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Multi-electron reactivity of a cofacial di-tin(II) cryptand: partial reduction of sulfur and selenium and reversible generation of $S_3^{3-}$†

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Cofacial bimetallic tin(II) ([Sn$_2$(mBDCA-5t)]$^{2-}$, 1) and lead(II) ([Pb$_2$(mBDCA-5t)]$^{2-}$, 2) complexes have been prepared by hexadeprotonation of hexacarboxamidic cryptand mBDCA-5t-H$_6$ together with double Sn(II) or Pb(II) insertion. Reaction of 1 with elemental sulfur or selenium generates di-tin polychalcogenide complexes containing $\mu$-E and bridging $\mu$-E$_5$ ligands where E = S or Se, and the Sn(II) centers have both been oxidized to Sn(IV). Solution and solid-state UV-Vis spectra of $[\mu$-$\text{S}_2$Sn$_2$$\mu$-$\text{S}$(mBDCA-5t)]^{2-}$ (4) indicate that the complex acts reversibly as a source of $S_3^{3-}$ in DMF solution with a $K_{eq} = 0.012 \pm 0.002$. Reductive removal of all six chalcogen atoms is achieved through treatment of $[\mu$-$\text{E}_5$Sn$_2$$\mu$-$\text{E}$(mBDCA-5t)]^{2-}$ with PR$_3$ ($R = \text{Bu, Ph, O}^+\text{Pr}$) to produce six equiv. of the corresponding EPR$_3$ compound with regeneration of di-tin(II) cryptand complex 1.

Introduction

Multi-electron transfer reactions are an area of intense interest due to their key role in both biological$^1$ and synthetic systems for the activation and transformation of small molecules germane to energy conversion. These systems have the ability to accommodate and deliver multiple electrons to reaction substrates at one time, and typically feature two or more redox active metal ions confined within a single structural unit. Synthetic organometallic complexes that undergo multielectron redox processes have been extensively studied for their applications in electrocatalysis,$^2$ sensing,$^3$ homogeneous,$^4$ and heterogeneous$^5$ catalysis. Many of these systems are based upon face-to-face dipyrophyrins, in which two metallocorphyrins are rigidly linked together in a cofacial arrangement.$^6$ Complexes of this type have received considerable interest due to their ability to carry out multi-electron processes such as oxygen reduction,$^7$ nitrogen reduction,$^8$ and H$_2$O$_2$ disproportionation.$^9$

We have shown previously that macro-bicyclic hexacarboxamide cryptand molecules,$^{10}$ in hexa-deprotonated form, serve as excellent frameworks engendering cofacial transition-metal bimetallic systems with a range of intermetal distances;$^{10,11}$ these systems are distinguished from bis-porphyrin constructs in that the metal ion coordination environment is trigonal rather than tetragonal. While transition metal complexes that carry out multi-electron reactions have, and continue to receive attention, functional p-block metal analogues have been far less studied.$^{12}$ Recent work has shown that the chemistry of some heavy main group elements can resemble that of transition-metal complexes, and main-group metal systems have displayed small-molecule reactivity previously thought to be the exclusive domain of d-block elements.$^{13}$

For the present work, in extending the approach we sought to access a pair of tin(II)/tin(IV) redox couples giving the potential for four-electron transformations within the capsular cryptand environment. We chose to investigate redox reactions involving the group 16 elements, the ensuing finding that clean and informative reactivity was observed for both sulfur and selenium forming the basis of the present work. We note that both the reduction of oxygen to peroxide dianion, and the reduction of sulfur to sulfide ion, are currently targets for the development of new battery chemistries; fundamental studies such as the present one have the potential to reveal how the reduction processes may become controlled and selective in response to the utilization of a pre-organized architecture.

