assuming that dipolar contributions are negligible, the hundred times sharpening of line widths in binuclear complex **1** with respect to mononuclear analogue **1a** can be quantitatively related to a decrease in τ_s by a factor of 50, due to the $1/2$ effect. If dipolar contributions are not completely negligible, their relative contribution to the line widths of **1** would be larger than those of **1a**, because the total line width is different and the dipolar contributions are similar. Therefore, the decrease in τ_s by a factor of 50 is actually a lower limit. For a typical starting τ_s value for mononuclear copper of about 3×10^{-9} s, this means that τ_s in the binuclear copper(II) complex would be around 6×10^{-11} s, or shorter.

A more precise value of τ_s can be calculated by making use of the T_1 data for both complexes **1** and **1a**. In both cases T_1 values are mainly due to dipolar relaxation mechanisms, as witnessed by the substantial agreement between the crystallographic distances and those calculated on the basis of a $1/r^6$ dependence (Table 1). Therefore, an estimate of the correlation time τ_c can be made (from the equations) in both cases. For mononuclear **1a**, a τ_c of around 4×10^{-11} s is obtained. This value coincides only with τ_r , while τ_s for the mononuclear species is two orders of magnitude longer. As far as the binuclear species is concerned, if τ_c were dominated by τ_r , a value of 4×10^{-11} s, or even slightly longer (the binuclear species is slightly heavier), is anticipated. Instead, a sizably shorter value of around 1×10^{-11} s is found. Thus, this is a clear indication that τ_s has decreased so much as to become dominant in τ_c for the binuclear complex. From eq 5, a τ_s value of 1.5×10^{-11} s for complex **1** is obtained. In conclusion, our

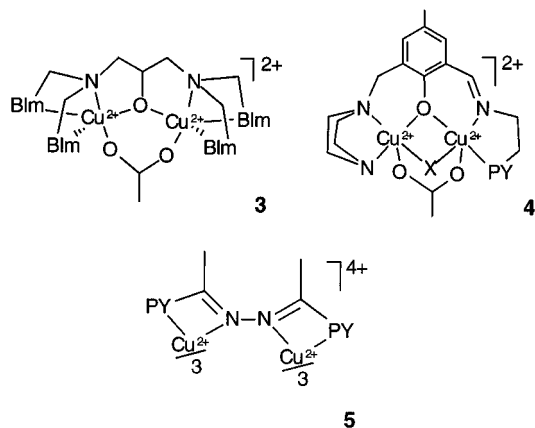
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Chart 2



estimate for the decrease of τ_s in this binuclear complex is of a factor of about 200. As far as complex **2** is concerned, on the average, τ_c is twice that of **1**. With the same τ_r value of 4×10^{-11} s for both complexes, τ_s goes to $\sim 3 \times 10^{-11}$ s.

This is the first documented case of a decrease in τ_s by almost two orders of magnitude, in a magnetically coupled binuclear copper(II) system, leading to significantly sharpened hyperfine shifted ^1H NMR signals. At variance with copper(II) being magnetically coupled with a metal ion whose electron(s) relax fast, where the electron of copper can take advantage of the electronic relaxation mechanisms of the other ion, in homobinuclear centers, to a first approximation, no significant increase in electron relaxation rate is expected upon establishment of magnetic coupling. For binuclear Cu(II), in the scheme of two energy levels characterized by $S = 0$ and 1, the transition probability among the various M_s levels can be calculated, and electronic T_1 and T_2 in the new environment predicted, under the assumption that the relaxation mechanisms are only those already available for each isolated metal. This approach follows that available in the literature by Ernst²⁵ for two scalar coupled nuclear spins of $I = 1/2$. The resulting $\tau_{s1,2}$ values, in the case where two metal ions are equivalent (like in the present case), are

$$\tau_{s1}(\text{binuclear}) = \tau_{s1}(\text{mononuclear}) \quad (7)$$

$$\tau_{s2}(\text{binuclear}) = \frac{2}{3}\tau_{s2}(\text{mononuclear}) \quad (8)$$

This result is independent of the sign of J as long as $|J| \ll kT$ because only the transitions among M_s levels of the paramagnetic $S = 1$ and 0 manifolds are considered, their energy order (positive or negative) being irrelevant. It is apparent that neither the $1/2$ coefficient nor the $2/3$ coefficient in τ_{s2} are able to account for the large decrease in $\tau_{s1,2}$. Therefore, the shortening of $\tau_{s1,2}$ must be due to additional mechanisms, specifically operative in the present binuclear copper(II) species, which make the $2/3$ correction irrelevant. It is therefore important to understand, at least qualitatively, the origin of the phenomenon, and a comparison of the ^1H NMR behavior of **1**, **2** among other complexes reported in the literature^{8,9,12,13,15} may help to delineate possible reasons.

