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Electrochemically driven reversible solid state metal exchange processes in polynuclear copper complexes

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Abstract The electrochemical characteristics of polynuclear di-copper and tetra-copper complexes of an expanded “Robson-type” macrocyclic ligand are explored by solid state voltammetry in aqueous media. When adhered to a graphite electrode surface in the form of microcrystalline powders and immersed in aqueous buffer solution, these water-insoluble polynuclear copper complexes show well-defined voltammetric reduction and re-oxidation responses. The di-copper metal complexes $[\text{Cu}_2(\text{H}_3\text{L})(\text{OH})][\text{BF}_4]_2$ and the tetra-copper complexes $[\text{Cu}_4(\text{L})(\text{OH})][\text{NO}_3]_3$ with an O_4N_4 octadentate macrocyclic ligand L are shown to exhibit inter-related and proton concentration sensitive solid state voltammetric characteristics. At sufficiently negative potential, copper is extracted from the complexes to form a solid copper deposit and the neutral form of the insoluble free ligand. Upon re-oxidation of the copper deposit, Cu^{2+} undergoes facile re-insertion into the ligand sphere to re-form solid di- and tetra-copper complexes at the electrode surface. The reduction process occurs in two stages, with two Cu^{2+} cations being extracted in each step. The ability of the macrocyclic ligand to efficiently release and accumulate copper is demonstrated.

Keywords Voltammetry · Copper · Macrocyclic ligand · Electro-insertion · Metal extraction

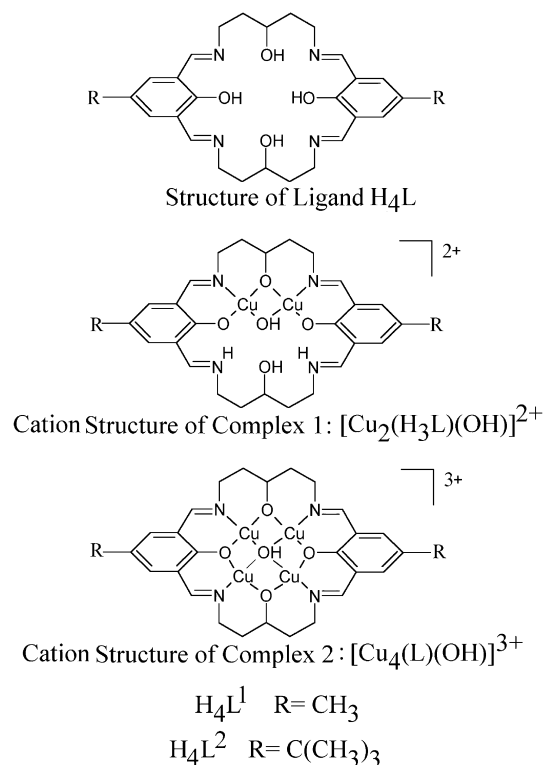
Introduction

Copper metalloproteins are of key importance in many natural redox systems [1] and have for many years been conveniently classified as type 1 (blue), type 2 (non-blue)

or type 3 (dinuclear). Much synthetic and biochemical effort has been directed towards understanding the structures and/or reactivity of these sites [2]. These systems were predominantly based on mono- or dinuclear copper complexes. More recently a number of polynuclear reaction sites (with up to four Cu centers), which fall outside this simple classification, have been characterized in redox active and in catalytically active metalloproteins. These new types of polynuclear copper sites include the average-valence Cu_A site in cytochrome *c* oxidase [3, 4, 5] and nitrous oxide reductase [6], the tri-copper site in blue copper oxidases [7] and, most recently, the Cu_4S (Cu_Z) site of nitrous oxide reductase [6]. For the Cu_A and Cu_Z sites particularly, it seems likely that the function of the biosite hinges on the close interactions between the copper ions. Consequently, it seemed important to investigate the redox chemistry of some synthetic polynuclear copper complexes in an aqueous electrolyte environment. The present study focuses on the initial characterization of the redox behaviour of some polynuclear copper complexes in the absence of coupled catalytic processes.

