DALTON
PERSPECTIVE

Russian doll assembled superanion capsule–metal ion complexes: combinatorial supramolecular chemistry in aqueous media

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The focus of this perspective is the self assembly in aqueous solutions ($pH < 3.5$) of the synthons sodium *p*-sulfonatocalix[4]arene and 18-crown-6, or related macrocycles, into globular superanions or ionic capsules, for example $\{Na^+\subset(18\text{-crown-6})(OH_2)_n\}\subset\{(p\text{-sulfonatocalix[4]arene}(4-))_2\}^{7-}$, $n = 0$ or 2. These can crystallise, often selectively, polynuclear hydrolytic metal(III) cations $[M_2(OH)_2(H_2O)_8]^{4+}$, $[M_3(OH)_4(H_2O)_{10}]^{5+}$, $[M_4(OH)_6(H_2O)_{12}]^{6+}$, M = Cr or Rh, or $[Al_{13}O_4(OH)_{24}(H_2O)_{12}]^{7+}$, depending on the pH and other synthetic parameters, which are established using a combinatorial approach. These superanions are ambivalent; two calixarenes shroud a crown ether with a central sodium ion bound also by two *trans*-water molecules or two oxygen centres of sulfonate groups from each of the calixarenes. Electrostatic repulsion between the negatively charged calixarenes is compensated by the large polynuclear cations interacting with the negatively charged hydrophilic equatorial region of the capsule, and some protonation of the sulfonate groups. Similarly, protonated cyclam forms a capsule with two calixarenes and crystallises $[Cr_2(OH)_2(H_2O)_8]^{4+}$. Lanthanide(III) ions form a range of complexes at specific pH in the presence of the calixarene and crown ether, including complexes containing the capsule $[\{18\text{-crown-6}\}\subset\{(M(H_2O)_7{}^{3+})_{1.33}(p\text{-sulfonatocalix[4]arene}(4-))\}_2]$, for the smaller lanthanides, or the ferris wheel type structure $[\{La^{3+}\subset(18\text{-crown-6})(OH_2)_3\}\cap\{(p\text{-sulfonatocalix[4]arene}(4-) + 2H^+)\}]^+$, for the larger lanthanide. Only some of the continuous structures have an up–down bilayer arrangement of calixarenes.

1 Introduction

Molecular capsules have received considerable attention in recent years, with their origins in the covalent encapsulation of small molecules, the so-called carcerands which were pioneered by Cram.[1] Contemporary developments in the chemistry of molecular capsules deal with non-covalent self assembly processes to build up such supermolecules. Complementarity of hydrogen bonding interactions between the supramolecular synthons or building blocks has yielded capsules with large internal cavities capable of holding two or more solvent molecules as a micro-solvent environment. This approach has been developed by Rebek and co-workers,[2,3] MacGillivray and Atwood,[4,5] and others,[6,7] and the design strategy involves the use of rigid curved or bowl shaped molecules such as calixarenes and resorcinarenes. Another approach has been to use coordination interactions/metal oxide oligomerisation to build up metal containing capsules,[8–11] also with internal volumes large enough to accommodate several molecules, in one case, as an example, four *o*-carboranes.[11] Related to these are the reversibly metal-directed assembled vesicles,[12] and the fabrication of metallo-supramolecular entities on the surface of charged nano-particles.[13]

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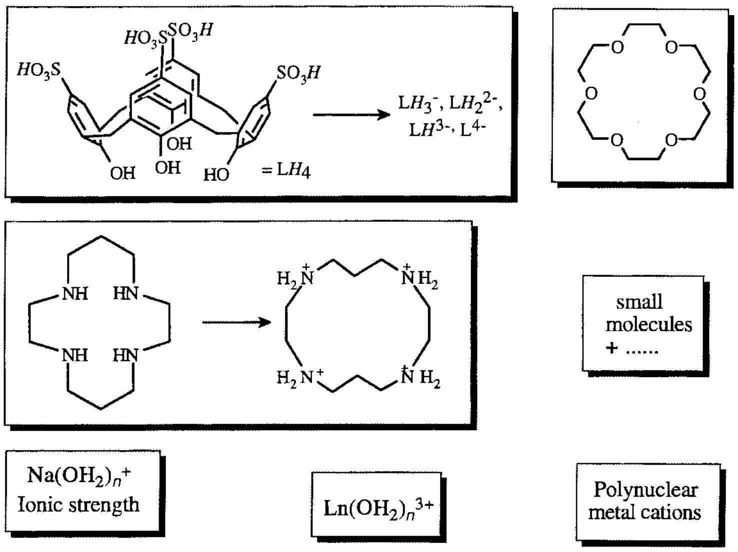


