

Efficient stabilization of copper(III) in tetraaza pseudo-macrocyclic oxime-and-hydrazide ligands with adjustable cavity size†

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Substitution of the amide donors in open-chain {2N(oxime), 2N(amide)} ligands by hydrazide donors gives new pseudo-macrocyclic copper complexes that show a significant decrease of the Cu^{3+/2+} redox potentials in both mono- and polynuclear systems, thus demonstrating a pronounced capacity of such ligand systems to efficiently stabilize the trivalent copper.

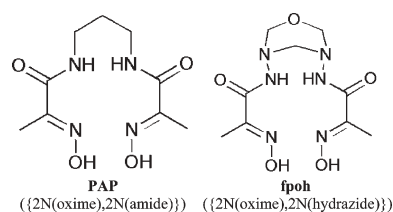
Biomimetic inorganic chemistry, which largely involves the synthesis and detailed structural and electrostatic characterization of model molecules, has contributed significantly to the elucidation of the structures and functions of native metalloenzymes.¹ Although the +3 oxidation state of copper is generally considered to be inaccessible in biology, there have been many biomimetic high-valent complexes studied in order to provide insights into the catalytic mechanism of action of copper monooxygenases and multicopper oxidases.^{2–5}

The ability of deprotonated hydrazide groups to stabilize trivalent copper is generally known and documented.^{6–9} Cu³⁺ complexes of hydrazide ligands may be very stable and form even in the presence of aerial oxygen from the corresponding Cu²⁺ species.^{6–9} However, close examination of the literature revealed that hydrazide groups have not been used together with other strong σ -donor groups in ligands with mixed donor sets, with the exception of those reported in our paper published in 1998,⁶ although such a combination should be particularly promising for the stabilization of high-valent metal ions. Also, up to now no direct electrochemical measurements revealing the “net” contribution of the hydrazide nitrogen donors to the effect of stabilizing Cu³⁺ have been performed. Moreover, no experimental comparison of the effects of deprotonated amide and hydrazide groups on the stabilization of 3d metals in high oxidation states has been reported in the literature.

In 1999 Krüger *et al.*¹⁰ reported some mononuclear Cu²⁺ and Cu³⁺ complexes with tetradentate open-chain ligands providing a

{2N(amide), 2N(oxime)} donor set which appeared to be quite efficient in stabilizing trivalent copper. The observed Cu^{3+/2+} redox potentials were found to be relatively low (0.31 V vs. the SCE redox couple in acetonitrile), and the corresponding Cu³⁺ compounds have been prepared and isolated both by chemical and electrochemical oxidation.¹⁰ Recently, we reported a different ligand family of tetradentate open-chain ligands with the same {2N(amide), 2N(oxime)} donor set (Scheme 1), which also indicated a pronounced capacity to efficiently stabilize the Cu³⁺ and Ni³⁺ species.¹¹ The measured Cu^{3+/2+} redox potentials of the complex PPh₄[Cu(PAP_{-3H})]·4.5H₂O (**1**) (0.485 V vs. the Ag/AgCl redox couple in acetonitrile) appeared to be close to those reported by Krüger.¹⁰ In further search of donor sets inducing even more efficient stabilization of trivalent copper we have launched a study of ligands with related {2N(hydrazide), 2N(oxime)} donor sets, anticipating that they would give rise to exceptionally stable Cu³⁺ complexes (Scheme 1).

