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Communication

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Isolation of a 2-Hydroxytetrahydrofuran Complex from Copper-Promoted Hydroxylation of THF

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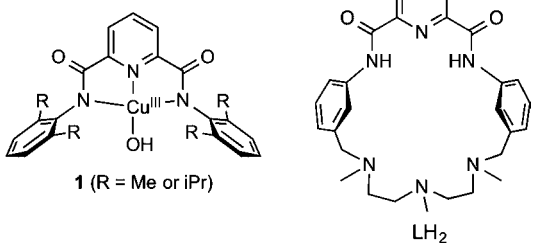
Supporting Information

ABSTRACT: A complex of a binucleating macrocyclic ligand comprising a $[Cu^{II}(\mu\text{-OH})Na]^{2+}$ core reacts with CuI in THF/CH_3CN to yield a novel species with a deprotonated 2-hydroxytetrahydrofuran (THF-2-ol) bridging between Cu^{II} and Na^{I} ions. The complexes were characterized by X-ray crystallography, electron paramagnetic resonance spectroscopy, and electrospray ionization mass spectrometry. ^{18}O-labeling studies support incorporation of the O atom from μ-OH into the coordinated THF-2-ol ligand.

In view of the significance of copper-catalyzed oxidations in biology[1] and for synthetic/industrial applications,[2] a key goal in current research is to understand mechanisms of oxidation catalysis by studying copper−oxygen intermediates.[3] In work aimed at addressing this goal, we recently reported the syntheses of **1** (R = Me[4] or iPr;[5] Scheme 1), examples of a new type of

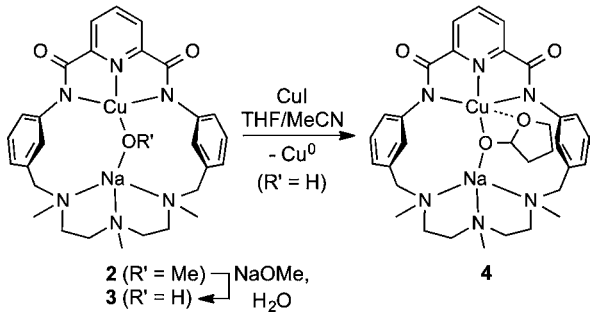
Scheme 1



copper−oxygen species with a $[Cu^{III}OH]^{2+}$ core, via one-electron oxidation of $[Cu^{II}OH]^{+}$ precursors. The thermally sensitive compounds **1** abstract H atoms from dihydroanthracene at high rates, on par with some of the most reactive iron or manganese oxo/hydroxo complexes in the literature.[6] As part of an effort to understand the basis for this reactivity and to develop even more useful oxidants, we asked the following: What would be the effect of a Lewis acid center in close vicinity to the $[Cu^{III}OH]^{2+}$ core? Perturbation of the properties of this core might be expected on the basis of a number of recent observations, such as notable effects of (a) Sc^{3+}[7] and Brønsted acids[8] on the reactivity of Fe^{IV}═O species, (b) Ca^{2+} ions on the properties of cobalt(III/IV) aquo/hydroxo species,[9] and (c) second-sphere hydrogen bonding on the properties of a variety of metal−oxygen moieties.[10]

With the objective of sequestering a group IA metal ion in close proximity to $Cu^{II/III}OH$ units akin to those in **1**, we focused on using proligand LH_2 (Scheme 1), with the idea that the pyridine(dicarboxamide) like that in **1** would support the $Cu^{II/III}OH$ unit and the triamine fragment would bind the group IA metal ion nearby. Building upon previous work showing that L^{2-} enables the synthesis of a variety of homo- and heterobimetallic complexes,[11] we report herein the synthesis and characterization of the desired complex **3**, comprising a $[Cu^{II}(\mu\text{-OH})Na]^{2+}$ core (Scheme 2). In a serendipitous