The synthesis and structural characterization of tetranucleating copper complexes [8] in which the bridged metal ions are held in close proximity (ca. 3 Å) using the macrocyclic ligand H_4L (see Scheme 1) have been reported previously. The ligand is formed by a template process and the free ligand H_4L has not been isolated. The simplest class of these complexes comprises the planar tetranuclear $\text{Cu}(\text{II})_4$ arrays [9, 10] (see structure of complex **2**). These can be dimerized under appropriate conditions (solvent, pH) to form octanuclear copper(II) complexes and both tetra- and octanuclear complexes incorporate open faces available for coordination of exogenous ligands (or substrates in catalysis). A metal-deficient template reaction has been exploited to synthesize di-copper(II) complexes in which two of the metal binding sites are vacant (see structure of complex **1**). It has been shown that these sites can then be filled by addition of a second type of metal cation to generate heterotetranuclear Cu_2M_2 complexes [11] and

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Scheme 1 Structures of the complexes **1** and **2**

larger supramolecular architectures [12]. This behaviour is consistent with a stepwise filling of binding sites with two or four Cu(II) being coordinated to the ligand.

In order to investigate the electrochemical characteristics of metal complexes **1** and **2** in aqueous media, a technique based on microparticle adhesion at carbon electrodes is employed. Several reports about this type of solid state electrochemical processes of water-insoluble metal complexes have appeared (see for example [13]). The electron transfer between solid and electrode surface is accompanied by insertion of ions into or expulsion of ions from the solid material for the overall process to obey charge neutrality. Both anion exchange [14, 15] and cation exchange processes [16] have been observed. In addition to the simple exchange of “spectator” ions, metal cations have also been reported to move into porphyrin ligand spheres [17], driven by the electrode potential applied to the ligand present in solid form at the electrode/solution interface.

In this study, the redox properties of di-copper and tetra-copper metal complexes **1** and **2** with a macrocyclic ligand sphere are explored by solid state voltammetry [18] in aqueous buffer solution environments. Two slightly different types of ligand, with R = Me and with R = *t*-Bu, are employed with essentially identical results. The metal complexes are mechanically adhered to a graphite electrode surface in the form of a microcrystalline powder. As a result, the redox properties in purely aqueous media of molecules at the solid/solution phase boundary can be studied and compared to the solution phase redox properties in organic solvent media.

It is shown that under solid state voltammetry conditions the water-insoluble macrocyclic di-copper metal complex $[Cu_2(H_3L)(OH)][BF_4]_2$ (see structure of complex **1**) and the tetra-copper metal complex $[Cu_4(L)(OH)][NO_3]_3$ (see structure of complex **2**) undergo overall reversible Cu(II) to copper metal reduction processes accompanied by proton insertion into the ligand. Owing to the ability of the free macrocyclic ligand to rapidly and efficiently capture Cu^{2+} , the redox processes are chemically reversible.

Experimental

Reagents

KH_2PO_4 , K_2HPO_4 , KOH, H_3PO_4 (85 wt%), NaOH, acetic acid, $Cu(NO_3)_2$, DMSO (spectrophotometric grade, Aldrich), and NBu_4PF_6 (electrochemical grade, Fluka) were obtained commercially and used without further purification. Demineralized and filtered water with a resistivity of not less than 18 M Ω cm was obtained from an Elgastat water purification system (Elga, Bucks, UK). Solutions were de-aerated with argon (Pureshield, BOC) for at least 15 min prior to undertaking experiments.

Instrumentation

Voltammetric experiments were carried out with a PGSTAT 30 Autolab potentiostat system (Eco Chemie, Netherlands) in a three-electrode conical glass cell. Rotating disc voltammetry measurements were conducted with an EG&G PARC model 616 RDE stand connected to the Autolab potentiostat. For experiments in DMSO solution, a Pt counter electrode, an Ag/AgO pseudo-reference electrode with ferrocene as internal standard, and a 3 mm diameter glassy carbon working electrode (BAS) were employed. In aqueous solution the counter electrode was a Pt gauze, the reference electrode was a saturated calomel electrode (SCE, Radiometer REF 401), and the working electrodes were prepared as follows. A 4.9 mm diameter basal plane pyrolytic graphite electrode, polished with SiC paper (1200 grit), was pushed into a 1–3 mg quantity of the metal compound on a clean filter paper (Whatman 1). By moving the electrode under gently applied pressure, a reproducible and even coverage of mechanically adhered microcrystalline particles was achieved. A typical SEM image (Cambridge Stereoscan 360 system) of the microparticles adhering to the graphite surface is shown in Fig. 1a. It can be seen that although some particles with several micron diameter are present at the surface of the electrode, predominantly micron sized and smaller particles are embedded into the graphite surface.

Metal complexes

The macrocyclic di-copper metal complexes $[Cu_2(H_3L)(OH)][BF_4]_2$ (see **1**) and the tetra-copper metal complexes $[Cu_4(L)(OH)][NO_3]_3$ (see **2**) were prepared and characterized following literature methods [9, 10, 11].

