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Synthesis, Molecular Structure, and Reactivity of (Alkylperoxo)copper(II) Complex

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Two-electron reduction of dioxygen to peroxide followed by protonation yielding (hydroperoxo)(porphinato)iron(III) complex is believed to be an indispensable reaction step in the catalysis of cytochrome P-450.[1] In light of this mechanism, (hydroperoxo)-copper(II) intermediate is suggested to play a key role in the monooxygenations catalyzed by copper enzymes. The involvement of such an intermediate has been proposed for the oxygenation catalyzed by dopamine β-monooxygenase.[2] The reaction chemistry of (alkylperoxo)copper(II) complex should be informative in considering the catalytic mechanism of copper monooxygenase since the reactivity of the complex may parallel that of the hypothetical hydroperoxo intermediate. Moreover, the direct involvement of an alkylperoxo intermediate is suggested in the catalysis of pterin-dependent copper monooxygenase, phenylalanine hydroxylase, wherein the initial formation of pterin hydroperoxide has been proposed.[3] In this communication, we report the first structurally characterized (alkylperoxo)copper(II) complexes with preliminary results concerning their reactivities.

Addition of an excess amount (4–5 equiv) of *tert*-butylhydroperoxide or cumylhydroperoxide into a pentane solution of bis(μ-hydroxo)copper(II) complex $[Cu(HB(3,5\text{-}iPr_2pz)_3)]_2(OH)_2$ (**1**)[4] at −20 °C results in formation of a deep bluish purple solution. Removal of the solvent followed by recrystallization from a pentane/octane mixture yielded $Cu(OOtBu)(HB(3,5\text{-}iPr_2pz)_3)$ (**2a**) and $Cu(OOCMe_2Ph)(HB(3,5\text{-}iPr_2pz)_3)$ (**2b**), respectively, both as a dark blue microcrystalline solid.[5] The structure of **2b** was determined by X-ray crystallography, and the ORTEP view is presented in Figure 1.[6] Complex **2b** adopts a monomeric structure with a slightly distorted tetrahedral coordination environment. The O–O distance of 1.46 Å is located in the range of the bond distances reported for other alkylperoxo transition-metal complexes.[7] The Cu–O bond of 1.81 Å is very short, but this is in accord with the general trend observed for other tetrahedral complexes with hindered tris(pyrazolyl) borates: $Cu(Cl)(HB(3,5\text{-}iPr_2pz)_3)$, Cu–Cl = 2.125(6) Å;[8] $Cu(OC_6H_4\text{-}p\text{-}$

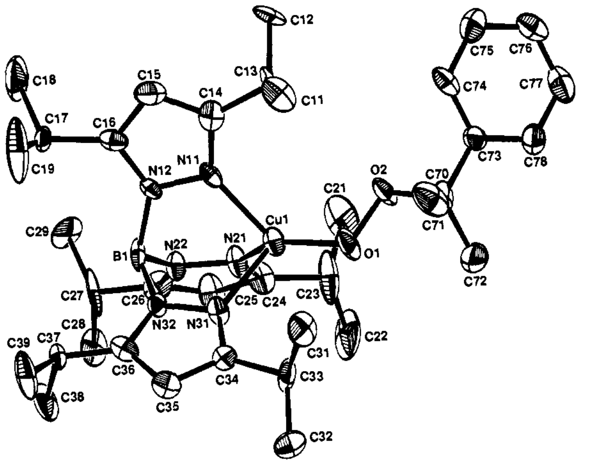
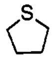
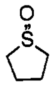
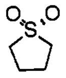
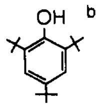
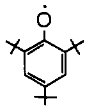
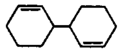
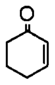
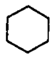


