Direct influence of hydrogen-bonding on the reduction potential of a Cu^{II} center†

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Two hydrogen-bonds from geometrically constrained OH groups to coordinated oxygen donors shift the reduction potential of a Cu^{II} complex by +270 mV as compared to the structurally analogous reference complex missing the OH groups.

The properties of transition metal ions are strongly correlated to their first coordination sphere. However, structural and spectroscopic studies on metalloproteins have shown that the reactivity of metal active sites depends on more than the metal coordination sphere. A controlled implementation of second sphere interactions is a promising approach for the improvement of functional synthetic models.[1] The control of the secondary coordination sphere to tune the electronic structure and hence the reduction potential E^0 is a crucial determinant for the function of redox-active enzymes[2] and electron-transfer proteins.[3] The protein environment significantly affects E^0 through a general reduction of the dielectric, the orientation of electric dipoles, the water accessibility to the metal active site and its location in the protein.[4] Additionally, hydrogen-bonds to the first coordination sphere ligands have been shown to have a significant effect on E^0 in iron-sulfur proteins.[5] However, this effect has not yet been evaluated for the blue copper ET sites.[6]

In order to mimic the rigid hydrogen-bonding network of proteins in model complexes, the hydrogen-bond donors must be placed in a rigid ligand framework close to the metal ion to avoid structural flexibility leading to unwanted intermolecular hydrogen-bonds with *e.g.* solvent molecules or counter ions.[1] Several model systems have been developed to obtain insight into the function of hydrogen-bonds between protein amide groups and sulfur ligands in iron-sulfur proteins.[7] While these model studies unequivocally demonstrate a positive shift of the reduction potential E^0 due to intramolecular hydrogen-bonding to the thiolate ligands, the hydrogen bonds lead to severe geometric distortions as compared to the unsubstituted reference compounds used. Especially the dihedral angle Fe–S–C–C differs significantly. It was shown that the bonding description and thus the electronic structure is strongly dependent on this dihedral angle.[8] Thus, the sole contribution of hydrogen-bonding on the reduction potential shift is difficult to quantify.

Herein, we report on the influence of hydrogen-bonding from two geometrically constrained OH groups to coordinated oxygen ligands on the reduction potential of a Cu^{II} complex. While there is no significant effect on the structural properties, the electronic properties are affected resulting in a positive shift of 270 mV in the reduction potential of the Cu^{II} complex.

In order to study the cooperative action of two proximate metal ions as in metalloenzymes[9] and/or the presence of an electrophilic and a nucleophilic site[10] in metal-salen derived catalysts,[11] we have synthesized the *'ring- and donor-increased'* derivative of salen-like ligands based on the 1,8-napthalenediol backbone, namely *N,N′*-bis(2-(1,8-naphthalenediol)methylidene)propylenediamine (H$_4$L^{OH}) and characterized its dinuclear Cu^{II}Cu^{II} complex.[12]

R = OH: H$_4$L^{OH} [(H$_2$L^{OH})Cu]   [L^{H}Cu]
R = H: H$_2$L^H
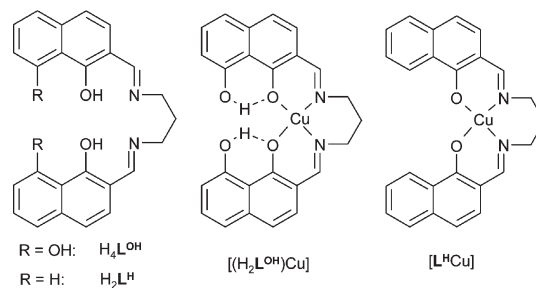
By reacting H$_4$L^{OH} with one equivalent of a Cu^{II} salt, we obtained the mononuclear complex [(H$_2$L^{OH})Cu^{II}] with the Cu^{II} ion coordinated by the N$_2$O$_2$ compartment and not by the O$_4$ compartment of the potentially dinucleating ligand. The non-coordinated OH groups form strong hydrogen-bonds with the oxygen atoms coordinated to the Cu^{II} ion (*vide infra*). In order to evaluate the effect of the hydrogen-bonding on the geometric and electronic structure quantitatively, we synthesized the corresponding ligand H$_2$L^H without the OH groups in the 8-position of the naphthalene backbone. This ligand was synthesized from 2-formyl-1-naphthol and 1,3-diaminopropane in accord with the published procedure for the synthesis of H$_4$L^{OH}.[12] Reaction of H$_2$L^H with copper acetate results in the mononuclear complex [L^{H}Cu^{II}] without the neighboring OH groups for hydrogen-bonding.

