The ability to control the chemoselectivity of enzymatic modification, apart from its synthetic value for aminoalcohols, if understood mechanistically (currently under investigation), might be extendable to other heterofunctional compounds.

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(13) This work was financially supported by Grant GM39794 from the National Institutes of Health. We are grateful to Professor Thorleif Anthonsen (University of Trondheim, Norway) for helpful discussions. The Thr-Thr dipeptide was synthesized by Dr. Dar-Fu Tai.

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## Dioxygen-Copper Reactivity. Comparisons of the Reactions of Electrophiles and Other Reagents with Three Classes of Peroxo-Dicopper(II), $\{Cu_2-O_2\}^{n+}$, Species

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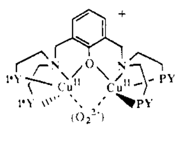
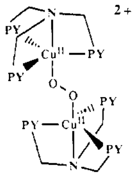
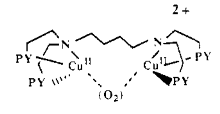
We have recently described three types of peroxo-dicopper(II) complexes, $\{Cu_2-O_2\}^{n+}$ (**1-3**, $n$ = 1 or 2, PY = 2-pyridyl), which



**1**



**2**



**3**

are formed reversibly by the addition of $O_2$ to either mono- or dinuclear copper(I) complexes at -80 °C in solution. $[Cu_2(XYL\text{-}O\text{-})(O_2)]^+$ (**1**), contains an unsymmetrically bound peroxo ligand ($\nu_{O-O}$ = 803 $cm^{-1}$) in a phenoxo-bridged dicopper(II) unit.[1] The X-ray crystal structure of **2** features a trans $\mu$-1,2-peroxo ligand bound to Cu(II) ions in $[(LCu)_2-(O_2)]^{2+}$ (L = tris[(2-pyridyl)methyl]amine).[2] We have also described a series of $\{Cu_2-O_2\}^{2+}$ complexes such as $[Cu_2(N4PY2)(O_2)]^{2+}$ (**3**), which possess tridentate nitrogen donor groups connected by various hydrocarbon units.[3] In order to provide insights into the structures of **1-3** and the nature (e.g., nucleophilic or electrophilic) of the bound dioxygen (peroxo) ligands, we are carrying out a series of reactivity studies. Here, we report preliminary results of reactions of complexes **1-3** with the reagents $SO_2$, $CO_2$, $H^+$, $ArC(O)^+$, $PPh_3$, and PhMgBr. We find that **1** and **2** react like other $M_n-O_2$ complexes which have a basic or nucleophilic peroxo moiety;[4] however, **3** behaves otherwise.

Sulfur dioxide and carbon dioxide are electrophilic reagents commonly used in reactivity studies involving metal-dioxygen species.[4] The $\{Cu_2-O_2\}^{n+}$ complexes (**1-3**) all react at -80 °C with $SO_2$ to give sulfato-containing dicopper(II) compounds.[5] However, with respect to addition of $CO_2$, dioxygen-copper complex **3** behaves differently than **1** or **2**, and there is no reaction. Carbon dioxide reacts with the latter leading to the formation of carbonato complexes. Thus, addition of $CO_{2(g)}$ to **1** at -80 °C in $CH_2Cl_2$ causes the loss of the characteristic 505-nm band[1] producing a green ($\lambda_{max}$ = 340 nm ($\epsilon$ = 3700) and 400 nm ($\epsilon$ = 3800)) solution, presumed to contain a peroxycarbonato species.[6] Either via thermal decomposition or by reaction of this solution with $PPh_3$ (producing $O{=}PPh_3$), a $\mu$-$CO_3^{2-}$ complex, $[Cu_2(XYL\text{-}O\text{-})(CO_3^{2-})]^+$, is formed.[7]

$$Cu^{II}_2(O_2^{2-}) + CO_2 \rightarrow Cu^{II}_2(CO_4^{2-}) + \text{warming} \rightarrow Cu^{II}_2(CO_3^{2-})$$

$$Cu^{II}_2(O_2^{2-}) + CO_2 \rightarrow Cu^{II}_2(CO_4^{2-}) + PPh_3 \rightarrow Cu^{II}_2(CO_3^{2-}) + O{=}PPh_3$$