Comparison of spectral data within **1** and **2**, and other weakly coupled binuclear copper(II) complexes^{12,13} (Chart 2) indicates that the sign of J is unimportant in determining factors responsible for narrow line widths. Complexes **3**, benzimidazole (Blm) analogues of **2**, with either Me^{13a} or H^{13b} substituted on the nonligated nitrogen atom, are weakly ferromagnetically

coupled ($J \sim +6 \text{ cm}^{-1}$), and have line widths comparable to **2** (but roughly twice that observed for **1**), vide supra. Similarly for **4** ($X = \mu\text{-}1,1\text{-OAc}^-$), which is weakly antiferromagnetic ($J \sim -8 \text{ cm}^{-1}$),¹² the line widths can also be estimated to be in the range seen for **2** and **3**. Likewise, the absolute magnitude of J also does not necessarily correlate with a shortening of τ_s . A relatively small J value of 26 cm^{-1} has been reported for dicopper superoxide dismutase,⁷ and a very small value of J ($< 1 \text{ cm}^{-1}$) for **5**:⁸ in both cases, nuclear relaxation is not appreciably decreased by exchange coupling with respect to the mononuclear analogues.

A possible hint to rationalization of the observed decrease in line widths and short τ_s for weakly coupled binuclear copper(II) systems comes from the observation that in the range of relatively high magnetic fields used, the electronic relaxation time is related to the lifetime of the energy levels of the coupled system. In magnetically coupled dicopper systems, fluctuations in geometry around Cu and/or the ligand-Cu framework can modulate the zero-field splitting (ZFS) of the $S = 1$ level. Among other sources ZFS is caused by dipolar coupling between the two copper centers. Relatively short distances between the copper ions and flexibility of the complex are expected to favor efficient modulation. Among complexes **1**, **2**, and **3** having a narrow range of intercopper distances 3.4–3.6 Å, complex **1** is likely to be more flexible (with most of its chelate rings around Cu being six-membered, as opposed to five-membered rings in **2** and **3**; such differences in ring size for binuclear copper(II) complexes have dramatic effects on properties, for instance Cu(II)/Cu(I) redox potentials),²⁶ while **5**, described by some of us with Drago,⁸ is probably the most rigid and exhibits broader signals. Complex **4**, with a short Cu...Cu distance (3.0 Å),¹² expected to modulate appreciable τ_s shortening, gives sharper resonances.²⁷ Indeed, this explanation may be applicable to the 2,6-dialkylphenolate systems, which often support short Cu...Cu distances.^{9c,12} On the other hand, when the distance is too long, as in superoxide dismutase (6 Å), the modulation of ZFS may be too small to allow any efficient τ_s shortening,²⁸ independent of the flexibility of the molecule.

Conclusion

In this article, we have shown that weakly coupled binuclear copper(II) centers may display sharp ligand ^1H -NMR signals due to rapid electron relaxations (shorter τ_s). Application of relevant theory and discussion of possible implications and mechanisms of enhanced relaxation have been presented here and discussed for the first time. Among other factors, the proximity of the two metal ions, flexibility around them due to ligand structure, and electronic delocalization are suggested to be responsible for this observation. The modulation of ZFS of the $S = 1$ state in the coupled systems is considered a likely source of electron relaxation. Modulation can be due to molecular rotation or to internal mobility. As the correlation time is shorter than τ_r , its origin cannot be due to molecular rotation. However, it could occur through internal mobility (i.e., fluctuations or rapid rearrangements of copper-ligands or copper-ligands-copper core). Ferro- or antiferromagnetic couplings could provide similar effects. Such zero-field splitting

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(27) A somewhat different explanation for τ_s shortening, especially in **1**, is provided by a referee. Here, electron delocalization onto a bridging atom of the alkylaminophenol ligand (i.e., formal oxidation of the phenolate oxygen with reduction of one copper(II) ion) may play a role, since this reduces the distance between spins.