Figure 1. ORTEP drawing of **2b** (40% probability thermal ellipsoids). Hydrogen atoms are omitted for clarity. There are two crystallographically independent molecules whose structural features are essentially identical. The molecule 1 is presented. Selected distances (Å) and angles (deg) are as follows. Molecule 1: Cu1–O1, 1.816(4); Cu1–N11, 1.982(6); Cu1–N21, 1.949(6); Cu1–N31, 2.161(6); O1–O2, 1.460(6); O2–C70, 1.457(8); O1–Cu1–N11, 122.2(2); O1–Cu1–N21, 140.3(2); O1–Cu1–N31, 107.8(2); N11–Cu1–N21, 92.3(2); N11–Cu1–N31, 90.9(2); N21–Cu1–N31, 88.9(2); Cu1–O1–O2, 112.1(4); O1–O2–C70, 106.8(5). Molecule 2: Cu2–O3, 1.814(4); Cu2–N41, 1.979(6); Cu2–N51, 1.960(6); Cu2–N61, 2.153(5); O3–O4, 1.454(6); O4–C80, 1.471(8); O3–Cu2–N41, 128.5(2); O3–Cu2–N51, 134.4(2); O3–Cu2–N61, 105.3(2); N41–Cu2–N51, 92.8(2); N41–Cu2–N61, 91.3(2); N51–Cu2–N61, 90.1(2); Cu2–O3–O4, 114.1(3); O3–O4–C80, 106.9(5).

Table I. Anaerobic Oxidation with **2a**

substrate	products (yield based on **2a**)[d]
—	tBuOH (59%), $tBuOOC_5H_{11}$ (20%)
PPh_3[a]	$OPPh_3$ (78%)
 [a]	NR[e]
 [a]	 (46%)
 [b]	 (228%) tBuOH (62%)
	 (20%) tBuOH (47%) $tBuOOC_5H_{11}$ (20%)
 [c]	 (120%) tBuOH (118%)
 [a]	NR

[a] tBuOH was not analyzed quantitatively. [b] The yield of the phenoxo radical was determined by the visible absorption band at 630 nm (ϵ 200).[17] [c] The reaction was performed under 1 atm O_2. [d] Ten equivalents of the substrate was added to the pentane solution of **2a** at −78 °C. The solution was warmed to room temperature and allowed to stand for 3 h. The products were analyzed and quantified by GC/MS and GC, respectively. [e] No reaction.

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(5) Complex **2a**. Anal. Calcd for $C_{31}H_{55}N_6BO_2Cu$: C, 60.23; H, 8.97; N, 13.60. Found: C, 60.20; H, 9.28; N, 13.85. IR (KBr; cm^{-1}): ν(BH) 2535. UV–vis (nm; $\epsilon/M^{-1}\cdot cm^{-1}$): 347 (2970), 582 (3450), 800 (380). FD-MS (*m*/*e*): 618. Complex **2b**. Anal. Calcd for $C_{36}H_{56}N_6BO_2Cu$: C, 63.66; H, 8.31; N, 12.37. Found: C, 63.25; H, 8.50; N, 12.11. IR (KBr; cm^{-1}): ν(BH) 2537. UV–vis (nm; $\epsilon/M^{-1}\cdot cm^{-1}$): 348 (4000), 569 (3600), 811 (400). FD-MS (*m*/*e*): 679.

(6) X-ray data for **2b**, FW 679.24, space group $P2_1/c$ at −60 °C: a = 20.098(5) Å, b = 21.392(2) Å, c = 19.097(4) Å, β = 110.78(2)°, V = 7676(5) Å^3, Z = 8. The structure was solved by the direct methods and refined by the full matrix least-squares technique with anisotropic thermal parameters for non-hydrogen atoms. All hydrogen atoms were included isotropically but not refined. For 5167 reflections with $I > 3\sigma(I)$ (2θ range, 3–45°), the current $R(R_w)$ factor is 5.41(3.82)%.