Fig. 1 Supramolecular synthons used in building up superanion capsules; libraries are virtual building blocks.

Using self assembly processes allows the exploitation of the hyper-energy surface for the interacting components, usually leading to the thermodynamically favoured products, and allows for the encapsulated species to be released by changing the micro-environment of the capsule. Our interest in capsules concerns the use of the large water soluble, highly charged sulfonated calix[4,5]arenes to gain access to novel nanostructures, relying on a combination of supramolecular interactions, notably coordination, hydrogen bonding, electrostatic and van der Waals, where there is size, shape and electronic complementarity between the molecular components. Highly charged anionic capsules, or superanions, may be formed by the head-to-head dimerisation of two such calixarenes with concomitant encapsulation of other molecule(s) within the capsule core. The presence of superanions requires highly charged counter cations and we have been utilising this chemistry for the isolation and crystallisation of large polynuclear metal(III) species. We use a reaction optimisation approach to build up virtual combinatorial libraries of the interacting synthons, including the degree of protonation of the calixarene and the relative ratios of the synthons. This is so-called combinatorial chemistry which has successfully been used by others in supramolecular chemistry.[7,9,10] Thus far we have restricted our studies to identifying complexes precipitating from solution, which usually occurs over a narrow pH regime. Successes thus far have been mainly at pH < 3.5 which corresponds to the calix[4]arene tetrasulfonate or its various protonated forms. For higher pH deprotonation of the lower rim phenolic OH groups prevails, and this can lead to nanostructures in the presence of lanthanides.[14] Our synthons are depicted in Fig. 1, and clearly there are many variables to be considered including the degree of protonation of the calixarenes, the nature of core species within the capsules such as crown ether or cyclam, the polynuclear counter ions and other large cations, lanthanide ions, ionic strength, and more. This is shown in Fig. 2 in cartoon form.

Work has thus far mostly been restricted to the calix[4]arene as it is readily available and usually adopts a cone or bowl conformation, and thus there is no compromise in any pre-organisation energy required for binding of hydrophilic moieties in the calixarene cavities. The same can be said for sulfonated calix[5]arene, for which we have made some advances, but for the higher calixarenes non-cone conformations are the lowest minimum energy structures. Atwood *et al.* have pioneered the supramolecular chemistry of *p*-sulfonatocalix[4,5]arenes which often result in clay-like bilayer structures, Fig. 3, with an up–down arrangement of the calixarenes, which show a diverse range of inclusion properties encompassing ionic guests and molecules including amino acids,[14–19] and, remarkably, water in the hydrophobic cavity associated with $H_2O\cdots\pi$-aromatic hydrogen bonding.[20] In the presence of lanthanide ions and pyridine *N*-oxide an up–up arrangement of sulfonated calix[4]arenes results, affording an icosahedral sphere comprised of 12 calixarene units, or infinite chiral, helical nanotubes.[14] Sulfonated calixarenes are also of interest in the binding of guests in solution.[15,21] Many of the capsules encountered in our work are essentially inclusion complexes of inclusion complexes and are reminiscent of Russian Matryoshka dolls, and are rare examples of second sphere supramolecular complexation. Other examples are limited to a metal–cryptate–cavitand assembly[3] as well as second sphere cyclodextrin complexes.[22]

