

Communication

Copper(I) / NO Reductive Coupling Producing a *trans*-Hyponitrite Bridged Dicopper(II) Complex – Redox Reversal Giving Copper(I) / NO Disproportionation

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Copper(I) / NO_(g) Reductive Coupling Producing a *trans*-Hyponitrite Bridged Dicopper(II) Complex – Redox Reversal Giving Copper(I) / NO_(g) Disproportionation

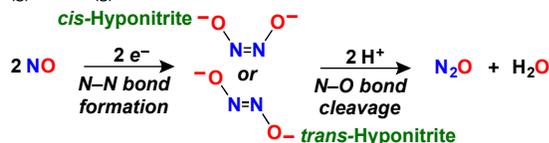
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Supporting Information Placeholder

ABSTRACT: A copper complex, [Cu^I(tmpa)(MeCN)]⁺, effectively reductively couples NO_(g) at RT in methanol, giving a structurally characterized hyponitrito-dicopper(II) adduct. Hydrogen-bonding from MeOH is critical for the hyponitrite complex formation and stabilization. This complex exhibits the reverse redox process in aprotic solvents, giving Cu^I + NO_(g), leading to Cu^I-mediated NO_(g) disproportionation. The relationship of this chemistry to biological iron and/or copper mediated NO_(g) reductive coupling to give N₂O_(g) is discussed.

The interactions and reactivity of redox active metal ions with nitrogen oxides has widespread implications/importance in environmental, practical and biological chemistries. Iron and copper provide for facile redox shuttling and one and/or the other in the presence of proton sources chemically or enzymatically facilitates reactions such as reduction of nitrite (NO₂⁻) to nitrogen monoxide (NO_(g); nitric oxide), reductive coupling of NO_(g) to nitrous oxide (N₂O_(g)) and reduction of N₂O_(g) to N_{2(g)}.¹



Biological roles of NO include it as a signaling agent, yet it can be toxic under oxidative conditions; NO is utilized in the human immune response, produced in elevated levels to effect invading pathogen biomolecule destruction (e.g., by oxidation or nitration).² Fighting back, bacteria/pathogens can upregulate NO-reductase (NOR) activity to eliminate toxic NO by its reductive coupling to give benign N₂O.³ Bacterial NOR's^{1d,4} possess heme/non-heme diiron active sites, effecting the coupling through a putative hyponitrito (N₂O₂²⁻) intermediate;⁵ the metal ion centers provide electrons (dia-

gram above). Evolutionarily related heme-Cu oxidases (HCO's) effect this reaction, albeit with lower efficiency.⁶

Our own interests encompass hemes and/or Cu,^{2a,7} and in this report we focus on the latter. In addition to HCO NO_(g) reductive coupling, copper nitrite reductases may also couple excess NO_(g) present to give N₂O_(g).^{1a} Further, in the presence of O_{2(g)}, Cu-NO reactivity can lead to peroxyxynitrite (O=NOO⁻).^{2b,8} Also, copper complexes are efficient at NO-disproportionation, 3NO_(g) + Cu^I → N₂O_(g) + Cu^{II}(NO₂⁻), possibly also involving hyponitrite-type intermediates.^{1b,9} As well, copper ion loaded zeolites are effective catalysts to decompose NO_x to N₂ and O₂; automobile catalytic converters may utilize Cu as a catalyst for NO_(g) reduction to N₂O_(g).¹⁰

With this background, we highlight the need to elucidate fundamental aspects of NO_(g) reductive coupling, details/requirements for (i) N-N bond formation and (ii) N-O bond cleavage for hyponitrite formation and N₂O elimination, respectively. Even though hyponitrite intermediates have been proposed/observed within enzymatic systems, details pertaining to their binding mode within the binuclear active site, protonation state(s), and the metal oxidation states, all remain elusive.¹¹ In this report, employing the copper(I) complex [Cu^I(tmpa)(MeCN)](B(C₆F₅)₄) (TMPA = tris-(2-pyridylmethyl)amine), we describe (i) the first example of a copper(I) complex whose NO_(g) reactivity leads to efficient reductive coupling to give the hyponitrite complex {[Cu^{II}(tmpa)}₂(μ-N₂O₂²⁻)²⁺, (ii) the first structurally characterized Cu-only hyponitrite complex, and (iii) the effective reversal of NO reductive coupling occurring for the hyponitrite complex in tetrahydrofuran (THF), i.e., formation of a putative {[Cu^I(tmpa)]⁺ + NO_(g)} solution mixture, followed by NO-disproportionation (Figure 1).

