

A copper thiolate centre for electron transfer: mononuclear vs. dinuclear complexes†

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Received 6th December 2011, Accepted 6th January 2012

DOI: 10.1039/c2dt12355j

We have structurally and spectroscopically investigated a rare example of a mononuclear aliphatic dithiolate Cu^{II} complex characterized by a reversible Cu^{II}/Cu^I redox couple. By DFT, we have shown that this system has a lower reorganization energy than its previously described bis(μ-thiolato) dicopper parent complex, which reversibly cycles between the Cu^{1.5}Cu^{1.5} and Cu^ICu^I redox states.

Investigation of aliphatic thiolate transition metal complexes has grown into an intense area of research, in a large part because of their fundamental and necessary role in numerous biological processes.^{1,2} In particular, copper thiolate complexes are used by nature as efficient electron transfer agents. They are found as mononuclear type 1 sites, cycling between the Cu^{II} and Cu^I oxidation states, in blue copper proteins (plastocyanin, azurin).³ On the other hand, a bis(μ-thiolato) dicopper complex, named Cu_A, cycles between the Cu^{1.5}Cu^{1.5} and Cu^ICu^I states, in cytochrome *c* oxidase and nitrous oxidase reductase.⁴ The presence of at least one copper–thiolate bond in these sites leads to peculiar spectroscopic properties related to their specific electronic structure, which has been investigated in great detail to tentatively explain the efficiency of these copper complexes as electron transfer agents.⁵ It has been shown that the dinuclear Cu_A site is much more efficient for transferring electrons than the mononuclear type 1 sites.⁶ This has been explained by a better delocalization of the unpaired electron over the {Cu₂S₂}⁺ core in Cu_A, especially with the presence of a Cu–Cu bond, and by a lower reorganization energy for Cu_A with respect to the mononuclear Cu^{II} complex.

Recently, we have isolated and investigated a Cu_A model complex which mimics most of the structural features and the redox properties of Cu_A.⁷ Indeed, in the presence of CuCl, the ligand L²⁻ reacts with CH₂Cl₂ to produce the dinucleating

L²⁻ ligand, leading to the formation of the dicopper [Cu₂L] (1) complex (Scheme 1). 1 can reversibly cycle between the Cu^{1.5}Cu^{1.5} and Cu^ICu^I states; both formal states, 1⁺ and 1, have been crystallographically characterized.⁷ Here, we have isolated and characterized a mononuclear dithiolate Cu complex from L²⁻, [Cu^{II}L] (2) (Scheme 1). The electrochemical investigation of 2 has demonstrated the reversibility of the [Cu^{II}L]/[Cu^IL]⁻ (2/2⁻) redox couple, allowing us to electrogenerate an unprecedented mononuclear aliphatic thiolate Cu^I complex, which has crystallized in the presence of K⁺ as the hetero-tetranuclear [Cu₂K₂L₂(THF)₂] complex (3). Finally, we have exploited the unique opportunity to compare the reorganization energy between the reduced and oxidized forms of these two parent copper systems, dithiolate monocopper (2/2⁻) vs. dithiolate dicopper (1⁺/1) by calculating their self-exchange inner-sphere reorganization energies.

The L²⁻ ligand reacts in THF with CuCl₂ leading to the immediate formation of a dark green precipitate corresponding to [CuL] (2) (Scheme 1). The X-ray structure (Fig. 1) unambiguously establishes the monomeric character of 2, which consists of a distorted square planar Cu^{II}S₂N₂ unit, isostructural to that of the previously described [Ni^{II}L]⁸ and [Zn^{II}L]⁹ complexes, with a pseudotetrahedral twist angle (Cu–S–S/Cu–N–N) of 35°. The structural features of 2 compare well with those reported for related *cis*-Cu^{II}S₂N₂ unit structures, with a larger deviation from planarity for the six-membered copper-aza-thiacyclohexane ring with respect to the more common five-membered copper-aza-thiacyclopentane ring complexes,^{10–12} combined in the case of 2 with the presence of the rigid bipyridine unit. The Cu–S bonds of 2 are longer than in type 1 sites (Cu–S_{cys}: 2.1 Å), due to the difference in both geometry (square planar vs. tetrahedral), and the sulfur environment in the coordination sphere (bisthiolate vs. thiolate–thioether).

