NMR spectra of (±)-isodrimenin and (±)-cinnamodial. Financial support was provided by the M. J. Murdock Charitable Trust.

**Supplementary Material Available:** IR, NMR, and mass spectral data for **1**, **3**, **5–8** and **10–15** (4 pages). Ordering information is given on any current masthead page.

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## A Monohydroxo Bridged, Strongly Antiferromagnetically Coupled Dicopper(II) Center in a Binucleating Macrocycle. Comparisons with Binuclear Copper Sites in Biology

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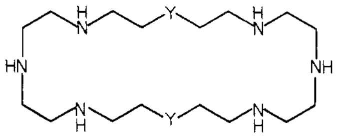
Strongly antiferromagnetically coupled ($J \leq -500$ cm$^{-1}$) dicopper(II) centers exist in met- and oxyhemocyanin, laccase, and related copper proteins.[1-3] The nature of the bridging ligand or ligands is unknown, although tyrosine or oxo oxygen atoms have been proposed.[3] Here we report that the binucleating macrocycle A, previously used to coordinate the imidazolate (im) bridged dicopper(II) ion (Cu–Cu distance, 5.86 Å),[4,5] readily incorporates



Macrocycles A (Y = O), A′ (Y = $CH_2$)

a monohydroxo bridged dicopper(II) center (Cu–Cu distance, 3.64 Å) that exhibits very strong antiferromagnetic coupling, $J \sim -500$ cm$^{-1}$. The large magnitude of the magnetic exchange interaction through a single bridging oxygen atom and the ability of the binucleating macrocycle to expand and contract to accommodate bridged binuclear copper(II) ions with variable metal–metal distances are features of likely relevance to binuclear copper centers in biology.

The compound was synthesized by dropwise addition of 2 mL of a 120 mM methanolic solution of $Cu(ClO_4)_2{\cdot}6H_2O$ to 4 mL of a stirred solution of the macrocycle[4] dissolved to 30 mM concentration in methanol, followed by dropwise addition of 0.116 mL of 1 N NaOH to the resulting dark blue solution. After 2 min a dark blue microcrystalline precipitate formed, leaving an almost colorless supernatant. When 1 mL of water was added to this mixture, the solid completely redissolved. Vapor diffusion of chloroform into this solution gave the product in 57% yield as dark blue monoclinic prisms. Analytical,[6] spectroscopic,[6] and X-ray crystallographic[7,8] data showed the composition to be $[Cu_2(OH)(ClO_4)\subset A](ClO_4)_2{\cdot}CHCl_3$.

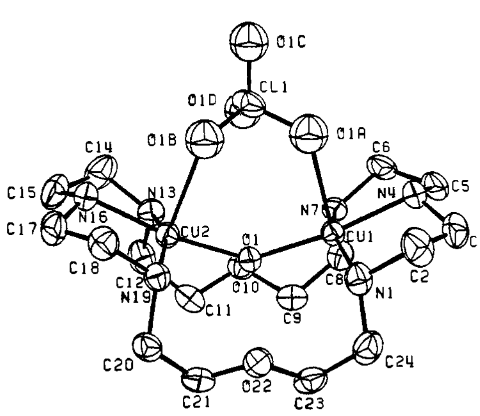


**Figure 1.** Structure of the $[Cu_2(OH)(ClO_4)\subset A]^{2+}$ cation showing the 40% probability thermal ellipsoids. For clarity, only one of two positions is depicted for the disordered, bridging perchlorate group, the oxygen atoms of which are assigned arbitrarily as spheres of 0.3 Å radius. Hydrogen atoms are omitted.

Table I. Selected Geometric Features of the $[Cu_2(OH)(ClO_4)\subset A]^{2+}$ Cation[a]

| distance, Å | | distance, Å | | angle, deg | |
|---|---|---|---|---|---|
| Cu1–O1 | 1.920 | Cu2–O1 | 1.912 | Cu1–O1–Cu2 | 143.7 |
| Cu1–N1 | 2.055 | Cu2–N13 | 2.056 | O1–Cu1–N4 | 171.7 |
| Cu1–N4 | 1.995 | Cu2–N16 | 1.988 | O1–Cu2–N16 | 170.6 |
| Cu1–N7 | 2.040 | Cu2–N19 | 2.053 | N1–Cu1–N7 | 158.2 |
| Cu1–O1A | 2.606 | Cu2–O1B | 2.594 | N13–Cu2–N19 | 160.5 |
| Cu1–Cu2 | 3.642 | | | | |

