CHEMISTRY LETTERS, pp. 1241-1244, 1982.

DIOXYGEN ABSORPTION BY A 2:1 COPPER(II)–DISULFIDE SYSTEM. PARTIAL INCORPORATION OF OXYGEN ATOMS FROM DIOXYGEN UPON COPPER(II)–CATALYZED DISULFIDE BOND CLEAVAGE TO SULFINATE

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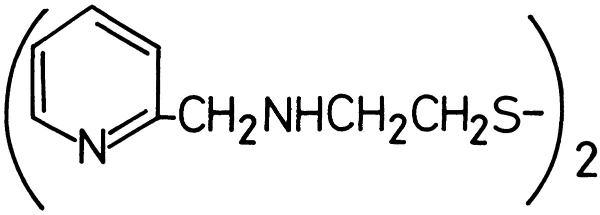
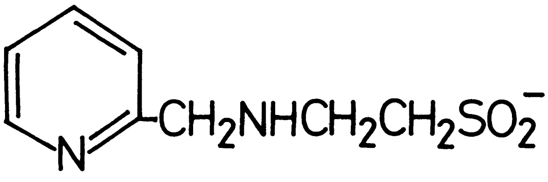
Synthetic and spectroscopic studies have established that the oxygen atoms from dioxygen are partly incorporated into the sulfinate moiety of the Cu(II)–2-[(2-pyridylmethyl)amino]ethylsulfinate complex upon the Cu(II)-catalyzed disulfide bond cleavage of bis{2-[(2-pyridylmethyl)amino]ethyl}disulfide under dioxygen.

Disulfide sulfurs are potential donor atoms in biological systems and have been proposed as the copper-binding sites in ceruloplasmin[1,2] and stellacyanin.[3,4] Under favorable conditions they may play a unique role in redox reactions, because they are versatile in nature regarding the electron transfer and copper(I)-disulfide systems are known to be in various oxidation states.[5,6] Disulfides RSSR in aqueous solution suffer heterolytic cleavage to RS^+ and RS^- by Ag(I), Hg(I), and other electrophiles with a high affinity for sulfur, RS^+ giving a thiol RSH and a sulfinic acid RSO_2H by the reaction with water and subsequent disproportionation.[7]

Recently we have found that a neutral solution containing $CuCl_2$ and bis{2-[(2-pyridylmethyl)amino]ethyl}disulfide (PMAD) in the molar ratio of 2:1 absorbs dioxygen to give the copper(II) complex of the oxidative cleavage product 2-[(2-pyridylmethyl)amino]ethylsulfinate (PMS), $[Cu(PMS)(H_2O)]Cl$.[8] The complex was isolated as crystals and disclosed by X-ray analysis to have a dimeric structure in the solid state, each complex unit involving PMS coordinating through the two nitrogen atoms and the water and sulfinate oxygen atoms (Fig. 1). We here report evidence showing that part of the dioxygen absorbed is directly incorporated into the SO_2 moiety of the sulfinate PMS during the copper(II)-catalyzed disulfide bond cleavage in aqueous solution.



PMAD



PMS

A brown-green 2:1 $CuCl_2$–PMAD system at pH ~7 exhibited absorption maxima centered at 330, 450, 640, and 760 nm, which finally merged to give 340- and 680-nm peaks corresponding to those exhibited by [Cu(PMS)(H_2O)]Cl in solution. The brown-green color of the fresh solution persisted under a nitrogen atmosphere, which indicates the spectral change is due to the presence of dioxygen. Polarographic measurements of the concentration of dioxygen in the solutions of various 2:1 Cu(II)-disulfide systems[9)] revealed that those with PMAD and cystine consume dioxygen rapidly at pH 9.0 and 12.5, respectively, whereas the system with bis(2-pyridyl)disulfide does not consume it at pH 12.0. When a dilute 2:1 $CuCl_2$-PMAD solution (pH ~7) was shaken under $^{18}O_2$ (purchased from CEA, France; 98.12 % isotopic purity) in place of $^{16}O_2$, greenish blue crystals of the Cu(II)-PMS complex with the same composition, [Cu(PMS)(H_2O)]Cl, were obtained. The infrared (IR) spectra of normal [Cu(PMS)(H_2O)]Cl and that prepared under $^{18}O_2$ are superimposable except in the region 850-1100 cm^{-1} where the SO_2^- vibrations are expected. The IR spectrum of the latter shows an additional peak at 873 cm^{-1} and a spectral pattern difference in the region 1000-1050 cm^{-1}, and the resonance Raman band observed at 1050 cm^{-1} splits into two peaks centered at 1040 and 1053 cm^{-1} (Fig. 2). Mass spectra (taken by the field-desorption method) indicate that the

