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Communication

Copper Hydroperoxo Species Activated by Hydrogen-Bonding Interaction with Its Distal Oxygen

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A novel copper(II)–OOH complex with functional ligand that can form a hydrogen bond with the distal oxygen of hydroperoxide has been designed and prepared as a structural/functional model of dopamine β-hydroxylases, whose spectroscopic characterization and decomposition rates have indicated that the hydroperoxide is activated through the hydrogen-bonding interaction with the distal oxygen.

Hydroperoxo−copper(II) complexes are very important as active intermediates in biological oxygenases such as dopamine β-hydroxylase (DβH).[1−4] In recent detailed researches on DβH, it has been described that the hydroperoxide ion is formed on Cu(II) ion and activated through a hydrogen-bonding interaction between noncoordinating hydroperoxide oxygen (distal oxygen) and Tyr-OH hydrogen (Scheme 1).[3,4] From such a structural/functional interest of hydroperoxo−copper(II) complexes, the preparations and characterizations of some hydroperoxo−copper(II) complexes have been reported.[5−10] We also previously challenged preparation of Cu(II)−OOH species using original ligand BPPA (bis(6-pivalamido-2-pyridylmethyl)(2-pyridylmethyl)amine), and succeeded in preparation, crystal structure analysis, and spectroscopic characterization of hydroperoxo−copper(II) complex with BPPA,[5] which was demonstrated to be stabilized by hydrogen-bonding interactions between two pivalamido NH hydrogens and coordinating oxygen of hydroperoxide (proximal oxygen). The hydroperoxide ion occupies the axial position of the Cu(II) ion with a trigonal bipyramidal geometry. However, the preparation of the Cu−OOH complex that can form a hydrogen bond with the distal oxygen of the hydroperoxide ion has not been reported to our best knowledge. So, we newly designed a novel hydroperoxo−copper(II) complex which has a functional group forming the hydrogen bond with the distal oxygen. In this work, we have investigated the synthesis, characterization, and reactivity of mononuclear copper(II)−hydroperoxo species using newly designed ligands, *N*-{2-[(2-bis(2-pyridylmethyl)aminoethyl)methylamino]ethyl}-2,2-dimethylpropionamide (**L1**) and *N*,*N*-diethyl-N',N'-bis(2-pyridylmethyl)ethylenediamine (**L2**),[11] where the former has a hydrogen-bonding site for the distal oxygen atom of a hydroperoxo species (Chart 1a) and the latter, which was synthesized as a comparison of the complex of L1, has no such site (Chart 1b).

Scheme 1

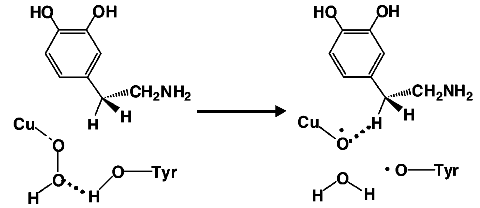

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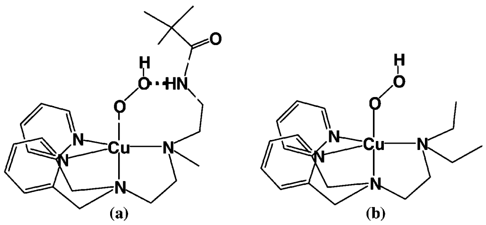
Chart 1



Syntheses of ligands L1 and L2 are given in the Supporting Information together with the physicochemical experimental details. The two copper(II) complexes have been prepared from reactions of $Cu(ClO_4)_2 \cdot 6H_2O$ with L1 and L2, respectively, in methanol, which were obtained as$[Cu(L1)](ClO_4)_2$ (**1**) and $[\{Cu(L2)\}_3CO_3](ClO_4)_4$ (**2**). The crystal structure of **1** revealed that the Cu(II) ion has a trigonal bipyramidal geometry with two pyridine and one tertiary amine nitrogen atoms in equatorial plane and tertiary amine nitrogen and pivalamido oxygen atoms in axial positions, as shown in Figure 1.[12] The complex **2** was isolated as a trinuclear complex in which three $[Cu(L2)]^{2+}$ cations were linked by carbonato anion with a trigonal planar geometry, in which the carbonato anion may be dissolved in the solution from air. Each Cu(II) ion is coordinated with two pyridine and one tertiary amine nitrogen, carbonate oxygen, and tertiary amine nitrogen atoms.[13]