Results and discussion

Cyclic voltammetry in solution

Dissolved in organic solvents, the di- and tetra-copper metal complexes **1** and **2** are redox active in a potential range characteristic for the reduction of Cu(II) metal

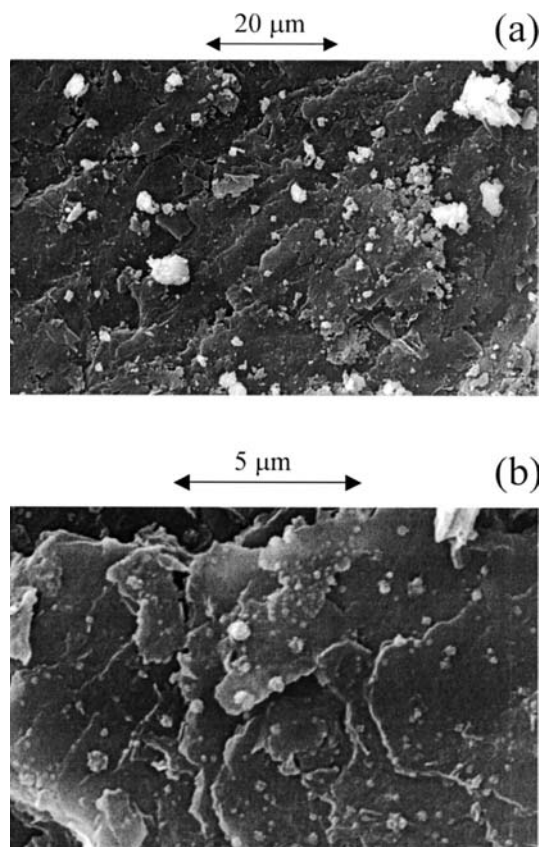


Fig. 1 SEM micrographs of microcrystalline solid (tetra-copper complex **2** with $R = t\text{-Bu}$) mechanically adhered to a basal plane pyrolytic graphite electrode (a) before and (b) after reduction at -1.0 V vs. SCE for 60 s in 0.1 M phosphate buffer at pH 4

complexes. A solution of 1.5 mM of the di-copper complex **1** in DMSO (0.1 M NBu_4PF_6) allows the reduction to be detected, commencing at a potential of -0.8 V vs. ferrocene (see Fig. 2). The reduction peak is broad and, after reversal of the scan direction, two small product peaks are observed. By comparison with voltammograms obtained for $\text{Cu}(\text{NO}_3)_2$ in DMSO, the two oxidation processes detected at $E_p = -0.85$ V and at

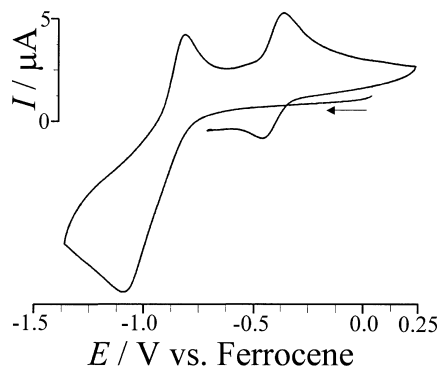


Fig. 2 Cyclic voltammogram (scan rate 0.1 V s^{-1}) for the reduction of 1.5 mM di-copper complex **1** with $R = \text{Me}$ in DMSO (0.1 M NBu_4PF_6) at a 3 mm diameter glassy carbon electrode

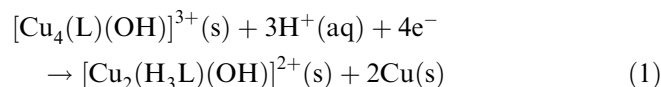
$E_p = -0.38$ V vs. ferrocene are readily identified as $\text{Cu}^{0/+}$ and $\text{Cu}^{2+/+}$ redox systems. From the voltammetric data it can be inferred that the electrochemical reduction of compound **1** is followed by rapid decomplexation and copper metal deposition. The fact that the free ligand formed during decomplexation diffuses into the solution phase causes the overall process to exhibit chemically irreversible and complex characteristics. Useful information about the properties of the copper complexes **1** and **2** are not easily extracted from this type of voltammetric data obtained in DMSO solution.

