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A New Intermediate in Copper Dioxygen Chemistry: Breaking the O−O Bond To Form a $\{Cu_2(\mu\text{-}O)_2\}^{2+}$ Core

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The significance of the binding and activation of dioxygen by copper ions in biological and catalytic systems has stimulated extensive research oriented toward uncovering the fundamental chemistry involved.[1] A key prerequisite for understanding the course of substrate oxidations promoted by copper ions is identification of the initial product of the reaction of Cu(I) with O_2. The recent definitive characterization of dicopper(II) peroxo[2] and monocopper(II) superoxo[3] complexes has provided important insights into the initial stages of dioxygen binding and activation, but much remains to be learned about the order and nature of subsequent O−O bond cleavage and substrate oxidation events. Herein we report the isolation, spectroscopic and theoretical characterization, and C−H bond activation chemistry of a new species derived from the reaction of a Cu(I) complex with dioxygen. The proposed $\{Cu_2(\mu\text{-}O)_2\}^{2+}$ core of this molecule is unprecedented in copper chemistry[4] and may be viewed as a possible intermediate in oxidation reactions catalyzed by multicopper enzymes and small-molecule catalysts.

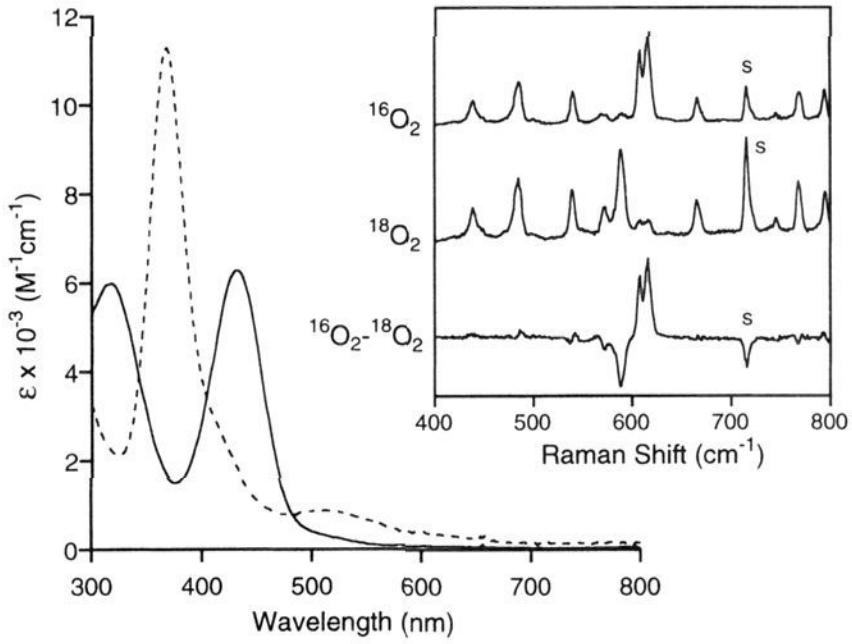
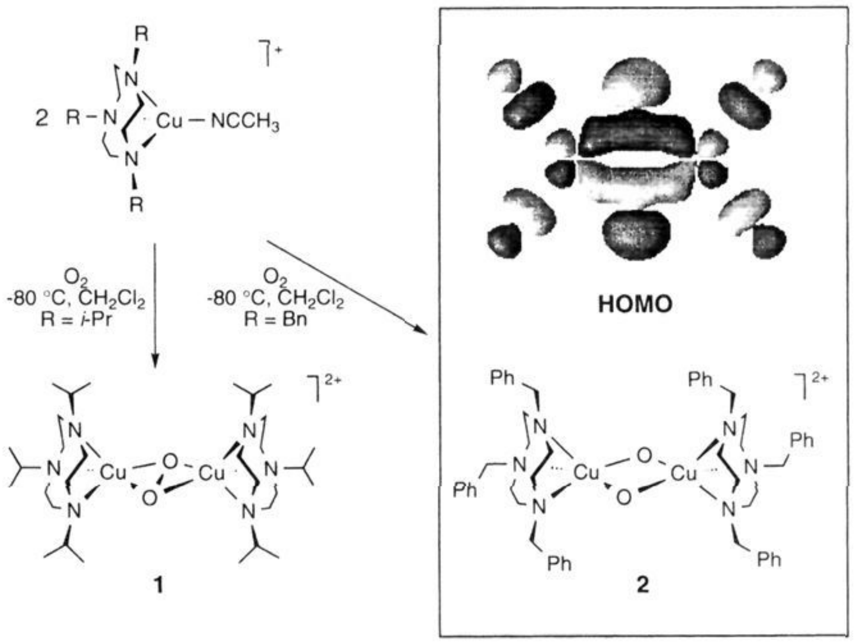


Figure 1. UV−vis spectra of solutions of **1** (- - -) and **2** (—) in CH_2Cl_2 at −80 °C and resonance Raman spectra of frozen solutions of **2** in CH_2Cl_2 prepared from the indicated gases (inset: lower spectrum is difference spectrum; s = solvent band).