Possible Hydrogen Bonding

| distance, Å | | angle, deg | | angle, deg | |
|---|---|---|---|---|---|
| O1–O10 | 3.025 | O1–O10–C9 | 82.6 | O1–O22–C21 | 85.21 |
| O1–O22 | 2.962 | O1–O10–C11 | 84.3 | O1–O22–C23 | 84.8 |

Best Planes Calculations

| through O1, N1, N4, N7 dev from plane, Å | | through O1, N13, N16, N19 dev from plane, Å | |
|---|---|---|---|
| O1 | −0.22 | O1 | −0.21 |
| N1 | +0.24 | N13 | +0.22 |
| N4 | −0.26 | N16 | −0.24 |
| N7 | +0.24 | N19 | +0.22 |
| Cu1 | −0.09 | Cu2 | −0.06 |

[a] Atoms are labeled as in Figure 1. Standard deviations in bond lengths are less than 0.02 Å and in interbond angles are less than 0.2°.

The structure of the $[Cu_2(OH)(ClO_4)\subset A]^{2+}$ cation is shown in Figure 1. Two copper atoms are coordinated to the two diethylenetriamine poles of the macrocycle as found previously[4,5] for $[Cu_2(im)(imH)_2\subset A]^{3+}$ and $[Cu_2(im)(MeIm)_2\subset A']^{3+}$. A single hydroxide ion bridges the two metal centers at $D_{2d}$ distorted square-planar coordination sites. The resulting Cu–O bonds (av, 1.916 Å) and the Cu–O–Cu angle of 143.7 (2)° may be compared with Cu–O distances of 1.90–1.93 Å and Cu–O–Cu angles of 96–104° observed in di-$\mu$-hydroxo bridged dicopper(II) complexes[9] and corresponding values of 1.930 (5) Å and 141.6 (3)° for another structurally well-characterized monohydroxo bridged dicopper(II)

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(6) Elemental analysis. Anal. Calcd for $Cu_2C_{17}H_{40}N_6O_{15}Cl_6$: C, 22.48; H, 4.44; N, 9.25; Cl, 23.42. Found: C, 22.68; H, 4.62; N, 9.39; Cl, 24.15. Infrared spectrum (Nujol mull) N–H stretches, 3288, 3264 cm$^{-1}$; O–H stretch, 3472 cm$^{-1}$. The assignment of this band to the O–H stretching mode is supported by its absence in $[Cu_2(im)(imH)_2\subset A](ClO_4)_3$.[4] Optical spectrum (aqueous solution) $\lambda_{max}$ ($\epsilon$, M$^{-1}$ cm$^{-1}$): 637 (240), 330 (1800, sh), 265 (9300) nm.

(7) The compound crystallizes in the space group $P2_1/c$ with four formulas in a unit cell of dimensions $a = 14.487$ (2), $b = 15.282$ (2), $c = 15.573$ (2) Å; $\beta = 91.79$ (1)°; $\rho_{calcd} = 1.751$, $\rho_{obsd} = 1.754$ (2) g cm$^{-3}$. The copper atom positional parameters were determined by direct methods and the other atoms were located on difference Fourier maps. When 4305 unique reflections [$3° \leq 2\theta \leq 50°$, $F_o > 4\sigma(F_o)$] collected at 26° by diffractometer using Mo K$\alpha$ radiation were used, the structure was refined to a current value of 0.054 for the discrepancy index $R_1 = \sum||F_o| - |F_c||/\sum|F_o|$. Full details, including the best model used to fit two disordered perchlorate anions, will be reported at a later date.

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complex, $[Cu_2(bpy)_4(OH)](ClO_4)_3$.[10] A disordered perchlorate group also bridges the resulting μ-hydroxo-dicopper(II) unit through axial bonds similar to those found previously in the structure of α-$[Cu(DMAEP)(OH)(ClO_4)]_2$, where DMAEP = 2-[2-(dimethylamino)ethyl]pyridine.[11] The hydrogen atom of the bridging hydroxide group could not be located on a final difference Fourier map. Geometric considerations suggest that it is disordered over two hydrogen bonded positions to the two ether oxygen atoms of the macrocycle (Table I). Charge balance considerations and the infrared spectral results[6] leave no doubt that this bridging ligand has been properly identified. Additional geometric information is summarized in Table I.