Solid state voltammetry in aqueous phosphate buffer

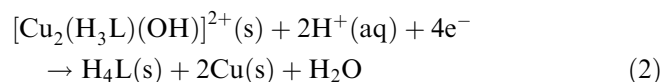
Next, the redox properties of macrocyclic di- and tetra-nuclear copper complexes **1** and **2** were explored in buffered aqueous solution environments. In these solutions, compounds **1** and **2** are essentially insoluble, although a gradual increase in solubility was observed at lower pH values (vide infra). Microcrystalline powders mechanically adhered to an electrode surface (see Fig. 1a) and then immersed in aqueous buffer solution give characteristic voltammetric responses. Figure 3 shows the voltammetric signals for the reduction of the tetra-copper complex **2** (Fig. 3a) and for the di-copper complex **1** (Fig. 3b), both in the form of a microcrystalline powder immersed in aqueous 0.1 M phosphate buffer at pH 6. Several reduction processes are detected in the potential range from -0.2 to -0.7 V vs. SCE. The reduction of the ligand itself is not expected in this potential range and therefore the processes are proposed to be copper based.

During the course of the first potential cycle, two reduction peaks are detected for the tetra-copper complex **2** (Fig. 3a) at $E_{p,C2} = -0.26$ V vs. SCE and at $E_{p,C3} = -0.51$ V vs. SCE. In contrast, for the di-copper complex **1** during the first potential cycle, only one reduction peak at $E_{p,C3} = -0.51$ V vs. SCE is detected (Fig. 3b). After reversal of the scan direction for both types of metal complexes, one anodic signal is detected at $E_{p,A1} = -0.05$ V vs. SCE. In order to explain these reduction and oxidation processes, we assume de-metalation and formation of copper metal at the electrode surface (see Eqs. 1 and 2):

Process C2 :



Process C3 :



Compositional details of the metal complexes in Eqs. 1 and 2 are inferred from published structure data

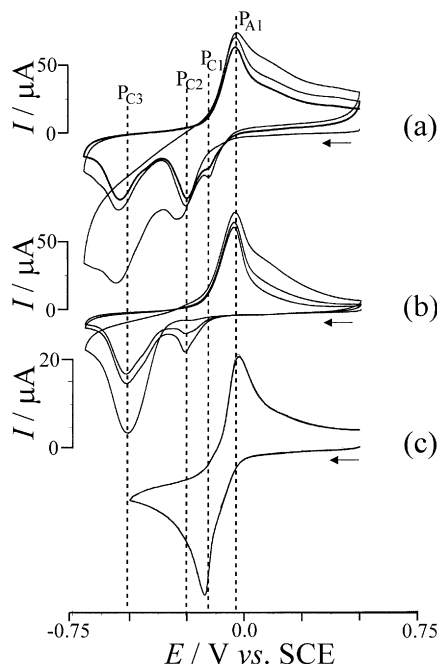


Fig. 3 Cyclic voltammograms (first four cycles shown for **a** and **b**, scan rate 0.1 V s^{-1}) for the reduction of solid tetra-copper complex **2** with $\text{R} = \text{Me}$ (**a**) and for solid di-copper complex **1** with $\text{R} = \text{Me}$ (**b**) mechanically adhered to a 4.9 mm diameter basal plane pyrolytic graphite electrode and immersed in aqueous 0.1 M phosphate buffer at pH 6. Voltammogram (**c**) shows the reduction of Cu^{2+} in a saturated solution in aqueous 0.1 M phosphate buffer at pH 6

[9, 10, 11]. The oxidation process associated with the two reduction processes involves anodic stripping of the copper metal deposit from the electrode surface. This can be confirmed in an experiment employing Cu^{2+} in solution. The voltammogram obtained for the reduction of Cu^{2+} in 0.1 M phosphate buffer at pH 6 is shown in Fig. 3c. Reduction at $E_{p,C1} = -0.17 \text{ V vs. SCE}$ is detected followed by an anodic response at $E_{p,A1} = -0.05 \text{ V vs. SCE}$. Stopping the potential cycle at -0.5 V vs. SCE causes accumulation of copper metal, with a corresponding increase in the oxidation response. Therefore the process associated with P_{A1} and P_{C1} can be identified as copper stripping and deposition, respectively (Eqs. 3 and 4):

Process A1 :



Process C1 :



It is interesting to follow the electrochemical processes associated with reduction of solid compounds **1** and **2** over several cycles. For the di-copper complex **1** a new reduction signal at $E_{p,C2} = -0.26 \text{ V vs. SCE}$ is detected in the second and the following potential cycles. This cathodic response can be identified as the reduction

of the tetra-copper complex **2** (see Eq. 2). Therefore complex **1** must have re-formed together with complex **2** surprisingly quickly after oxidation of the copper deposit.

