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Synthesis and Structural Characterization of a Mononuclear Copper Nitrosyl Complex

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The interactions of nitrogen oxides with copper ions in biological systems are important in the global nitrogen cycle.[1] Copper-containing enzymes play a central role in denitrification, whereby bacteria use NO_3^- and NO_2^- as terminal electron acceptors ultimately to produce gaseous nitrogenous products (NO, N_2O, and/or N_2).[2] A copper-NO species has been suggested to be a key intermediate in biological nitrogen oxide reduction,[3] and nitrosyl adducts to other copper proteins also have been postulated.[4] In the nitrite reductase (NiR) from *Achromobacter cycloclastes*, the nitrosyl is believed to form at a single copper ion that, in the resting enzyme, is coordinated by three histidines and an aquo or hydroxo moiety in an unusual pseudotetrahedral array.[3,5,6] Although well-known for most transition metals, nitrosyl complexes of copper are rare,[7-9] and no mononuclear copper compound with a terminal NO ligand has been isolated. We report the first example of such a molecule, prepared by treatment of a novel dicopper(I) complex with NO(g).

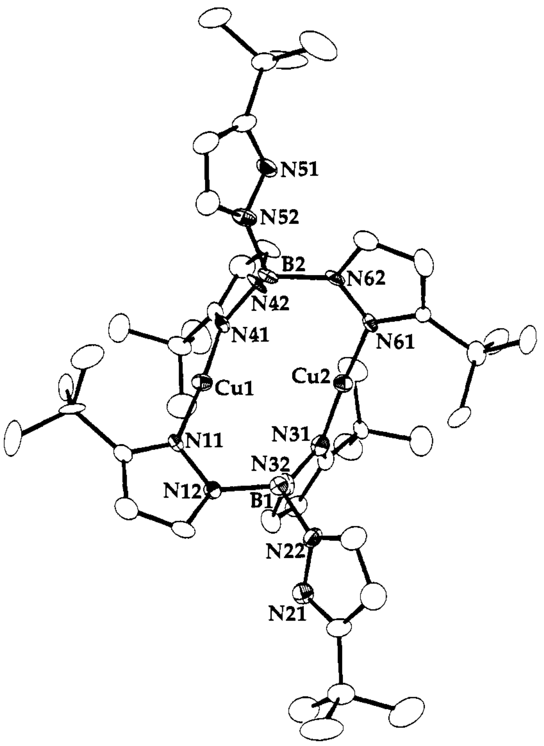

Figure 1. ORTEP drawing of $\mathbf{1}\cdot C_4H_{10}O$ showing 60% probability thermal ellipsoids and atom labels for all non-hydrogen atoms (excluding Et_2O solvate molecule; atom labels for carbon atoms omitted for clarity). Selected interatomic distances (Å) and angles (deg) are as follows: Cu1-N11, 1.874 (9); Cu1-N41, 1.883 (9); Cu2-N31, 1.882 (9); Cu2-N61, 1.860 (8); Cu···Cu, 3.284 (8); N11-Cu1-N41, 176.7 (4); N31-Cu2-N61, 176.5 (4).

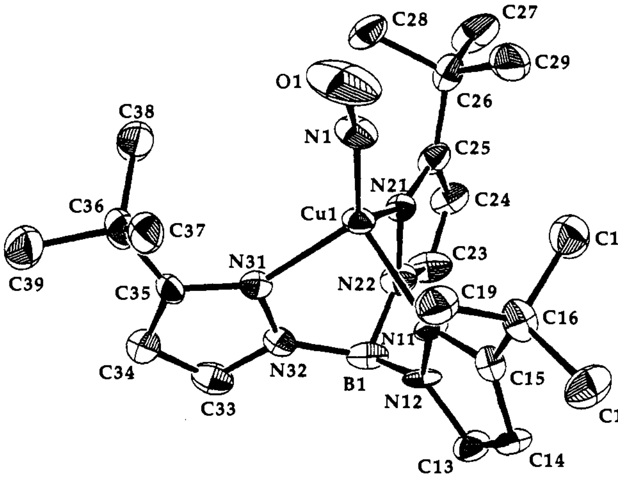

Figure 2. ORTEP drawing of $\mathbf{4}\cdot 0.5C_9H_{12}$ showing 40% probability thermal ellipsoids and atom labels for all non-hydrogen atoms (excluding the mesitylene solvate molecule). Selected interatomic distances (Å) and angles (deg) are as follows: Cu1-N1, 1.759 (6); Cu1-N11, 2.054 (5); Cu1-N21, 2.091 (5); Cu1-N31, 2.044 (5); N1-O1, 1.108 (7); Cu1-N1-O1, 163.4 (6); N1-Cu1-N11, 124.3 (2); N1-Cu1-N21, 120.4 (2); N1-Cu1-N31, 124.6 (2); N11-Cu1-N21, 92.9 (2); N11-Cu1-N31, 93.4 (2); N21-Cu1-N31, 92.7 (2).

