Published in final edited form as:

J Am Chem Soc. 2018 July 25; 140(29): 9042–9045. doi:10.1021/jacs.8b04671.

Intramolecular Hydrogen Bonding Enhances Stability and Reactivity of Mononuclear Cupric Superoxide Complexes

Mayukh Bhadra[†], Jung Yoon C. Lee[†], Ryan E. Cowley[‡], Sunghee Kim[†], Maxime A. Siegler[†], Edward I. Solomon^{*,‡}, and Kenneth D. Karlin^{*,†}

[†]Department of Chemistry, The Johns Hopkins University, Baltimore, Maryland 21218, United States

[‡]Department of Chemistry, Stanford University, Stanford, California 94305, United States

Abstract

$[(L)Cu^{II}(O_2^{\bullet-})]^+$ (i.e., cupric-superoxo) complexes, as the first and/or key reactive intermediates in (bio)chemical Cu-oxidative processes, including in the monooxygenases PHM and D β M, have been systematically stabilized by intramolecular hydrogen bonding within a TMPA ligand-based framework. Also, gradual strengthening of ligand-derived H-bonding dramatically enhances the $[(L)Cu^{II}(O_2^{\bullet-})]^+$ reactivity toward hydrogen-atom abstraction (HAA) of phenolic O–H bonds. Spectroscopic properties of the superoxo complexes and their azido analogues, $[(L)Cu^{II}(N_3^-)]^+$, also systematically change as a function of ligand H-bonding capability.

The activation of molecular oxygen with copper is of considerable interest in nature, as well as in oxidative synthetic procedures and in addressing energy concerns (e.g., fuel-cell O₂ reduction catalysts).¹ Reduction of O₂ with Cu^I leads to complexes with singly or doubly reduced dioxygen (superoxo or (hydro)peroxo, respectively); further important downstream intermediates (viz. Cu^{II}–O[•]) form following reductive O–O cleavage.² Various Cu^I–O₂ derived species are suggested to initiate substrate attack leading to O atom incorporation i.e., net hydroxylation in copper monooxygenases such as peptidylglycine- α -hydroxylating monooxygenase (PHM) and dopamine- β -monooxygenase (D β M).^{3a-e} For these cases, along with the dehydrogenation of RCH₂OH in galactose oxidase (GO), copper amine oxidase iminosemiquinone H atom abstraction (HAA), and GO cofactor biogenesis (HAA from cysteine S–H),^{3f} a mononuclear cupric superoxide (Cu^{II}–O₂^{•-}) intermediate is implicated in effecting key H atom abstraction (HAA) chemistry.^{3b,c,4}

Thus, there have been considerable efforts in the design of appropriate synthetic ligands to probe the factors affecting the formation, stabilization, and reactivity of these metastable $[LCu^{II}(O_2^{\bullet-})]^+$ species.^{2b,c,5} For example, increasing electron donation to Cu,⁵ providing

*Corresponding Authors edward.solomon@stanford.edu, karlin@jhu.edu.

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/jacs.8b04671.

Synthetic and analytical details (methodologies and UV–vis, EPR, NMR, and FT-IR spectra) (PDF)

Crystallographic data for $[(BA)Cu^{II}(N_3)](ClO_4)$ (CIF), $[(F_5BA)Cu^{II}]_2$ (CIF), $[(F_5BA)Cu^{II}(N_3)](OTf)$ (CIF), and $[(F_5BA)Cu^{II}(CH_3COCH_3)(OCIO_3)](ClO_4)$ (CIF)

The authors declare no competing financial interest.

steric interactions,⁶ controlling coordination geometry,⁷ and employing cryogenic conditions and suitable solvents^{5–8} have each been shown to stabilize the superoxide species and prevent its subsequent reaction with a second equiv of the Cu^I precursor to yield thermodynamically favored binuclear peroxo-bridged dicopper(II) complexes (Eqs 1 and 2).⁹