The copper(II) complexes, Li₂[Cu(fpoh_{-3H})₂]·H₂O·CH₂O (**2a**) and PPh₄[Cu(fpoh_{-3H})]·H₂O (**2b**), with a ligand belonging to the new family have been prepared by template condensation of the anionic copper(II) complex of 2-hydroxyiminopropanhydrazide {CH₃C(=NOH)C(=O)NHNH₂, poh⁻},⁶ [Cu(poh_{-2H})(poh_{-H})]⁻, with formaldehyde in aqueous media. Reaction of **2a** with 2 equiv. of sodium peroxodisulfate in aqueous solution was accompanied by a colour change from dark-brown to black. Subsequent extraction of the reaction mixture with chloroform followed by solvent removal gave a black powder identified as Cu^{III}(fpoh_{-3H})·H₂O (**3a**) which upon recrystallization from CHCl₃/DMSO/acetone produced crystals of [Cu^{III}(fpoh_{-3H})](DMSO) (**3b**) containing neutral molecules of the Cu³⁺ complex. **2a,b** and **3a,b** are air-stable in the solid state as well as in non-aqueous solutions, however, the copper(III) complexes are decomposed in aqueous solution within several hours. Interestingly, the reaction of **1** with peroxodisulfate in aqueous media, as well as with ammonium-cerium(IV) nitrate in methanol or acetonitrile, was also accompanied by a significant colour change suggesting oxidation of the copper(II) species. However, attempts to isolate the corresponding



Scheme 1

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Cu³⁺ complexes were not successful, presumably due to a short life time of the oxidized species. **3a** and **3b** are EPR-silent and diamagnetic and give good quality ¹H NMR spectra without any signal broadening and without paramagnetic shifts, which is consistent with the presence of low-spin Cu³⁺.

1, **2a**, and **2b** exhibit similar UV-VIS and EPR-spectral parameters typical for CuN₄ coordination. Analysis of a variety of spectral results obtained for **1**, **2a**, and **3b** allows the conclusion that in all cases the ligands are coordinated in a tetradentate mode *via* the nitrogen atoms, which was also confirmed by X-ray crystallography of all three complexes.†

Comparison of the crystallographic results for **2a** (Fig. S1†) and **3b** (Fig. 1) revealed the same coordination mode of the ligand and very similar overall coordination spheres, but also significant differences in geometrical and conformational parameters, as expected for the presence of central atoms in different oxidation states. In both complexes the triply deprotonated ligands bind tetradentately *via* the nitrogen atoms of the deprotonated hydrazide and semideprotonated oxime groups. One of the latter, bearing the hydrogen atom, forms an intermolecular H-bond typical of oximate complexes, thus closing the ligand framework into the pseudomacrocylic conformation. The Cu–N distances in **2a** and **3b** (Table 1) are noticeably different 1.899(3)–1.969(3) Å for **2a** and 1.888(2)–1.924(2) Å for **3b** which reflects the different ionic radii of bi- and trivalent copper.¹² The O···O separations between the oxime oxygen atoms are also significantly different 2.667(1) and 2.623(1) Å for **2a** and 2.487(4) Å for **3b** which is a consequence of the different Cu–N distances, so that the pseudomacrocylic cavity in **3b** seems to be more compressed. As expected, in **3b** the angular distortions of the coordination sphere are less pronounced than in **2a**.

XPS spectral measurements allowed the unambiguous confirmation of the presence of trivalent copper in **3a** (Fig. S4†). The binding energy Cu 2p_{3/2} (934.7 eV) is some 0.95 eV higher than that observed in the spectra of **2a** and **2b** (933.85 eV) (Fig. S5, Table S2†). This difference is typical for corresponding Cu³⁺ and Cu²⁺ species and is in agreement with the literature data.^{13,14} Besides this, a distinguishing feature of the spectra of complexes **2a** and **2b** is the presence of the “satellite peaks”, characteristic of copper(II) compounds (Fig. S5†).

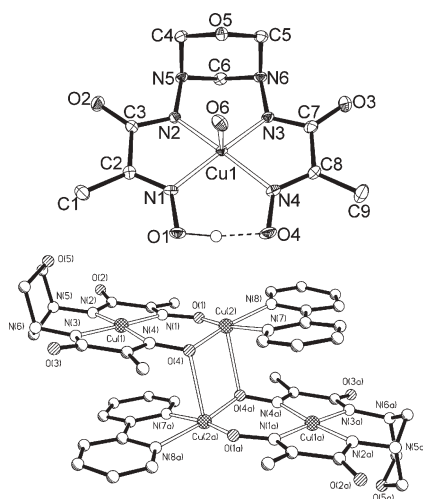


Fig. 1 Molecular structure of complexes **3b** (upper) and **5** (bottom). The atoms labeled “a” are at $(-x, -y + 1, -z + 1)$ position.

