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Communication

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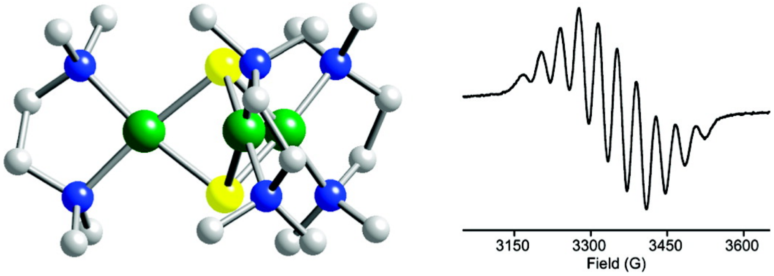

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$[Cu_3(\mu\text{-}S)_2]^{3+}$ Clusters Supported by N-Donor Ligands: Progress Toward a Synthetic Model of the Catalytic Site of Nitrous Oxide Reductase

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Nitrous oxide reductase (N_2OR) is an environmentally important respiratory metalloenzyme that catalyzes the two-electron reduction of N_2O to N_2 and H_2O during bacterial denitrification.[1] Recent X-ray crystallographic[2] and spectroscopic studies[1,3] have revealed a novel structure for the resting form of the catalytic site (Cu_Z) that features a tetracopper cluster at the [$Cu^I_3Cu^{II}$] oxidation level with a distorted tetrahedral μ_4-sulfido bridge (Figure 1a). The enzyme exists in a variety of different redox active forms, including several mixed-valent states and a fully reduced Cu^I_4 form that apparently reacts with N_2O.[1,3c−e,4] The μ_4-S^{2-} moiety is proposed to be involved in electron delocalization in the oxidized form(s) of the cluster and, thus, may play a key structural and/or functional role in the N_2O reduction reaction.

The structural novelty of the Cu_Z site and provocative mechanistic hypotheses for N_2OR catalysis[1b] provide ample inspiration for synthetic model studies, particularly those aimed at understanding the electronic structures and reactivity of N-donor ligated $[Cu_x(\mu\text{-}S)_y]^{n+}$ clusters. While there are many examples of multicopper(I) complexes with bridging sulfido and abiological phosphine supporting ligands,[5] we are unaware of examples at higher oxidation levels supported by N-donors, such as those found in N_2OR. In previous efforts aimed at generating such clusters, we found that reactions of S_8 with Cu^I complexes of sterically bulky β-diketiminate and anilido-imine ligands (L) yielded $[Cu^{II}_2(\mu\text{-}\eta^2\text{:}\eta^2\text{-}S_2)]^{2+}$ complexes (**1**, Scheme 1).[6] Related copper complexes have been reported with other tri- and tetradentate N-donor ligands.[7] Upon treatment of **1** with additional Cu^I complexes, S−S bond cleavage did not occur; only exchange of the disulfido ligands was observed. Indeed, and in contrast to analogous O_2 activation chemistry,[8] DFT calculations predict that cleavage of the S−S bond to form the isomeric $[Cu^{III}_2(\mu\text{-}S)_2]^{2+}$ core is highly unfavorable.[9] Herein we report that when less sterically hindered and neutral bidentate N-donor supporting ligands are used S−S bond scission occurs to yield clusters with novel delocalized mixed-valence $[Cu_3(\mu\text{-}S)_2]^{3+}$ cores relevant to the Cu_Z site.

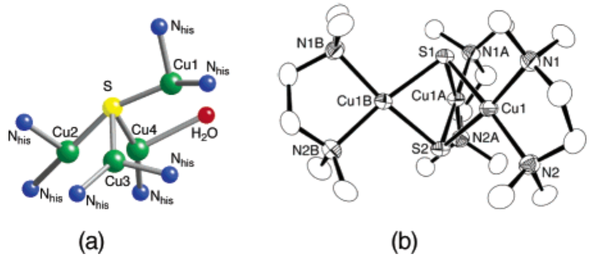
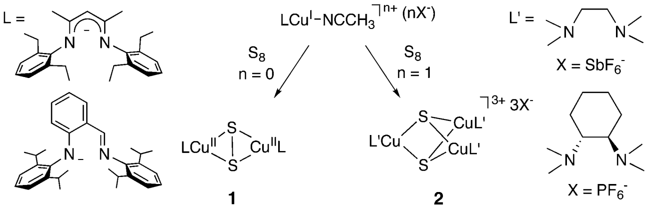


Figure 1. (a) Cu_Z site of N_2OR (ref 2a, pdb 1FWX). Selected interatomic distances (Å): Cu1−S, 2.30; Cu2−S, 2.23; Cu3−S, 2.25; Cu4−S, 2.24; Cu1−Cu4, 3.36; Cu1−Cu3, 3.36; Cu2−Cu3, 2.55; Cu2−Cu4, 2.55; Cu3−Cu4, 3.00. (b) Molecular structure of the cationic portion of **2a** (50% ellipsoids, H atoms excluded). Selected interatomic distances (Å): Cu1−Cu1A, 3.0956(7); Cu1−S1, 2.2467(9); Cu1−S2, 2.2479(9); Cu1−N1, 2.027(3); Cu1−N2, 2.028(3).