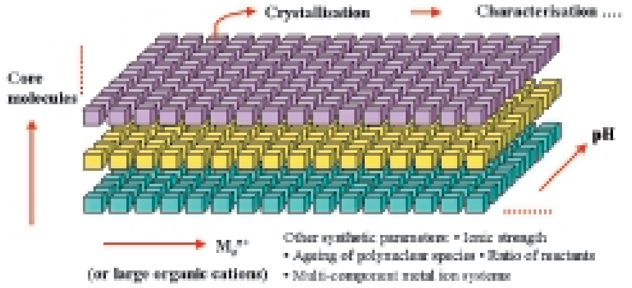


Fig. 2 Reaction optimisation in forming superanion capsules.

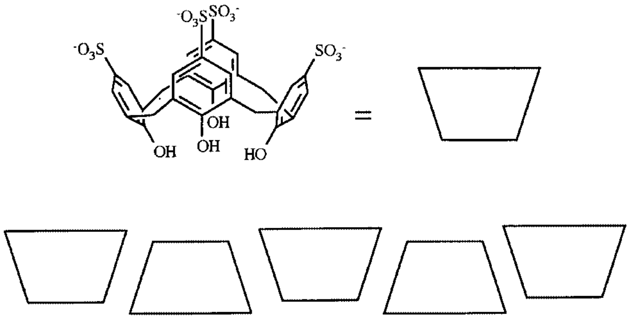
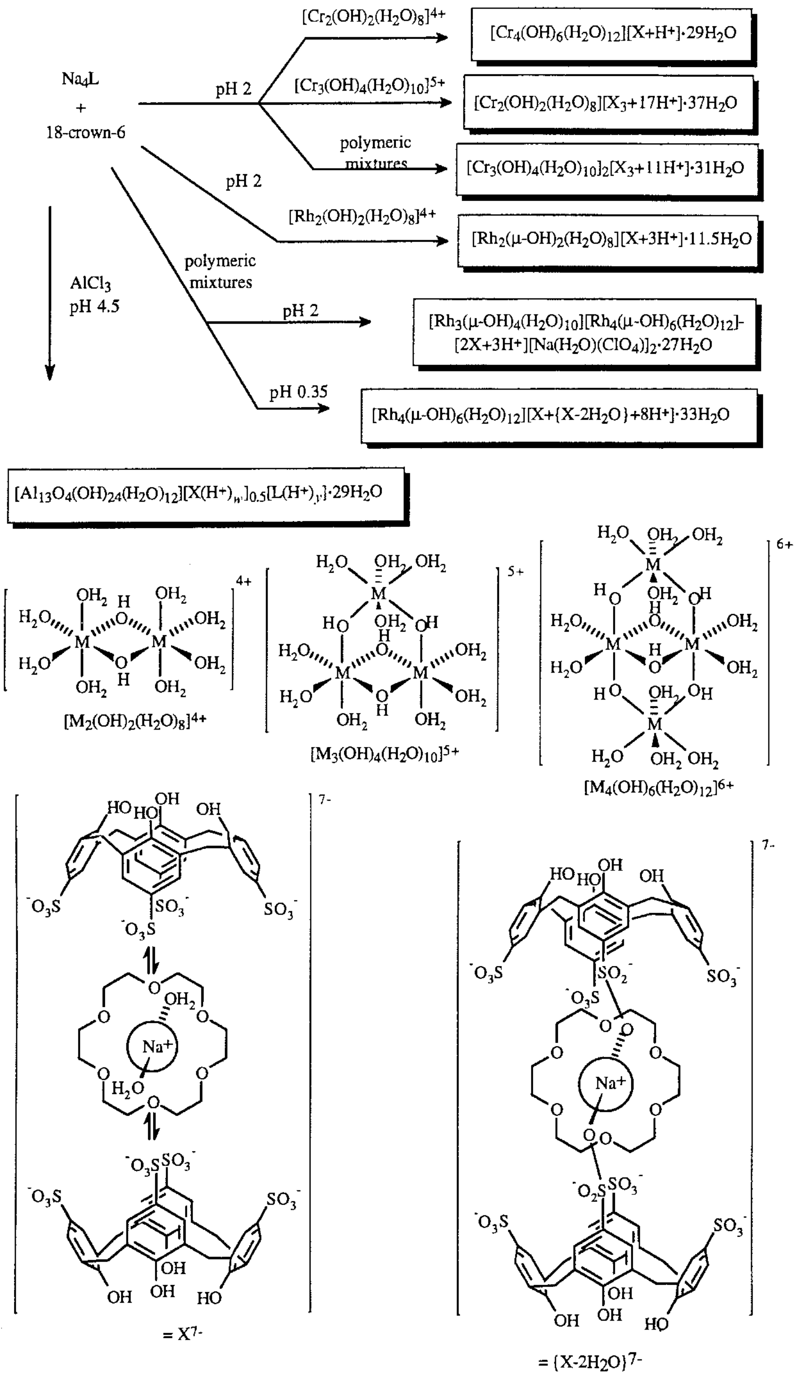