Results and discussion

Double insertion of tin(II) or lead(II) into the cryptand proceeds upon treatment of mBDCA-5t-H$_6$ (ref. 15) with KO'Bu in the presence of Sn[N(SiMe$_3$)$_2$]$_2$, or Pb[N(SiMe$_3$)$_2$]$_2$ (ref. 16) in THF. This procedure affords the $[K_4$(THF)]$[Sn_2$(mBDCA-5t)]$[K_4$(THF)]
(1) and [K₂(THF)][Pb₂(mBDCA-5t)] (Scheme 1) as colorless powders in 68, and 69% yield, respectively. In their "H NMR spectra, both 1 (Fig. S1*) and 2 (Fig. S7*) display two resonances corresponding to the aryl protons of the three phenylene spacers, and four resonances are observed for the tren (tren = tris-2-aminoethylamine) methylene residues, suggesting that these bimetallic dianions retain their approximate C_{3h} symmetry in solution at room temperature. Complexes 1 and 2 display single resonances in their "H NMR spectra (I = 1/2, δ = 381.6 ppm, DMSO-d_s, Fig. 5c), and 209Pb NMR spectra (I = 1/2, δ = 2641.4 ppm, DMSO-d_s, Fig. S9†), similarly consistent with the presence of a horizontal mirror plane now relating the tin and lead ions in their C_{3h} geometry. The formulation of both dianions 1 and 2 has also been confirmed by ESI-MS (−) with m/z values of 541.12 (calc’d, 541.13, Fig. S4†), and 630.18 (calc’d, 630.21, Fig. S10†), respectively.

Crystals of both 1 and 2 as their [K(Kryptofix 2,2,2)]^± salts were grown by vapor diffusion of Et₂O into saturated DMF solutions over the course of 48 h at 23 °C. Single-crystal X-ray diffraction studies provided the structures of 1 and 2 shown in Fig. 1 and S51,† respectively. [K(Kryptofix 2,2,2)]_2[1] and [K(Kryptofix 2,2,2)]_2[2] are isostructural, crystallizing in the hexagonal space group P6_3/m, with the bimetallic M–M cores lying on a crystallographic three-fold axis of rotation. Both anions 1 and 2 have effective C_{3h} point group symmetry with the metal centers adopting a trigonal pyramidal coordination environment (Fig. 1) as expected for triamidostannate(u) systems. The solid-state structures of 1 and 2 reveal Sn⋯Sn and Pb⋯Pb intermetal separations of only 3.5373(7), 3.5274(5) Å, respectively, distances which are significantly shorter than the average M⋯M distances that span 6.080 to 6.495 Å for the bimetallic cyanide complexes of metal(u) ions previously reported, where M = Mn, Fe, Co, Ni, Zn, and wherein the transition-metal ions adopt the trigonal monopyramidal coordination motif as they sink deeper into the tren-based N₃N binding pockets.\textsuperscript{11}

Being interested in the potential multi-electron redox reactivity of these p-block metal cryptates, we carried out computations of electronic structure for complex 1 (see Fig. 2 for details); the HOMO consists largely of an out-of-phase combination of the two tin lone pairs, while the HOMO–1 is an in-phase combination whose appearance nicely suggests that these metal ions are within bonding distance. The largely metal-centered nature of the HOMO and HOMO–1 electron pairs of 1 is fully in line with the expected metal-centered redox activity.

With access to salts of 1 and 2 on scales approaching 300 mg per synthesis, we were able to initiate exploratory reactivity studies involving the group 16 elements. While the di-lead(u) complex 2 displayed no reaction with chalcogenes, the di-tin(u) cryptate 1 was found to react cleanly with both elemental sulfur and selenium. There are hundreds of fully characterized transition-metal cyclic polysulfide and polyselenide complexes known in the literature,\textsuperscript{23} however, significantly fewer examples of polychalcogenide main group metal complexes exist. Polychalcogenide complexes containing group 14 metal ions are especially rare,\textsuperscript{24} and there are only two structurally characterized examples we are aware of where a polysulfide or polyselenide ring (with n > 3 for S, or Se) bridges two group 14 centers.\textsuperscript{25} Even though tin(u) amide compounds are known to react with sulfur and selenium to typically form thermodynamically favored bis-\(\mu\)-chalcogenide products,\textsuperscript{26,27} we were interested to determine whether the preorganization offered by

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**Scheme 1** Protocol for double Sn(II) or Pb(II) insertion into the mBDCA-5t-H₆ cryptand (together with hexadeprotonation) to generate [Sn₂(mBDCA-5t)]^{2−} (1) and [Pb₂(mBDCA-5t)]^{2−} (2).
the mBDCA-5t cryptand framework would direct the system into new assemblages of atoms otherwise inaccessible in the absence of such a supramolecular construct.