Scheme 1



We recently reported that addition of O_2 to $[(i\text{-}Pr_3TACN)Cu(CH_3CN)]O_3SCF_3$ in CH_2Cl_2 at −80 °C reversibly afforded a $(\mu\text{-}\eta^2{:}\eta^2\text{-peroxo})$dicopper(II) complex (**1**, Scheme 1) that was formulated on the basis of a low ν_{O-O} in its resonance Raman spectrum [722 cm^{-1}; $\Delta\nu(^{18}O_2) = 42$ cm^{-1}), EPR silence, and diagnostic UV−vis features [$\lambda_{max} = 365$ (ϵ 11 000 M^{-1} cm^{-1}), 510 (1000) nm] (Figure 1).[2c,5] When the same reaction was performed using $[(Bn_3TACN)Cu(CH_3CN)]X$ ($X = ClO_4^-$ or SbF_6^-) as starting material,[6] rapid uptake of 1 O_2 per 2.2(2) Cu(I) ions (by manometry, average of five runs) and formation of an orange-brown species **2** (Scheme 1) with spectroscopic features clearly distinct from those exhibited by **1** were observed [Figure 1, $\lambda_{max} = 318$ (ϵ 6000 M^{-1} cm^{-1}), 430 (7000) nm]. Like **1**, however, **2** decomposed upon warming to afford a blue-green solution, from which a bis(μ-hydroxo)dicopper(II) complex, $\{[(Bn_3TACN)Cu]_2(OH)_2\}(X)_2$ (**3**) was isolated (60% yield for $X = ClO_4^-$).[6] Extraction of the copper ions from the crude green solution with aqueous NH_4OH yielded intact Bn_3TACN, the dealkylation product Bn_2HTACN (40%), and benzaldehyde (40%), clearly indicating that the ligand was oxidatively attacked during the decomposition of **2**.[7] The rate-determining step of this decomposition involves benzyl substituent C−H bond cleavage, as shown by a large kinetic isotope effect (KIE) for the first-order loss of **2** containing Bn_3TACN or $(Bn\text{-}d_7)_3TACN$ ligands ($k_H/k_D = 50$ at −50 °C; 13 at 25 °C by extrapolation from activation parameters).[8a] The magnitudes of the KIE, $\Delta\Delta H^\ddagger$, and $\Delta\Delta S^\ddagger$ differ from those measured previously for the analogous reaction of **1** involving isopropyl substituent C−H bond cleavage[2c,8b] [**1**, $\Delta\Delta H^\ddagger$ (H−D) ≈ 0 kcal mol^{-1}, $\Delta\Delta S^\ddagger \approx +4$ eu; **2**, $\Delta\Delta H^\ddagger \approx -2.4$ kcal mol^{-1}, $\Delta\Delta S^\ddagger \approx -3$ eu] but are

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(4) Dicopper bis(μ-oxo) species have been proposed, however. See, for example: (a) Demmin, T. R.; Swerdloff, M. D.; Rogíc, M. M. *J. Am. Chem. Soc.* **1981**, *103*, 5795−5804. (b) Jallabert, C.; Lapinte, C.; Riviere, H. *J. Mol. Catal.* **1980**, *7*, 127−136.

(5) (a) Abbreviations used: i-Pr_3TACN, 1,4,7-triisopropyl-1,4,7-triazacyclononane; Bn_3TACN, 1,4,7-tribenzyl-1,4,7-triazacyclononane. (b) Beissel, T.; Della Vedova, B. S. P. L.; Wieghardt, K.; Boese, R. *Inorg. Chem.* **1990**, *29*, 1736−1741.

(6) Synthetic procedures and characterization data for all new compounds are reported in the supporting information.

(7) For other examples of benzylic oxidation by copper dioxygen adducts, see: (a) Itoh, S.; Kondo, T.; Komatsu, M.; Ohshiro, Y.; Li, C.; Kanehisa, N.; Kai, Y.; Fukuzumi, S. *J. Am. Chem. Soc.* **1995**, *117*, 4714−4715. (b) Réglier, M.; Amadéi, E.; Alilou, E. H.; Eydoux, F.; Pierrot, M.; Waegell, B. In *Bioinorganic Chemistry of Copper*; Karlin, K. D., Tyeklár, Z., Eds.; Chapman & Hall: New York, 1993; pp 348−362. (c) Sanyal, I.; Mahroof-Tahir, M.; Nasir, M. S.; Ghosh, P.; Cohen, B. I.; Gultneh, Y.; Cruse, R. W.; Farooq, A.; Karlin, K. D.; Liu, S.; Zubieta, J. *Inorg. Chem.* **1992**, *31*, 4322−4332.