The crystal and molecular structures of [(H$_2$L^{OH})Cu^{II}] and [L^{H}Cu^{II}] have been established by single-crystal X-ray diffraction analysis.‡ The two compounds are isotypic indicating that the additional OH groups have no significant influence on the intermolecular interactions and packing of the molecules. Additionally, the molecular structures are closely related despite the two additional OH groups in [(H$_2$L^{OH})Cu^{II}] (Fig. 1).

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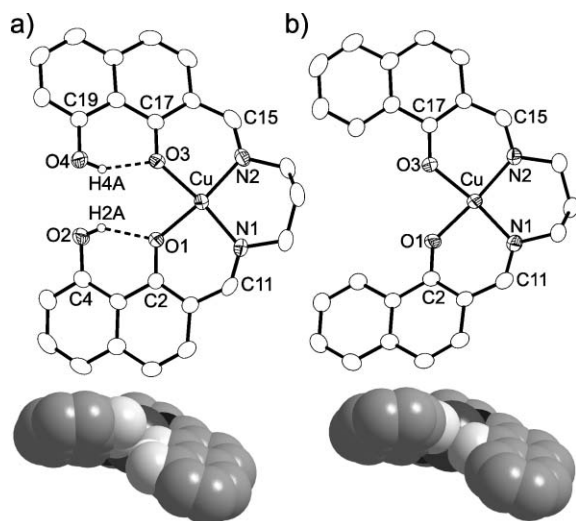
Fig. 1 Molecular structures of a) $[(H_2L^{OH})Cu]$ and b) $[L^HCu]$; hydrogen atoms except those of the OH groups are omitted for clarity. Top: ORTEP plots with thermal ellipsoids shown at the 50% probability level; Bottom: Space filling model to illustrate the helical distortion. Selected interatomic distances [Å] and angles (°) for $[(H_2L^{OH})Cu]$ $\{[L^HCu]\}$: Cu–O1 1.916(2) {1.918(2)}, Cu–O3 1.923(2) {1.909(2)}, Cu–N1 1.956(2) {1.959(2)}, Cu–N2 1.951(2) {1.970(2)}, O1–C2 1.309(3) {1.297(3)}, O3–C17 1.309(3) {1.296(3)}, N1–C11 1.286(3) {1.296(3)}, N2–C15 1.285(3) {1.298(3)}; O1–Cu–N1 92.3(1) {92.0(1)}, O3–Cu–N2 91.1(1) {93.0(1)}, O1–Cu–O3 83.6(1) {84.5(1)}, N1–Cu–N2 98.7(1) {97.1(1)}, O1–Cu–N2 157.1(1) {162.6(1)}, O3–Cu–N1 162.9(1) {155.8(1)}.

The OH groups in 8-position (O2 and O4) form strong hydrogen-bonds to the coordinated aryloxide oxygen atoms (O1 and O3) with distances O1–O2 of 2.547(3) Å and O3–O4 2.531(2) Å. The hydrogen atoms were located from difference Fourier maps and refined independently. The resulting parameters, which should be handled with care as usual for X-ray diffraction data on hydrogen-bonding, are O2–H2A 0.798(22) Å, O4–H4A 0.799(24) Å, O1···H2A 1.850(23) Å, O3···H4A 1.806(24) Å, O2–H2A–O1 145(3)°, O3–H4A–O4 150(3)°.

A comparison of the bond distances in $[(H_2L^{OH})Cu]$ and $[L^HCu]$ might indicate that there is a slight trend in these values by adding the OH groups (increasing O–Cu and O–C bond lengths, decreasing Cu–N and N=C bond lengths) but these differences are not significant on a $\pm 3\sigma$ level. As it is well known for copper-salen complexes,[13] the overall geometry of the complexes is not rigorously flat but the two aromatic units exhibit a helical distortion with angles between the naphthalene planes of 39.9° for $[(H_2L^{OH})Cu^{II}]$ and 38.1° for $[L^HCu^{II}]$ (Fig. 1 bottom). This helical distortion is accompanied by a small deformation of the Cu^{II} coordination geometry from square-planar towards tetrahedral. As a measure for this deformation, we calculated the angle ξ between the N1–Cu–N2 and O1–Cu–O3 planes which should be zero for a square-planar coordination and 90° for a tetrahedral coordination. It is quite remarkable that the presence of the hydrogen-bonds induces no significant distortion on this parameter (26.4° for $[(H_2L^{OH})Cu^{II}]$ and 28.4° for $[L^HCu^{II}]$). In summary, the crystal and molecular structures of $[(H_2L^{OH})Cu^{II}]$ and $[L^HCu^{II}]$ exhibit no significant differences due to the presence of the additional OH groups. Thus, changes in the electronic structure can be solely related to the effect of hydrogen-bonding.
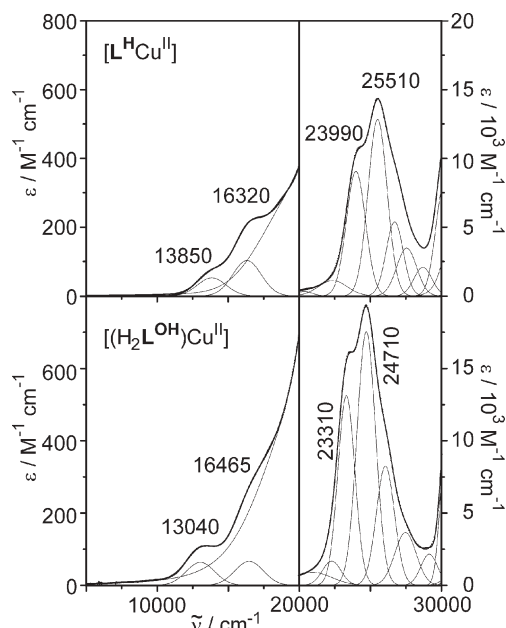