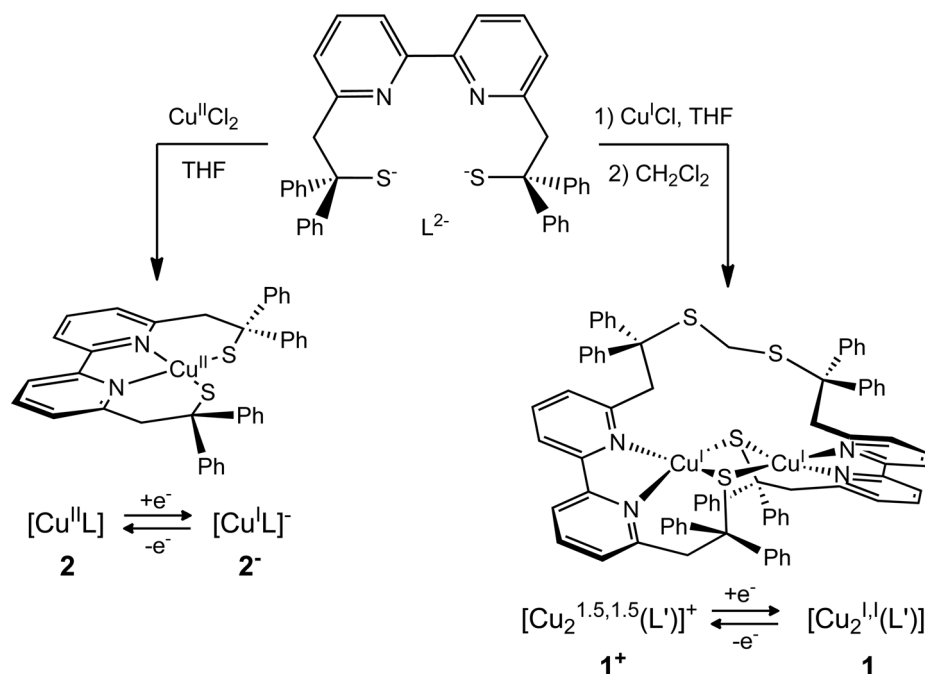
The X-band EPR spectrum of 2 recorded in DMF (Fig. 2) displays a typical quasi-axial *S* = 1/2 signal demonstrating that the mononuclear structure is retained in solution. The *g* values are consistent with a d_{x²-y²} ground state. The EPR properties of 2 are similar to those of the reported Cu^{II}S₂N₂ complexes.^{10–13} Note that the presence of nitrogen superhyperfine splitting, absent for the blue copper proteins, in addition to the relatively small *g*_{||} value in 2 (*g*_{||} near 2.20 for type 1 copper)¹⁴ suggests a strong nitrogen character in the single occupied molecular orbital.

The electrochemical behavior of complex 2 has been investigated in DMF. The cyclic voltammogram shown in Fig. 3

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† Electronic supplementary information (ESI) available: Additional experimental (synthesis, crystallographic and spectroscopic data) and computational details. Crystal and refinement data for 2 and 3 in CIF format. CCDC reference numbers 854562 and 854563. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/c2dt12355j