A similar behavior is observed with **2**, and reaction with $CO_2$ (-80 °C) causes bleaching of the characteristic bands at 525 and 590 nm. The resulting solution reacts with $PPh_3$ to give $O{=}PPh_3$ (97% conversion) and $[(LCu^{II})_2(CO_3^{2-})]^{2+}$.[8] The structure[9,10] of this complex (Figure 1) shows that it contains a bridged-bidentate carbonato group in a dinuclear unit, with each copper(II) ion in a distorted square-pyramidal geometry (axial pyridine N3 and N7).[11,12] This is a somewhat unusual geometry for Cu(II) complexes of L, which normally are found in trigonal bipyramidal coordination.[2]

In reactions with $H^+$, the dioxygen ligands in **1** and **2** are readily protonated. Addition of 1 mol-equiv of $HBF_4$ or $HPF_6$ at -80 °C to **1** gives a hydroperoxo-dicopper(II) complex, $[Cu_2(XYL\text{-}O\text{-})(OOH)]^{2+}$.[13] With 2 or more equiv, $H_2O_2$ is produced in 88%

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[1] (a) Karlin, K. D.; Cruse, R. W.; Gultneh, Y.; Farooq, A.; Hayes, J. C.; Zubieta, J. *J. Am. Chem. Soc.* **1987**, *109*, 2668-2679. (b) Pate, J. E.; Cruse, R. W.; Karlin, K. D.; Solomon, E. I. *J. Am. Chem. Soc.* **1987**, *109*, 2624-2630. (c) Blackburn, N. J.; Strange, R. W.; Cruse, R. W.; Karlin, K. D. *J. Am. Chem. Soc.* **1987**, *109*, 1235-1237.

[2] Jacobson, R. R.; Tyeklar, Z.; Farooq, A.; Karlin, K. D.; Liu, S.; Zubieta, J. *J. Am. Chem. Soc.* **1988**, *110*, 3690-3692, and references cited therein.

[3] (a) Karlin, K. D.; Haka, M. S.; Cruse, R. W.; Meyer, G. J.; Farooq, A.; Gultneh, Y.; Hayes, J. C.; Zubieta, J. *J. Am. Chem. Soc.* **1988**, *110*, 1196-1207, and references cited therein. (b) Blackburn, N. J.; Strange, R. W.; Farooq, A.; Haka, M. S.; Karlin, K. D. *J. Am. Chem. Soc.* **1988**, *110*, 4263-4272.

[4] (a) Gubelmann, M. H.; Williams, A. F. *Struct. Bonding (Berlin)* **1983**, *55*, 1. (b) Sheldon, R. A.; Kochi, J. K. *Metal-Catalyzed Oxidations of Organic Compounds*; Academic Press: New York, 1981.

[5] The sulfato complexes produced, recrystallized, and characterized are $[Cu_2(XYL\text{-}O\text{-})SO_4]PF_6 \cdot 0.25CH_2Cl_2$ (70% yield): Anal. Calcd for $C_{36.25}H_{39.5}Cl_{0.5}Cu_2F_6N_6O_5PS$: C, 45.30; H, 4.14; N, 8.68. Found: C, 44.94; H, 4.24; N, 8.68: IR (Nujol) $\nu$ (SO) = 1230 (s), 1130 (vs), 970 (s) $cm^{-1}$. $[(LCu)_2(SO_4)](PF_6)_2$ (59% yield): Anal. Calcd for $C_{36}H_{36}Cu_2F_{12}N_8O_4P_2S$: C, 39.53; H, 3.52; N, 10.24. Found: C, 40.39; H, 3.59; N, 10.15: IR (Nujol) $\nu$ (SO) = 1220 (s), 1125 (s), 1000 (s) $cm^{-1}$. $[Cu_2(N4PY2)(CH_3CN)_2](SO_4)(PF_6)_2 \cdot Et_2O$ (54% yield): Anal. Calcd for $C_{40}H_{56}Cu_2F_{12}N_8O_5P_2S$: C, 40.78; H, 4.79; N, 9.51. Found: C, 41.03; H, 4.69; N, 9.77: IR (Nujol) $\nu$ (SO) = 1100 (br) $cm^{-1}$.

[6] Examples of $M-O_2$ systems reacting with $CO_2$ to form peroxycarbonato species are as follows: (a) Hayward, P. J.; Blake, D. M.; Wilkinson, G.; Nyman, C. J. *J. Am. Chem. Soc.* **1970**, *92*, 5873. (b) Tatsuno, Y.; Otsuka, S. *J. Am. Chem. Soc.* **1981**, *103*, 5832. (c) Schappacher, M.; Weiss, R. *Inorg. Chem.* **1987**, *26*, 1190-1192.