Scheme 1



Dark-green clusters **2a**,**b** (**2a**: L′ = TMEDA, X = SbF_6^-; **2b**, L′ = TMCHD, X = PF_6^-)[10] were isolated in high yields (**2a**, 66%; **2b**, 74%) as powders from reactions of [L′Cu(MeCN)]X with S_8 in CH_2Cl_2 at room temperature. The 173 K X-ray crystal structures (**2a**, Figure 1b; **2b**, Figure S2) show three symmetry-related four-coordinate, square planar Cu centers capped by two bridging μ_3-sulfides.[11] The presence of three counterions demonstrates an overall 3+ charge for each cluster, consistent with a $Cu^{II}_2Cu^{III}$ formal oxidation level assignment. The Cu_3S_2 cores are trigonal bipyramidal, with **2a** lying on a crystallographic 3-fold axis, such that the four-coordinate Cu centers exhibit identical Cu−S and Cu−N bond lengths. In **2b**, although two of the Cu centers are unique and the third is generated by symmetry (a 2_1 screw axis), the Cu−S and Cu−N bond distances also are similar. Within experimental error, these distances are identical for the two clusters: Cu−S(avg.) = 2.247(2) Å (**2a**), 2.250(3) Å (**2b**); Cu−N(avg.) = 2.028(7) Å (**2a**), 2.018(8) Å (**2b**). These distances also are closely similar to those reported for the Cu_Z site, where the average Cu−S and Cu−N bond lengths are ∼2.26 and 2.03 Å, respectively.[2] Notably, the Cu_Z subcluster defined by Cu2, Cu3, Cu4, and S resembles half of the cores of **2a**,**b**, the additional Cu1 and short intercopper distances of ∼2.5 Å in Cu_Z being key differences yet to be replicated via synthesis. The high symmetry of the $[Cu_3(\mu\text{-}S)_2]^{3+}$ cores for **2a**,**b** is particularly noteworthy, as the previously reported oxygen analogue of **2b** contains an asymmetric $[Cu^{II}_2Cu^{III}(\mu\text{-}O)_2]^{3+}$ core in which one of the Cu atoms has much shorter Cu−O and Cu−N distances.[12] This structural information, in conjunction with the results of spectroscopic experiments and theoretical calculations,[13] was interpreted to indicate that the $[Cu^{II}_2Cu^{III}(\mu\text{-}O)_2]^{3+}$ cluster is valence localized. In contrast, the symmetrical cores in **2a**,**b** suggest delocalization of the two valence electrons, which is supported by spectroscopic data and theoretical calculations as described below.

The UV−vis spectra of **2a** and **2b** in CH_2Cl_2 are essentially identical and feature multiple intense absorptions, most notably a

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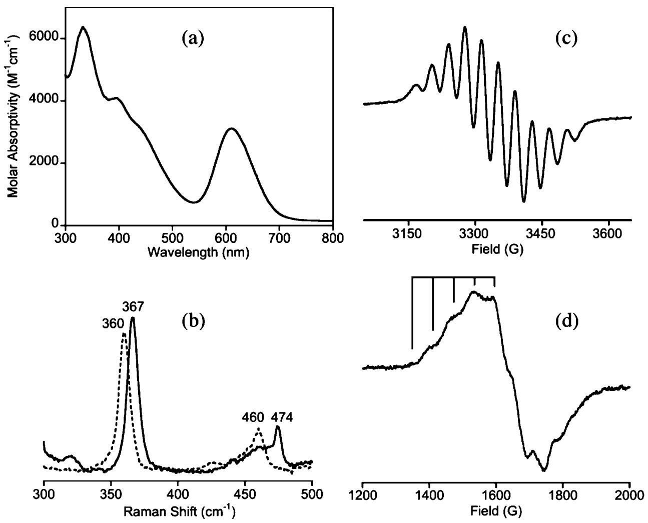
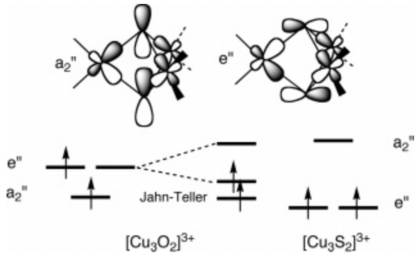