Scheme 1

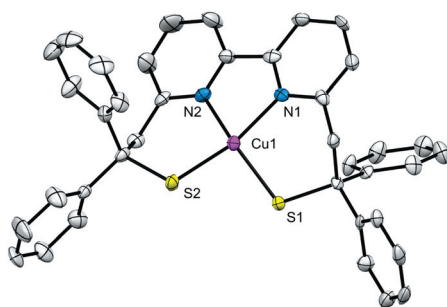


Fig. 1 Molecular drawing of $[\text{CuL}]$ (**2**). The thermal ellipsoids are drawn at 50% probability level. All hydrogen atoms are omitted for clarity. Selected bond distances (\AA): $\text{Cu}(1)\text{--S}(1) = 2.227(1)$, $\text{Cu}(1)\text{--S}(2) = 2.227(1)$, $\text{Cu}(1)\text{--N}(1) = 2.014(4)$, $\text{Cu}(1)\text{--N}(2) = 2.016(4)$.

displays a single one-electron reversible reduction process located at $E_{1/2} = -1.2$ V vs. Fc/Fc^+ ($\Delta E_p = 60$ mV), and a poorly reversible oxidation process at $E_{p_a} = -0.12$ V. Bulk electrolysis at 0.0 V shows that the oxidized species is not stable. Therefore, we cannot conclude whether the oxidation is a metal- or ligand-based process. The one-electron reduced form of **2**, 2^- , quantitatively generated by exhaustive electrolysis at $E = -1.3$ V (Fig. 3b) is EPR silent, consistent with the formation of a Cu^{I} complex. The reduction process is associated with significant changes in UV-visible absorption (ESI \dagger) with the drastic decrease in intensity of two intense features of **2** at 575 nm ($\epsilon = 2600$ $\text{M}^{-1} \text{cm}^{-1}$) and 382 nm ($\epsilon = 7900$ $\text{M}^{-1} \text{cm}^{-1}$), confirming the metal-based reduction process. The complete reversibility of the $2/2^-$ redox couple is indicative of the retention of mononuclearity for 2^- , and of its notable stability.

The redox potential of $2/2^-$ (-1.3 V) is lower than that of $1^+/1$ (-0.79 V).⁷ Of the relevant biological transfer agents, the mononuclear type 1 copper site of the plastocyanin ($+0.37$ V vs.

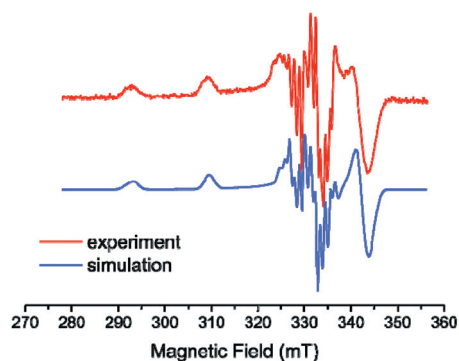


Fig. 2 Experimental (red line) and simulated (blue line) X-band EPR spectra of **2** in DMF at 100 K. Parameters for simulation: $g_{\parallel}(\text{Cu}) = 2.098$, $g_{\perp}(\text{Cu}) = 2.013$, $A_{\parallel}(\text{Cu}) = 160 \times 10^{-4} \text{ cm}^{-1}$, $A_{\perp}(\text{Cu}) = 22 \times 10^{-4} \text{ cm}^{-1}$, $A_{\parallel}(\text{N}) = 5 \times 10^{-4} \text{ cm}^{-1}$, $A_{\perp}(\text{N}) = 10 \times 10^{-4} \text{ cm}^{-1}$.

NHE^{15} converted to -0.33 V vs. $\text{Fc}^+/\text{Fc}^{16}$) and the dinuclear centre of Cu_A ($+0.24$ V vs. $\text{NHE}^{17,18}$ converted to -0.44 V vs. Fc^+/Fc) display the highest redox potentials. The low redox potential of $2/2^-$ can be rationalized by the charge donation of one supplementary RS^- ligand in **2** with a RS^- – Cu ratio of 2, while this ratio is 1 for the type 1 copper centres, Cu_A and **1**.