H-bonding in the secondary coordination sphere is known to stabilize binuclear $[(\text{L})\text{Cu}^{\text{II}}]_2(\text{O}_2^{2-})^{2+}$ and mononuclear $[(\text{L})\text{Cu}^{\text{II}}(\text{OOH})]^+$ complexes with N_3O and N_4 ligand architecture.¹¹ Considering extensive recent efforts in studying H-bonding influences on model complexes¹² and in biological systems (for example, this plays a crucial role in stabilizing and activating O_2 -intermediates,¹³ effecting nitrite reduction,¹⁴ and facilitating neural NOS activity¹⁵), the importance of H-bonding on $[(\text{L})\text{Cu}^{\text{II}}(\text{O}_2^{\bullet -})]^+$ chemistries still remains a fundamental and critical area for study.

In this report, we demonstrate that the imposition of progressively enhancing H-bonding moieties in a series of TMPA-based L–Cu complexes {Figure 1; pK_{a} s of related relevant organic groups: pentafluorobenzylamine (~ 7) < benzylamine (9.3),¹⁶ and note that pivalamide and other amides are more acidic than 2° amines} (i) inhibits the formation of corresponding binuclear *trans*- μ -1,2-peroxo $[(\text{L})\text{Cu}^{\text{II}}]_2(\text{O}_2^{2-})^{2+}$ complex, in favor of monocopper $[(\text{L})\text{Cu}^{\text{II}}(\text{O}_2^{\bullet -})]^+$ species, while (ii) also significantly enhances the HAA reactivity of the superoxo species toward phenolic substrates.

When a 0.4 mM solution of $[(\text{TMPA})\text{Cu}^{\text{I}}(\text{MeCN})]\text{B}(\text{C}_6\text{F}_5)_4$ in MeTHF was subjected to dioxygen bubbling at -135°C and allowed to equilibrate for 30 min, the resulting mixture consisted of the known⁹ end-on superoxide (i.e., $\text{Cu}^{\text{II}}-\text{O}-\text{O}^{\bullet -}$) complex **A** $\{[(\text{TMPA})\text{Cu}^{\text{II}}(\text{O}_2^{\bullet -})]^+\}$ (63% based on Cu (see Section 4.3(a) in the SI); $\lambda_{\text{max}} = 423\text{ nm}$, $\epsilon = 5600\text{ M}^{-1}\text{cm}^{-1}$; 752 nm)¹⁰ and the known *trans*-peroxide dicopper(II) complex $\{[(\text{TMPA})\text{Cu}^{\text{II}}]_2(\text{O}_2^{2-})^{2+}$ (37%; $\lambda_{\text{max}} = 525, 610\text{ nm}$) (Figure 2).¹⁰ With its ligand derived weak H-bonding (vide infra),¹⁷ O_2 -bubbling of $[(\text{BA})\text{Cu}^{\text{I}}]^+$ significantly increased relative amounts of **B** $\{[(\text{BA})\text{Cu}^{\text{II}}(\text{O}_2^{\bullet -})]^+\}$ (83% (see Section 4.3(b) in the SI); $\lambda_{\text{max}} = 418\text{ nm}$, $\epsilon = 4100\text{ M}^{-1}\text{cm}^{-1}$; 750 nm), compared to $\{[(\text{BA})\text{Cu}^{\text{II}}]_2(\text{O}_2^{2-})^{2+}$ (17%; $\lambda_{\text{max}} = 500, 605\text{ nm}$).¹⁰ However, dramatic stabilization is observed with utilization of F_5BA , a new ligand capable of stronger H-bonding than in BA, cupric superoxide $[(\text{F}_5\text{BA})\text{Cu}^{\text{II}}(\text{O}_2^{\bullet -})]^+$ (414 nm, $\epsilon = 4000\text{ M}^{-1}\text{cm}^{-1}$; 748 nm), is generated exclusively.¹⁰ Employing MPPA,^{11c,18} possessing the strongest H-bonding moiety, complex **D** $\{[(\text{MPPA})\text{Cu}^{\text{II}}(\text{O}_2^{\bullet -})]^+\}$ is formed. These superoxo species, **C** and **D**, are very stable in solution (-135°C); they are fully formed, and there appears to be no hint of any peroxide analog present.^{10,19}

