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Trinuclear, Antiferromagnetically Coupled Cu^{II} Complex with an EPR Spectrum of Mononuclear Cu^{II}: Effect of Alcoholic Solvents

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A rigid trinuclear copper pyrazolato framework supports the solvolytic exchange of μ_3-X by μ_3-OR ligands (X = Cl and Br; R = alkyl group), converting the trinuclear ferromagnetically coupled $S = {}^3/_2$ system to antiferromagnetically coupled $S = {}^1/_2$ in the solid state. In contrast, we propose that, in alcoholic solutions, solvolysis results in unsymmetrical coordination of the Cu_3 cluster, magnetically decoupling one Cu center from the other two. This disguises the intact triangular Cu$^{II}{}_3$ system as a mononuclear Cu^{II} complex in its electron paramagnetic resonance spectrum.

Trinuclear Cu complexes have attracted recent attention because of their relationship to the active centers of laccase, ceruloplasmin, ascorbate oxidase, and particulate methane monooxygenase (pMMO).[1] The present work was inspired by the controversy surrounding the nature of the active site of pMMO. The Cu centers of pMMO have been proposed to be organized into a trinuclear catalytic or electron-transfer cluster, according to one interpretation of magnetic susceptibility data and electron paramagnetic resonance (EPR) spectra of fully oxidized enzyme obtained from three different pMMO-containing bacteria.[2−4] However, a second interpretation of EPR spectra from similarly isolated pMMO samples supports a mononuclear active center.[5] More recently, crystallography of a membrane preparation of pMMO at 2.8-Å resolution has identified only one mononuclear and one distant, possibly dinuclear, metal site per enzyme unit.[6] However, the crystalline sample was found to be catalytically inactive, possibly because of Cu depletion.

We have previously shown that the pH-dependent exchange of μ_3-E ligands on a trinuclear copper(II) pyrazolato framework [E = O(H), Cl, Br] is accompanied by an orderly transition from strong to weak antiferromagnetic coupling and finally to ferromagnetic exchange among the three Cu centers.[7,8] The halogen-biscapped ferromagnetic complexes $[Cu_3(\mu_3\text{-}X)_2(\mu\text{-}pz^*)_3X_3]^{2-}$ (X = Cl, Br; pz* = pyrazolato, or 4-substituted pyrazolato anion), in particular, have focused our attention on the similarities between the trinuclear copper pyrazolate complexes and the physical properties of pMMO. We report here solution EPR and electrospray ionization mass spectrometry (ESI-MS) studies of halogen-biscapped $[Bu_4N]_2[Cu_3(\mu_3\text{-}X)_2(\mu\text{-}4\text{-}O_2N\text{-}pz)_3X_3]$ [X = Cl (**1**) and Br (**2**)] along with the isolation and crystallographic characterization of their solvolytic/hydrolytic alkoxo/hydroxo-monocapped products: $[Bu_4N][Cu_3(\mu_3\text{-}OMe)(\mu\text{-}4\text{-}O_2N\text{-}pz)_3Cl_3]$ (**3**), $[Bu_4N][Cu_3(\mu_3\text{-}OH)(\mu\text{-}4\text{-}O_2N\text{-}pz)_3Cl_3(ROH)]$ where R = Me (**4a**) and Et (**5**), and $[Bu_4N][Cu_3(\mu_3\text{-}OH)(\mu\text{-}4\text{-}O_2N\text{-}pz)_3Cl_3]$ (**6**), as well as the crystal structure of the PPN salt analogue of **4a**, **4b**.

Scheme 1 summarizes the transformations of the trinuclear Cu complexes described here, as established by a sequence of crystallographically characterized species. The (μ_3-X)-biscapped complexes **1** and **2** can be recrystallized from ^{n}PrOH/CH_3CN (9:1).[9] Recrystallization of **2** is also possible from either MeOH or 95% EtOH. In contrast, **1** is hydrolyzed in 95% EtOH, forming **5**, while in MeOH, it is solvolyzed/hydrolyzed, first to yield **3**. Upon removal from the mother liquor and exposure to atmospheric humidity, **3** is hydrolyzed to **4a**, and eventually all three complexes, **3**, **4a**, and **5**, decompose to **6**. X-ray crystallography of **3**, **4a**, **4b**, and **5** was carried out on single crystals sealed in quartz capillary tubes under their respective mother liquor.