We were able to obtain crystals of the Cu^{I} species in the presence of K^+ in THF. \ddagger The X-ray structure corresponds to an unprecedented hetero-tetranuclear Cu_2/K_2 complex, $[\text{Cu}_2\text{K}_2\text{L}_2(\text{THF})_2]$ (**3**) (Fig. 4). A similar structure has also been obtained with Na^+ instead of K^+ (data not shown). In **3**, the two K^+ cations bridge two mononuclear $[\text{CuL}]^-$ units, avoiding a direct $\text{Cu}\cdots\text{Cu}$ interaction ($\text{Cu}\cdots\text{Cu} = 5.301$ \AA). Indeed, each K^+ atom bridges the two $[\text{CuL}]^-$ units asymmetrically *via* one thiolate to one side and *via* two thiolates to the other. The remarkable increase of the $\text{Cu}\cdots\text{S}/\text{Cu}\cdots\text{N}\cdots\text{N}$ angles in **3** (60.31 and 59.13°)

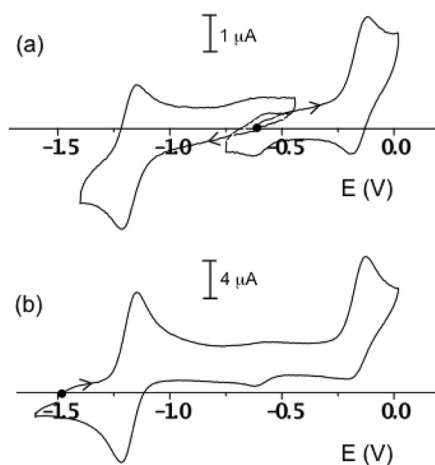


Fig. 3 Cyclic voltammogram of: (a) a saturated suspension of **2** in DMF, 0.1 M Bu₄NPF₆ at a vitreous carbon electrode; (b) after an exhaustive electrolysis at -1.30 V (formation of completely soluble 2⁻, 1 mM); $\nu = 100 \text{ mV s}^{-1}$. Potentials are given vs. Fc⁺/Fc.

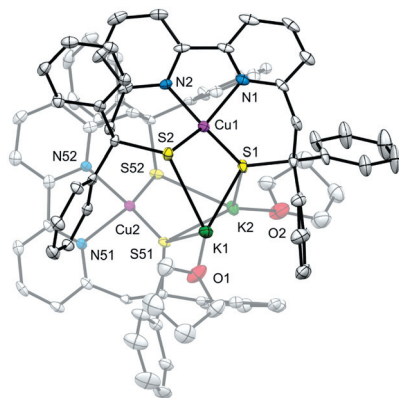


Fig. 4 Molecular drawing of [Cu₂K₂L₂(THF)₂]·0.5THF (**3**·0.5THF). The thermal ellipsoids are drawn at 30% probability level. All hydrogen atoms and cocrystallized solvent molecules are omitted for clarity. Both Cu ions display identical coordination environments and, as a result, only one is highlighted. Selected bond distances (Å): Cu(1)–S(1) = 2.2940(14), Cu(1)–S(2) = 2.2512(16), Cu(1)–N(1) = 2.058(5), Cu(1)–N(2) = 2.011(4).

with respect to **2** (35°) is consistent with different oxidation states of the copper centres.

The [Cu^IL]⁻ unit is very reactive. It immediately reacts with CH₂Cl₂ producing **1** via presumably an S_N2 mechanism as was proposed for comparable cases with Ni and Ru complexes.^{19,20} In the presence of K⁺, this Cu^I species leads to **3** in which the [Cu^IL]⁻ units are isolated from each other by K⁺ bridges. Note that such a structure is very unusual since, to the best of our knowledge, no mononuclear aliphatic thiolate Cu^I complex has been described in the literature so far. Indeed, aromatic thiolates are required for stabilizing the Cu^I state, but even with such ligands mononuclear complexes are scarce.^{21–24}