This systematic H-bonding enhancement of $[(L)Cu^{II}(O_2^{\bullet-})]^+$ stabilization is further supported by corresponding UV-vis data obtained at $[(L)Cu^I]^+$ initial concentrations of 0.1 mM (see Figures S5–S8).¹⁰ Analogous to synthetic and protein derived oxy-heme adducts (formally $Fe^{III}-O_2^{\bullet-}$ species), the primary effect of the H-bonding (e.g., for the distal His residue in hemo- or myoglobins) is to dramatically decrease the rate of O_2 dissociation, hence lowering k_{-1} thereby increasing K_1 (Eq 1). With stronger H-bonding, $[(L)Cu^{II}(O_2^{\bullet-})]^+$ species becomes systematically more stable across **B–D**. Without the H-bond in $[(TPMA)Cu^{II}(O_2^{\bullet-})]^+$ (**A**), k_{-1} is significant, more Cu(I) becomes available, and $[(L)Cu^{II}(O_2^{\bullet-})]^+$ readily reacts to yield the thermodynamic $\{[(L)Cu^{II}]_2(O_2^{2-})\}^{2+}$ product (Eq 2).

Resonance Raman (rR) spectroscopy was used to characterize the effect of H-bonding in the series of superoxide complexes **A–D** in frozen MeTHF solution. Laser excitation (413.1 nm) of each superoxide complex (~1 mM) revealed two sets of $^{16/18}O$ isotope-sensitive enhanced modes at around 460 and 1120 cm^{-1} (Figure 1), which are characteristic of $\nu(Cu-O)$ and $\nu(O-O)$, respectively (the latter appears as a Fermi doublet (Figure 1), consistent with previous observations²¹), of end-on cupric superoxides (see Section 5 in the SI for details).
5a,c,6a,7,18,21b,c

Interestingly, a systematic trend is observed for the **A–D** complexes where the $\nu(O-O)$ values¹⁸ increased with enhancing H-bonding ability of the systematically stronger N–H dipoles present across **B–D**. Analogous to previously reported cases,^{18,21c} we presume the observed incremental trend in $\nu(O-O)$ across **B–D** is caused by enhanced structural vibrational coupling and alignment of increased O–O dipole opposite to the systematically increasing N–H dipole. $[(TPMA)Cu^{II}(O_2^{\bullet-})]^+$ (**A**), without any H-bonding moiety, exhibited the lowest (weakest) O–O stretch as expected.

In parallel, the doubly occupied superoxide π_{σ}^* (LMCT donor MO) undergoes more electrostatic stabilization compared to the $Cu^{II}-d_z^2$ (LMCT acceptor MO) with increasing H-bonding across the **A–D** $[(L)Cu^{II}(O_2^{\bullet-})]^+$ series, which increases the energy of the LMCT ($\pi_{\sigma}^* \rightarrow Cu^{II}-d_z^2$) transition;¹⁰ hence, a systematic blue shift is observed in the higher energy LMCT absorption, ranging from 423 to 410 nm across **A–D** (Figure 2 and Table 1).