Scheme 2



discovery, we found that the reaction of **3** with CuI yields a novel complex **4** containing a deprotonated 2-hydroxytetrahydrofuran (THF-2-ol) derived from the apparent oxidation of a THF solvent molecule. Isotope-labeling experiments indicate that the hydroxide in **4** is the source of the O atom in the product. The unique transformation yielding **4** complements the few previous reports of the hydroxylation of THF from species derived from the reactions of Cu^{I} complexes with O_2.[12,13]

Treatment of the previously described[11c] complex Na[LCuCl] with excess NaOMe yielded the methoxide complex **2**, which was isolated as a purple solid (Scheme 2). Although definitive structural information was not obtained because of a lack of X-ray-diffraction-quality crystals, the indicated formulation for **2** is supported by the results of elemental analysis, negative-ion electrospray ionization mass spectrometry (ESI-MS; peak envelope simulated as $[\mathbf{2}-Na^{+}]^{-}$; Figure S1 in the Supporting Information, SI), and electron paramagnetic resonance (EPR) spectroscopy [axial signal with parameters similar to other reported pyridine(dicarboxamide)copper(II) complexes; Figure S2 in the SI]. Exposure of **2** to H_2O in the presence of NaOMe or,

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in an alternate route, the addition of H_2O to the preparation starting from Na[LCuCl] resulted in the formation of **3**, which was isolated as an analytically pure purple powder in moderate yield (45−55%).

An X-ray crystal structure of **3** (Figure 1a) shows a hydroxide bridging between a four-coordinate Cu^{II} ion bound to the pyridine(dicarboxamide) and a Na^{I} ion bound to the triamine portion of the macrocyclic ligand, with a Cu···Na distance of 3.568(2) Å. The metal−ligand bond distances, including the short Cu^{II}−OH bond distance of 1.867(2) Å,[14] are consistent with expectations. Interestingly, the complex crystallizes as a dimer, with the two symmetry-related macrocyclic LCu(OH)Na moieties linked via a pair of bonds from a carboxamide carbonyl in one "monomer" to the Na^+ ion in the other (Figure 1b). Thus, the Na^{I} ion is five-coordinate, with a distorted square-pyramidal geometry (τ = 0.83)[15] and variable Na−N/O distances in the range 2.2−2.9 Å (Na−O < Na−N). The dimeric structure also appears in the negative-ion ESI-MS spectrum; peak envelopes for $[\mathbf{3}{-}Na^+]^-$ at m/z 564 and for $[(\mathbf{3})_2{-}(Na^+)_2{-}OH^-]^-$ at m/z 1111 were observed (Figure S3 in the SI). The formulation of **3** was further supported by CHN analysis and EPR spectroscopy (axial signal similar to that of **2**; Figure S2 in the SI).