The reaction of $Tl[HB(t\text{-}Bupz)_3]$[10] with CuCl in THF yielded colorless $\{[HB(t\text{-}Bupz)_3]Cu\}_2$ (**1**), an unusual dimer containing linear 2-coordinate Cu(I) ions linked by $\eta^2\text{-}[HB(t\text{-}Bupz)_3]^-$ ligands

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(1) (a) Smil, V. *Carbon Nitrogen Sulfur: Human Interference in Grand Biospheric Cycles*; Plenum Press: New York, 1985; pp 115-250. (b) Delwiche, C. C. *Ambio* **1977**, *6*, 106-111.

(2) *Denitrification, Nitrification, and Atmospheric Nitrous Oxide*; Delwiche, C. C., Ed.; John Wiley & Sons: New York, 1981. (b) Payne, W. J. *Denitrification*; John Wiley & Sons: New York, 1981. (c) Hochstein, L. I.; Tomlinson, G. A. *Annu. Rev. Microbiol.* **1988**, *42*, 231-261. (d) Zumft, W. G.; Viebrock, A.; Körner, H. In *The Nitrogen and Sulphur Cycles*; Cole, J. A., Ferguson, S. J., Eds.; Cambridge University Press: Cambridge, 1988; pp 245-280.

(3) (a) Hulse, C. L.; Averill, B. A.; Tiedje, J. M. *J. Am. Chem. Soc.* **1989**, *111*, 2322-2323. (b) Ye, R. W.; Toro-Suarez, I.; Tiedje, J. M.; Averill, B. A. *J. Biol. Chem.* **1991**, *266*, 12848-12851. (c) Jackson, M. A.; Tiedje, J. M.; Averill, B. A. *FEBS Lett.* **1991**, *291*, 41-44.

(4) (a) Gorren, A. C. F.; de Boer, E.; Wever, R. *Biochim. Biophys. Acta* **1987**, *916*, 38-47. (b) Tahon, J.-P.; Hoof, D. V.; Vinckier, C.; Witters, R.; Ley, M. D.; Lontie, R. *Biochem. J.* **1988**, *249*, 891-896. (c) Wever, R.; Boelens, R.; de Boer, E.; Van Gelder, B. F.; Gorren, A. C. F.; Rademaker, H. *J. Inorg. Biochem.* **1985**, *23*, 227-232. (d) Schoot Uiterkamp, A. J. M. *FEBS Lett.* **1972**, *20*, 93-96. (e) Schoot Uiterkamp, A. J. M.; Van der Deen, H.; Berendsen, H. C. J.; Boas, J. F. *Biochim. Biophys. Acta* **1974**, *372*, 407-425. (f) Schoot Uiterkamp, A. J. M.; Mason, H. S. *Proc. Natl. Acad. Sci. U.S.A.* **1973**, *70*, 993-996. (g) Verplaetse, J.; Tornout, P. V.; Defreyn, G.; Witters, R.; Lontie, R. *Eur. J. Biochem.* **1979**, *95*, 327-331. (h) Van der Deen, H.; Hoving, H. *Biochemistry* **1977**, *16*, 3519-3525. (i) Himmelwright, R. S.; Eickman, N. C.; Solomon, E. I. *Biochem. Biophys. Res. Commun.* **1978**, *81*, 237-242. (j) Himmelwright, R. S.; Eickman, N. C.; Solomon, E. I. *Biochem. Biophys. Res. Commun.* **1979**, *86*, 628-634. (k) Spira, D. J.; Solomon, E. I. *Biochem. Biophys. Res. Commun.* **1983**, *112*, 729-736. (l) Rotilio, G.; Morpurgo, L.; Graziani, M. T.; Brunori, M. *FEBS Lett.* **1975**, *54*, 163-166. (m) Dooley, D. M.; Rawlings, J.; Dawson, J. H.; Stephens, P. J.; Andreasson, L.-E.; Malmstrom, B. G.; Gray, H. B. *J. Am. Chem. Soc.* **1979**, *101*, 5038-5046. (n) Martin, C. T.; Morse, R. H.; Kanne, R. M.; Gray, H. B.; Malmstrom, B. G.; Chan, S. I. *Biochemistry* **1981**, *20*, 5147-5155. (o) Van Leeuwen, X. R.; Van Gelder, B. F. *Eur. J. Biochem.* **1978**, *87*, 305-312. (p) Wever, R.; Van Leeuwen, F. X. R.; Van Gelder, B. F. *Biochim. Biophys. Acta* **1973**, *302*, 236-239.