To obtain better insight into the H-bonding in these $[(L)Cu^{II}(O_2^{\bullet-})]^+$ complexes, we examined the structures of the azido analogs, $[(BA)Cu^{II}(N_3^-)]ClO_4$, $[(F_5BA)Cu^{II}(N_3^-)]ClO_4$, and $[(F_5BA)Cu^{II}(OCIO_3)(acetone)]ClO_4$ (for syntheses, see the SI).¹⁰ Azide ion bound to Cu^{II} complexes have been previously used to model both electronic and connectivity structural aspects for coordination of a peroxide dianion.²² With respect to a cupric-superoxide complex, a $Cu^{II}-N_3$ moiety would be expected to have a very similar $Cu^{II}-N-N-N$ binding mode (e.g., bond distances and the $\angle Cu^{II}-N-N$ angle). The crystal structure of $[(BA)Cu^{II}(N_3^-)]^+$ (Figure 3) experimentally determined via single-crystal X-ray crystallography revealed a weak but clearly observable intramolecular H-bond found between the benzyl amino N–H hydrogen atom and the azido N atom (2.17(2) Å) proximal to the Cu(II) ion. The $N_{amino}-H \cdots N_{azido}$ distance is 2.965(2) Å with $\angle N_{amino}-H \cdots N_{azido} = 163(2)^\circ$. Similar H-bonding is observed in the F_5BA analog mentioned above.¹⁰ This interaction, also observed in other $Cu^{II}(X)$ ($X = N_3^-$, ^-OOH , or peroxo-Cu) instances with

TMPA based ligands possessing internal H-bonding groups,^{11,23} supports the notion that the H-bonding in complexes **B–D** occurs to the proximal O atom, as depicted in Figure 1.

To further support our suppositions concerning the Hbonding in these $[(L)Cu^{II}(O_2^{\bullet-})]^+$ complexes, we examined the antisymmetric N_3^- IR stretch (see Section 7 in the SI)¹⁰ for the full series of complexes $[(L)Cu^{II}(N_3^-)]^+$. The characteristic ν_{N-N} values (Table 1) increased progressively with H-bonding strength across **A–D**, presumably due to an increase in the triplebond character of the azido ligand, resulting from removal of electron density from the copper-bound N_{azido} atom, mirroring the increase in rRaman O–O stretches in **A–D**. Additionally, the azido $\rightarrow Cu^{II}$ LMCT band shifts progressively to higher energy with increased ligand H-bonding (Table 1, also see Section 7 in the SI),¹⁰ consistent with the increasing trend in $O_2^{\bullet-} \rightarrow Cu^{II}$ LMCT energy across **A–D**.

Elucidation of the oxidative capability and scope of reactivity for $[(L)Cu^{II}(O_2^{\bullet-})]^+$ complexes is a major objective. We expected that systematic increased H-bonding to the $O_2^{\bullet-}$ should stabilize its π^* orbital and also increase its electrophilicity. Indeed, we have found a striking difference in the reactivity toward phenols (electrophilic HAA) with varying O–H bond strengths, across the **A–D** series.

Reactions with 2,6-di-*tert*-butyl-4-methoxyphenol (DTBP) with a weak O–H bond (BDE = 82.0 kcal/mol in DMSO²⁴) were first investigated. $[(TMPA)Cu^{II}(O_2^{\bullet-})]^+$ (**A**) reacts with a second-order rate constant of $3.11 \times 10^{-1} M^{-1} s^{-1}$ (–135 °C, MeTHF; Figure 4) as determined by monitoring absorbance decrease at 752 nm due to **A**. $[(TMPA)Cu^{II}OOH]^+$ (~80% yield, see Figure S42) and the corresponding phenoxyl radical were observed, demonstrating a net H atom transfer from phenol to superoxo.^{5b,10} Importantly the corresponding peroxodicopper(II) complex $[(TMPA)Cu^{II}]_2(O_2^{2-})^{2+}$ is observed to be completely unreactive toward phenols (see Figure S27).¹⁰