Treatment of 1 with elemental selenium (6 equiv.) in DMF solution was found to elicit a color change from colorless to deep red upon thorough mixing (Scheme 2). After workup, the selectively formed product of this reaction, \([\mu\text{-Se}_5]\text{Sn}_2[\mu\text{-E}]\text{mBDCA-5t}]^2\) (3), was isolated in 71% yield as a brick red solid. The \(^1H\) NMR spectrum of 3 (Fig. S12†) features three distinct tert-butyl resonances, each with integrations of nine protons, and six aryl resonances with integrations of one and two protons in a 1 : 1 ratio. The \(^{119}\text{Sn}\) NMR spectrum of 3 consists of one singlet (\(\delta = 876.5\) ppm, Fig. 5a, \(J_{119\text{Sn};77\text{Se}} = 3381\) Hz), and the \(^{77}\text{Se}\) NMR spectrum contains four resonances that are attributed to the four distinct selenium environments of complex 3. The resonances located at \(\delta 537.2, 884.4\) ppm contain well-resolved satellite peaks corresponding to \(J_{119\text{Sn};77\text{Se}}\) coupling of 3371 and 785 Hz, respectively (Fig. 3). While the \(^1\text{H}\) NMR spectrum revealed that the three arms of the cryptand are inequivalent, the \(^{119}\text{Sn}\) NMR data indicate that 3 contains only one tin environment, indicating that a lowering of symmetry from \(C_{3v}\) to \(C_s\) has occurred through the reaction of 1 with selenium.

A solid-state structure established the identity of this species as \([\text{K}_2(\text{DMF})_3][\mu\text{-Se}_5]\text{Sn}_2[\mu\text{-E}]\text{mBDCA-5t}]^2\) (3), and Fig. 4 shows a thermal ellipsoid plot of the dianion in this complex salt. X-ray quality dark red crystals of \([\text{K}_2(\text{DMF})_3][\mu\text{-Se}_5]\text{Sn}_2[\mu\text{-E}]\text{mBDCA-5t}]^2\) were grown by vapor diffusion of diethyl ether into a saturated DMF solution of the salt over the course of 12 h at 23 °C. The solid-state molecular structure of 3 reveals that the two Sn(n) ions reside in a distorted octahedral environment, each coordinated to the three carboxamide nitrogen atoms from the cryptand as well as one \(\mu\text{-Se}_5\) ligand and one selenium from the five membered \(\text{Se}(\text{Se})_3\text{Se}\) pentaselenide chain that links the two tin(n) centers. The observed molecular structure of dianion 3 provides the first glimpse of a conformation in which two cryptand arms are splayed apart in a manner that permits the pentaselenide chain to bridge the tin(n) ions in between them, revealing a degree of flexibility we had not previously appreciated for this type of bimetallic hexacarboxamide ligand architecture. The selective formation of this product shows that elemental selenium reacts with complete consumption of all four reducing equivalents stored in the di-tin(n) reservoir of dianion 1, while the level of reduction of the elemental selenium, to Se\(^{2–}\) and Se\(^{3–}\), is such that only one-third of the complete oxidizing power of 6 Se\(^0\) is quenchcd and four reducible Se–Se bonds remain.

