A Stabilized μ-η²:η² Peroxodicopper(II) Complex with a Secondary Diamine Ligand and Its Tyrosinase-like Reactivity

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The activation of dioxygen (O_2) by Cu(I) complexes is known to play an important role in biological and industrial oxidation processes.[1–3] The structure–reactivity relationships of the binuclear copper enzymes, such as tyrosinase, have been extensively investigated, and model complexes have aided these studies.[4–6] In line with the native systems, most model complexes use facial-capping trinitrogen ligation of the copper, and all such structurally characterized Cu–O_2 species exhibit a weak association with the axial nitrogen ligand. An emerging trend exists in which bidentate nitrogenous ligands are used, and such ligation does not generally compromise the stability of the formed Cu–O_2 complexes. A reactivity advantage with externally added substrates may also be realized as the Cu/O_2 cores are potentially more accessible.[7,8] Bidentate ligation of peralkylated diamine ligands (PDL) to Cu(I) is sufficient to allow O_2 activation to yield either a pure bis μ-oxodicopper(III) species (**O**),[3,9,10] or an equilibrium mixture of the isoelectronic μ-η²:η²-peroxodicopper(II) (**P**) and **O** species.[11] Here we report a stabilized **P** complex that employs a bidentate secondary diamine ligand (DBED, Scheme 1). Beyond potential biological relevance, our interest in the Cu(I)–DBED/O_2 reactivity stems from its use in the catalytic oxidative polymerization of phenols to the thermoplastic polyphenylene oxide (PPO).[12,13]

Conventional wisdom suggests that secondary amine ligands are unsuitable for stabilizing the Cu–O_2 species, due to the amine protons.[14,15] Yet, this **P** complex exhibits thermal stability comparable to the other Cu–O_2 species formed using PDL.[9,11,16] Interestingly, this new complex exhibits tyrosinase-like reactivity by hydroxylating phenolates to catechols (vide infra), in yields comparable to those of other reported systems.[17,18] The reaction of N,N′-di-*tert*-butyl-ethylenediamine (DBED) with [Cu(MeCN)₄](X) (X = $CF_3SO_3^-$, ClO_4^-, SbF_6^-, BF_4^-) yields a trigonal-planar Cu-(I) complex, [(DBED)Cu(MeCN)](X) (**1·X**).[19] Solutions of **1·X** in aprotic solvents (THF, CH_2Cl_2, acetone, toluene) react rapidly with O_2 at 193 K to generate thermally sensitive dark green to orange complexes, depending on the counteranion. Spectroscopic and analytical data support a μ-η²:η²-peroxodicopper(II) complex, formulated as [{Cu^{II}(DBED)}₂(O_2)](X)₂ (**2·X₂**) (vide infra).[20] These complexes are EPR silent, NMR active, and have a 2:1 (Cu:O_2) stoichiometry established by spectrophotometric titrations with O_2.[16] The complex **2·(CF₃SO₃)₂** in THF exhibits characteristic LMCT absorptions,[5,6,21] except that the extinction coefficient of the low-energy feature at 350 nm is exceptionally large (Figure 1).[22] Resonance Raman (rR) spectroscopy of **2·(CF₃SO₃)₂** in THF confirms a **P** structure,[23] with a low v_{o-o} = 721 cm^{-1} ($\Delta(^{18}O_2)$ =
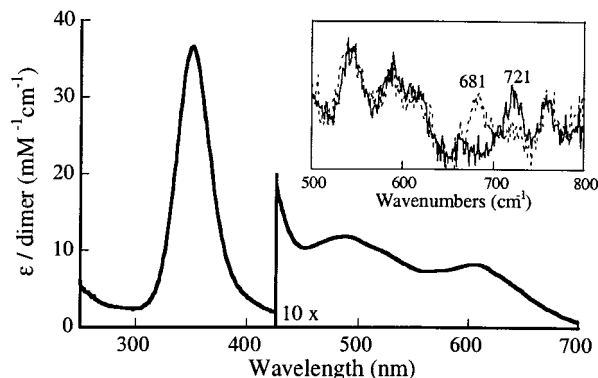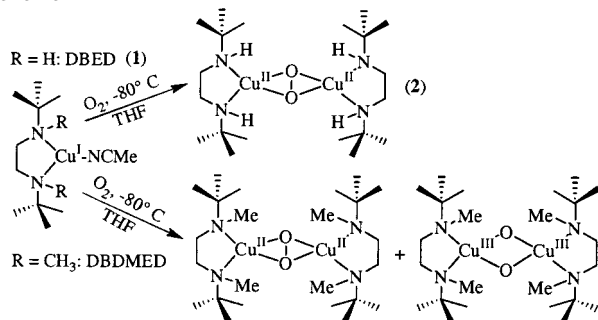

Figure 1. UV–vis spectrum of **2·(CF₃SO₃)₂** (THF, 193 K, [Cu] ≈ 1 mM). Inset: Resonance Raman spectra of **2·(CF₃SO₃)₂** (λ_{ex} = 351.1 nm, THF, 77 K, [Cu] ≈ 4 mM) using $^{16}O_2$ (solid line) or $^{18}O_2$ (dashed lined).