(8) (a) For **2** and **2**-d_{42}: $\Delta H^\ddagger_H = 12.9(5)$ kcal mol^{-1}, $\Delta H^\ddagger_D = 15.3(5)$ kcal mol^{-1}, $\Delta S^\ddagger_H = -14(2)$ eu, and $\Delta S^\ddagger_D = -11(2)$ eu. A list of rate constants, a representative first-order plot, and Eyring plots are provided as supporting information (Table S1 and Figures S1 and S2). (b) For **1** and **1**-d_{42}: $\Delta H^\ddagger_H = 13.5(5)$ kcal mol^{-1}, $\Delta H^\ddagger_D = 14.0(5)$ kcal mol^{-1}, $\Delta S^\ddagger_H = -12(1)$ eu, and $\Delta S^\ddagger_D = -16(1)$ eu.[2c]

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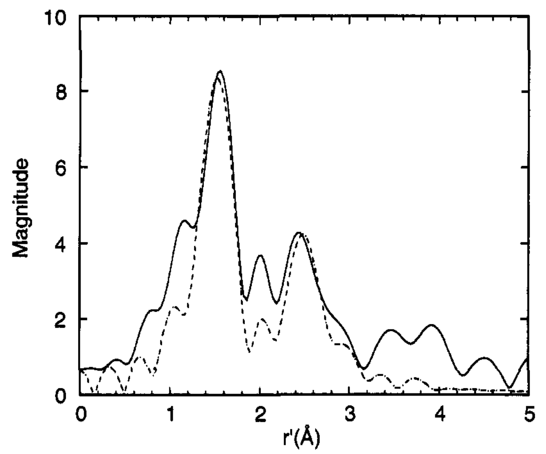

Figure 2. Fourier transformed EXAFS data (—) and preliminary simulation (- - -) of **2** ($k = 2-12$ Å^{-1}). The experimental data (Fourier filtered from $r' = 1-3.2$ Å) were fitted by using 4 N/O at 1.96 Å, 6 C at 2.97 Å, and 1 Cu at 2.78 Å.

similar to those cited for the decomposition of $[(\mathrm{Tp}^{i\text{-Pr,Me}}\mathrm{Co})_2(\mu\text{-}O_2)]$ ($\Delta\Delta H^{\ddagger} \approx -2.8$ kcal mol^{-1}, $\Delta\Delta S^{\ddagger} \approx -4$ eu), for which tunneling was postulated.[9] Detailed comparisons indicative of divergent compositions for the species involved aside, the fact that **1** and **2** undergo analogous first-order, ligand-based C−H bond activation reactions upon warming implicates similar oxidizing capabilities for their respective cores.

Insight into the structure of **2** has been obtained from spectroscopic and theoretical studies. The complex is EPR silent and exhibits a relatively sharp ^{1}H NMR spectrum,[6] ruling out formulation as a mononuclear Cu(II) species. Electrospray MS results support its dinuclear composition.[10] Resonance Raman spectra (457 nm excitation) of frozen CH_2Cl_2 solutions of **2** derived from $^{16}O_2$ and $^{18}O_2$ lack oxygen isotope-sensitive features in the peroxide O−O stretching region and, instead, contain peaks at 602 and 608 cm^{-1} that shift to 583 cm^{-1} upon ^{18}O substitution (Figure 1, inset). The conversion of two peaks to one suggests that the 602/608 cm^{-1} pair is a Fermi doublet, with the magnitude of the isotope shift (23 cm^{-1}) being consistent with assignment of the fundamental to a Cu−O vibration.[11] The X-ray absorption K-edge measured for a solid sample occurs at ~8987 eV, consistent with the presence of Cu(II) ions in the complex.[12] The r'-space EXAFS spectrum (Figure 2) contains two distinct features, a first-shell peak that was fit by 4 N/O at 1.96 Å and a second peak indicative of a relatively rigid scatterer at ~2.8 Å. This feature, which is similar to ones observed in EXAFS spectra of complexes containing $Fe_2(\mu\text{-}O)_2$ and $Fe_2(\mu\text{-}O)(\mu\text{-}OH)$ cores,[13] was fit analogously as a 2.78 Å Cu−Cu vector. Additional contributions from 6 C at 2.97 Å (Bn_3TACN backbone carbons) improved the overall fit.