Table 1 Selected bond lengths [Å] and angles [°] in PPh₄[Cu(PAP-_{3H})]·4.5H₂O (**1**), [Cu(fpoh-_{3H})·DMSO] (**3b**) and Li₂[Cu(fpoh-_{3H})]·2H₂O·CH₂O (**2a**)

	2a			
	1	3b	Monomer A	Monomer B
Cu(1)–N(1)	1.945(2)	1.9042(2)	1.964(3)	1.969(3)
Cu(1)–N(2)	1.907(2)	1.8985(2)	1.910(3)	1.922(3)
Cu(1)–N(3)	1.909(2)	1.8882(2)	1.899(3)	1.900(3)
Cu(1)–N(4)	1.942(2)	1.9241(2)	1.939(3)	1.947(3)
Cu(1)–O(6)	—	2.3178(2)	2.534(2)	2.270(3)
O(1)···O(4)	2.514(2)	2.487(4)	2.667(4)	2.623(4)
O(1)–H···O(4)	1.54(4)	1.460(5)	1.75	1.64
N(1)–Cu(1)–N(4)	96.14(7)	98.63(8)	98.87(1)	97.0(1)
N(1)–Cu(1)–N(2)	82.38(7)	82.82(8)	80.5(1)	80.8(1)
N(2)–Cu(1)–N(3)	98.54(7)	94.49(8)	96.0(1)	96.0(1)
N(3)–Cu(1)–N(4)	83.01(6)	82.85(8)	82.9(1)	82.1(1)
N(3)–Cu(1)–N(1)	178.74(7)	171.68(7)	172.6(1)	160.5(1)
N(2)–Cu(1)–N(4)	174.98(7)	171.26(7)	165.5(1)	167.8(1)

The electrochemical properties of complexes **1** and **2b** were investigated by cyclic voltammetry in acetonitrile and methanol solution (Fig. 2, Table 2). Observed values of the formal Cu^{3+/2+} redox potentials demonstrate quite efficient thermodynamic stabilization of the trivalent state in both mononuclear complexes. However, comparison of the cyclic voltammograms of **1**, **2a** and **2b** reveals that the formal Cu^{3+/2+} redox potential shifts dramatically upon substitution of the two deprotonated amide donors by the two deprotonated hydrazide groups. **1** and **2b** revealed electrochemically quasi-reversible oxidation behaviour with *E*_{1/2} values of 485 and 187 mV in methanol or 354 and 245 mV in acetonitrile, respectively (values *vs.* Ag/AgCl). This effect can be ascribed to the significantly stronger σ -donor properties of the nitrogen donor atoms of the deprotonated hydrazide groups. The significant difference in the *E*_{1/2} values of **1**

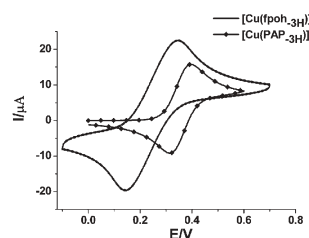


Fig. 2 Cyclic voltammograms of PPh₄[Cu(PAP-_{3H})]·4.5H₂O (**1**) and PPh₄[Cu(fpoh-_{3H})]·H₂O (**2b**) (conditions as indicated in Table 2).