In order to compare the capability of the two 1^{+/1} and 2/2⁻ redox systems to transfer electrons, we have calculated their reorganization energy (λ), a parameter related to the electron transfer kinetics. According to Marcus,²⁵ λ can be separated in two

terms, the outer-sphere (λ_o) and inner-sphere reorganization energies (λ_i). As λ_o is almost constant for a class of compounds in a given solvent, we have calculated λ_i by DFT, which represents the energy increment associated with the structural change of the reactants in order to proceed from the initial to the final states. The calculated λ_i values, 43.5 and 169.0 kJ mol⁻¹ for 2/2⁻ and 1^{+/1}, respectively, are consistent with the fact that the mononuclear redox 2/2⁻ system should be faster than the dinuclear 1^{+/1} one. This result is opposite to that observed in biological systems, for which it has been shown that the reorganization energy is larger for the blue copper proteins than for the Cu_A centre of the cytochrome *c* oxidase.^{26–29}

The rigidity of the N₂S₂ ligand prevents important structural modifications between the two oxidation states of the 2/2⁻ system, leading to a small reorganization energy which is of the same order of magnitude as that found for the proteins.^{26–29} In particular, the ligand preorganizes a six-membered copper-azathiacyclohexane ring, which offers a geometry between a tetrahedral and a square planar, ideally designed for stabilizing both Cu^{II} and Cu^I, thus explaining the low reorganization energy of this model.

On the other hand, the larger λ_i observed for the dinuclear 1^{+/1} system can be related to the notable increase of the Cu...Cu distance during the oxidation of **1** leading to significant structural modifications around the two Cu ions.⁷ Conversely, in Cu_A, the Cu...Cu distance does not vary between the two formal oxidation states, thus ensuring a low reorganization energy. Indeed, in contrast to the model complexes, the copper sites of the biological electron transfer agents are confined inside the polypeptide chain thus avoiding significant structural modifications between the two redox states. Therefore the nuclearity of the system becomes a critical factor in ensuring the best possible delocalization of the unpaired electron in the oxidized form, explaining the better efficiency of Cu_A with respect to the type 1 copper centre.

Acknowledgements

MG thanks the CNRS for his post-doctoral fellowship.

Notes and references

‡ Crystal data for **2**: C₃₈H₃₀N₂S₂Cu, $M_r = 642.34$, triclinic, space group $P\bar{1}$, $a = 9.109(2)$, $b = 12.802(3)$, $c = 13.188(2)$ Å, $\alpha = 88.37(1)$, $\beta = 76.90(2)$, $\gamma = 84.81(2)$, $V = 1491.7(6)$ Å³, $Z = 2$, $T = 200$ K, $D_c = 1.430 \text{ g cm}^{-3}$, 19 203 reflections collected with 5202 unique ($R_{\text{int}} = 0.1532$), R_1 (wR_2) = 0.0653 (0.0672) for 5202 reflections with $I > 2\sigma(I)$. CCDC 854562. Crystal data for **3**: C₈₆H₈₀N₄O_{2.5}S₄Cu₂K₂, $M_r = 1543.06$, monoclinic, space group $P2_1/c$, $a = 15.7411(4)$, $b = 14.8294(4)$, $c = 32.7134(13)$ Å, $\alpha = 90$, $\beta = 91.330(3)$, $\gamma = 90$, $V = 7634.2(4)$ Å³, $Z = 4$, $T = 150$ K, $D_c = 1.343 \text{ g cm}^{-3}$, 29 519 reflections collected with 15 396 unique ($R_{\text{int}} = 0.0537$), R_1 (wR_2) = 0.0635 (0.1499) for 15 396 reflections with $I > 2\sigma(I)$. The 55 restraints correspond to the geometry and displacement parameters of THF solvent molecule: Distances between adjacent atoms were restraint to 1.4 and 1.45 Å for O–C and C–C distances respectively, and also 2.3 Å for O3–C112, C111–C113, C112–C114, C113–O3 distances. Displacement parameters were refined to be closer from U_{eq} (ISOR function), similar to the neighbouring atoms (SIMU function) and in the direction of the bond (DELU function). CCDC 854563.

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