The UV-Vis spectrum of 3 in DMF solution shows two major absorptions located at \(\lambda_{\text{max}} = 452 (\epsilon = 4207 \, \text{M}^{-1} \, \text{cm}^{-1})\) and \(585 (\epsilon = 842 \, \text{M}^{-1} \, \text{cm}^{-1})\) nm (0.26 mM, Fig. S16†). Both observed bands are in good agreement with the literature reported absorption values for Se\(_{\text{n}}\) of \(\lambda_{\text{max}} = 440 \) and 598 nm in DMA solution.29

Similarly, the reactivity of 1 with elemental sulfur was investigated. Treatment of 1 with 3/4 eq. S\(_8\) in DMF solution elicits a rapid color change from colorless to blue green. Addition of Et\(_2\)O to the crude reaction mixture results in the precipitation of the \([\text{K}_2(\text{DMF})_3][\mu\text{-S}_8]\text{Sn}_2[\mu\text{-S}]\text{mBDCA-5t}]\) complex (4, Scheme 2) as a bright yellow solid in 63% yield. Although suitable crystals were not obtained for an X-ray diffraction study, the structure of the sulfur-containing product
Reactions of tin(II) amide compounds with oxygen, sulfur, or selenium typically result in complexes containing terminal Sn=E bonds or thermodynamically favored bis-μ-chalcogenide products, with complete reduction to the oxide, sulfide, or selenide ion, E^2- (E = O, S, Se). In our system, however, the preorganization of the cryptand architecture has o

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in agreement with the literature reported EPR signal of $S_{1}^{<}$.$^{37}$ Therefore, the observed data suggest that in solution, the sulfur atoms of complex 4 undergo dissociation from the di-tin cryptand to release $S_{1}^{<}$.

The presence of $S_{1}^{<}$ upon dissolution of 4 may be a result of initial release of $S_{2}^{2-}$ followed by dissociation into two equivalents of $S_{1}^{<}$. According to this overall stoichiometry, dissociation of two equivalents of $S_{1}^{<}$ from the dianionic complex 4 would require the concomitant formation of a neutral [Sn$_2$-(mBDCA-56)] species. Although this is perhaps the most straightforward explanation, we cannot definitely rule out $S_{3}^{2-}$ or $S_{2}^{2-}$ as the source of $S_{1}^{<}$. While more work is required to substantiate this proposal, such a postulated neutral [Sn$_2$-(mBDCA-56)] species may exist as a Sn–Sn bonded hexaaminodistannane analogous to one which Gade et al. obtained upon oxidative coupling of a tin(n) triamidostannane and for which the Sn–Sn interatomic distance was reported to be 2.8204(4) Å.$^{38}$ The metal–metal single bond in such a species corresponds to the HOMO–1 of complex 1 (Fig. 2b).

In an effort to drive to full completion the level of sulfur/selenium reduction in this system, we probed the reaction of 3 and 4 with PR$_3$ reductants (R = Bu, Ph, OPr, Scheme 2). Proceeding accordingly, we found that treatment of either complex with PR$_3$ (6 equiv.) resulted in abstraction of all six chalcogen atoms and quantitative regeneration of di-tin(n) complex 1! Incomplete conversion of 3 and 4 to 1 was the result when using <6 equiv. PR$_3$, with no other species observed by $^1$H or $^{119}$Sn NMR spectroscopy. Treatment of either 3 or 4 with PM$_3$S$_2$ (excess), however, led to no observed reaction, this being explicable in terms of steric effects. Dechalcogenation of transition$^{39}$ and group 14 (ref. 31 and 40) metal cyclic polychalcogenide complexes is commonly accomplished using tertiary phosphines or electron deficient alkenes and alkenes. These reactions, however, typically result in only partial reduction in the size of the chalcogen ring or conversion to the typical bis-µ-chalcogen thermodynamic product instead of complete dechalcogenation. The present polychalcogen/di-tin cryptand complexes are very unusual inasmuch as PR$_3$ compounds are capable of complete de-chalcogenation and reduction of tin back to the +2 oxidation state, suggesting in turn that the macrobicyclic nature of bimetallic complex 1 imbrues the tin(n) oxidation state with comparatively greater stability than is typical sans such structural constraints.

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