[7] $[Cu_2(XYL\text{-}O\text{-})CO_3]PF_6 \cdot 0.5\ CH_2Cl_2$ (87% yield): Anal. Calcd for $C_{37.5}H_{40}ClCu_2F_6N_6O_4P$: C, 47.62; H, 4.23; N, 8.88. Found: C, 47.96; H, 4.32; N, 9.12. IR (Nujol) $\nu$ (CO) = 1535 (m), $cm^{-1}$.

[8] $[L_2Cu_2(CO_3)](ClO_4)_2$ (84% yield): Anal. Calcd for $C_{37}H_{36}Cl_2Cu_2N_8O_{11}$: C, 45.97; H, 3.75; N, 11.59. Found: C, 45.94; H, 3.68; N, 11.61. IR (Nujol) $\nu$ (CO) = 1520 (s), 1340 (vs), 880 (m), 690 (m) $cm^{-1}$. $\mu_{RT} = 1.37\ \mu_B/Cu$.

[9] $[(LCu)_2(CO_3)](ClO_4)_2 \cdot (CH_3CH_2CN)_2$ crystallizes in the triclinic space group $P\bar{1}$ with $a$ = 13.174 (3) Å, $b$ = 13.994 (4) Å, $c$ = 13.978 (4) Å, $\alpha$ = 108.08 (2)°, $\beta$ = 92.01 (2)°, $\gamma$ = 101.49 (2)°, $V$ = 2387 (1) $Å^3$, and $Z$ = 2. A Nicolet R3m/V diffractometer was used in the $\omega$-scan mode to collect 6544 unique reflections of which 3569 reflections with $F_o \geq 6\sigma|F_o|$ were used in the solution and refinement. The positional parameters of the copper atoms were determined by the Patterson method. The remaining non-hydrogen atoms were located on subsequent difference Fourier maps. Hydrogen atoms were calculated and fixed at 0.96 Å for carbon. Anisotropic refinement was carried out on all non-hydrogen atoms of the cation and chlorine atoms in the anions; two molecules of lattice propionitrile per dinuclear unit were identified and located in the final stages of refinement (some disorder is seen for one anion). The structure was refined to the current residual values of $R$ = 0.0748 and $R_w$ = 0.0775 (Mo $K\alpha$, $\lambda$ = 0.71073 Å). For some atoms, the $U$'s are peculiarly anisotropic (Table IV, Supplementary Material); these may be a result of 30% crystal decomposition which was indicated by the decrease in average intensity of three check reflections monitored during data collection.

[10] Supplementary Material.

[11] References to complexes with a similarly coordinated carbonato group are as follows: (a) Gagne, R. R.; Gall, R.; Lisensky, G. C.; Marsh, R. E.; Speltz, L. M. *Inorg. Chem.* **1979**, *18*, 771-781. (b) Churchill, M. R.; Lashewycz, R. A.; Koshy, K.; Dasgupta, T. P. *Inorg. Chem.* **1981**, *20*, 376. (c) Healey, P. C.; White, A. H. *J. Chem. Soc., Dalton Trans.* **1972**, 1913.

[12] Dinuclear bridging tridentate carbonato coordination to Cu(II) is also common: (a) Churchill, M. R.; Davies, G.; El-Sayed, M. A.; Hutchinson, J. P. *Inorg. Chem.* **1982**, *21*, 1002-1007, and references cited therein. (b) Davis, A. R.; Einstein, F. W. B. *Inorg. Chem.* **1980**, *19*, 1203-1207.

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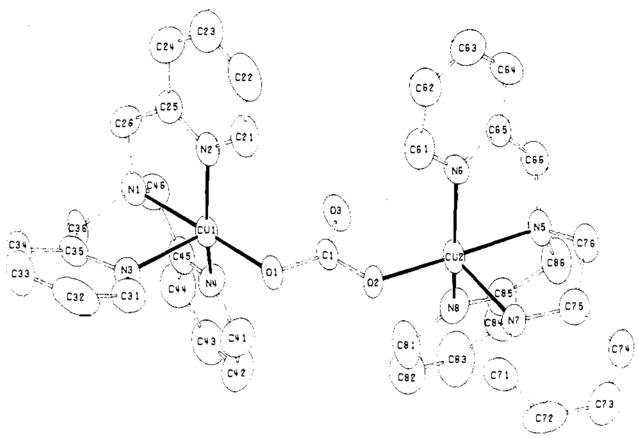

