# Dioxygen–copper reactivity at trinuclear centers: formation of hexanuclear and mixed-valent adducts

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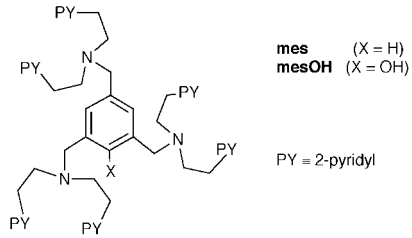
**New copper(I) complexes $[Cu^{I}_3(mesO^-)]^{2+}$ (3) and $[Cu^{I}_3(mesOH)]^{3+}$ (4) have been generated from a phenol-containing trinucleating ligand, mesOH; reactions with $O_2$ reflect the unsymmetrical ligand environment, and lead to peroxo and/or hydroperoxo cluster complexes, including those with mixed-valent copper ion centers.**

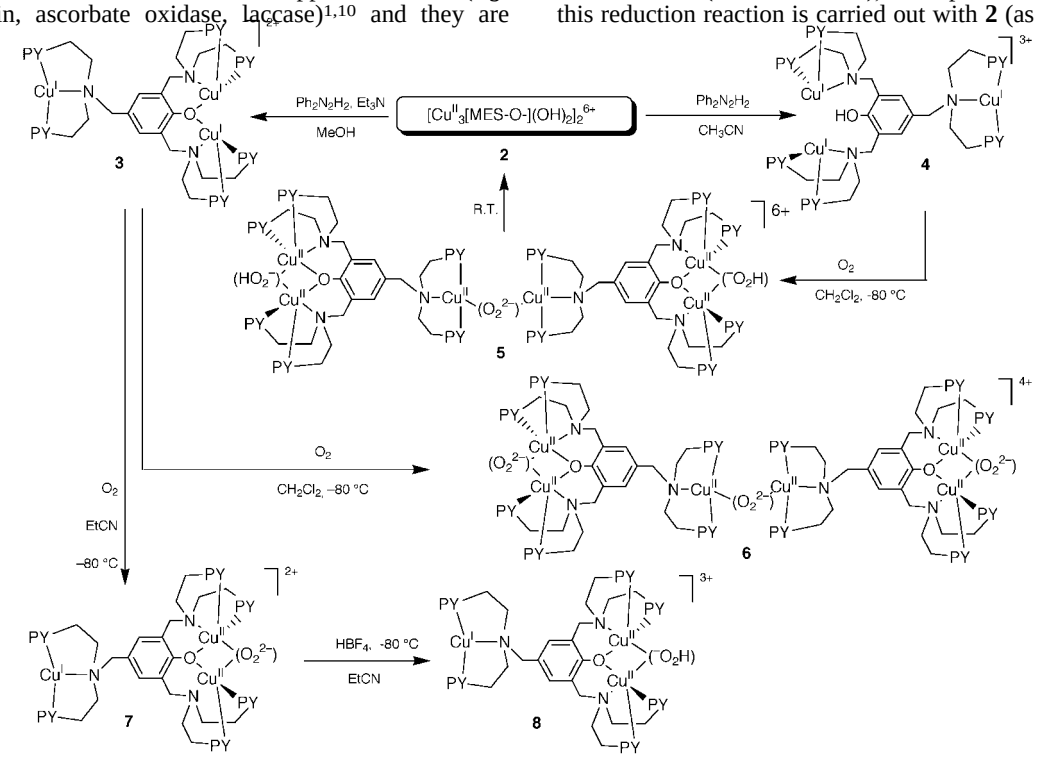
Continuing interest in studies of the reactivity of $O_2$ with discrete copper(I) complexes is for the most part driven by bioinorganic interests, *i.e.* the occurrence of copper-dioxygen carrier proteins, oxygenases which insert O-atoms into substrates, and oxidases which couple substrate oxidations to copper-mediated $O_2$-reduction to water or $H_2O_2$.[1,2] Our own efforts in elucidating fundamental aspects of (ligand)$Cu^{I}/O_2$ reactivity, and those of others, have focused on mono- or binuclear copper(I) compounds, their kinetics/thermodynamics of reaction,[3] the structures and spectroscopy of $O_2$-adducts, and substrate reactivity.[2–5] The products most often form *via* a $Cu:O_2$ 2:1 reaction stoichiometry, leading to bridged peroxo [μ-1,2- or μ-$\eta^2:\eta^2$-peroxodicopper(II)], hydroperoxo- or bis-μ-oxo[dicopper(III)] species.[2–5] An exception was described by Stack and co-workers,[6] where a $(L')Cu^{I}:O_2$ 3:1 reaction occurs, producing a mixed-valent cluster, $[Cu_3(\mu\text{-}O)_2(L')_3]^{3+}$ (L′ = *N*,*N*,*N*′,*N*′-tetramethyl-(1*R*,2*R*)-cyclohexanediamine).