In the solid state voltammetric responses for the tetra-copper complex **2**, a further reduction signal appears in the second and third cycles at $E_{p,C1} = -0.17 \text{ V vs. SCE}$. This reduction response is believed to be associated with copper, $\text{Cu}^{2+}(\text{aq})$, formed during the preceding oxidation process (see Eq. 4). This process is not detected for the di-copper complex **1** (see Fig. 3b) because of the more favourable ratio of ligand to $\text{Cu}^{2+}(\text{aq})$.

The voltammetric responses are not significantly affected by rotating the electrode during the course of measurements. This observation confirms that solids are formed in the reduction process. Also, comparison of the voltammetric characteristics for copper complexes with ligands of type L^1 ($\text{R} = \text{Me}$) and L^2 ($\text{R} = t\text{-Bu}$) suggests that minor alterations of the ligand have essentially no effect on the solid state voltammetric responses.

In summary, although complex, the overall reaction sequence during solid state voltammetry of the di- and tetra-copper metal complexes **1** and **2** may be explained based on Eqs. 1, 2, 3, 4. A schematic presentation of the process is shown in Fig. 4. The reduction of the metal complex yields copper metal and free ligand as products deposited on the electrode surface. Figure 1a shows SEM images of the tetra-copper complex **2** adhered to the graphite electrode surface in the form of microparticles. After reduction for 1 min at -1.0 V vs. SCE in aqueous 0.1 M phosphate buffer at pH 4, copper deposits of typically 100 nm size are formed (confirmed by energy dispersive X-ray analysis) at the electrode surface (see Fig. 1b).

Effect of pH on the solid state voltammetric response

The voltammetric characteristics observed for both complexes **1** and **2** are highly sensitive towards changes in the concentration of protons. Figure 5 shows a series of first and second cycle solid state voltammograms for the reduction of microcrystalline di-copper complex **1** mechanically adhered to a basal plane pyrolytic graphite electrode. It can be seen that (1) a shift of the voltammetric responses towards more positive potential occurs and (2) a considerable increase in peak

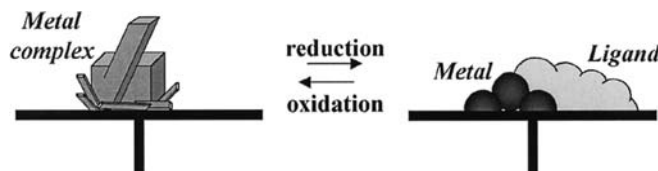


Fig. 4 Schematic representation of the reversible solid state conversion of metal complex to metal deposit and free ligand

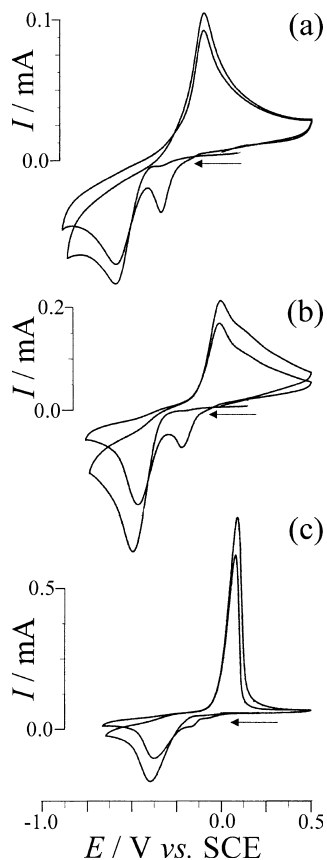


Fig. 5 Cyclic voltammograms (first and second cycle shown, scan rate 0.1 V s^{-1}) for the reduction of solid di-copper complex **1** ($R = \text{Me}$) mechanically adhered to a 4.9 mm diameter basal plane pyrolytic graphite electrode immersed in aqueous 0.2 M phosphate buffer at (a) pH 8, (b) pH 6 and (c) pH 4

current is detected upon increasing the proton concentration. Voltammetric data are summarized in Table 1. The shift in peak potentials indicates that proton electro-insertion and expulsion processes accompany the redox process. In the plots shown in Fig. 6 the shift for the peak potentials $E_{p,C3}$, $E_{p,C2}$ and $E_{p,A1}$ can be seen to be approximately 44 mV per pH unit (see lines) over a limited pH range from 4 to 8. This observation may be explained by a process involving uptake of three protons for every four electrons transferred. The release of the Cu^{2+} from the ligand during reduction requires proton uptake into the ligand (see Eqs. 1 and 2). The stoichiometry of proton uptake given in the equation for process C2 is in