**Figure 1.** ORTEP diagram of $[(LCu^{II})_2(CO_3^{2-})]^{2+}$, showing the atom labeling scheme. Selected bond lengths (Å) and angles (deg) are as follows: Cu1⋯Cu2, 5.375 (1); Cu1–O1, 1.920 (7); Cu1–N1, 2.075 (9); Cu1–N2, 2.002 (8); Cu1–N3, 2.218 (10); Cu1–N4, 1.996 (9); C1–O1, 1.299 (12); C1–O2, 1.306 (13); C1–O3, 1.238 (14); Cu1⋯O3, 2.836, Cu2⋯O3, 2.819; O1–Cu1–N1, 178.8 (3); O1–Cu1–N2, 97.7 (3); O1–Cu1–N3, 97.5 (3); O1–Cu1–N4, 98.8 (3); N1–Cu1–N2, 83.0 (4); N1–Cu1–N3, 81.5 (4); N1–Cu1–N4, 81.0 (4); N2–Cu1–N3, 96.2 (3); N2–Cu1–N4, 150.6 (4); N3–Cu1–N4, 105.6 (3); Cu1–O1–C1, 113.6 (8); Cu2–O2–C1, 113.5 (7); O1–C1–O2, 114.8 (12); O1–C1–O3, 123.0 (11); O2–C1–O3, 122.2 (10).

yield from **1** and 81% yield[2] from **2** (iodometric titration). Under similar conditions, however, addition of 3–4 equiv of $H^+$ to **3** resulted in no UV–vis spectral change,[14] and addition of excess acid provides a chemical yield of only 12% hydrogen peroxide. Furthermore, phenols act as proton donors toward **1** and **2**, with liberation of $H_2O_2$ and production of phenoxo–copper(II) complexes; by contrast, they react with **3** by hydrogen atom abstraction, giving oxidatively coupled products typical of those found from the production of phenol radicals.[15]

$$\mathbf{1}\text{ or }\mathbf{2} + H^+ \rightarrow H_2O_2 + \text{Cu(II) products}$$

$$\mathbf{3} + H^+ \rightarrow \text{no reaction}$$

Acylation reactions of **1**–**3** at −80 °C follow the trend observed for protonation. Reactions of ArC(O)Cl with **1** are rapid, and, when followed by removal of $Cl^-$, they give $\mu$-1,1-acylperoxo–dicopper(II) complexes, $[Cu_2(XYL\text{-}O\text{-})(OOC(O)Ar)]^{2+}$.[16] These react quantitatively with $PPh_3$ to give $O{=}PPh_3$ and $[Cu_2(XYL\text{-}O\text{-})(OC(O)Ar)]^{2+}$[17] In the case of **2**, benzoyl chloride reacts slowly, and protonation is required to then cause oxygenation of added $PPh_3$.[18] Surprisingly, there is *no* reaction of acyl chlorides with **3**.

Differences in the observed reactivity of substrates with **1** and **2** compared to that for **3** also are seen in reactions with PhMgBr (source of $Ph^-$). Here, a preference for reaction with **1** or **2** to produce PhOH is observed (e.g., oxygen atom transfer), where the other product is biphenyl, derived from radical coupling ($PhOH/Ph_2$ is 75:25 and 84:16 for **1** and **2**, respectively). By contrast, reactions of **3** with PhMgBr give a $PhOH/Ph_2$ ratio of 43:57, showing a preference for one-electron oxidation of the added reagent, similar to that seen in the reactions with phenols.

The preliminary results thus indicate that in **1** and **2**, the dioxygen (peroxo) ligand can act as a base (e.g., protonates readily) or nucleophile (e.g., with respect to reactions with $CO_2$ or $SO_2$). By contrast, in $[Cu_2(N4PY2)(O_2)]^{2+}$ (**3**), the bound dioxygen ligand cannot be protonated or acylated, and it is unreactive toward $CO_2$ and is relatively more reactive with substrates capable of facile one-electron-transfer reactions. A species closely related to **3** has been shown by us to be capable of the hydroxylation of an arene,[19] and the behavior described for $[Cu_2(N4PY2)(O_2)]^{2+}$ (**3**) is consistent with an electrophilic nature for this type of $\{Cu_2\text{–}O_2\}^{2+}$ unit, more typical of early transition-metal–peroxo complexes.[4,20] The differences in reactivity may be attributed to the presence of fewer ligand donors per copper in **3** compared to that found in **1** or **2**. On the basis of solution X-ray absorption studies,[3b] we have also suggested that an unusual $\eta^2,\eta^2\text{-}O_2$ structural moiety be considered for **3**. Further investigations will be necessary to unambiguously determine the nature of the bound $O_2$ ligand in **3** or its analogues and unravel the novel chemical reactivity.