Addition of H_2O_2 (10 equiv) to an acetonitrile solution of **1** containing Et_3N (2 equiv) at −40 °C generated a pale green colored species (**3**). The electronic absorption spectra of **3** in acetonitrile showed an intense absorption band at 381 nm ($\epsilon = 1000\ M^{-1}\ cm^{-1}$) assignable to LMCT ($OOH^- \rightarrow Cu$) and d−d bands at 635 nm ($\epsilon = 140\ M^{-1}\ cm^{-1}$) and 770 nm ($\epsilon = 130\ M^{-1}\ cm^{-1}$), and the corresponding spectrum of species **3** prepared in methanol gave an intense LMCT band at 369 nm ($\epsilon = 1300\ M^{-1}\ cm^{-1}$) and d−d bands at 653 nm ($\epsilon = 145\ M^{-1}\ cm^{-1}$) and 850 nm ($\epsilon = 160\ M^{-1}\ cm^{-1}$), both of which are characteristic of a trigonal bipyramidal geometry. The ESR spectra of **3** exhibited typical ones suggesting the formation of trigonal bipyramidal mononuclear copper(II) complexes with a coordinated hydroperoxide ion; $g_{\|} = 1.99$, $g_{\perp} = 2.21$, $|A_{\|}| = 82$ G, $|A_{\perp}| = 114$ G in acetonitrile and $g_{\|} = 1.98$, $g_{\perp} = 2.20$, $|A_{\|}| = 71$ G, $|A_{\perp}| = 103$ G in methanol. The resonance Raman spectra of **3** measured in methanol at −80 °C (using 406.7 nm laser excitation) gave a weak resonance-enhanced Raman band at 853 cm^{-1}, which shifted to 807 cm^{-1} ($\Delta\nu = 46\ cm^{-1}$) when ^{18}O-labeled H_2O_2 was used. The formation of **3** was also confirmed from the ESI mass spectrum measured in acetonitrile at −40 °C; a parent peak was observed at m/z 479 corresponding to the positive ion $[Cu(L1)(OOH)]^+$.

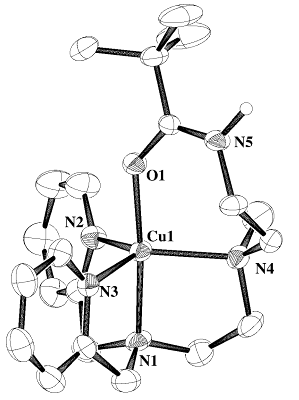


Figure 1. ORTEP view of **1**, showing 30% probability thermal ellipsoids. The counteranions and hydrogen atoms except for NH proton are omitted for clarity.

Addition of H_2O_2 (10 equiv) to an acetonitrile solution of **2** containing Et_3N (2 equiv) at −40 °C also gave a pale green colored species (**4**). The electronic absorption spectra of **4** in acetonitrile exhibited an LMCT band at 372 nm ($\epsilon = 1000\ M^{-1}\ cm^{-1}$) and d−d bands at 662 nm ($\epsilon = 90\ M^{-1}\ cm^{-1}$) and 814 nm ($\epsilon = 80\ M^{-1}\ cm^{-1}$), and those in methanol were observed at 369 nm ($\epsilon = 1100\ M^{-1}\ cm^{-1}$) and at 654 nm ($\epsilon = 120\ M^{-1}\ cm^{-1}$) and 825 nm ($\epsilon = 150\ M^{-1}\ cm^{-1}$). The ESR spectra of **4** exhibited typical ones suggesting the formation of trigonal bipyramidal copper(II) complexes with a coordinated hydroperoxide ion; $g_{\|} = 1.98$, $g_{\perp} = 2.23$, $|A_{\|}| = 75$ G, $|A_{\perp}| = 116$ G in acetonitrile; $g_{\|} = 1.97$, $g_{\perp} = 2.21$, $|A_{\|}| = 76$ G, $|A_{\perp}| = 103$ G in methanol. The resonance Raman spectra of a methanol solution of **4** measured at −80 °C (using 406.7 nm laser excitation) exhibited a weak resonance-enhanced Raman band at 848 cm^{-1}, which shifted to 803 cm^{-1} ($\Delta\nu = 45\ cm^{-1}$) when ^{18}O-labeled H_2O_2 was employed. The formation of **4** was also confirmed from an ESI mass spectrum measured in acetonitrile at −40 °C; a parent peak was observed at m/z 394 corresponding to the positive ion $[Cu(L2)(OOH)]^+$.