(5) Suzuki, S.; Yoshimura, T.; Kohzuma, T.; Shidara, S.; Masuko, M.; Sakurai, T.; Iwasaki, H. *Biochem. Biophys. Res. Commun.* **1989**, *164*, 1366-1372.

(6) Godden, J. W.; Turley, S.; Teller, D. C.; Adman, E. T.; Liu, M.-Y.; Payne, W. J.; LeGall, J. *Science* **1991**, *253*, 438-442.

(7) Functional modeling of NiR involving dicopper species: Paul, P. P.; Karlin, K. D. *J. Am. Chem. Soc.* **1991**, *113*, 6331-6332.

(8) (a) Yordanov, N. D.; Terziev, V.; Zhelyazkowa, B. G. *Inorg. Chim. Acta* **1982**, *58*, 213-216. (b) Mercer, M.; Fraser, R. T. M. *J. Inorg. Nucl. Chem.* **1963**, *25*, 525-534. (c) Doyle, M. P.; Siegfried, B.; Hammond, J. J. *J. Am. Chem. Soc.* **1976**, *98*, 1627-1629.

(9) Paul, P. P.; Tyeklar, Z.; Farooq, A.; Karlin, K. D.; Liu, S.; Zubieta, J. *J. Am. Chem. Soc.* **1990**, *112*, 2430-2432.

(10) Trofimenko, S.; Calabrese, J. C.; Thompson, J. S. *Inorg. Chem.* **1987**, *26*, 1507-1514.

0002-7863/92/1514-4407$03.00/0

(Figure 1).[11,12] The structure, which differs from that of $\{[HB(pz)_3]Cu\}_2$ and $\{[HB(3,5\text{-}Me_2pz)_3]Cu\}_2$[13] because of the noncoordinated pyrazolyl rings, is retained in solution (MW measurements[14] and ^1H NMR at −50 °C, with intramolecular exchange of bound and unbound pyrazolyl groups evident from NMR peak broadening and coalescence at higher temperatures).

Complex **1** afforded monomeric, pseudotetrahedral $[HB(t\text{-}Bupz)_3]CuX$ species in the presence of added ligands [X = CH_3CN (**2**), CO (**3**), or NO (**4**)].[11] Notably, treatment of a colorless solution of compound **1** or **2** in aromatic solvent at room temperature with NO (1 atm) yielded a deep red solution that deposited $[HB(t\text{-}Bupz)_3]Cu(NO)\cdot nS$ (**4**·*n*S; S = toluene, *n* = 1; S = mesitylene, *n* = 0.5) as red prisms upon cooling to −20 °C.[11] Identification of **4** as the first example of a molecule containing a terminal nitrosyl ligand bonded to copper is based on observation of a strong absorption in its FTIR spectrum at 1712 cm^{-1} [$\nu(^{15}NO)$ = 1679 cm^{-1}], hyperfine coupling of the unpaired electron to Cu and NO in the X- and S-band EPR spectra of ^{14}NO and ^{15}NO adducts,[15] and a low-temperature (−101 °C) X-ray crystal structure determination (Figure 2).[16] Like most other transition metal nitrosyls,[17] the Cu1–N1 distance in **4** is short [1.759 (6) Å], indicating the presence of some degree of multiple bonding. Small but significant bending of the unique, electron-rich $\{CuNO\}^{11}$ unit [Cu1–N1–O1 angle = 163.4 (6)°] suggests some occupation of antibonding π-type orbitals, however.[17a,c] The overall geometry about copper is approximately tetrahedral [dihedral angles = 90 (1)°], although intraligand angles between the pyrazole nitrogens (N_{pz}) are less than 109.5° (average N_{pz}–Cu–N_{pz} = 93.0°), N1–Cu1–N_{pz} angles are greater than that value (average = 123.1°), and N1 resides 0.083 Å from the normal of the plane defined by the N_{pz} atoms.