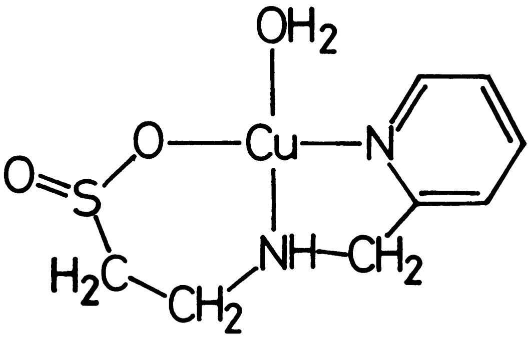


Fig. 1. Structure of Cu(PMS)(H_2O)$^+$.[8)]

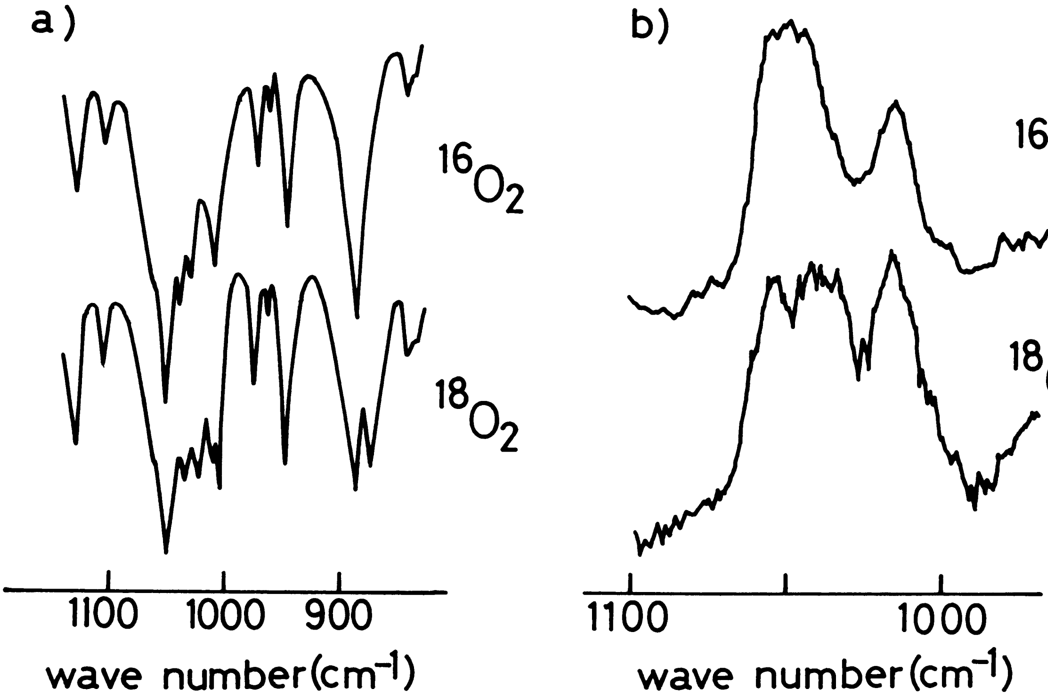


Fig. 2. Infrared (a) and resonance Raman (b) spectra of [Cu(PMS)(H_2O)]Cl and the ^{18}O analog in the SO_2^- frequency region. The KBr disk method; 50 mW, 488.0-nm laser excitation.

complex isolated from the $^{18}O_2$-treated system gives the fragments corresponding to $Cu(PMS)^+$ (M^+ = 262 for ^{63}Cu and ^{16}O; the natural abundance of ^{65}Cu is 30.91 %) with m/e(fractional amount among the $Cu(PMS)^+$ fragments) 262(0.31), 264(0.50), and 266 (0.19), whereas the normal complex gives those with m/e 262(0.72), 264(0.28), and 266(0). The IR spectra of the normal complex in the region 850-1050 cm^{-1} remained the same before and after recrystallization from $H_2{}^{18}O$ (purchased from CEA, France; 50 % isotopic purity), indicating that exchange of the sulfinate oxygen atoms with those of water molecules is negligible. These lines of evidence strongly support the view that the oxygen atoms of the SO_2 moiety of PMS are partly incorporated from dioxygen.