The cupric superoxo complexes possessing intramolecular Hbonds (**B–D**) react more efficiently with DTBP under the same conditions (Figure 4b), with $k_2 = 5.73 \times 10^{-1} M^{-1} s^{-1}$ (**B**), $11.47 \times 10^{-1} M^{-1} s^{-1}$ (**C**), and $9.88 \times 10^{-1} M^{-1} s^{-1}$ (**D**). In each case, the phenoxy radical was directly observed by both EPR ($g \approx 2.0$) and UV–vis (407 nm) spectroscopies (see Section 9.2 in the SI).¹⁰ Formation of the hydroperoxo product (86% yield) by **C** via net HAA from DTBP is also verified by spectrophotometric quantitative analysis of the amount of H_2O_2 released upon acidification; see Section 9.3 in the SI. Although the spectroscopic data imply that **D** is the most activated in the series, it is less reactive toward DTBP than **C**. We presume that this apparent anomaly is due to the larger steric interaction of the *tert*-butyl group in **D**, inhibiting bulky substrate approach and decreasing the advantage **D** should have, with its strongest Hbonding pivalamido group. Notably, **C** could also exert π – π stacking interactions with DTBP, facilitating a much favorable substrate approach compared to **D**, hence resulting in its slightly enhanced reaction rate.

Further, we tested our $[(L)Cu^{II}(O_2^{\bullet-})]^+$ complexes **A–D** toward 4-methoxyphenol (MP), a substrate with a stronger O–H bond (BDE = 87.6 kcal/mol in DMSO²⁴). $[(TMPA)Cu^{II}(O_2^{\bullet-})]^+$ was completely unreactive toward 250 equiv of MP at –135 °C (Figure 4c). $[(BA)Cu^{II}(O_2^{\bullet-})]^+$ (**B**) exhibited exceedingly slow reactivity (completion took >6 h), and

$[(F_5BA)Cu^{II}(O_2^{\bullet-})]^+$ (**C**) reacted considerably faster.¹⁰ However, the kinetic behavior was complicated in these cases, and the final copper complex product could not be identified, similar to the observation by Tolman and co-workers²⁵ in MP HAA by a Cu^{III} -hydroxide complex. The MP reaction with $[(MPPA)Cu^{II}(O_2^{\bullet-})]^+$ (**D**) was much cleaner and followed clear secondorder decay ($k_2 = 2.33 \times 10^{-2} M^{-1} s^{-1}$). The corresponding hydroperoxo-Cu(II) product was also observed in UV-vis spectroscopy (Figure 4d). This is the first example of a much stronger phenol being oxidized by a mononuclear cupric superoxide compared to the previously reported cases.

In conclusion, we report for the first time how H-bonding strength in the ligand secondary coordination sphere can be tuned to systematically stabilize cupric superoxide ($[LCu^{II}(O_2^{\bullet-})]^+$) species, control the superoxide-peroxide equilibrium, and concurrently activate the superoxide toward enhanced exogenous O-H substrate oxidation. This was achieved by systematically increasing the electrophilicity of $[LCu^{II}(O_2^{\bullet-})]^+$ via implementation of differing H-bonding moieties. The structures of the $[(L)Cu^{II}(N_3^-)]^+$ analogs suggest that H-bonding occurs to the proximal O-atom in $([LCu^{II}(O_2^{\bullet-})]^+)$ complexes. Further use of H-bonding or other ligand modifications in order to generate cupric-superoxide complexes with greater oxidative capabilities is being explored.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

■ ACKNOWLEDGMENTS

The research support of the NIH (DK031450 to E.I.S.; GM28962 to K.D.K.) is gratefully acknowledged.