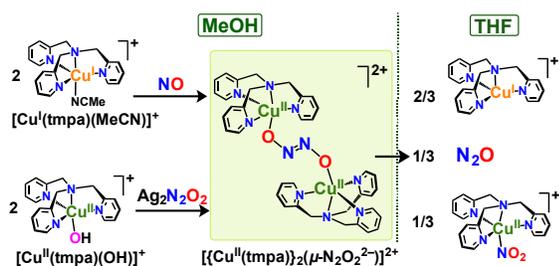


Figure 1. Divergent synthetic routes to $[[\text{Cu}^{\text{II}}(\text{tmpa})]_2(\mu\text{-N}_2\text{O}_2^{2-})]^{2+}$ in MeOH, and its unique redox behavior in THF, effecting Cu^I-mediated NO-disproportionation.

When excess $\text{NO}_{(\text{g})}$ is bubbled through a RT MeOH solution of $[\text{Cu}^{\text{I}}(\text{tmpa})(\text{MeCN})]^+$, the initial pale yellow solution immediately transforms to forest green giving electronic absorption features: $\lambda_{\text{max}} = 310$ ($\epsilon = 3800 \text{ M}^{-1} \text{ cm}^{-1}$), 675 ($\epsilon = 180 \text{ M}^{-1} \text{ cm}^{-1}$), and 870 ($\epsilon = 240 \text{ M}^{-1} \text{ cm}^{-1}$) (Figure 2). An EPR spectrum of the green solution reveals a classic reverse axial pattern ($g_{\perp} > g_{\parallel}$) indicating a d_{z^2} ground state, with a single type of mononuclear copper(II) environment occurring in a trigonal bipyramidal (TBP) geometry; this also indicates that the copper(II) ions are electronically site-isolated, i.e., no magnetic/electronic interaction between the two copper(II) ions occurs. Upon solvent removal, this new complex was obtained in near stoichiometric yields (> 97%) and it is the hyponitrito complex $[[\text{Cu}^{\text{II}}(\text{tmpa})]_2(\mu\text{-N}_2\text{O}_2^{2-})](\text{B}(\text{C}_6\text{F}_5)_4)_2 \cdot 2\text{H}_2\text{O} \cdot 2\text{CH}_3\text{OH}$, (Eq. 1).¹²

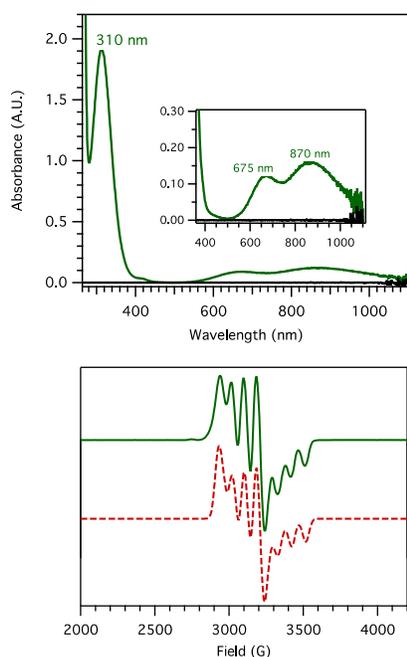
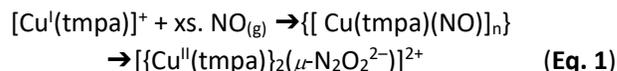


Figure 2. Top: Electronic absorption spectrum resulting from the $\text{NO}_{(\text{g})}$ reactivity with 1 mM $[\text{Cu}^{\text{I}}(\text{tmpa})(\text{MeCN})]^+$ in MeOH at RT. Bottom: EPR spectra (experimental (green) and simulated (red)) of $[[\text{Cu}^{\text{II}}(\text{tmpa})]_2(\mu\text{-N}_2\text{O}_2^{2-})]^{2+}$ (2 mM in MeOH/EtOH = 1:1 glass) at 20 K ($g_{\perp} = 2.18$, $g_{\parallel} = 1.99$; $A_{\perp} = 82 \text{ G}$, $A_{\parallel} = 90 \text{ G}$).