Table 2 Redox characteristics of the mono- and tetranuclear complexes in methanol solutions at a C-foil electrode, 293 K, sweep rate 100 mV s⁻¹, *vs.* Ag/AgCl ([**1**], [**2a**] and [**2b**] = 3 × 10⁻³ M, [**4**] and [**5**] = 2 × 10⁻³ M)

Compounds	$\Delta E/V$	<i>i</i> _a / <i>i</i> _c	<i>E</i> _f /V
PPh ₄ [Cu(PAP- _{3H})] (1)	0.089	1.0	0.485
	0.078 ^a	1.0 ^a	0.354 ^a
Li ₂ [Cu(fpoh- _{3H})] ₂ (2a)	0.375	0.85	0.242
PPh ₄ [Cu(fpoh- _{3H})] (2b)	0.112	0.9	0.187
	0.210 ^a	0.9 ^a	0.245 ^a
{[Cu(phen)Cu(PAP- _{4H})(H ₂ O) ₂] ₂ } (4)	0.088	1.0	0.613
{[Cu(dipy)Cu(fpoh- _{4H})] ₂ } (5)	0.083	1.0	0.246
Ferrocene	0.078	1.0	0.410
	0.081 ^a	1.0 ^a	0.441 ^a

^a In acetonitrile.

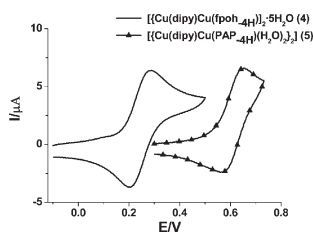


Fig. 3 Cyclic voltammograms of $[\{\text{Cu}(\text{dipy})\text{Cu}(\text{PAP}_{-4\text{H}})(\text{H}_2\text{O})_2\}_2]$ (**4**) and $[\{\text{Cu}(\text{dipy})\text{Cu}(\text{fpoh}_{-4\text{H}})\}_2]\cdot 5\text{H}_2\text{O}$ (**5**) at a C-foil electrode in methanol at a scan sweep of 100 mV s^{-1} , vs. Ag/AgCl ([**4**] and [**5**] = $2 \times 10^{-3} \text{ M}$).

and **2b** clearly indicates that stabilization of the +3 oxidation state is much more efficient in the case of the hydrazide-containing system. One can conclude that the copper(III) ion is better accommodated by the small-size ring of the triply-deprotonated tetradentate ligand **fpoh**, obtained by template reaction and containing the 14-membered pseudo-macrocylic ring.

In the solid state, the complex anions of **2a** appear to be dimerized *via* the bridging functions of the oxime group of one complex anion and the ether oxygen of the second. As a result, heterodimeric molecules are formed in the crystal. Note, that the dimeric species **2a** are not stable in solution and are disaggregated to the mononuclear anionic species $[\text{Cu}(\text{fpoh}_{-3\text{H}})]^-$ which is confirmed by ESI mass spectrometry and DPP experiments, the latter proving that the complex undergoes only mono-electronic oxidation, which is consistent with the presence of only mononuclear species.

The bridging oxime proton in mononuclear anionic oximate complexes can be easily substituted by a metal ion of a suitable ionic radius, thus giving rise to bi- or polynuclear species with double *cis*-oximate bridges.^{11,15} Indeed, interaction of the mononuclear anionic complexes **2a,b** with cationic species $[\text{Cu}(\text{L})(\text{H}_2\text{O})_4]^{2+}$ (where **L** is a bidentate amine ligand used in order to block two sites in the coordination sphere of the copper(II) ion) results in substitution of the bridging oxime proton. The formed binuclear species undergo spontaneous dimerization due to the ability of the oxime-O to act as a μ_3 -(out-of-plane) bridging function and the presence of potentially vacant sites in the coordination sphere of the second copper ion. As a result, tetranuclear neutral complexes are formed, a series of which was investigated by X-ray analyses. Cyclovoltammetric studies of two tetranuclear complexes $[\{\text{Cu}(\text{dipy})\text{Cu}(\text{PAP}_{-4\text{H}})(\text{H}_2\text{O})_2\}_2]$ (**4**) and $[\{\text{Cu}(\text{dipy})\text{Cu}(\text{fpoh}_{-4\text{H}})\}_2]$ (**5**) in methanol revealed effects similar to those observed for their mononuclear precursors (Table 2). The π -acceptor nature of the **dipy** ligands can result in some increase of the redox potentials (cyclic voltammograms contain only one oxidation wave corresponding to a quasireversible oxidation). However, in the present case the difference in the values of the redox potentials of the amide- and hydrazide-containing complexes (**4** vs. **5**) is 0.367 V (Fig. 3), *i.e.* even more pronounced than in the case of **1** and **2a,b**.