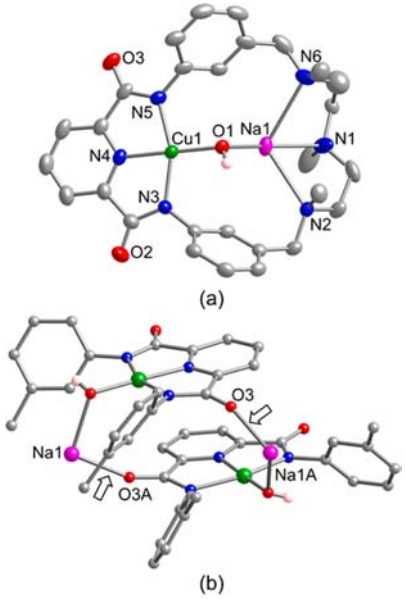

Figure 1. Representations of the X-ray crystal structure of **3**, showing (a) the monomeric complex with all non-H atoms as 50% thermal ellipsoids and all H atoms omitted for clarity, except that on the bridging hydroxide, and (b) a portion of the dimer as a ball-and-stick model with the *N*,*N*′,*N*″-trimethyltriamine fragments omitted for clarity; the carboxamide−sodium interactions linking the monomer units are indicated by arrows. and the involved Na and O atoms are labeled. Selected interatomic distances (Å) and angles (deg): Cu1−O1, 1.865(2); Cu1−N4, 1.927(3); Cu1−N3, 1.999(3); Cu1−N5, 2.010(3); Na1−O1, 2.292(3); Na1−N1, 2.447(3); Na1−N2, 2.731(3); Na1−O3A, 2.325(4); Na1−N6, 2.861(4); Cu1···Na1, 3.568(2); O1−Cu1−N4, 178.19(12); O1−Cu1−N3, 100.37(11); N4−Cu1−N3, 79.82(12); O1−Cu1−N5, 100.05(11); N4−Cu1−N5, 79.82(13); N3−Cu1−N5, 159.49(12); O1−Na1−N1, 164.96(14); O1−Na1−N2, 103.07(10); N1−Na1−N2, 69.36(11); O1−Na1−N6, 104.31(11); N1−Na1−N6, 69.23(12); N2−Na1−N6, 115.01(11).

however, suggesting that CuI acted as an oxidant,[16] and the only discrete product we isolated was **4** (∼20% yield). An X-ray crystal structure of **4** revealed 2-hydroxytetrahydrofuran (THF-2-ol), in deprotonated form, bridging the Cu^{II} and Na^{I} ions, with a weak interaction between Cu1 and O8 suggested by an interatomic distance of 2.513(9) Å (Figure 2). Like **3**, the complex crystallizes as a dimer via carboxamide O/Na interactions, such that the Na^{I} ion is five-coordinate, but in this case, the two monomers are not symmetry-related (Figure S4 in the SI). Further support for the formulation of **4** came from CHN analysis and EPR spectroscopy (axial signal similar to that of **3**; Figure S2 in the SI). Attempts to observe a parent ion in both positive- and negative-ion-mode ESI-MS spectra failed, but an ion corresponding to $[Cu(O{-}THF)]^+$ (Figure S5 in the SI) was identified as a major peak in the positive-ion spectrum and was used as a marker for isotope-labeling experiments (see below).

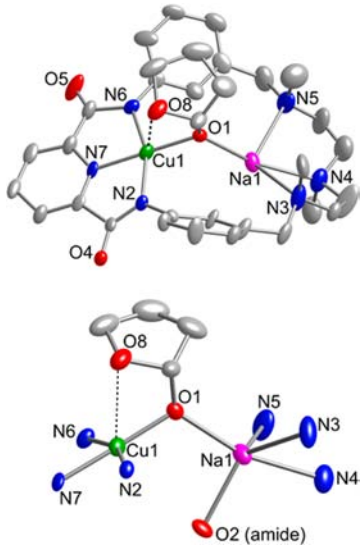

Figure 2. Representations of the X-ray crystal structure of **4**, showing the monomeric complex with all non-H atoms as 40% thermal ellipsoids and all H atoms omitted for clarity (top) and the core with all C atoms except those in the THF-2-ol portion omitted (bottom). The "O2 (amide)" refers to the carboxamide O atom from the other complex in the dimer. Selected interatomic distances (Å) and angles (deg): Cu1−O1, 1.909(9); Cu1−N7, 1.934(12); Cu1−N2, 2.000(11); Cu1−N6, 2.057(11); Cu1−O8, 2.513(9); Cu1···Na1, 3.609(5); Na1−O1, 2.320(11); Na1−N4, 2.463(13); Na1−N5, 2.662(13); Na1−N3, 2.768(14) Na1−O2(amide), 2.334(10); O1−Cu1−N7, 177.8(4); O1−Cu1−N2, 101.2(4); N7−Cu1−N2, 77.2(5); O1−Cu1−N6, 99.2(5); N7−Cu1−N6, 82.4(5); N2−Cu1−N6, 159.5(5); O1−Na1−N4, 164.5(5); O1−Na1−N5, 107.7(4); N4−Na1−N5, 67.4(4); O1−Na1−N3, 101.1(4); N4−Na1−N3, 70.2(4); N5−Na1−N3, 116.9(5).