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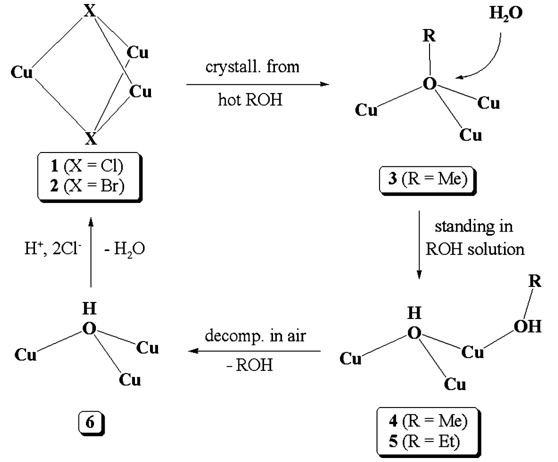
10.1021/ic061186r CCC: $33.50

Scheme 1



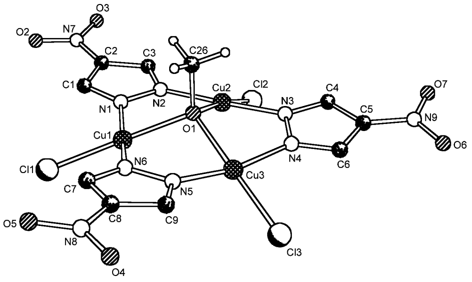


Figure 1. (a) Structure of the $[Cu_3(\mu_3\text{-}OMe)(\mu\text{-}4\text{-}O_2N\text{-}pz)_3Cl_3]^-$ anion of **3**. Selected bond lengths (Å) and angles (deg): Cu−Cu, 3.287(2)−3.352(2); Cu−O, 2.024(4)−2.074(5); Cu−N, 1.942(6)−1.957(7); Cu−Cl, 2.241(3)−2.310(2); Cu−O−Cu, 105.3(2)−110.3(2).

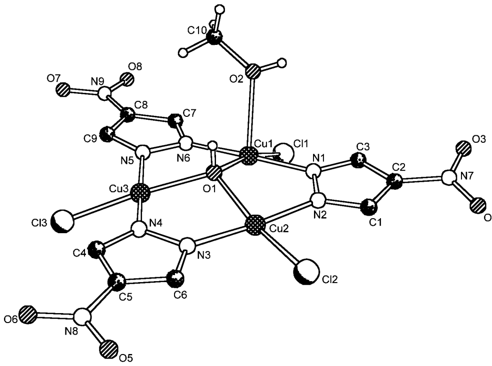


Figure 2. Structure of the $[Cu_3(\mu_3\text{-}OH)(\mu\text{-}4\text{-}O_2N\text{-}pz)_3Cl_3(MeOH)]^-$ anion of **4b**. Selected bond lengths (Å) and angles (deg): Cu−Cu, 3.3629(6)−3.3833(6); Cu−O, 2.013(2)−2.028(2); Cu−N, 1.942(3)−1.961(3); Cu−Cl, 2.237(1)−2.3104(9); Cu−O−Cu, 112.7(1)−113.5(1); O2−Cu1−O1, 88.6(1); O2−Cu1−Cl1, 102.64(8); O2−Cu1−N1, 92.2(1); O2−Cu1−N6, 89.1(1); O1−Cu1−Cl1, 168.77(7); N1−Cu1−N6, 177.3(1).