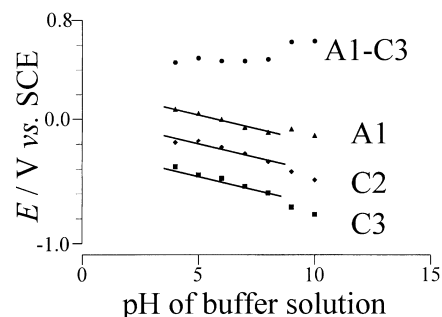


Fig. 6 Plot of peak potential versus pH data obtained from cyclic voltammograms (second cycle, scan rate 0.1 V s^{-1}) for the reduction of solid di-copper complex **1** ($R = \text{Me}$) mechanically adhered to a 4.9 mm diameter basal plane pyrolytic graphite electrode immersed in aqueous 0.2 M phosphate buffer. Lines correspond to a shift of 44 mV per pH unit

agreement with the experimentally observed shift. However, processes C3 and A1 are not quantitatively consistent with the magnitude of the experimental shift. It is likely that these processes are overall more complex (e.g. involving anion exchange and proton expulsion from the ligand).

The increase in peak current observed at increased proton concentration suggests that the reduction as well as the re-oxidation processes in the presence of acid penetrate further into the solid. Increasing the concentration of protons to pH 2 leads to dissolution and decomposition of the polynuclear copper complexes in the aqueous buffer solution.

The shift in reduction peak potential observed between the reduction of free Cu^{2+} in the aqueous buffer phase (process C1) and the reduction of Cu^{2+} bound in complex **1** (process C3) or bound in complex **2** (process C2) is indicative for strong copper binding. The absence of reaction intermediates such as complexes with one or three copper cations bound into the ligand can be rationalized based on interactions in the metal complex. The presence of the first Cu^{2+} in one of the two upper coordination sites (see structure) favours coordination of a second Cu^{2+} in the second upper coordination site. In order to fill the remaining two vacant coordination sites, protons have to be removed and the metal-ligand interaction for the first two Cu^{2+} is probably weakened. Bond length data from X-ray crystallographic studies support this view [9, 12]. In the di-copper complexes the Cu-OH bond distances average 1.935 Å; however, in the tetra-copper complexes the central cavity is slightly

Table 1 Voltammetric data (second cycle, scan rate 0.1 V s^{-1}) obtained from solid state voltammograms for the reduction of di-copper complex **1** ($R = \text{Me}$) recorded in aqueous 0.2 M phosphate buffer solution at different pH values

Redox system	$E_{p,C2}$ (V vs. SCE)	$I_{p,C2}$ (μA) ^a	$E_{p,C3}$ (V vs. SCE)	$I_{p,C3}$ (μA) ^a	$E_{p,A1}$ (V vs. SCE)	$I_{p,A1}$ (μA) ^a
pH 8	-0.33	-42	-0.57	-79	-0.09	67
pH 6	-0.20	-75	-0.45	-192	0.0	158
pH 4	-0.18	-45	-0.38	-166	0.07	545

^aThe peak current I_p may change by $\pm 30\%$, depending on the amount of deposit at the electrode surface

larger than optimal for the hydroxide ion and the Cu-OH distances are significantly longer (average 2.105 Å). Further evidence comes from the observation [12] that, while template synthesis using four equivalents of copper ions yields the tetra-copper complex, “metal-deficient” template synthesis using only two equivalents of copper gives a good yield of the di-copper complex without contamination by the tetranuclear analogue. This implies that the di-copper complex is preferred, at least kinetically.

In future work it will be interesting to extend the experimental work to include other metal cations competing for coordination sites with copper.

Conclusions

It has been shown that di- and tetra-copper metal complexes may be reversibly de-metalated in a solid state electrochemical process. In aqueous solution at a sufficiently negatively polarized electrode, the insoluble tetra-copper complex releases two Cu²⁺ cations to form copper metal and the di-copper complex. In a second reduction step the di-copper complex releases two more Cu²⁺. Both the di- and the tetra-copper complexes are re-formed upon oxidation. Analysis of the solid state voltammetric data indicates that, in aqueous buffer solution, strong binding of the solid expanded “Robson-type” macrocyclic ligand H₄L to copper occurs.

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