Solutions of **4** are stable for weeks when stored at −20 °C, but the UV–vis absorption features [λ_{max} (ε): 356 (1870), 490 (940) nm] at room temperature bleached upon brief application of vacuum or purging with argon, signaling ejection of NO (identified by GC). Readdition of NO (1 atm) restored the original spectrum, implicating reversible binding of NO to either **1** or **2**. In contrast, displacement of NO from **4** by CO (1 atm) quantitatively (UV–vis), rapidly, and irreversibly afforded **3**. Complex **4** also immediately reacted with O_2 at room temperature to yield $[HB(t\text{-}Bupz)_3]Cu(NO_3)$.[10,18]

Complex **4** provides the first unequivocal chemical precedent for NO coordination to isolated copper sites in proteins. Because of its pseudotetrahedral geometry and biomimetic triad of heterocyclic N donor ligands, the compound is a particularly suitable model for the *A. cycloclastes* NiR active site. Although it differs from the proposed enzymatic nitrite dehydration product with respect to oxidation level [$\{CuNO\}^{11}$ for **4** vs $\{CuNO\}^{10}$ proposed for NiR],[3] a species resembling **4** both in terms of structure and lability of coordinated NO may be envisioned to arise either upon one-electron reduction of the purported NiR nitrosonium intermediate by the nearby type 1 copper center[6] or upon binding of NO(g) to a previously reduced active site.[19] Such a species may play a significant role in denitrification pathways,[3,19] as well as in nitrogen oxide reactions with other copper proteins.[4] Future studies of the chemistry of **4** and other related molecules[20] will assess these possibilities.

Acknowledgment. We thank Professor Doyle Britton for his work on the X-ray structure of **4**, Professors Kenneth D. Karlin, Elinor T. Adman, and Bruce A. Averill for supplying preprints of refs 7, 6, and 3c, respectively, Professor John Lipscomb for providing access to his EPR facility, and the University of Minnesota for financial support.

Supplementary Material Available: Analytical and spectroscopic data for **1**–**4**, procedures used for analysis of the X-ray crystallographic data for $\mathbf{4}\cdot 0.5C_9H_{12}$, and tables of bond lengths and angles as well as atomic positional and thermal parameters for $\mathbf{1}\cdot C_4H_{10}O$ and $\mathbf{4}\cdot 0.5C_9H_{12}$ (30 pages). Ordering information is given on any current masthead page.

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(11) Analytical and spectroscopic data for compounds **1**–**4** are reported in the supplementary material.

(12) Crystal data for $\mathbf{1}\cdot C_4H_{10}O$, size 0.55 × 0.35 × 0.10, M_r = 963.91, space group $P2_1/n$ (No. 14), at −101 °C: a = 19.001 (8) Å, b = 13.629 (8) Å, c = 21.490 (7) Å, β = 113.01 (3)°, V = 5122 (8) $Å^3$, Z = 4, σ_{calcd} = 1.250 g cm^{-3}. For a total of 8123 unique, observed reflections with $I > 2\sigma(I)$ and 541 variable parameters, the discrepancy indices are R = 0.082 and R_w = 0.075. Full tables of bond lengths, bond angles, and atomic positional and thermal parameters for $\mathbf{1}\cdot C_4H_{10}O$ are available in the supplementary material.

(13) Mealli, C.; Arcus, C. S.; Wilkinson, J. L.; Marks, T. J.; Ibers, J. A. *J. Am. Chem. Soc.* **1976**, *98*, 711–718.

(14) MW found (calcd) = 940 (890) g mol^{-1} (Signer method: Burger, B. J.; Bercaw, J. E. In *Experimental Organometallic Chemistry: A Practicum in Synthesis and Characterization*; Wayda, A. L., Darensbourg, M. Y., Eds.; ACS Symposium Series 357; American Chemical Society: Washington, DC, 1987; pp 80–98).

(15) Estimated values from simulations of X- and S-band data are $A(Cu_\perp)$ = 65 G, $A(Cu_\parallel)$ = 117 G, $A(^{14}NO)$ = 34 G, and $A(^{15}NO)$ = 43 G (Antholine, W. E.; Ruggiero, C. E.; Carrier, S. M.; Tolman, W. B. Unpublished results). A full description of the EPR properties of **4** will be presented elsewhere.