Negative-mode ESI-MS spectra (see the Supporting Information) of **1** and **2** in CH_2Cl_2 show the presence of only the corresponding $\{[Bu_4N][Cu_3(\mu_3\text{-}X)_2(\mu\text{-}4\text{-}O_2N\text{-}pz)X_3]\}^-$ ions at $m/z = 945.7$ (X = Cl) and 1167.4 (X = Br). The ^1H NMR spectrum of **1**/CD_3CN (insufficient solubility in CD_2Cl_2) also shows the presence of a single species (s, 50.75 ppm) in solution. In contrast, the ESI-MS spectrum of a MeOH solution of **1** (and **2**) shows peaks at $m/z = 662.6$ (796.4) and 941.8 (1119.6), consistent respectively with monocapped $[Cu_3(\mu\text{-}OMe)(\mu\text{-}4\text{-}O_2N\text{-}pz)_3X_3]^-$ and biscapped $\{[Bu_4N][Cu_3(\mu_3\text{-}OMe)(\mu_3\text{-}X)(\mu\text{-}4\text{-}O_2N\text{-}pz)_3X_3]\}^-$. The μ_3-OH analogue of the latter species has been crystallographically characterized previously as an unsymmetrically biscapped minor intermediate in the transformation of **1** to **6**.[7] Consistent with the ESI-MS results, the ^1H NMR of **1**/CD_3OD shows the presence of two species in solution: s, 43.98 ppm, and s, 48.43 ppm. The corresponding μ_3-OR species (R = Et and ^iPr) were observed in the ESI-MS spectra of **1** in EtOH and ^{i}PrOH.

Crystalline samples of the solvolysis products were obtained only in the case of MeOH solutions and pz* = 4-O_2N-pz. Dark-green crystals of **3** were visually separated from the blue-green ones of **4a**. The structure of **3** (Figure 1) consists of a trinuclear $[Cu(\mu\text{-}4\text{-}O_2N\text{-}pz)Cl]_3$ framework capped by a μ_3-OMe ligand. All bond lengths and angles within the copper pyrazolato ring deviate only slightly from those of its parent complex **1** or those of the related $[Cu_3(\mu_3\text{-}OH)(\mu\text{-}pz)_3Cl_3]^-$.[7] The μ_3-OMe group caps the complex almost symmetrically, with the O atom 0.723 Å out of the best-fit plane of the three approximately square-planar Cu atoms. Because the structure of **4a** suffers from severe crystallographic disorder, the ordered structure of its PPN analogue **4b** is described instead. The structure of **4b** (Figure 2) contains the trinuclear copper pyrazolato framework of **1** and **3** but now with a μ_3-OH capping ligand in addition to a MeOH molecule coordinated at the axial position of a five-coordinate square-pyramidal Cu atom. The structures of **5** and **6** (see the Supporting Information) are unexceptional and similar respectively to those of **4** and a previously reported analogue with nonsubstituted pz ligands.[7]

In a CH_2Cl_2 glass at 77 K, the ferromagnetic complexes **1** and **2** show EPR spectra (Figure 3) analogous to those of their solid-state spectra, which have been previously assigned to transitions within the $S = {}^3/_2$ manifold.[8] This is also consistent with the ESI-MS results in CH_2Cl_2 solutions (vide supra). However, their corresponding 77 K MeOH/glass EPR spectra are distinctly different: Two resonances of approximately equal intensities, with $g_{\|} = 2.40$ and 2.45 and Cu hyperfine coupling constants $A_{\|} = 400$ and 360 MHz, respectively, are evident in the parallel region of the spectrum of **1**/MeOH. Similarly, the EPR spectrum of **2**/MeOH shows two resonances of 4:1 intensities, with the same $g_{\|}$ and $A_{\|}$ values as those of **1**/MeOH. While two components are always seen in the MeOH/glass spectra of **1** and **2**, the relative intensities of the two components in each spectrum are variable and dependent on the sample preparation and solvent quality. The integrated resonance intensities [relative