Few discrete trinuclear copper(I) complexes exist,[7–9] and still fewer have associated $O_2$-chemistry.[7,8] Yet, (ligand)-$Cu^{I}_3/O_2$ chemistry is of considerable interest, since trinuclear copper cores occur in 'blue' multicopper oxidases (*e.g.* ceruloplasmin, ascorbate oxidase, laccase)[1,10] and they are

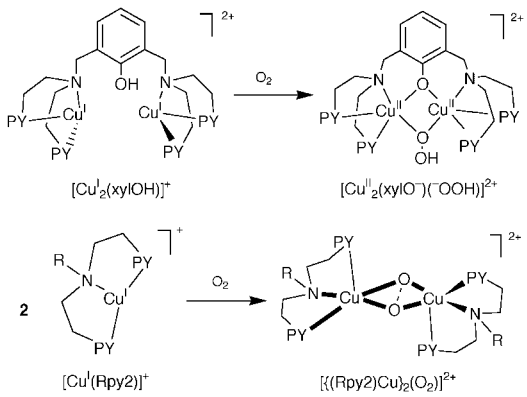



implicated at active sites in the copper-dependent methane monooxygenase.[1,11] It also has been shown in certain systems[12] that three-electron reduction of $O_2$ (*i.e.* from three Cu(I) ions) is essential for O–O bond reductive cleavage, of relevance in $O_2$-activation processes. In this report, we describe novel results in (ligand)$Cu^{I}_3/O_2$ reactivity studies, employing mesOH as an unsymmetrical trinucleating ligand.

Ligand mesOH was obtained following oxygenation of the tricopper(I) complex $[Cu^{I}_3(mes)]^{3+}$ (**1**); the hydroxylation reaction affords a hexanuclear cluster complex $[\{Cu^{II}_3(mesO^-)(OH^-)_2\}_2]^{6+}$ (**2**),[8]† from which mesOH is isolated following copper removal and extraction. By adapting the reactions used to synthesize analogous phenolate-[13] or phenol-containing[14] dinuclear copper(I) compounds, two new trinuclear copper(I) complexes possessing unsymmetrical Cu(I) coordination were prepared (Scheme 1). The bright orange ($CH_2Cl_2$; $\lambda_{max}$ 370 nm, $\varepsilon$ 16600 $M^{-1}$ $cm^{-1}$) compound $[Cu^{I}_3(mesO^-)](ClO_4)_2$ (**3**) was prepared by diphenylhydrazine reduction of **2** (as a $ClO_4^-$ salt), in the presence of $Et_3N$. When this reduction reaction is carried out with **2** (as a $BF_4^-$ salt) in




**Scheme 1**




**Scheme 2**

the absence of base, a yellow compound, $[Cu^{I}_3(mesOH)](BF_4)_3$ (**4**), was isolated.‡ For each of these trinuclear complexes, two of the three copper ions possess features found in dinuclear analogues with phenol or phenoxide groups, $[Cu^{I}_2(xylOH)]^{2+}$ (Scheme 2) and $[Cu^{I}_2(xylO^-)]^+$.[13,14] Consistent with their compound formulations, **3** and **4** are diamagnetic ($^1H$ and $^{13}C$ NMR spectroscopies).

Reaction of $O_2$ with **4** in $CH_2Cl_2$ at −80 °C leads to an intensely green colored solution dominated by strong 368 ($\varepsilon$ 14000) and 408 nm (sh, $\varepsilon$ 9500 $M^{-1}$ $cm^{-1}$) charge-transfer (CT) absorptions. The latter band is characteristic of the μ-$^-$OAr/μ-1,1-$^-$OOH dicopper coordination observed for $[Cu^{II}_2(xylO^-)(^-OOH)]^{2+}$ {395 nm ($\varepsilon$ 8000 $M^{-1}$ $cm^{-1}$),[14] while the 368 nm absorption is characteristic of the intense LMCT observed for copper complexes $[\{Cu(Rpy2)\}_2(O_2)]^{2+}$ {$\lambda_{max}$ 350–365 nm, $\varepsilon \geqslant 12000$ $M^{-1}$ $cm^{-1}$},[15] with intermolecular μ-$\eta^2$:$\eta^2$-peroxo-dicopper(II) ligation (Scheme 2).¶ Thus, the oxygenation product of **4** is formulated as a hexanuclear species, $[\{Cu_3(mesO^-)(OOH)\}_2(O_2)]^{6+}$ (**5**), (Scheme 1). Consistent with this formulation, **5** is observed to be EPR silent (frozen $CH_2Cl_2$) and manometric $O_2$-uptake measurements (−80 °C, $CH_2Cl_2$) reveal a reaction stoichiometry of $Cu:O_2$ = 6 : 2.9 (±10%)‖