The magnetic properties of a solid sample of $[Cu_2(OH)(ClO_4)\subset A](ClO_4)_2\cdot CHCl_3$ were investigated by the Faraday method over the temperature range 4.2 K $\leq T \leq$ 300 K. The effective magnetic moment of 0.29 $\mu_B$ at 280 K shows that the two copper atoms are strongly antiferromagnetically coupled. The 150–300-K susceptibility data were fit by least-squares methods to the Bleaney–Bowers equation resulting in $J \sim -500$ cm$^{-1}$.[8,12] The powder electron spin resonance spectra are also indicative of a strongly coupled system. The room temperature spectrum exhibits appreciable zero-field splitting ($D \sim 0.1$ cm$^{-1}$), and the only feature in the 150-K spectrum is readily assigned to a mononuclear copper(II) impurity. From the low temperature susceptibility results, we estimate the latter to be no more than 1.7% of the sample.

The antiferromagnetic coupling observed for the $[Cu_2(OH)(ClO_4)\subset A]^{2+}$ cation is larger than found for di-μ-hydroxo-dicopper(II) complexes with square-pyramidal structures and $J$ values between +86 and −255 cm$^{-1}$, depending upon the Cu–O–Cu bridge angles.[9] This difference may be due to the greater sp character of the bridging oxygen orbitals that arises when the Cu–O–Cu bond angle opens to a value as large as 143.7°. The present $J$ value of −500 cm$^{-1}$ also exceeds that found for other monohydroxo bridged dicopper(II) complexes $[Cu_2(OH)(bpy)_4](ClO_4)_3$ ($J = -161$ cm$^{-1}$)[10] and $[Cu_2(OH)(tren)_2]X_3$ ($X = PF_6^-$, $J = -350$ cm$^{-1}$; $X = ClO_4^-$, $J = -380$ cm$^{-1}$).[13] This difference probably does not arise from an additional spin exchange pathway through the bridging perchlorate group, since it is only weakly coordinated to the copper atoms through orbitals that are nearly orthogonal to the copper $d_{x^2-y^2}$ orbitals containing the unpaired electrons.

The preservation of the 637 nm visible absorption band over the pH range 6–11 in aqueous solution suggests that the hydroxo bridged dicopper(II) center is exceptionally stable. Preliminary work with other $[Cu_2L_n\subset A]^{m+}$ cations, where $L_n$ is one or more of a variety of bridging anions, shows them to be easily converted to the hydroxo bridged dicopper(II) unit in basic solution.[14] A μ-hydroxo bridged dicopper(II) complex of a related Schiff base macrocycle has also been mentioned in the recent literature;[15] while this paper was being reviewed, a μ-monohydroxo bridged complex having a Cu–OH–Cu angle of 132.2° and $J = -410$ cm$^{-1}$ was reported.[16] The near agreement between the exchange coupling constants in $[Cu_2(OH)(ClO_4)\subset A]^{2+}$ and those estimated for laccase and oxyhemocyanin,[1] the presence of a 330 nm band in the optical spectrum of $[Cu_2(OH)(ClO_4)\subset A]^{2+}$, which is characteristic of binuclear copper centers in biology,[3] and the similarity between the Cu–Cu distance in $[Cu_2(OH)(ClO_4)\subset A]^{2+}$ and those reported for oxyhemocyanin (3.67[17] and 3.55 Å[18]) all support the viability of proposals that the biological chromophore incorporates the Cu–O(R)–Cu unit, where R = protein side chain.[19] In fact, the stability and ubiquity of the $Cu_2OH^{3+}$ unit suggest that the "endogenous" protein bridging ligand might simply be the hydroxide ion.

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**Supplementary Material Available:** Tables S1 and S2 listing, respectively, positional and thermal parameters and the observed and calculated molar susceptibilities and effective magnetic moments for $[Cu_2(OH)(ClO_4)\subset A](ClO_4)_2\cdot CHCl_3$ (3 pages). Ordering information is given on any current masthead page.

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## α-Silyl- or -Stannyl-Substituted Crotyl-9-borabicyclo[3.3.1]nonane as a New Reagent for the Stereoregulated Synthesis of Acyclic Systems

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Macrolide, ansamycin, and polyether antibiotics belong to the rapidly expanding class of natural products. Their biological activities and considerable commercial importance, coupled with the intriguing structural problems, have stimulated intense efforts directed toward their total synthesis.[1] The procedures for the stereo-, regio-, and chemoselective synthesis of their key intermediates generally commence with the crossed aldol reactions,[2] the condensation of organometallic compounds with aldehydes,[3] the reactions via bicyclic compounds,[4] the epoxidation of allylic alcohols,[5] the hydroboration of olefinic compounds,[6] the reduction of carbonyl derivatives,[7] or the conjugate addition.[8] A need for

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