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modulation in binuclear copper(II) metalloproteins could as well occur through internal motions, an exciting prospect and possible fruitful area for future research. Indeed, copper(II) substituted aminopeptidase binuclear metalloproteins have very recently been shown to exhibit very sharp and hyperfine shifted proton spectra.¹⁴ The present results (according to a reviewer) may be relevant also for the oxidized Cu_A fragment of cytochrome *c* oxidase which contains two copper ions with total $S = 1/2$ and show sharp NMR signals.³⁰

Experimental Section

Synthesis. The binuclear copper(II) compound [Cu₂(PD-O⁻)(OAc⁻)](ClO₄)₂ (**1**) was synthesized following the procedure reported by us.¹⁰ [Cu₂(P1-O⁻)(OAc⁻)](ClO₄)₂ (**2**) was obtained by direct addition of the solution of Cu(ClO₄)₂·6H₂O (0.34 g, 0.92 mmol) in EtOH (5.0 mL) to the predissolved ligand P1-OH, 1,3-bis[bis(2-pyridylmethyl)amino]hydroxypropane (0.25 g, 0.5 mmol), AcOH (31.0 mg, 0.5 mmol), and NEt₃ (104 mg, 1 mmol) in EtOH (15 mL). A blue precipitate that crashed out was washed with excess EtOH to obtain a microcrystalline product (0.34 g, 92%). Recrystallization from acetonitrile gave bright-blue crystals, Cu₂(P1-O⁻)(OAc⁻)](ClO₄)₂·CH₃CN, suitable for X-ray diffraction. Anal. Calcd for Cu₂(P1-O⁻)(OAc⁻)](ClO₄)₂·C₂₉H₃₂N₆Cl₂Cu₂O₁₁: C, 41.54; H, 3.85; N, 10.02. Found: C, 41.51; H, 3.79; N, 10.07. IR (mull): 1080 cm⁻¹, ν(ClO₄⁻). UV-vis [λ_{\max} ($\epsilon = \text{mol}^{-1}, \text{cm}^{-1}$) CH₃CN]: 902 (1102), 703 (sh, 660), 290 (4897). Magnetic moment (Evans, CD₃NO₂): 1.88 $\mu\text{B}/\text{Cu}$ at room temperature. Magnetic susceptibility (solid, -J): 44.2 cm⁻¹. Synthesis of [Cu₂(P1-O)(CD₃CO₂⁻)](ClO₄)₂ was achieved similarly, using instead deuterated acetic acid. Complex **2**, deuterated selectively at the methylene positions of the ligand P1-OH, was prepared similarly using the ligand treated by refluxing in glacial acetic acid-*d*₃ for 2 days. The synthesis and characterization of mononuclear complex [Cu(AP-O⁻)(DMF)](ClO₄)⁻ is described elsewhere.¹¹

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NMR. The 1D and 2D proton experiments were performed on Bruker AMX 300 and Varian UNITY 400- or 500-MHz spectrometers. 1D proton spectra were typically obtained by using a 100 kHz spectral width and 0.1-s delays between a 90° pulse of 7.2 or 4.2 μs , respectively. All the chemical shifts were referenced to internal nitromethane and/or TMS which in turn was calibrated against external nitromethane. The shift values reported are measured at room temperature, except when specified; those positive to TMS are downfield and those negative are upfield shifted. Longitudinal relaxation times (T_1) were measured by the inversion-recovery method. Test T_1 values were chosen to range from much less than the fastest relaxing peak to much longer than the slowest one. Magnetization recovery was exponential within experimental error. From the fitting of these curves, T_1 values were obtained within an estimated error of ± 0.1 ms. T_2 values were estimated from the peak half-widths. The inter copper–proton distances were determined from the crystal structure measurements. COSY spectra were obtained at room temperature by collecting 1024 $F_2 \times 512 F_1$ data points, with a repetition time of 0.1 s; typically for a 10–20 mM sample, collection time was about 12 h. A zero-degree-shifted sine bell combined with a Gaussian function was applied in both dimensions and zero filled to 1024 in the F_1 dimension prior to Fourier transformation and symmetrization.

Magnetic Susceptibility. Susceptibilities for solids **1** and **2** were obtained by SQUID measurements on powdered polycrystalline samples in the temperature range 4–305 K.¹¹ Solution magnetic moment measurements were obtained using the Evans method.²⁹

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Supporting Information Available: Variable-temperature ¹H-NMR spectra and plots of chemical shifts (δ) vs $1/T$ (K⁻¹) for **1** and **2**, Figures 4–7 (4 pages). See any current masthead page for ordering and Internet access instructions.

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