With the intention of further supporting our complex formulation, we probed the $\text{Cu}^{\text{I}}/\text{NO}_{(\text{g})}$ stoichiometry; $[\text{Cu}^{\text{I}}(\text{tmpa})(\text{MeCN})]^+$ was titrated with varying amounts of $\text{NO}_{(\text{g})}$ from a $\text{NO}_{(\text{g})}$ -saturated MeOH solution $\{[\text{NO}_{(\text{g})}] = 14.5 \text{ mM}$ at RT.¹² The data clearly indicates that the $\text{Cu}^{\text{I}}/\text{NO}_{(\text{g})}$ stoichiometry, as measured in this manner, lies between 1 and 1.5, very close to the expected 1:1 stoichiometry.¹²⁻¹³ It is presumed that $\text{NO}_{(\text{g})}$ reaction with $[\text{Cu}^{\text{I}}(\text{tmpa})(\text{MeCN})]^+$ gives a Cu^I-NO adduct, perhaps like that previously reported on (but in EtCN),¹⁴ prior to $\text{NO}_{(\text{g})}$ -coupling to give the hyponitrito-dicopper(II) complex (Eq. 1).⁵

$[[\text{Cu}^{\text{II}}(\text{tmpa})]_2(\mu\text{-N}_2\text{O}_2^{2-})]^{2+}$ can also be generated by a metathesis reaction involving the Cu^{II}-OH complex, $[\text{Cu}^{\text{II}}(\text{tmpa})(\text{OH})]^+$, generated and isolated by reaction of tetrabutylammonium hydroxide with $[\text{Cu}^{\text{II}}(\text{tmpa})(\text{MeCN})](\text{ClO}_4)_2$ in MeCN at RT ($\nu(\text{O-H}) = 3533 \text{ cm}^{-1}$).¹² Freshly generated $[\text{Cu}^{\text{II}}(\text{tmpa})(\text{OH})]^+$ mixing with $\frac{1}{2}$ equiv $\text{Ag}_2\text{N}_2\text{O}_2$ in MeOH, with sonication, gave a color change from light green to forest green. The UV-vis changes correspond with those seen for the hyponitrito-dicopper(II) complex obtained via the $\{[\text{Cu}^{\text{I}} + \text{NO}_{(\text{g})}]\}$ reaction.¹² Isolation of the solid product and redissolution into a MeOH/EtOH = 1:1 solution also gives the same EPR spectrum (20 K).¹²

X-ray quality crystals of $[[\text{Cu}^{\text{II}}(\text{tmpa})]_2(\mu\text{-N}_2\text{O}_2^{2-})](\text{ClO}_4)_2$ could be obtained from MeOH at $-35 \text{ }^\circ\text{C}$, and the structure of the dicationic portion is shown in Figure 3. The complex possesses a dicopper-bridged $\eta^1\text{-O-trans}$ -hyponitrite species with a Cu...Cu distance of 5.5647(5) Å; the dication possesses a centrosymmetric structure. Each copper(II) ion is pentacoordinate, with the four N-atoms from the TMPA chelate plus the anionic hyponitrito O-atoms (O1 or O1'; Figure 3). However, there also exists a clear interaction of Cu ions with the distal N-atom of the $\text{N}_2\text{O}_2^{2-}$ moiety, (Cu-N = 2.851(2) Å), i.e., Cu1 interacts with N5', with Cu1' interacting with N5 (Figure 3, shown in broken lines). See the SI (page S10) for information and arguments in support of this point. We hypothesize that this weak interaction transforms into a "true" metal-ligand bond when $[[\text{Cu}^{\text{II}}(\text{tmpa})]_2(\mu\text{-N}_2\text{O}_2^{2-})]^{2+}$ is put into aprotic solvents (*vide infra*; Scheme 1).