■ REFERENCES

- (1). McCann SD; Stahl SS *Acc. Chem. Res.* 2015, 48, 1756. [PubMed: 26020118]
- (2). (a)Lee JY; Karlin KD *Curr. Opin. Chem. Biol.* 2015, 25, 184. [PubMed: 25756327] (b)Elwell CE; Gagnon NL; Neisen BD; Dhar D; Spaeth AD; Yee GM; Tolman WB *Chem. Rev.* 2017, 117, 2059. [PubMed: 28103018] (c)Itoh S *Acc. Chem. Res.* 2015, 48, 2066. [PubMed: 26086527]
- (3). (a)Klinman JP *Chem. Rev.* 1996, 96, 2541. [PubMed: 11848836] (b)Klinman JP *J. Biol. Chem.* 2006, 281, 3013. [PubMed: 16301310] (c)Solomon EI; Heppner DE; Johnston EM; Ginsbach JW; Cirera J; Qayyum M; KieberEmmons MT; Kjaergaard CH; Hadt RG; Tian L *Chem. Rev.* 2014, 114, 3659. [PubMed: 24588098] (d)Whittaker JW *Chem. Rev.* 2003, 103, 2347. [PubMed: 12797833] (e)Cowley RE; Tian L; Solomon EI *Proc. Natl. Acad. Sci. U. S. A.* 2016, 113, 12035. [PubMed: 27790986] (f)Cowley RE; Cirera J; Qayyum MF; Rokhsana D; Dooley DM; Hedman B; Hodgson KO; Solomon EI *J. Am. Chem. Soc.* 2016, 138, 13219. [PubMed: 27626829]
- (4). Prigge ST; Eipper BA; Mains RE; Amzel LM *Science* 2004, 304, 864. [PubMed: 15131304]
- (5). (a)Maiti D; Fry HC; Woertink JS; Vance MA; Solomon EI; Karlin KD *J. Am. Chem. Soc.* 2006, 129, 264. (b)Lee JY; Peterson RL; Ohkubo K; Garcia-Bosch I; Himes RA; Woertink J; Moore CD; Solomon EI; Fukuzumi S; Karlin KD *J. Am. Chem. Soc.* 2014, 136, 9925. [PubMed: 24953129] (c)Kim S; Lee JY; Cowley RE; Ginsbach JW; Siegler MA; Solomon EI; Karlin KD *J. Am. Chem. Soc.* 2015, 137, 2796. [PubMed: 25697226]
- (6). (a)Würtele C; Gaoutchenova E; Harms K; Holthausen MC; Sundermeyer J; Schindler S *Angew. Chem., Int. Ed.* 2006, 45, 3867. (b)Fujisawa K; Tanaka M; Morro-oka Y; Kitajima NJ *Am. Chem. Soc.* 1994, 116, 12079.
- (7). Kunishita A; Kubo M; Sugimoto H; Ogura T; Sato K; Takui T; Itoh SJ *Am. Chem. Soc.* 2009, 131, 2788.