The above findings indicate that in both cases the Cu(II) ions form trigonal bipyramidal complexes with HOO^- ion in an end-on fashion in both solvents. However, it is very interesting that the spectral behavior of two complexes is subtly affected by solvents as shown in Table 1: The λ_{max} values of LMCT and d−d bands and ESR parameters for **3** in MeCN are significantly different from the spectroscopic behavior of **3** in MeOH and **4** in both MeOH and MeCN, although the latter are quite similar to each other. Considering that MeOH is a protic solvent that enables destruction of the hydrogen-bonding network,[14] the species **3** in MeOH and **4** in both MeOH and MeCN are thought all to form the same coordination geometry. The slightly larger λ_{max} of LMCT and larger $|A_{\|}|$ value for **3** in MeCN in comparison with the other cases must imply that the coordination of hydroperoxide ion to Cu(II) has been weakened by the hydrogen bond

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(12) Crystal data for **1**: $C_{48}H_{64}Cl_4Cu_2N_{10}O_{18}$, $M = 1337.99$, orthorhombic, space group $Pca2_1$ (No. 29), $a = 20.1500(4)$ Å, $b = 11.6300(5)$ Å, $c = 23.9100(5)$ Å, $V = 5603.2(3)$ Å^3, $Z = 4$, $D_{calcd} = 1.586$ g cm^{-3}, $R_1 = 0.056$, $R_w = 0.138$. Elemental anal. Calcd for $\mathbf{1} \cdot 0.25CH_3CN$ ($C_{22}H_{33}Cl_2CuN_5O_9 \cdot 0.25CH_3CN$): C, 41.18; H, 5.18; N, 11.21. Found: C, 41.36; H, 5.16; N, 10.84.

(13) Crystal data for **2**: $C_{55}H_{78}Cl_4Cu_3N_{12}O_{19}$, $M = 1543.74$, monoclinic, space group $P2_1/n$ (No. 14), $a = 13.251(1)$ Å, $b = 25.035(3)$ Å, $c = 20.5707(5)$ Å, $\beta = 94.2597(5)°$,$V = 6805(1)$ Å^3, $Z = 4$, $D_{calcd} = 1.507$ g cm^{-3}, $R_1 = 0.075$, $R_w = 0.190$. Elemental anal. Calcd for **2** ($C_{55}H_{78}Cl_4Cu_3N_{12}O_{19}$): C, 42.79; H, 5.09; N, 10.89. Found: C, 42.53; H, 5.06; N, 10.76.

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Table 1. Summary of Spectroscopic and Kinetic Data of Cu−L−OOH Complexes

		λ_{max}/nm (ϵ/M^{-1} cm^{-1})		ESR				rR/cm^{-1} ν(^{16}O−^{16}O) (ν(^{18}O−^{18}O))	dec rate, k_{obs}/min^{-1}
	solvent	LMCT	d−d	$g_{\parallel}$	$g_{\perp}$	$\lvert A_{\parallel}\rvert$/G	$\lvert A_{\perp}\rvert$/G		
[Cu(L1)(OOH)]$^+$	MeCN	381 (1000)	635 (140), 770 (130)	1.99	2.21	82	114		$2.4(2) \times 10^{-2}$
	MeOH	369 (1300)	653 (145), 850 (160)	1.98	2.20	71	103	853 (807)	$3.5(2) \times 10^{-3}$
[Cu(L2)(OOH)]$^+$	MeCN	372 (1000)	662 (90), 814 (80)	1.98	2.23	75	116		$7.3(6) \times 10^{-3}$
	MeOH	369 (1100)	654 (120), 825 (150)	1.97	2.21	76	103	848 (803)	$2.0(3) \times 10^{-3}$

between the distal oxygen of hydroperoxide and NH hydrogen of L1.

Furthermore interestingly, the effect of the hydrogen bond, when their decomposition rates were followed using decrease in the absorption intensities of LMCT bands, was apparently found out in the reactivity and stability of these hydroperoxide complexes. The decomposition rates of **3** and **4** measured at −30 °C exhibited good first-order kinetics in both solvents. In an aprotic solvent such as MeCN, the rate of **3** ($k_{obs} = 2.4(2) \times 10^{-2}$ min^{-1}) was much faster than that of **4** ($k_{obs} = 7.3(6) \times 10^{-3}$ min^{-1}). On the other hand, in a protic solvent such as MeOH, that of **3** ($k_{obs} = 3.5(2) \times 10^{-3}$ min^{-1}) was only slightly faster than that of **4** ($k_{obs} = 2.0(3) \times 10^{-3}$ min^{-1}). The decomposition rates of **3** are significantly affected by difference of solvents, although those of **4** are also slightly influenced. These findings clearly indicate that **3** has been activated by the intramolecular hydrogen-bonding interaction, which strongly suggests that the hydrogen-bonding interaction with the distal oxygen of Cu-coordinated hydroperoxide in DβH might contribute to activation of the hydroperoxide ion.

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Supporting Information Available: Crystallographic files in CIF format. Experimental procedures, Scheme S1, and Figures S1−S5 as PDF files. This material is available free of charge via the Internet at http://pubs.acs.org.

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