We propose a novel $\{Cu_2(\mu\text{-}O)_2\}^{2+}$ structure with significant covalent character for **2** on the basis of its composition (MS), the stoichiometry of its formation ($Cu:O_2 = 2:1$), its diamagnetism (EPR, NMR), its oxidizing capability, and similarities of the observed resonance Raman and EXAFS features to those reported for other $M_2(\mu\text{-}O)_2$ (M = Fe, Mn) rhombs.[13b,14,15] Such a core can be envisioned to arise from homolysis of the O−O bond in a $(\mu\text{-}\eta^2\text{:}\eta^2\text{-peroxo})$dicopper(II) precursor with attendant shortening of the intermetal distance (3.5[2a] to 2.8 Å). We suggest a (simplified) electronic structure for **2** in which two Cu(II) ions are bridged by oxyl radicals, with extensive spin-coupling to yield an $S = 0$ ground state. In support of this covalent description, preliminary *ab initio* calculations[16,17] predict a stable (energy minimum) singlet state for C_{2h} $\{[(NH_3)_3Cu]_2(\mu\text{-}O)_2\}^{2+}$. There is good agreement between the observed (*vide supra*) and predicted values [ν(calc) = 638 cm^{-1}; $\Delta\nu$(^{18}O calc) = 26 cm^{-1}] for the A_{1g} vibrational frequency for the $Cu_2(\mu\text{-}O)_2$ rhomb, as well as between the calculated (2.72 Å) and observed (2.78 Å) intermetal distance. The calculated HOMO (Scheme 1) is comprised of strong bonding interactions between the two Cu $d_{x^2-y^2}$ and the antisymmetric combination of O p_y orbitals; this rationalizes the observed diamagnetic ground state. Note that this HOMO is qualitatively similar to one we have calculated at the same level of theory for a previously described[18] $(\mu\text{-}\eta^2\text{:}\eta^2\text{-peroxo})$dicopper(II) species, i.e., 2Cu $d_{x^2-y^2}$ + peroxo σ^*. The orbital coefficients differ, however, in a manner consistent with cleavage of the O−O bond in the $(\mu\text{-}O)_2$ species (see supporting information).

Compound **2** represents a new structural motif in copper dioxygen chemistry that we propose may form immediately subsequent to dioxygen adduct formation in oxidation processes promoted by multicopper sites. The relevance of this intermediate to biological oxidase and oxygenase activity in particular will be addressed in future work oriented toward ascertaining a thorough understanding of its formation, structure, and reactivity.

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Supporting Information Available: Preparative procedures and characterization data for all new compounds, list of rate constants (Table S1), representative first-order plot (Figure S1) and Eyring plots (Figure S2) for the decomposition of **2**, electrospray MS data (Figure S3), Cartesian coordinates for the optimized *ab initio* structure (Table S2), and orbital coefficients (RHF/STO-3G*) for the HOMO-1, HOMO, and LUMO of $\{[(NH_3)_3Cu]_2(\mu\text{-}O)_2\}^{2+}$ and $\{[(NH_3)_3Cu]_2(\mu\text{-}\eta^2\text{:}\eta^2\text{-}O_2)\}^{2+}$ (Table S3) (11 pages). This material is contained in many libraries on microfiche, immediately follows this article in the microfilm version of the journal, can be ordered from the ACS, and can be downloaded from the Internet; see any current masthead page for ordering information and Internet access instructions.

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[10] Measured for ClO_4^- and SbF_6^- salts of **2**-d_{42}. Peak envelopes centered at *m/z* 1099 and 1235 matched calculated isotope patterns for $\{(\mathbf{2}\text{-}d_{42})(ClO_4)\}^+$ and $\{(\mathbf{2}\text{-}d_{42})(SbF_6)\}^+$, respectively (shown for the latter in Figure S3).

[11] For a Cu−O harmonic oscillator, $\nu(^{18}O)/\nu(^{16}O) = 1.0476$, giving $\Delta\nu(^{18}O) = 28$ cm^{-1}.

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[16] Geometry was optimized at the RHF/STO-3G(*) level (r_{Cu-Cu} = 2.716 Å, r_{O-O} = 2.295 Å, r_{Cu-O} = 1.778 Å). Harmonic frequencies were calculated at the same level of theory. In addition, broken symmetry single-point Xα calculations on the singlet state [RHF geometry using RHF orbitals with all Cu(1) coefficients zeroed for the α-HOMO and all Cu(2) coefficients zeroed for the β-HOMO] converged smoothly to fully symmetric solutions (i.e., indistinguishable from restricted Xα calculations). This is in contrast to broken-symmetry Xα results for a previously described $(\mu\text{-}\eta^2\text{:}\eta^2\text{-peroxo})$dicopper(II) species (ref 18) and supports the assignment of covalent bonding character to the $(\mu\text{-}O)_2$ complex. Mulliken analysis indicates a population of 9.21 electrons in the copper d orbitals, consistent with a Cu(II) assignment as a simplified view.

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