- (8). Zhang CX; Kaderli S; Costas M; Kim E; Neuhold YM; Karlin KD; Zuberbühler AD *Inorg. Chem.* 2003, 42, 1807. [PubMed: 12639113]
- (9). (a)Karlin KD; Kaderli S; Zuberbühler AD *Acc. Chem. Res.* 1997, 30, 139.(b)Karlin KD; Wei N; Jung B; Kaderli S; Zuberbühler AD *J. Am. Chem. Soc.* 1991, 113, 5868.
- (10). See Supporting Information.
- (11). (a)Wada A; Harata M; Hasegawa K; Jitsukawa K; Masuda H; Mukai M; Kitagawa T; Einaga H *Angew. Chem., Int. Ed.* 1998, 37, 798.(b)Yamaguchi S; Masuda H *Sci. Technol. Adv. Mater.* 2005, 6, 34.(c)Yamaguchi S; Wada A; Funahashi Y; Nagatomo S; Kitagawa T; Jitsukawa K; Masuda H *Eur. J. Inorg. Chem.* 2003, 42, 4378.(d)Yamaguchi S; Kumagai A; Nagatomo S; Kitagawa T; Funahashi Y; Ozawa T; Jitsukawa K; Masuda H *Bull. Chem. Soc. Jpn.* 2005, 78, 116.(e)Mann SI; Heinisch T; Ward TR; Borovik AS *J. Am. Chem. Soc.* 2017, 139, 17289. [PubMed: 29117678] (f)Dahl EW; Dong HT; Szymczak NK *Chem. Commun.* 2018, 54, 892.
- (12). (a)Nagaraju P; Ohta T; Liu J-G; Ogura T; Naruta Y *Chem. Commun.* 2016, 52,7213.(b)Matson EM;Park YJ;Fout AR *J. Am. Chem. Soc.* 2014, 136, 17398. [PubMed: 25470029] (c)Macbeth CE; Gupta R; MitchellKoch KR; Young VG, Jr ; Lushington GH; Thompson WH; Hendrich MP; Borovik AS *J. Am. Chem. Soc.* 2004, 126, 2556. [PubMed: 14982465] (d)Borovik AS *Acc. Chem. Res.* 2005, 38, 54. [PubMed: 15654737]
- (13). (a)Yang J; Kloek AP; Goldberg DE; Mathews FS *Proc. Natl. Acad. Sci. U. S. A.* 1995, 92, 4224. [PubMed: 7753786] (b)Lukin JA; Simplaceanu V; Zou M; Ho NT; Ho C *Proc. Natl. Acad. Sci. U. S. A.* 2000, 97, 10354. [PubMed: 10962034] (c)Arroyo Mañez P; Lu C; Boechi L; Martí MA; Shepherd M; Wilson JL; Poole RK; Luque FJ; Yeh SR; Estrin DABiochemistry 2011, 50, 3946. [PubMed: 21476539] (d)Sheng Y; Abreu IA; Cabelli DE; Maroney MJ; Miller AF; Teixeira M; Valentine JS *Chem. Rev.* 2014, 114, 3854. [PubMed: 24684599] (e)Huang X; Groves JT *Chem. Rev.* 2018, 118, 2491. [PubMed: 29286645]
- (14). Merkle AC; Lehnert N *Dalt. Trans* 2012, 41, 3355.
- (15). Poulos TL; Li H *Acc. Chem. Res.* 2013, 46, 390. [PubMed: 23030042]
- (16). (a) Advanced Chemistry Development (ACD/Labs) Software, V11.02; ACD/Labs, 2018.(b)Hall HK *J. Am. Chem. Soc.* 1957, 79, 5441.(c)Mareque Rivas JC; Hinchley SL; Metteau L; Parsons S *Dalton Trans.* 2006, 2316.
- (17). Kim S; Saracini C; Siegler MA; Drichko N; Karlin KD *Inorg.Chem.* 2012, 51, 12603. [PubMed: 23153187]
- (18). Peterson RL; Himes RA; Kotani H; Suenobu T; Tian L; Siegler MA; Solomon EI; Fukuzumi S; Karlin KD *J. Am. Chem. Soc.* 2011, 133, 1702. [PubMed: 21265534]
- (19). A similar correlation between the H-bonding strength of the ligand and the stability of the superoxo complex is also observed at temperatures above -135°C , where cupric superoxide adducts with weak or no H-bonding readily transform into the corresponding transperoxide species when compared with strongly H-bonded systems.)
- (20). (a)Momenteau M; Reed CA *Chem. Rev.* 1994, 94, 659.(b)Birukou I; Schweers RL; Olson JS *L. Biol. Chem.* 2010, 12, 8840.(c)Momenteau M; Lavalette DJ *Chem. Soc., Chem. Commun* 1982, 341.
- (21). The O–O stretch was observed as a Fermi resonance in at least one isotopologue of each complex, where $\nu(\text{O}=\text{O})$ is split by an unenhanced mode with the same symmetry at similar energy. This assignment is supported by the different relative intensities of the doublet between ^{16}O and ^{18}O isotopologues, which is expected for Fermi resonance between isotope-sensitive and isotope-insensitive modes. The presence of multiple species is less likely since the ratio in a mixture should be independent of the isotopologue. Fermi resonances have been observed in other cupric superoxides; Ref 18. Woertink JS; Tian L; Maiti D; Lucas HR; Himes RA; Karlin KD; Neese F; Würtele C; Holthausen MC; Bill E; Sundermeyer J; Schindler S; Solomon EI *Inorg. Chem.* 2010, 49, 9450. [PubMed: 20857998] Peterson RL; Ginsbach JW; Cowley RE; Qayyum MF; Himes RA; Siegler MA; Moore CD; Hedman B; Hodgson KO; Fukuzumi S; Solomon EI; Karlin KD *J. Am. Chem. Soc.* 2013, 135, 16454. [PubMed: 24164682] Cao R; Saracini C; Ginsbach JW; Kieber-Emmons MT; Siegler MA; Solomon EI; Fukuzumi S; Karlin KD *J. Am. Chem. Soc.* 2016, 138, 7055 The pre-interaction values of $\nu(\text{O}=\text{O})$ for A–D given in Figure 1 were determined from the intensity-weighted average of the two observed vibrations.