**Acknowledgment.** We thank the National Institutes of Health through Grants GM 28962 and GM 34909 for support of this research. We also thank Professor Ken Suslick for useful discussions.

**Supplementary Material Available:** Listing of atomic coordinates and temperature factors, bond lengths, bond angles, anisotropic temperature factors, and hydrogen coordinates and temperature factors (7 pages). Ordering information is given on any current masthead page.

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(13) (a) Karlin, K. D.; Cruse, R. W.; Gultneh, Y. *J. Chem. Soc., Chem. Commun.* **1987**, 596–600. (b) Karlin, K. D.; Ghosh, P.; Cruse, R. W.; Farooq, A.; Gultneh, Y.; Jacobson, R. R.; Blackburn, N. J.; Strange, R. W.; Zubieta, J. *J. Am. Chem. Soc.* **1988**, *110*, 6769–6780.

(14) (a) Haka, M. S., Ph.D. Dissertation, State University of New York at Albany, 1987. (b) Farooq, A., Ph.D. Dissertation, State University of New York at Albany, 1987.

(15) Tyeklar, Z.; Karlin, K. D., et al. To be published.

(16) The X-ray structure for the derivative Ar = $m\text{-}ClC_6H_4$ has been determined: Ghosh, P.; Tyeklar, Z.; Karlin, K. D.; Jacobson, R. R.; Zubieta, J. *J. Am. Chem. Soc.* **1987**, *109*, 6889–6891.

(17) At −80 °C, triphenylphosphine displaces $O_2$ when reacted with **1** or **2** giving $PPh_3$-coordinated Cu(I) products.[1a,2] A similar reaction does not occur with **3**.

(18) We speculate that the slow reaction is due to steric hindrance of the coordinated peroxo ligand, producing a sterically hindered $\{LCu^{II}\text{-}OOC(O)\text{-}Ar\}^+$ moiety plus $\{LCu^{II}\text{-}Cl\}^+$; protonation, however, liberates RC(O)OOH causing oxygenation of $PPh_3$.

(19) The ligand has a *m*-xylyl, rather than $-(CH_2)_4-$ connecting moiety, and a similar $\{Cu_2\text{–}O_2\}^{2+}$ moiety has been shown to form prior to hydroxylation of the arene containing ligand. See: (a) Karlin, K. D.; Gultneh, Y.; Hayes, J. C.; Cruse, R. W.; McKown, J.; Hutchinson, J. P.; Zubieta, J. *J. Am. Chem. Soc.* **1984**, *106*, 2121–2128. (b) Tyeklar, Z.; Ghosh, P.; Karlin, K. D.; Farooq, A.; Cohen, B. I.; Cruse, R. W.; Gultneh, Y.; Haka, M. S.; Jacobson, R. R.; Zubieta, J. In *Metal Clusters in Proteins*; Que, L., Jr., Ed.; ACS Symposium Series, 1988; Vol. 372, Chapter 5, pp 85–104.

(20) It is also interesting to note that the distinctive UV–vis spectral characteristics of **3** and its relatives show a striking similarity to that observed for oxyhemocyanin ($O_2$-carrier) and oxytyrosine (monooxygenase),[21] much more so than do complexes **1** or **2**.

(21) (a) Solomon, E. I.; Penfield, K. W.; Wilcox, D. E. *Struct. Bonding (Berlin)* **1983**, *53*, 1–57. Solomon, E. I. In *Metal Ions in Biology*; Spiro, T. G., Ed.; Wiley-Interscience: New York, 1981; Vol. 3, pp 41–108.

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## A New Synthesis of Substituted Azulenes

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More than 100 years have passed since the first azulene was isolated by Piesse from the distillation of chamomile oil. Today the azulenes constitute the most well-known class of polycyclic nonbenzenoid aromatic compounds, and with their unusual electronic structure and remarkable colors they continue to be a source of fascination for organic chemists.[1] Recently, the novel electronic properties and biological activity of certain natural and synthetic azulene derivatives have led to commercially important applications of these compounds in fields such as medicine and

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(1) For recent reviews of the chemistry of azulenes, see: (a) Zeller, K.-P. in *Methoden der Organischen Chemie*; Kropf, H., Ed.; Georg Thieme Verlag: Stuttgart, 1985; Vol. V/2c, p 127. (b) Lloyd, D. *Non-benzenoid Conjugated Carbocyclic Compounds*; Elsevier: Amsterdam, 1984; pp 352–377. (c) Mochalin, V. B.; Porshnev, Yu. N. *Russ. Chem. Rev.* **1977**, *46*, 530.