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(9) X-ray diffraction data were collected with a Bruker AXS SMART 1K CCD diffractometer, graphite-monochromated Mo Kα radiation at 299−301 K, and corrected for Lorentz and polarization effects. Structure solution by direct methods and refinement by full-matrix least squares based on F^2. For **3** ($C_{26}H_{45}Cl_3Cu_3N_{10}O_7$): $M_r = 906.69$, monoclinic, space group $P2_1/n$, $a = 9.062(4)$ Å, $b = 25.341(10)$ Å, $c = 17.698(7)$ Å, $\beta = 99.307(7)°$, $V = 4011(3)$ Å^3, $Z = 4$, $\rho_{calc} = 1.502$ g/cm^3, $2\theta_{max} = 46.72°$, 17 197 reflections measured [5754 independent, R(int) = 0.1552], R1 = 0.0537 and wR2 = 0.1220 for 3273 reflections with $I > 2\sigma(I)$ (0.1086 and 0.1474 for all data). For **4b** ($C_{48}H_{49}Cl_3Cu_3N_{10}O_{10}P_2$): $M_r = 1284.88$, triclinic, space group $P\bar{1}$, $a = 10.203(1)$ Å, $b = 17.297(2)$ Å, $c = 17.370(2)$ Å, $\alpha = 114.253(2)°$, $\beta = 97.668(2)°$, $\gamma = 91.018(2)°$, $V = 2761.0(5)$ Å^3, $Z = 2$, $\rho_{calc} = 1.546$ g/cm^3, $2\theta_{max} = 46.62°$, 12 203 reflections measured [7934 independent, R(int) = 0.0232], R1 = 0.0326 and wR2 = 0.0765 for 6249 reflections with $I > 2\sigma(I)$ (0.0480 and 0.0834 for all data).

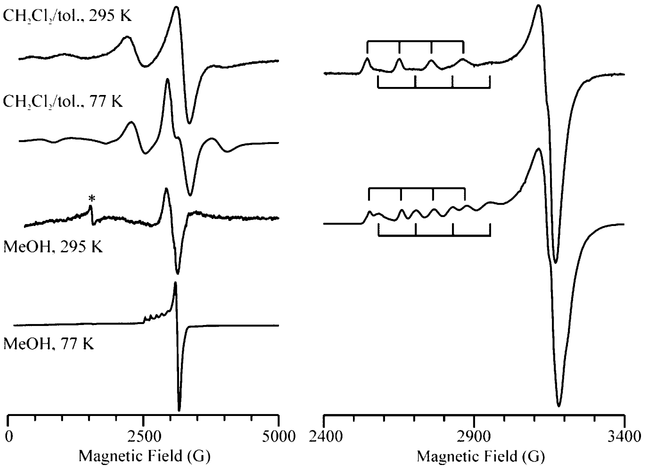
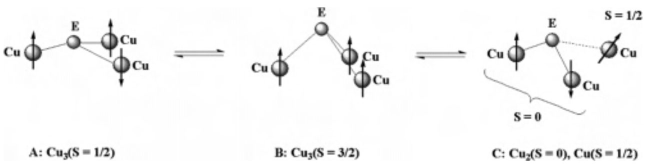


Figure 3. Left: X-band (9.2-GHz) EPR spectra of **1** in different solvents and temperatures. The sample in MeOH at 295 K was in a glass capillary tube having a paramagnetic impurity indicated by an asterisk. Right: X-band, 77 K, EPR spectra of species generated from **1** (lower trace) and **2** (upper trace) in neat MeOH. Both spectra exhibit $g_\perp = 2.08(2)$, $A_\perp \approx 50$ MHz, and $g_{||} = 2.40$, $A_{||} = 400$ MHz (component indicated by a lower set of "goalposts") and $g_{||} = 2.45$, $A_{||} = 360$ MHz (component indicated by upper "goalposts").

to an external Cu(NO$_3$)$_2$/MeOH standard] correspond to one-third of the total Cu concentration present in either **1** or **2**. Consequently, the EPR parameters of the species forming in MeOH solutions of **1** and **2** are consistent with the presence, in each solution, of two slightly different species with EPR parameters typical of mononuclear Cu^{II}: axial symmetry and a $d_{x^2-y^2}$ orbital ground state ($2.00 \approx g_\perp < g_{||}$).[10] A solid sample of **3** is EPR-silent at 77 K, as was the corresponding [$Cu_3(\mu_3\text{-OH})(\mu\text{-pz})_3Cl_3$]$^-$ species described earlier.[7] The 4 K Q-band EPR spectrum of a related Cu$_3$-(μ_3-OMe)−pyrazolate complex with unsymmetrical peripheral substitution consists of a broad band, distinctly different from the spectra of **1** and **2**.[11]