- (22). Pate JE; Ross PK; Thamann TJ; Reed CA; Karlin KD; Sorrell TN; Solomon EI *J. Am. Chem. Soc.* 1989, 111, 5198.
- (23). Wada A; Honda Y; Yamaguchi S; Nagatomo S; Kitagawa T; Jitsukawa K; Masuda H *Inorg. Chem.* 2004, 43, 5725. [PubMed: 15332825]
- (24). Warren JJ; Tronic TA; Mayer JM *Chem. Rev.* 2010, 110, 6961. [PubMed: 20925411]
- (25). Dhar D; Yee GM; Markle TF; Mayer JM; Tolman WB *Chem. Sci.* 2017, 8, 1075. [PubMed: 28572905]

Figure 1. [(L)Cu^{II}(O₂^{•-})]⁺ complexes without (A, L = TMPA; tris(2pyridyl-methyl)amine) and with internal H-bonding substituents (B–D, L = BA, F₅BA, and MPPA), and corresponding resonance Raman spectra ($\lambda_{\text{ex}} = 413.1$ nm) of complexes A–D in frozen 2methyltetrahydrofuran (MeTHF) solutions prepared with ¹⁶O₂ (blue) and ¹⁸O₂ (red). Labels indicate the center of the Fermi doublets. See Supporting Information for tabulation of $\nu(\text{Cu}-\text{O})$ values.¹⁰

Figure 2. UV-vis spectra of oxygenated mixtures of $\sim 0.4\text{ mM}$ of $[(L)Cu^I]B(C_6F_5)_4$ (L = TMPA, BA, F₅BA, and MPPA) at $-135\text{ }^\circ\text{C}$ in MeTHF after 30 min. H-bonding stabilizes superoxide species and prevents trans-peroxide formation (see Figures S1–S4).¹⁰

Figure 3. Displacement ellipsoid plot (50% probability level) of the cationic $[(BA)CuII(N3-)]^+$ at 110(2) K. A list of relevant bond distances and angles is also provided. The H-bonding between the benzylamine and the proximal azide nitrogen is highlighted

Figure 4.

(a) UV-vis monitoring of the reaction of **A** and 2,6-di-tert-butyl-4-methoxyphenol; (b) contrasting rates of oxidation by **A–D** (k_2 values are given in the text); (c) UV-vis spectra of reaction of **A** with 4-methoxyphenol, showing no reaction; (d) reaction of **D** with 4-methoxyphenol and (inset) kinetic trace of the decay of 741 nm band of **D**. See Section 6 in the SI for details.

Table 1.

Summary of Spectroscopic Features (UV-vis, IR, and rRaman) for [(L)Cu^{II}(O₂^{•-})]⁺ and [(L)Cu^{II}(N₃⁻)]⁺ Complexes

	TMPA	BA	F₅BA	MPPA
rR O–O stretch { ¹⁸ O ₂ } (cm ⁻¹)	1119 {-61}	1123 {-64}	1126 {-64}	1130 {-63}
λ_{max} Cu ^{II} –O ₂ ^{•-} (nm)	423	418	414	410
λ_{max} Cu ^{II} –N ₃ ⁻ (nm)	413	402	399	395
IR N≡N stretch (cm ⁻¹)	2046	2049	2052	2063