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F)(HB(3,5-iPr$_2$pz)$_3$), Cu–O = 1.729(7) Å;[9] Cu(N$_3$)(HB(3-tBu-5-Mepz)$_3$), Cu–N = 1.908(2) Å.[9] The occurrence of this unusual feature, particularly with O-donors, will be discussed elsewhere.[10] Associated with this short Cu–O bond length, the EPR of **2b** exhibits a slightly rhombic reverse signal attributable to the d$_{z^2}$ ground state (the d$_{z^2}$ lobe is oriented along the Cu–O bond), whose feature is similar to that of Cu(Cl)(HB(3,5-iPr$_2$pz)$_3$).[7]

While both **2a** and **2b** are stable below –20 °C for a week, they decompose spontaneously at room temperature. For instance, **2a** decomposes completely within 2 h in pentane at room temperature, whereby tBuOH and tBuOOC$_5$H$_{11}$ are formed (see Table I). The formation of tBuOOC$_5$H$_{11}$[11] is indicative of the involvement of tBuOO$^{\bullet}$ as an initial reaction intermediate in the spontaneous decomposition of **2a**. The radical generation is most rationally interpreted in terms of the Cu–O bond cleavage in **2a** accompanied by reduction of the cupric ion. In this senario, the formation of tBuOH is explained either by the redox decomposition of tBuOOC$_5$H$_{11}$ or by the homolysis of the O–O bond in **2a** to afford tBuO$^{\bullet}$, which subsequently abstracts H$^{\bullet}$ from the solvent. Under comparable reaction conditions, oxidations of several substrates were attempted, and the results are summarized in Table I. In the oxidations of 2,4,6-tri-*tert*-butylphenol, tetramethylene sulfoxide, and PPh$_3$, the addition of the substrate apparently accelerated the consumption rate of **2a**, implying that a bimolecular-type reaction pathway is responsible for these oxidations.[12] On the other hand, the addition of cyclohexene did not affect the consumption rate of **2a**. This indicates that the rate-determining step in the cyclohexene oxidation is the same as in the spontaneous decomposition of **2a**. Accordingly, the products obtained are all expected by classical-type radical reactions initiated by tBuOO$^{\bullet}$ or tBuO$^{\bullet}$; anaerobic oxidation of cyclohexene afforded dicyclohexenyl, while under dioxygen, 2-cyclohexen-1-one was produced. Whereas tetramethylene sulfoxide is oxidized to tetrahydrothiophene 1,1-dioxide, tetrahydrothiophene is not. This suggests nucleophilic reactivity of **2a** rather than electrophilic.[13] Overall, the reactivity of **2a** is low, as is the case for the acylperoxo complex Cu(OOC(O)C$_6$H$_4$-*m*-Cl)(HB(3,5-iPr$_2$pz)$_3$) which we reported previously.[14] The low reactivities of these copper complexes are in striking contrast to that known for a related (acylperoxo)(porphinato)iron(III) complex in which heterolysis of the O–O bond yields a very electrophilic oxo–ferryl porphyrin π-cation radical which epoxides cyclohexene even at –78 °C.[15] The highly steric bulk of the tris(pyrazolyl) borate employed for synthesizing the alkylperoxo and acylperoxo complexes may cause inefficacy in the oxo-transfer reactions. However, the low reactivity of the complexes seems to be an essential property, since the μ-1,1-hydroperoxo and -acylperoxo dinuclear copper(II) complexes reported by Karlin et al. are also ineffective for oxo-transfer reactions except for PPh$_3$.[16] These facts thus lead us to suggest that the (hydroperoxo)-copper(II) intermediate supposed to be formed in the catalytic cycle of copper monooxygenase is not very effective for oxo-transfer reactions and that the heterolytic cleavage of the O–O bond of the hydroperoxo intermediate accepted for cytochrome P-450 does not occur. Rather the reductive decomposition of Cu^{II}OOH to Cu^{I} + HOO$^{\bullet}$ or the O–O bond homolysis giving HO$^{\bullet}$ is more likely to be responsible for the enzymatic reactions.

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Supplementary Material Available: Experimental and crystallographic details, atomic coordinates, isotropic and anisotropic thermal parameters of non-hydrogen atoms, and bond distances and bond angles (15 pages); observed and calculated structure factors (19 pages). Ordering information is given on any current masthead page.

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[10] The short Cu–O distance may be associated with a π–bonding contribution. To provide a theoretical basis for this interpretation, MO calculations are being performed.

[11] The structure of tBuOOC$_5$H$_{11}$ was not identified definitely, whereas the MS data are indicative of the formation of secondary pentyl peroxide(s).

[12] The consumption rate of **2a** was determined by following the intensity decrease of the 582 nm band.

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