Fig. 2 Electronic absorption spectra of $[L^HCu^{II}]$ (top) and $[(H_2L^{OH})Cu^{II}]$ (bottom). Thin lines represent Gaussian band shape simulations. Their sums are shown by the thick lines. Selected peak maxima given in cm^{-1}.

While the structural analysis yields no evidence for the influence of the presence of the OH groups on the copper coordination properties, the physical properties clearly show such an influence. A visual impression is revealed by the colour of solutions of these two complexes. While CH_2Cl_2 solutions of $[L^HCu^{II}]$ are green those of $[(H_2L^{OH})Cu^{II}]$ are brown. A comparison of the electronic absorption spectra is given in Fig. 2. The lowest d–d transition $(d_{xy} \rightarrow d_{x^2-y^2})$ in $[L^HCu^{II}]$ is observed at 13850 cm^{-1} and is red-shifted by *ca.* 800 cm^{-1} to 13040 cm^{-1} in $[(H_2L^{OH})Cu^{II}]$. This low-energy shift associated with the two neighboring OH groups indicates a reduced charge donation (lower ligand-field strength) of the coordinated aryloxide donors associated in hydrogen-bonding. Additionally, the CT bands at 23990 and 25510 cm^{-1} in $[L^HCu^{II}]$ are shifted to lower energy at 23310 and 24710 cm^{-1} in $[(H_2L^{OH})Cu^{II}]$ with increased intensity.

This lower charge donation in the complex with OH groups is exceedingly reflected in the electrochemical properties. Fig. 3 displays the cyclic voltammograms of $[(H_2L^{OH})Cu^{II}]$ and $[L^HCu^{II}]$
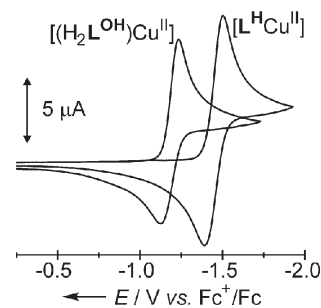
Fig. 3 Cyclic voltammograms of $[L^HCu^{II}]$ and $[(H_2L^{OH})Cu^{II}]$ in CH_2Cl_2 (0.10 M $[(n\text{-}Bu)_4N](PF_6)$) at a glassy carbon working electrode at a scan rate of 50 mV s^{-1}.

in CH_2Cl_2 (0.10 M [(n-Bu)$_4$N](PF$_6$)). Both compounds exhibit an electrochemically quasi-reversible one-electron transfer wave corresponding to the reduction of Cu^{II} to Cu^{I}. The unsubstituted complex [$\mathbf{L^H}$Cu^{II}] is reduced at $E^{1/2}$ = −1.45 V *vs.* Fc$^+$/Fc. The occurrence of hydrogen-bonded OH groups in [(H$_2\mathbf{L^{OH}}$)Cu^{II}] results in an anodic shift to $E^{1/2}$ = −1.18 V *vs.* Fc$^+$/Fc. This represents a positive shift of 270 mV.