(16) (a) Crystal data for $\mathbf{4}\cdot 0.5C_9H_{12}$ ($C_{25.5}H_{40}BCuN_7O$), size 0.60 × 0.50 × 0.40 mm, M_r = 535.00, space group $P2_1/n$ (No. 14), at −101 °C: a = 10.28 (1) Å, b = 17.40 (2), Å, c = 16.12 (1) Å, β = 90.0 (1)°, V = 2882 (8) $Å^3$, Z = 4, ρ_{calcd} = 1.233 g cm^{-3}. Although the cell dimensions suggested an orthorhombic unit cell, the Laue symmetry, $2/m$, indicated a monoclinic cell. For 3399 unique, observed reflections with $I > 2\sigma(I)$ and 287 variables, least-squares refinement converged with unsatisfactory values for the discrepancy indices R and R_w of 0.128 and 0.155, respectively, due to twinning that was estimated[13b] to be 10–15% from the pattern of observed intensities of pairs of reflections *hkl* and *h,k−l*. In the absence of any untwinned crystals, refinements continued with the program CRYSTALS (Chemical Crystallography Laboratory, Oxford University, Oxford, England) using calculated structure factors that included contributions from the twin elements (see supplementary material for full description of procedure used). Least-squares refinements then converged smoothly to values for R and R_w of 0.052 and 0.065 for 2866 reflections having $I > 3\sigma(I)$ and 293 variable parameters. (b) Britton, D. *Acta Crystallogr., Sect. A* **1972**, *28*, 296–297.

(17) (a) Feltham, R. D.; Enemark, J. H. In *Topics in Stereochemistry*; Geoffroy, G. L., Ed.; Wiley: New York, 1981; Vol. 12, pp 155–215. (b) Michael, D.; Mingos, P.; Sherman, D. J. *Adv. Inorg. Chem.* **1989**, *34*, 293–377. (c) The CuNO unit in **4** is described according to the $\{M(NO)_m\}^n$ formalism described in ref 17a, where *n* denotes the sum of metal d and NO π^* electrons.

(18) Han, R.; Parkin, G. *J. Am. Chem. Soc.* **1991**, *113*, 9707–9708.

(19) Free NO(g) is an intermediate in denitrification by some organisms; see ref 3 and the following: Braun, C.; Zumft, W. G. *J. Biol. Chem.* **1991**, *266*, 22785–22788 and references therein.

(20) Tolman, W. B. *Inorg. Chem.* **1991**, *30*, 4877–4880.

Novel Construction of Polycyclic Systems Fused to Cyclobutane by Tandem Intramolecular Michael–Aldol Reaction

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A number of polycyclic compounds possessing a cyclobutane, such as endiandric acids A (**1a**),[1] B (**1b**),[1] and C (**2**),[1] trihydroxydecipiadiene (**3**),[2] italicene (**4a**),[3] and isoitalicene (**4b**),[3] have been found in nature (Chart I). Although several methods are available for the synthesis of cyclobutane derivatives having a high degree of ring strain, [2 + 2] photocycloaddition is the most common synthetic method for assembling the cyclobutane skeleton.[4] Here we disclose a novel construction of polycyclic ring

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(1) Banfield, J. E.; Black, D. St. C.; Johns, S. R.; Willing, R. I. *Aust. J. Chem.* **1982**, *35*, 2247–2256. Nicolaou, K. C.; Petasis, N. A.; Zipkin, R. E.; Uenishi, J. *J. Am. Chem. Soc.* **1982**, *104*, 5555–5557.

(2) Ghisalberti, E. L.; Jefferies, P. R.; Sheppard, P. *Tetrahedron Lett.* **1975**, 1775–1778. Greenlee, M. L. *J. Am. Chem. Soc.* **1981**, *103*, 2425–2426. Dauben, W. G.; Shapiro, G. *J. Org. Chem.* **1984**, *49*, 4252–4258.

(3) Leimner, J.; Marschall, H.; Meier, N.; Weyerstahl, P. *Chem. Lett.* **1984**, 1769–1772. Honda, T.; Ueda, K.; Tsubuki, M.; Toya, T.; Kurozumi, A. *J. Chem. Soc., Perkin Trans. 1* **1991**, 1749–1754.

0002-7863/92/1514-4408$03.00/0