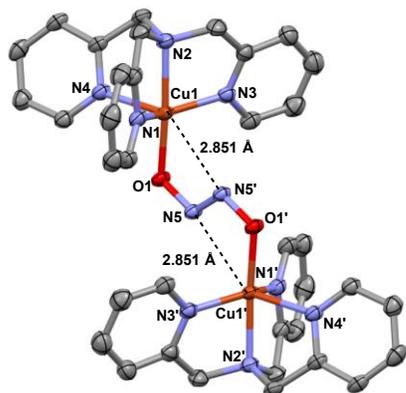
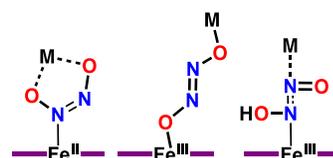


Figure 3. X-ray diffraction ORTEP diagram (50% probability thermal ellipsoids) of $[\{\text{Cu}^{\text{II}}(\text{tmpa})\}_2(\mu\text{-N}_2\text{O}_2^{2-})]^{2+}$ along with the atom numbering scheme. Hydrogen atoms and noncoordinating perchlorate counteranions are omitted for clarity.¹²

Thus, the copper(II) ions in this structure are distorted octahedrally ligated (six-coordinate), which contrasts greatly with other many well characterized $[\text{Cu}^{\text{II}}(\text{tmpa})(\text{X})]^{n+}$ species such as those with $\text{X} = \text{Cl}^-$ ($n = 1$),¹⁵ $\text{X} = \text{nitrito} (\text{NO}_2^-, \text{O-bound}; n = 1)$ ¹⁶ and $\text{X} = \text{NCCH}_3$ ($n = 2$).¹⁷ Recall that methanolic solutions of $[\{\text{Cu}^{\text{II}}(\text{tmpa})\}_2(\mu\text{-N}_2\text{O}_2^{2-})]^{2+}$ possess a well-defined TBP coordination geometry, as distinctly and unambiguously observed from frozen solution EPR spectra (*vide supra*). In fact, this hyponitrito-dicopper(II) complex $[\{\text{Cu}^{\text{II}}(\text{tmpa})\}_2(\mu\text{-N}_2\text{O}_2^{2-})]^{2+}$ is only stable in alcoholic solvents; we thus conclude that the latter observation indicates that MeOH hydrogen-bonds to the $\text{N}_2\text{O}_2^{2-}$ ligand of the complex, probably with the lone pairs on the central N-atoms. Such an interaction has recently been suggested by Liaw and coworkers¹⁸ although in that case H-bonding to the $\text{Co}^{\text{II}}\text{-NO}$ O-atom is proposed, which aids the formation of a hyponitrite meta-stable species. Such H-bonding in solution would ‘relieve’ the structurally observed weak interaction between N5 or N5’ with copper(II) ion, leaving only the O1-to-Cu1 (and O1’-to-Cu1’) bond interaction in addition to N4 ligation from TMPA, allowing for strict TBP coordination (as expected from EPR spectra).

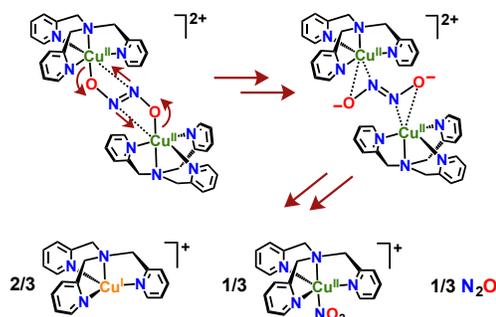
Further aspects of the solid-state structure of $[\{\text{Cu}^{\text{II}}(\text{tmpa})\}_2(\mu\text{-N}_2\text{O}_2^{2-})]^{2+}$ are as follows: (a) The N–N and N–O distances of the *trans*-hyponitrite moiety are 1.257(3) Å and 1.361(2) Å respectively, which compare well with the N=N double bond (1.256(2) Å) and N–O single bond (1.3622(11) Å) distances of *trans*-sodium hyponitrite.^{5b} (b) The Cu...Cu distance of 5.565(7) Å is much shorter compared with the Fe–Fe distance (6.7 Å) in $[(\text{OEP})\text{Fe}^{\text{III}}\text{-ONNO-Fe}^{\text{III}}(\text{OEP})]$ (OEP = octaethylporphyrinate), with extended hyponitrito; O,O’ bonding to iron(III) occurs, but there are no Fe...N_(hyponitrite) interactions.^{20c} (c) The Cu...Cu distance here is virtually identi-