In order to determine the source of the O atom in the deprotonated THF-2-ol ligand in **4**, we first tested the purity of the THF solvent by gas chromatography/mass spectrometry, reasoning that small amounts of THF-2-ol impurity (perhaps derived from autoxidation) might be the source of this ligand in the product. Comparison to standard samples of THF-2-ol in THF showed that no THF-2-ol was present in the THF used in the reaction to form **4** (0.5 mM detection limit, with a concentration of 11 mM being required to rationalize the isolated yield of **4** from THF-2-ol impurity). To evaluate if the O atom in the product arose from the hydroxide in **3**, the CuI reaction was repeated with ^{18}O-labeled **3** (labeled at the same level as $H_2{}^{18}O$ used in the synthesis, 97%, as shown by ESI-MS;

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Figure S5 in the SI). The positive-ion ESI-MS spectrum of the product showed a 79:21 mixture of $[Cu(^{18}O-THF)H]^+$/$[Cu(^{16}O-THF)H]^+$ ions (Figure S6 in the SI), consistent with the hydroxide ligand in **3** being the predominant source of the O atom in the deprotonated THF-2-ol in **4**.[17]

Attempts to reproduce the synthesis of **4** using various other oxidants[18] failed, including I_2, acetylferrocenium hexafluoroantimonate, and tris(4-bromophenyl)aminium hexachloridoantimonate. These results suggest that a more complicated role is played by CuI in the reaction, but in the absence of additional mechanistic data, we can only speculate about that role. One notion is that the oxidant contains a Cu−O(H?)−Cu bridge generated by the interaction of a $[CuOH]^{n+}$ (n = 1 or 2) moiety with the added copper reagent. It is intriguing that THF hydroxylation was not observed in THF solutions of **1** or upon treatment of the copper(II) precursor of **1** with CuI, implying involvement of the bound Na^+ ion within the macrocyclic ligand framework (L^{2-}) in the C−H activation process.

In conclusion, a complex with a $[Cu^{II}(\mu\text{-OH})Na]^{2+}$ core (**3**) hydroxylates the THF solvent via C−H bond activation upon reaction with CuI to yield a novel complex **4**, which contains a deprotonated THF-2-ol ligand. Isotope-labeling studies indicate that the hydroxide O atom in **3** transfers to the THF-2-ol ligand in the product. This reaction is a rare example of THF hydroxylation by a copper moiety[12,13] and contrasts with previous reports insofar as it yields a copper complex of the product and does not involve Cu/O_2 chemistry.

■ ASSOCIATED CONTENT

Supporting Information

Experimental details, spectroscopic data, and X-ray crystallographic data in CIF format. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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■ REFERENCES

(1) (a) Solomon, E. I.; Sundaram, U. M.; Machonkin, T. E. *Chem. Rev.* **1996**, *96*, 2563−2605. (b) Klinman, J. P. *Chem. Rev.* **1996**, *96*, 2541−2561. (c) Solomon, E. I.; Chen, P.; Metz, M.; Lee, S.-K.; Palmer, A. E. *Angew. Chem., Int. Ed.* **2001**, *40*, 4570−4590.

(2) Wendlandt, A. E.; Suess, A. M.; Stahl, S. S. *Angew. Chem., Int. Ed.* **2011**, *50*, 11062−11087.

(3) (a) Mirica, L. M.; Ottenwaelder, X.; Stack, T. D. P. *Chem. Rev.* **2004**, *104*, 1013−1045. (b) Lewis, E. A.; Tolman, W. B. *Chem. Rev.* **2004**, *104*, 1047−1076. (c) Itoh, S. *Curr. Opin. Chem. Biol.* **2006**, *10*, 115−122. (d) Cramer, C. J.; Tolman, W. B. *Acc. Chem. Res.* **2007**, *40*, 601−608. (e) Himes, R. A.; Karlin, K. D. *Curr. Opin. Chem. Biol.* **2009**, *13*, 119−131.

(4) Tehranchi, J.; Donoghue, P. J.; Cramer, C. J.; Tolman, W. B. *Eur. J. Inorg. Chem.* **2013**, online (http://dx.doi.org/10.1002/ejic.201300328).

(5) Donoghue, P. J.; Tehranchi, J.; Cramer, C. J.; Sarangi, R.; Solomon, E. I.; Tolman, W. B. *J. Am. Chem. Soc.* **2011**, *133*, 17602−17605.