A related hexanuclear complex **6** also appears to form from $O_2$-reaction with **3**.‖ This product lacks the the protons available in **4**, thus leading to peroxo species $[\{Cu_3(mesO^-)(O_2)\}_2(O_2)]^{6+}$ (**6**) (Scheme 1) {($CH_2Cl_2$, −80°C); $\lambda_{max}$ 340 ($\varepsilon$ 12000), 384 (sh, $\varepsilon$ 11000), 482 ($\varepsilon$ 6500), 594 nm (sh, $\varepsilon$ 2500 $M^{-1}$ $cm^{-1}$)}. This is suggested to possess two peroxo $Cu_2$-$O_2$ moieties similar to that observed for $[Cu^{II}_2(xylO^-)(O_2^{2-})]^+$ {385 ($\varepsilon$ 2900), 505 ($\varepsilon$ 6000), 610 (sh, $\varepsilon$ 6500 $M^{-1}$ $cm^{-1}$},[13] and an intramolecular peroxo species again similar to that in $[\{Cu(Rpy2)\}_2(O_2)]^{2+}$. Accurate manometric $O_2$-uptake experiments were thwarted by the instability of **6**.

Interestingly, mixed-valent $Cu^{I}Cu^{II}_2$ clusters **7** and **8** were obtained *via* oxygenation of **3** at −80 °C in EtCN as solvent (Scheme 1). The spectrum that develops in the CT region following $O_2$-reaction with **3** consists of primarily only the 482 and 594 nm (sh) absorptions, again very similar to the spectrum expected for $[Cu^{II}_2(xylO^-)(O_2^{2-})]^{+}$[13] and that found for **6**. The lack of formation of a more intense band in the 340–380 nm regions indicates that the $Cu^{I}$(Rpy2) moiety in **3** does not react with dioxygen; this is as previously observed for discrete $[Cu^{I}(Rpy2)]^+$ complexes[15] and is explained by the strong nitrile (solvent) coordination, especially at low temperatures. Manometric measurements are also in accord with the formulation of **7**, since $Cu:O_2$ = 3 : 0.95 (±10%) (EtCN, −80 °C). Further confirmation comes from reaction of **7** with excess acid ($HBF_4$·$Et_2O$) and workup, which generates hydrogen peroxide in *ca*. 85% of the expected yield (1 $H_2O_2$ per molecule of **7**), as determined by iodometric titration. A hydroperoxo-containing mixed-valent cluster analogue, **8** ($\lambda_{max}$ 395 mm), can be generated by addition of one equiv. of $H^+$ ($HBF_4$·$Et_2O$) to **7** (Scheme 1).

In summary, mes-OH as a trinucleating ligand affords novel tricopper(I) complexes **3** or **4**, in which an unsymmetrical ligation for the three copper ions occurs, as observed for the enzymes.[1,10] Based on previously established chemistry for phenoxide (or phenol) dicopper(I) compounds (Scheme 2), we have shown that phenoxide with peroxo- (or hydroperoxo-) dicopper(II) species form upon $O_2$-reactions with **3** or **4**, and in $CH_2Cl_2$ as solvent, this leaves the third copper ion to react with $O_2$ in an intermolecular fashion, affording hexanuclear complexes. In EtCN as solvent, the latter reaction is suppressed, and mixed-valent species form, in which a copper(I) moiety survives oxidation even in the presence of a nearby (hydro)-peroxo-dicopper(II) center. The reasons for this are currently unclear. Evidence for a related hydroperoxo-tricopper [including Cu(I)] entity has been presented by Solomon and co-workers,[1] as an intermediate in the four-electron reduction of $O_2$ by the enzyme laccase. Further investigations of tricopper(I)/$O_2$ reactivity patterns are in progress.

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## Notes and references

† This product **2** is obtained if $ClO_4^-$ or $CF_3SO_3^-$ are utilized as the counteranion (unpublished results). We previously[8] mistakenly identified **2** as the product formed when using $PF_6^-$, which is actually a bis-μ-$F^-$ complex, $[\{Cu^{II}_3(mesO^-)(OH^-)(F^-)\}_2]^{6+}$. See also ref. 15(*a*) and S. C. Lee and R. H. Holm, *Inorg. Chem.*, 1993, **32**, 4745.

‡ Satisfactory analytical data (NMR and mass spectral for mesOH; C, H, N combustion analysis for complexes **3** and **4**) have been obtained.

§ A band assignable to the $\nu$(O–H) stretch, expected for **4** in its IR spectrum, was not observed, probably due to interaction of the Ar–OH group with Cu(I) ion(s). The same phenomenon was observed for $[Cu^{I}_2(xylOH)]^{2+}$; for a bis $PPh_3$ adduct, the expected $\nu$(O–H) stretch was detected.[14]

¶ Some decomposition to a bis-μ-$F^-$ complex may also be occurring, since **4** contains $BF_4^-$, with fluoride. See footnote † above.

‖ The hexanuclear formaulation is also supported by the existence of the very similar mesO$^-$-containing hexanuclear compound **2** (with X-ray structure). See ref. 8 and footnote †.


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