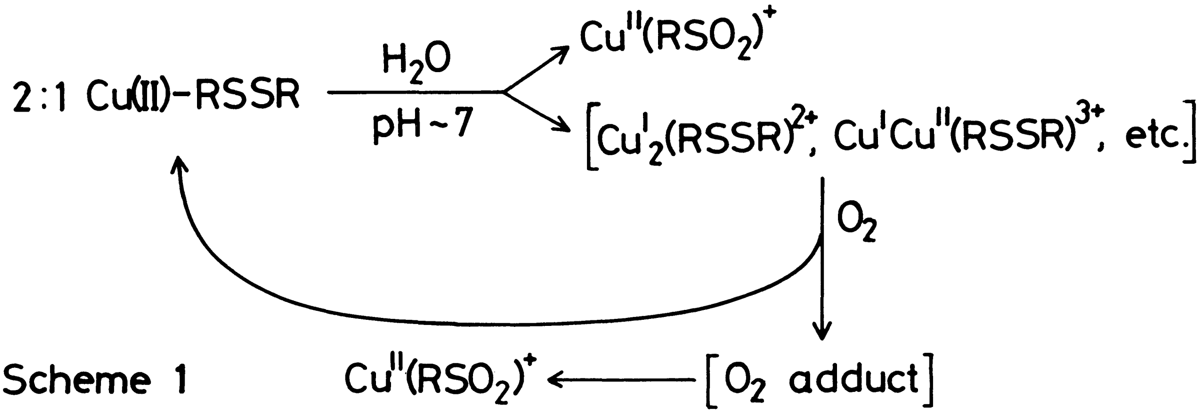
Earlier studies by Seff and his co-workers have shown that the reaction of copper(II) with bis(2-pyridyl)disulfide gives the copper(I)-disulfide and copper(II)-2-pyridylsulfinate complexes.[10] They explained the reaction by heterolytic disulfide bond cleavage and the subsequent redox reaction between Cu(II) and the resulting thiol RSH[7,11-13] to afford Cu(I) and RSSR:

$$7Cu^{2+} + 13RSSR + 4H_2O \longrightarrow Cu^{II}(RSO_2)_2 + 6Cu^{I}(RSSR)_2{}^{+} + 8H^{+} \qquad (1)$$

This reaction was found to be feasible under a nitrogen atmosphere, which is in accord with our measurements of dioxygen consumption. Similarly, the 2:1 Cu(II)-PMAD system probably gives $Cu^{I}{}_2(RSSR)^{2+}$ and $Cu^{II}(RSO_2)^+$ in a series of reactions that do not involve dioxygen:

$$8Cu^{2+} + 4RSSR + 4H_2O \longrightarrow 2Cu^{II}(RSO_2)^{+} + 3Cu^{I}{}_2(RSSR)^{2+} + 8H^{+} \qquad (2)$$

Binuclear Cu(I) or mixed valence Cu(I)-Cu(II) complexes of RSSR expected from Eq. 2 or other Cu(I) complexes may then form an adduct with dioxygen, activating it to attack the disulfide bond (Scheme 1).



Scheme 1

The assumption that binuclear complexes are formed is supported by the fact that a copper(II) complex, $Cu_2(PMAD)Cl_4$, was successfully prepared in ethanol and isolated as crystals,[14] although the corresponding copper(I) complex could not be obtained. From the fractional amounts of the fragments due to $Cu(PMS)^+$ in the mass spectra, the oxygen atoms incorporated from dioxygen are estimated to account for 25-30 % of the total oxygen atoms of the sulfinate moiety. This implies that the sulfinate formation according to Eq. 2 is predominant and that the dioxygen absorbed is also used for reoxidation of Cu(I) to Cu(II) (Scheme 1). Interestingly, a cobalt(III) complex of PMS has been obtained by the reaction of cobalt(II) with the reduced form of PMAD in the presence of hydrogen peroxide.15)

The present finding suggests that similar oxygenation reactions may occur with other disulfides via formation of dioxygen adducts if they have donor groups which can effectively bind copper(II) and probably copper(I) in the vicinity of the disulfide bond.

We are grateful to Dr. Katsunosuke Machida of Kyoto University for the measurement and discussion of the resonance Raman spectra and to Miss Tokie Ueda of Kanazawa University for the mass spectra. This work was supported by a Grant-in-Aid for Special Project Research (No. 56209007) by the Ministry of Education, Science, and Culture, to which our thanks are due.

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(Received May 29, 1982)