(6) For example, see: Xue, G.; De Hont, R.; Münck, E.; Que, L. *Nat. Chem.* **2010**, *2*, 400−405.

(7) Morimoto, Y.; Kotani, H.; Park, J.; Lee, Y.-M.; Nam, W.; Fukuzumi, S. *J. Am. Chem. Soc.* **2010**, *133*, 403−405.

(8) Park, J.; Lee, Y.-M.; Nam, W.; Fukuzumi, S. *J. Am. Chem. Soc.* **2013**, *135*, 5052−5061.

(9) Lacy, D. C.; Park, Y. J.; Ziller, J. W.; Yano, J.; Borovik, A. S. *J. Am. Chem . Soc.* **2012**, *134*, 17526−17535.

(10) Borovik, A. *Acc. Chem. Res.* **2005**, *38*, 54−61.

(11) (a) Huang, D.; Holm, R. H. *J. Am. Chem. Soc.* **2010**, *132*, 4693−4701. (b) Zhang, X.; Huang, D.; Chen, Y.-S.; Holm, R. H. *Inorg. Chem.* **2012**, *51*, 11017−11029. (c) Halvagar, M. R.; Neisen, B.; Tolman, W. B. *Inorg. Chem.* **2012**, *52*, 793−799.

(12) Zhang, C. X.; Liang, H.-C.; Kim, E.-I.; Shearer, J.; Helton, M. E.; Kim, E.; Kaderli, S.; Incarvito, C. D.; Zuberbühler, A. D.; Rheingold, A. L.; Karlin, K. D. *J. Am. Chem. Soc.* **2003**, *125*, 634−635.

(13) Luckay, R. C.; Sheng, X.; Strasser, C. E.; Raubenheimer, H. G.; Safin, D. A.; Babashkina, M. G.; Klein, A. *New J. Chem.* **2010**, *34*, 2835.

(14) (a) Berreau, L. M.; Mahapatra, S.; Halfen, J. A.; Young, V. G., Jr.; Tolman, W. B. *Inorg. Chem.* **1996**, *35*, 6339−6342. (b) Lee, S. C.; Holm, R. H. *J. Am. Chem. Soc.* **1993**, *115*, 11789−1198. (c) Comparison to the experimentally determined Cu−OH distance in the copper(II) precursor of **1** (R = iPr), which lacks a Na ion, is complicated by compositional disorder in that structure, but the density-functional-theory-calculated distance for **1** (R = iPr) of 1.863 Å closely agrees with that in **3** (ref 5).

(15) Addison, A. W.; Rao, T. N.; Reedijk, J.; von Rijn, J.; Verschoor, G. C. *J. Chem. Soc., Dalton Trans.* **1984**, 1349−1356.

(16) (a) Graves, C. R.; Schelter, E. J.; Cantat, T.; Scott, B. L.; Kiplinger, J. L. *Organometallics* **2008**, *27*, 5371−5378. (b) Zhang, Q.; Wilson, P.; Li, Z.; McHale, R.; Godfrey, J.; Anastasaki, A.; Waldron, C.; Haddleton, D. M. *J. Am. Chem. Soc.* **2013**, *135*, 7355−7363.

(17) The reason for the presence of 21% ^{16}O-labeled product is unclear; we speculate that a small amount of leakage of $H_2{}^{16}O$ into the reaction mixture during the experiment is to blame. In independent experiments, the addition of $H_2{}^{16}O$ to solutions of ^{18}O-labeled **3** resulted in rapid label exchange (ESI-MS), indicating high lability of the bound hydroxide ligand.

(18) The cyclic voltammogram of **3** exhibited an irreversible oxidation at +0.077 V vs Fc/Fc^+ (CH_3CN, 0.15 M Bu_4NPF_6; Figure S7 in the SI), similar to E_{ox} for the reversible redox wave ($E_{1/2}$ = −0.076 V) reported in ref 5 for the $Cu^{II/III}$ couple for **1** (R = iPr) in acetone.