The crystallographic, MS, NMR, and EPR data show that while CH$_2$Cl$_2$ is an innocent solvent in the context of this work, alcohols are not. A shift of λ_{max} is also observed between the electronic spectra of **1** in CH$_2$Cl$_2$ (14 550 cm^{-1}) and MeOH (14 430 cm^{-1}). Coordination of alcohol/alkoxide by displacing the μ_3-Cl of **1** has been crystallographically demonstrated in the cases of **3**−**5**. However, the crystallographically determined species are EPR-silent. Dissolution of complexes **1** or **2** in MeOH generates evidently new trinuclear species containing a single EPR-active Cu^{II} center (type 2 center), along with two EPR-silent ones (type 3 centers), per trinuclear complex. To reconcile those results, we propose the presence of unsymmetrically monocapped species (case C in Scheme 2), similar to those detected by ESI-MS, in alcoholic solutions. These species result from the μ_3-OR ligand swinging toward two Cu atoms (becoming a μ_2-OR), leaving either a vacant or a solvent-filled coordination site on the third Cu atom: a species similar to **4** (Scheme 1) with the capping ligand disconnected from the unique Cu atom. The presence of two EPR-active species argues for the possible presence of both solvated and nonsolvated forms, even though the former has not been detected by MS. A similar spin system has been described for a polymer containing Cu$_3$ units.[12]

Scheme 2



Scheme 2 summarizes the magnetostructural results of the present and earlier studies of the trinuclear copper(II) pyrazolate system, wherein the bridging pyrazole ligands hold the three Cu centers at distances between 3.20 and 3.45 Å, while μ_3-E ligands are exchanged. When the μ_3-E ligand is coplanar or slightly out of the Cu$_3$ plane (A), a dominant through-E antiferromagnetic exchange results in a Cu$_3$($S = {}^1/_2$) system, with the magnitude of the J_{Cu-Cu} constant depending on the Cu−E−Cu angle.[8] A pyramidal distortion resulting from withdrawing E further out of the Cu$_3$ plane (B), *on-center* with respect to the three Cu ions, is expected to make the exchange ferromagnetic, resulting in a Cu$_3$($S = {}^3/_2$) system. This is the case for a pyramidal (μ_3-O)Cu$_3$ complex described recently by Solomon et al.[13] as well as for the biscapped complexes **1** and **2** containing trigonal-bipyramidal Cu centers.[8] In contrast, an *off-center* shift of E toward two of the three Cu centers (C) leads to antiferromagnetic coupling between these two Cu−(μ_2-E)−Cu centers, which are rendered EPR-silent: Cu$_2$($S = 0$). This off-center shift of E magnetically decouples the third Cu, so that the EPR spectrum of the complex appears as that of a typical mononuclear Cu($S = {}^1/_2$) center. Within the Cu$_3$ cluster of a protein, a mechanism interconverting the three species of Scheme 2 might operate if E is a terminal alkoxide whose coordination is affected by stereochemical or protonation changes in its environment or E is a dangling alkoxo group (i.e., a tyrosine phenoxide), which is displaced with regard to a rigid trinuclear core following the protein backbone rearrangements during its various stages of catalytic activity. We are not aware of a protein example, but Nature still holds many secrets.

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Supporting Information Available: Synthesis and characterization details for **1** and **2** and X-ray crystallographic data in CIF format. This material is available free of charge via the Internet at http://pubs.acs.org.

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(10) An alternative interpretation of the hyperfine-split quartet has been presented by Belinsky (*Inorg. Chem.* **2004**, *43*, 739), attributing it to a spin-frustrated Cu$_3$ cluster ($S = {}^1/_2$). This interpretation requires strict 3-fold symmetry, which is not the case with complex **3**. Furthermore, the MeOH/glass EPR spectra of Figure 3 would require two different, but both 3-fold symmetric, spin-frustrated species.

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