Figure 2. Spectroscopic data for **2b**: (a) UV−vis spectrum in CH_2Cl_2. (b) Resonance Raman spectrum (CH_2Cl_2, 77 K, $\lambda_{ex} = 615$ nm) prepared with ^{32}S (solid line) and ^{34}S (dashed line). (c) X-band EPR spectrum (CH_2Cl_2, 298 K). (d) "Half-field" portion of the 10 K X-band EPR spectrum (CH_2Cl_2), with vertical lines drawn at ∼62 G intervals to illustrate the Cu hyperfine features.

distinct low-energy band with $\lambda_{max} = 605$ (**2a**) or 609 (**2b**) nm and $\epsilon = 3000-4000$ M^{-1} cm^{-1} (**2b**, Figure 2(a); **2a**, Figure S5). This band resembles the S → Cu^{II} charge-transfer feature in the resting form of the enzyme ($\lambda_{max} \sim 640$ nm).[1,3] Assignment of this band in the synthetic clusters to a S → Cu^{II} CT is supported by resonance Raman spectra collected using more soluble **2b** ($\lambda_{ex} = 615$ nm). Peaks are observed at 367 and 474 cm^{-1} that shift upon isotopic labeling with ^{34}S (Figure 2b). We assign these features as Cu−S vibrational modes and note that the 367 cm^{-1} peak is similar to a 382 cm^{-1} feature attributed to a Cu−S vibration in Cu_Z (form "Z_{mv}"),[3a,b] and both features are within or close to the region reported for Fe−(μ_3-S) vibrations in $Fe_{3/4}S_4$ clusters (335−445 cm^{-1}).[14] The magnetic moment of **2b** in CD_2Cl_2 was determined to be 2.7 μ_B at 24 °C (Evans method), which is consistent with two unpaired electrons. Full delocalization of these unpaired electrons at room temperature is indicated by the X-band EPR spectrum (Figure 2c), which exhibits an isotropic signal centered at $g = 2.05$ with a distinctive 10-line hyperfine pattern due to coupling to three equivalent Cu ions ($I = {}^3/_2$, $A_{Cu} = 42$ G). The spectrum at 10 K contains features at $g \sim 2$ (Figure S6) and $g = 4$, the latter confirming a $S = 1$ state for the complex (Figure 2d). The resolved lines in the $g = 4$ feature are consistent with an even line [1,3,6,10,12,12,10,6,3,1] pattern derived from hyperfine coupling to three equivalent Cu ions. In sum, the available data support a local D_{3h}-symmetric geometry and a fully delocalized $S = 1$ ground state for the $[Cu^{II}_2Cu^{III}(\mu\text{-}S)_2]^{3+}$ cores of **2a**,**b**, distinct from the asymmetry and localization reported previously for the $[Cu^{II}_2Cu^{III}(\mu\text{-}O)_2]^{3+}$ analogue.

We used DFT calculations in order to understand these structural differences.[15] The calculated electronic structures of **2a** and its $[Cu_3(\mu\text{-}O)_2]^{3+}$ analogue[13] agreed well with those obtained by experiment and provided important insights. In brief, the metal d orbitals that host the two unpaired electrons of the $[Cu_3(\mu\text{-}X)_2]^{3+}$ (X = O, S) core are the a_2'' and e'' combinations of the three x^2-y^2-type orbitals (Scheme 2). These orbitals are nearly degenerate for X = O, in qualitative agreement with the previous report,[13] thus favoring the triplet state and a Jahn−Teller distortion that underlies the localized electronic structure. Replacement of X = S for O results in an orbital reversal and a significant gap between a_2'' and the e'' set. This is due to more effective σ-type overlap between the S p orbitals, which strongly destabilizes a_2''. The reversed orbital sequence results in a fully delocalized $(e'')^2$ triplet state, consistent with experiment (see Supporting Information for calculated J values).

Scheme 2



In summary, we have prepared a novel $[Cu_3(\mu\text{-}S)_2]^{3+}$ cluster supported by N-donor ligands that models structural attributes of the N_2OR Cu_Z site. Experimental data support a delocalized mixed-valent electronic structure distinct from the localized core of a previously reported oxygen analogue,[12] and this difference is rationalized by the results of DFT calculations.

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Supporting Information Available: Experimental and calculation details (PDF) and crystallographic information (CIF). This material is available free of charge via the Internet at http://pubs.acs.org.

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(10) Abbreviations used: TMEDA = *N,N,N′,N′*-tetramethylethylenediamine, TMCHD = *N,N,N′,N′*-tetramethyl-*trans*-1*R*,2*R*-diaminocyclohexane.
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