In order to obtain more insight into the influence of the hydrogen-bonded OH groups, we have performed DFT calculations on [(H$_2\mathbf{L^{OH}}$)Cu^{II}] and [$\mathbf{L^H}$Cu^{II}].[14] The geometry optimized structures in the gas phase closely resemble those of the experimental solid-state structures. The angles ξ (25.4° for [(H$_2\mathbf{L^{OH}}$)Cu^{II}] and 20.5° for [$\mathbf{L^H}$Cu^{II}]) are in the same range as the experimentally obtained ones but with an inverted trend. These differences might be attributed to packing effects in the solid state, as the considered structures show some flexibility with respect to this angle. For a further comparison with experiment, we have simulated the UV absorption spectra by TD-DFT calculations and obtained the same trend as observed in the experimental data. By going from [$\mathbf{L^H}$Cu^{II}] to [(H$_2\mathbf{L^{OH}}$)Cu^{II}], the main transition shifts to lower energy from 30700 cm^{-1} to 29200 cm^{-1} accompanied by an intensity increase from 16.8 × 10^3 M^{-1} cm^{-1} to 21.1 × 10^3 M^{-1} cm^{-1}. While these transitions have frequently been assigned to phenolate-to-copper LMCT bands, our calculations show that the involved orbitals are strongly delocalized over the whole ligand with only a small contribution of the copper ion.

To further evaluate the influence of the hydrogen-bonds, we calculated the reduction potentials for both compounds by optimizing the anionic species and comparing their total energies to the neutral complexes. We obtained a positive shift of 400 mV by going from [$\mathbf{L^H}$Cu^{II}] to [(H$_2\mathbf{L^{OH}}$)Cu^{II}]. Although this calculated shift is slightly higher as compared to the experimental one (270 mV), it manifests the observation that the OH groups destabilize the Cu^{II} oxidation state. In order to assign this destabilization of Cu^{II} to hydrogen-bonding of the OH groups to the coordinated aryl-oxygen atoms and not to an effect through the naphthalene ring (which should stabilize Cu^{II} due to the electron-donating capacity of the OH groups), we generated a new model compound [(H$_2\mathbf{L^{OH,rot}}$)Cu^{II}] with the OH groups rotated by 180° excluding hydrogen-bonding. The calculated shift in the reduction potential by going from [$\mathbf{L^H}$Cu^{II}] to [(H$_2\mathbf{L^{OH,rot}}$)Cu^{II}] is −180 mV. This smaller shift of opposite sign demonstrates the stabilization of the Cu^{II} oxidation state by the OH groups through the naphthalene ring and is a clear indication that the destabilization of Cu^{II} in [(H$_2\mathbf{L^{OH}}$)Cu^{II}] is due to the hydrogen-bonding effect of the neighboring OH groups to the coordinated aryloxide donors.

In conclusion, we have demonstrated the synthesis of an extended salen-like Cu^{II} complex which exhibits two closely placed OH groups hydrogen-bonded to the coordinated aryloxide donors. We have shown by comparison with the analogous complex lacking these two OH groups that the two OH groups destabilize the Cu^{II} oxidation state due to hydrogen-bonding. In this respect, this study implicates that hydrogen-bonding to the first coordination sphere observed in blue copper proteins might have a functional role. Additionally, the shift in the reduction potential clearly demonstrates that a control of the secondary coordination sphere provides a handle to control the electronic structure and hence the reactivity of transition metal complexes. In this respect,

we will use our 'ring- and donor-increased' salen-like ligands to evaluate the influence of variable hydrogen-bonding on the catalytic performance in organic transformations which are known to be catalyzed by the parent metal-salen complexes.

Notes and references

‡ Crystal data for [(H$_2\mathbf{L^{OH}}$)Cu^{II}]: M = 475.97, monoclinic, $C2/c$, a = 22.210(2), b = 10.2458(11), c = 17.7739(19) Å, β = 100.842(2)°, V = 3972.4(7) Å^3, Z = 8, μ = 1.138 mm^{-1}, T = 153(2) K, 18963 reflections collected ($\pm h$, $\pm k$, $\pm l$), [(sinθ)/λ] = 0.65 Å^{-1}, 4547 independent (R_{int} = 0.072) and 3271 observed reflections [$I \geqslant 2\sigma(I)$], 369 refined parameters, R = 0.036, wR^2 = 0.067, CCDC 273718. [(L^H)Cu^{II}], M = 443.97, monoclinic, $C2/c$, a = 22.060(1), b = 10.158(1), c = 17.598(1) Å, β = 100.97(1)°, V = 3871.4(5) Å^3, Z = 8, μ = 1.154 mm^{-1}, T = 198(2) K, 15324 reflections collected ($\pm h$, $\pm k$, $\pm l$), [(sinθ)/λ] = 0.66 Å^{-1}, 4601 independent (R_{int} = 0.051) and 3542 observed reflections [$I \geqslant 2\sigma(I)$], 271 refined parameters, R = 0.036, wR^2 = 0.094, CCDC 273719. For crystallographic data in CIF or other electronic format see DOI: 10.1039/b517340j

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