cal to that (5.566 Å) of the Agapie’s¹⁹ copper-yttrium complex with bridged copper-bound hyponitrite adduct. (d) A number of differing structures have been proposed based on computational analyses for HCO, NOR or other protein hyponitrite species (see diagram below; M = Fe or Cu).^{4e,6d,20}



When solid samples of $[\{\text{Cu}^{\text{II}}(\text{tmpa})\}_2(\mu\text{-N}_2\text{O}_2^{2-})]^{2+}$ (as $(\text{B}(\text{C}_6\text{F}_5)_4)^-$ or ClO_4^- salts) are dissolved in THF, or excess THF is added to the complex already dissolved in MeOH, a reaction takes place, and a mixture of products are formed (Figure 1), which we hypothesize to arise from a rearrangement of the $\text{N}_2\text{O}_2^{2-}$ ligand,²¹ followed by transformations leading to the products seen from reaction of $\text{Cu}^{\text{I}}(\text{tmpa})]^+ + \text{NO}_{(\text{g})}$ in non-alcoholic solvents, namely $\text{NO}_{(\text{g})}$ -disproportionation, $3\text{NO}_{(\text{g})} + \text{Cu}^{\text{I}} \rightarrow \text{N}_2\text{O}_{(\text{g})} + \text{Cu}^{\text{II}}\text{-NO}_2^-$. We speculate that either THF effects a “reverse” reaction to give a $\{\text{Cu}^{\text{I}}(\text{tmpa})\}^+ + \text{NO}$ solutions, or $[\{\text{Cu}^{\text{II}}(\text{tmpa})\}_2(\mu\text{-N}_2\text{O}_2^{2-})]^{2+}$ reacts to give $\text{N}_2\text{O}_{(\text{g})}$ and the Cu^{II} -nitrito complex by an as yet undetermined mechanism. However, since there is only one equiv. of $\text{NO}_{(\text{g})}$ per Cu(I) ion present, excess $[\{\text{Cu}^{\text{I}}(\text{tmpa})\}]^+$ is left over, giving the mixture of products described by Scheme 1.

Scheme 1. Proposed decay of $[\{\text{Cu}^{\text{II}}(\text{tmpa})\}_2(\mu\text{-N}_2\text{O}_2^{2-})]^{2+}$ placed in THF, giving a final product mixture consisting of $[\text{Cu}^{\text{I}}(\text{tmpa})]^+$, $[\text{Cu}^{\text{II}}(\text{tmpa})(\text{NO}_2)]^+$, and $\text{N}_2\text{O}_{(\text{g})}$.



Experiments carried out on the final product solution confirm the identity, yields and relative-yields of the transformation of $[\{\text{Cu}^{\text{II}}(\text{tmpa})\}_2(\mu\text{-N}_2\text{O}_2^{2-})]^{2+}$ originally formed by the $\{\text{Cu}^{\text{I}} + \text{NO}_{(\text{g})}\}$ reaction (*vide supra*) (with stoichiometry of Scheme 1). (a) Cooling the decay product mixture in THF to -80°C and bubbling with $\text{O}_2_{(\text{g})}$ led to the formation of the well-known *trans*-peroxodicopper(II) complex, $[\{\text{Cu}^{\text{II}}(\text{tmpa})\}_2(\mu\text{-O}_2^{2-})]^{2+}$,²² with known molar absorptivities, one could related back to the finding of a 96% yield of $[\text{Cu}^{\text{I}}(\text{tmpa})]^+$.^{12,22} (b) Previously published methodologies¹⁶ were followed to de-