Scheme 1

40 cm^{-1}, Figure 1, inset), and two isotope-insensitive stretches in the 300 cm^{-1} region (Table 1).[16,24]

Solution Cu K edge X-ray absorption spectroscopy (XAS) exhibits a preedge feature at 8979.5 eV, consistent with a Cu(II) complex.[16] The EXAFS fit clearly requires a Cu···Cu contribution at a distance of 3.45 Å, a distance similar to other structurally characterized **P** complexes.[5,6,25] The coordination around each Cu is best fit as five- rather than four-coordinate with four N/O[26] ligands at 1.96 Å and an additional O/N ligand at 2.53 Å.[27] The latter distance is consistent with an axially bound oxygen atom from a $CF_3SO_3^-$ counteranion.[10] The variation of the UV–vis and rR spectra with counteranion and not with solvent suggests an intimate interaction of the counteranions with the complex. **2·(SbF₆)₂** exhibits the characteristic UV–vis absorptions and rR shifts of a **P** complex distinct from **2·(CF₃SO₃)₂** (Table 1).

The **2·(CF₃SO₃)₂** complex is remarkably stable at 193 K ($t_{1/2}$ ≈ 20 days) given the secondary diamine ligation, yet decays in a first-order process at elevated temperatures ($\Delta H^{\ddagger}$ = 14.8 ± 0.3 kJ mol^{-1}, $\Delta S^{\ddagger}$ = 10 ± 1 J mol^{-1} K^{-1}, T = 193−273 K, THF).[28] Deuteration

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Table 1. Spectroscopic Features of **2·(X)₂** in THF

complex	UV–vis features λ, nm (ϵ, mM^{-1} cm^{-1})	rR features ν, cm^{-1} ($\Delta^{18}O_2$, cm^{-1})
2·(CF₃SO₃)₂	350 (36)	244 (0)
	485 (1.2)	313 (0)
	605 (0.9)	721 (40)
2·(SbF₆)₂	353 (38)	241 (0)
	425 (1.7)	308 (0)
	472 (2.1)	728 (40)

of the N—H groups does not alter the thermal decay rate of **2·(CF₃SO₃)₂** in THF at 233 K, indicating that the rate-determining step of thermal decay does not involve N—H bond cleavage.[29]

The stability of **2·(CF₃SO₃)₂** allows the reactivity with exogenous substrates to be examined. The isoelectronic species **P** and **O** are thought to exhibit different reactivity, with the former a better oxygen-atom transfer reagent,[30] and the latter a better hydrogen-atom acceptor.[11] Consistent with these previous observations, **2·(CF₃SO₃)₂** reacts stoichiometrically with PPh₃ at 193 K in THF to yield PPh₃O (>95%) under pseudo-first-order conditions of PPh₃, yet does not couple 2,4-di-*tert*-butylphenol to 3,3′,5,5′-tetra-*tert*-butyl-2,2′-biphenol.[31] This lack of phenolic coupling supports an attenuated hydrogen-atom abstracting ability of **2·(CF₃SO₃)₂**.[11] The reaction of **2·(CF₃SO₃)₂** with catechol, benzyl alcohol, and benzylamine gives good yields of quinone (95%), benzaldehyde (80%), and benzonitrile (70%), respectively.[16] The reactivity of a **P** species with the latter two substrates is unprecedented.[10,32,33]

In contrast to the lack of phenol reactivity, **2·(CF₃SO₃)₂** reacts rapidly with sodium or lithium salts of 2,4-di-*tert*-butylphenol at 193 K, as assessed by optical spectroscopy.[16,34] An analysis of the products reveals a ~1:1 mixture of 3,5-di-*tert*-butylcatechol and 3,5-di-*tert*-butyl-1,2-benzoquinone as products accounting for ~80% of the oxidizing equivalents of **2·(CF₃SO₃)₂**.[35] The use of ¹⁸O₂ in the formation of **2·(CF₃SO₃)₂** followed by a reaction with phenolate clearly shows that a single oxygen atom is transferred to the catechol and quinone products, supporting direct oxygen-atom transfer.[16] This places **2·(CF₃SO₃)₂** in a limited class of synthetic **P** species that efficiently hydroxylates phenolates, similar to tyrosinase.[17,18]

The contrast in O₂ reactivity between the copper complexes of DBED and its bulkier dimethylated analogue DBDMED (*N,N′*-di-*tert*-butyl-*N,N′*-di-methyl-ethylenediamine) is striking, but not unprecedented (Scheme 1).[36,37] Steric escalation within a series of PDL clearly shows that bulkier ligands bias the formation of the Cu—O₂ species toward **P** rather than **O**.[10,27] Yet, the less bulky DBED yields only detectable amounts of **P** while DBDMED yields an equilibrium mixture of **P** and **O**.[11,38] A subtle interplay of electronics and structure are obviously operative in stabilizing each isomer, ultimately controlling the reactivity with externally added substrates.

Supporting Information Available: Experimental details including synthetic procedures, UV–vis, resonance Raman, spectrophotometric titration, XAS, kinetic measurements, and product analysis (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

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(27) Inclusion in the least-squares fits to the data of the fifth ligand reduced the normalized error (χ^2) from 0.22 to 0.17 (G. N. George, SSRL, EXAFSPAK calculation of normalized error).
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