It should be also noted that the values of the formal $\text{Cu}^{3+/2+}$ redox potentials undergo noticeable anodic shifts in comparison to the corresponding mononuclear complexes, which comes from the different overall charge, *i.e.* the effect of electrostatic destabilization of the cationic species that are formed as a result of electrochemical oxidation (Table 2). The electrochemical studies of the tetranuclear

complexes thus confirm the efficient thermodynamic stabilization of copper(III) in a metallomacrocylic surrounding, consisting of $\{2\text{N}(\text{oxime}), 2\text{N}(\text{amide})\}$ and $\{2\text{N}(\text{oxime}), 2\text{N}(\text{hydrazide})\}$ donor sets.

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Notes and references

‡ Crystal data: **1**. $\text{C}_{33}\text{H}_{42}\text{CuN}_4\text{O}_{8.5}\text{P}$, $M = 725.22$, triclinic, space group $P\bar{1}$, $Z = 2$, $a = 11.2410(6)$, $b = 12.6521(7)$, $c = 13.0200(7)$ Å, $V = 1688.56(16)$ Å³, $\mu(\text{Mo-K}\alpha) = 0.752 \text{ mm}^{-1}$, $T = 190(2)$ K, of a total of 9960 reflections collected, 9960 were independent ($R_{\text{int}} = 0.0000$), final $R1 = 0.0414$ [$I > 2\sigma(I)$] and $wR2 = 0.1078$ (all data). **2a**. $\text{C}_{19}\text{H}_{30}\text{Cu}_2\text{Li}_2\text{N}_{12}\text{O}_{12}$, $M = 759.51$, monoclinic, space group $P2_1/c$, $Z = 4$, $a = 15.0247(6)$, $b = 11.6299(6)$, $c = 18.2082(8)$ Å, $V = 3031.5(2)$ Å³, $\mu(\text{Mo-K}\alpha) = 1.481 \text{ mm}^{-1}$, $T = 120(2)$ K, of a total of 18356 reflections collected, 5717 were independent ($R_{\text{int}} = 0.0597$), final $R1 = 0.0422$ [$I > 2\sigma(I)$] and $wR2 = 0.1071$ (all data). **3b**. $\text{C}_{11}\text{H}_{19}\text{CuN}_6\text{O}_6\text{S}$, $M = 426.92$, triclinic, space group $P\bar{1}$, $Z = 2$, $a = 8.144(2)$, $b = 9.362(2)$, $c = 11.394(2)$ Å, $V = 807.3(3)$ Å³, $\mu(\text{Mo-K}\alpha) = 1.527 \text{ mm}^{-1}$, $T = 190(2)$ K, of a total of 6554 reflections collected, 3596 were independent ($R_{\text{int}} = 0.0548$), final $R1 = 0.0328$ [$I > 2\sigma(I)$] and $wR2 = 0.0843$ (all data). **5**. $\text{C}_{19}\text{H}_{30}\text{Cu}_2\text{N}_8\text{O}_{10}$, $M = 657.59$, monoclinic, space group $P2_1/c$, $Z = 4$, $a = 12.8590(13)$, $b = 7.0434(8)$, $c = 27.665(2)$ Å, $V = 2500.7(4)$ Å³, $\mu(\text{Mo-K}\alpha) = 1.772 \text{ mm}^{-1}$, $T = 293(2)$ K, of a total of 11475 reflections collected, 5490 were independent ($R_{\text{int}} = 0.0424$), final $R1 = 0.0534$ [$I > 2\sigma(I)$] and $wR2 = 0.1489$ (all data). CCDC 610646–610649. For crystallographic data in CIF or other electronic format see DOI: 10.1039/b608236j

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