termine and quantify the nitrite content in the final decay mixture, giving >85 % yields,¹² and (c) the headspace of the decay product mixture was sampled by gas chromatographic analysis for the identification and quantitation of product N₂O_(g); yields of ~85 % were obtained.¹² The decay of [{Cu^{II}(tmpa)}₂(μ-N₂O₂²⁻)]²⁺ originally formed by the {Cu^{II}-OH + Ag₂N₂O₂} method (*vide supra*), gave 96 % [Cu^I(tmpa)]⁺, > 85 % yield of nitrite and 98 % yield N₂O_(g),¹² again all based on the Scheme 1 reaction stoichiometry.

Finally, to further verify the solvent effect for the {[Cu^I(tmpa)]⁺ + NO_{(g)}} reaction, we carried out separate experiments. When [Cu(tmpa)(MeCN)]⁺ is subjected to excess NO_(g) in THF solution at RT, the pale yellow solution immediately turns to an olive green color exhibiting the UV-vis features corresponding to the nitrito complex [Cu^{II}(tmpa)(NO₂)]⁺ (96 % yield) λ_{max} = 303 (ε = 3360 M⁻¹ cm⁻¹), 420 (ε = 1340 M⁻¹ cm⁻¹) nm. N₂O_(g) is also produced, so we can conclude that NO-disproportionation occurs.^{1b} As described in detail above, in MeOH as solvent, the hyponitrito dicopper(II) complex forms. It is remarkable how the reactivity between [Cu^I(tmpa)]⁺ and NO_(g) modify to such great extent merely by altering the solvent properties.

In summary, herein we report the first Cu-only system that mediates the reductive coupling of NO_(g), stoichiometrically yielding the corresponding hyponitrito-dicopper(II) complex in MeOH at RT. We suggest that H-bonding to the N₂O₂²⁻ ligand is key to its stabilization and this course of reaction. Unlike other synthetic bio-inspired examples,^{5a,7b,19,23} this reaction does not require any low-temperature conditions, and is independent of the equiv of added NO_(g). The new hyponitrito complex possesses versatile synthetic pathways, and is characterized by X-ray crystallography. Dissolution in aprotic solvents triggers its decay with essentially the reversal of NO_(g) coupling, leading to products of Cu^I-mediated NO-disproportionation. We should also note that addition of HCl to [{Cu^{II}(tmpa)}₂(μ-N₂O₂²⁻)]²⁺ in MeOH gives rise to the release of N₂O_(g).¹² Such unique redox behavior involving copper and NO_(g) is unprecedented, and may have implications in metalloenzyme related NO_(g)/nitrogen-oxide biochemistry. A deeper understanding is needed as pertains to the NO-coupling mechanism (N–N bond formation), the oxidation and/or protonation state of the N₂O₂-type intermediate formed^{6a,9,11,24} and the mechanism of (N–O bond cleavage) N₂O_(g) formation.

ASSOCIATED CONTENT

Synthetic and analytical details (methodologies and UV-Vis, EPR, NMR and FT-IR spectra; gas chromatograms); X-ray diffraction data collection details and CIF file. This ma-

terial is available free of charge via the Internet at <http://pubs.acs.org>.

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No competing financial interests have been declared.

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(12) See Supporting Information.

(13) $\text{NO}_{(\text{g})}$ -saturated solutions used likely lose some $\text{NO}_{(\text{g})}$ into the headspace of the Ar-filled cuvette containing $[\text{Cu}^{\text{I}}(\text{tmpa})(\text{MeCN})]^+$ during each experiments, while $\text{NO}_{(\text{g})}$ equilibrates between the liquid-gas interface. Thus, the actual $\text{Cu}^{\text{I}}:\text{NO}_{(\text{g})}$ stoichiometry could be slightly smaller than the experimentally observed ratio.

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TOC Graphic