Fig. 3 Diagrammatic representation of the hydrophilic–hydrophobic bilayer structure often adopted by *p*-sulfonatocalix[4]arenes.[14–19]

2 Crystallisation of polynuclear metal(III) aqua ions

2.1 Chromium(III) ions

Solutions of non-labile polynuclear Cr^{3+} aqua ions are formed on the base hydrolysis of $[Cr(H_2O)_6]^{3+}$ followed by immediate



Scheme 1

quenching with perchloric acid.[23] The solutions contain $[Cr_2(OH)_2(H_2O)_8]^{4+}$, $[Cr_3(OH)_4(H_2O)_{10}]^{5+}$, $[Cr_4(OH)_6(H_2O)_{12}]^{6+}$ and higher oligomeric cations. The foregoing polynuclear cations are stable towards the formation of higher polynuclear species provided the pH of the solution is $\leqslant 3$.[23,24] Aqueous solutions of the tetrasodium salt of *p*-sulfonatocalix[4]arene and 18-crown-6 at *ca.* pH 2 with solutions of purified dinuclear and trinuclear Cr^{3+} species (perchlorate salts) afford the superanion complexes $[Cr_2(OH)_2(H_2O)_8][X_3 + 17H^+]$ and $[Cr_3(OH)_4(H_2O)_{10}]_2[X_3 + 11H^+]$, $X^{7-} = \{Na^+ \subset (18\text{-crown-6})(OH_2)_2\} \subset \{(p\text{-sulfonatocalix[4]arene}(4-))_2\}^{7-}$, Scheme 1.[25] Using a mixture of the polynuclear cations results in the crystallisation of the complex $[Cr_4(OH)_6(H_2O)_{12}][X + H^+]$ where the tetranuclear Cr^{3+} cation has been selectively retrieved from solution.[25] Prior to this finding, the only structurally authenticated polynuclear Cr^{3+} species was the dinuclear cation $[Cr_2(OH)_2(H_2O)_8]^{4+}$, as was the case for the analogous non-labile, dinuclear Rh^{3+} (see below)[26] and mixed Cr^{3+} and Rh^{3+} species.[27] These complexes are extensively hydrated and are typically formed in *ca.* 60% yield. The ratios of cations to anions in the solid for the di-, tri- and tetra-nuclear Cr^{3+} complexes are 2 : 3, 1 : 2 and 1 : 1 respectively and this is maintained even when varying the ratio of calixarene : crown ether and calixarene : polynuclear cation, despite the different charge and size of the cations and the different degree of protonation of the superanion, X^{7-}, required to balance charge. This highlights a remarkable property of the superanion, the ability to accommodate differently charged species by varying the degree of protonation of the sulfonate groups. In the case of the dinuclear and trinuclear cations this is achieved within the same packing array of the superanions (see below).

The superanions, $X^{7-} + nH^+$, are globular like structures with axial symmetry, approximately D_{2h}, comprised of a central sodium ion bound by a crown ether and two *trans*-water molecules, which snugly fits into two calixarenes, Fig. 4. The capsules are held together by a number of interactions, most

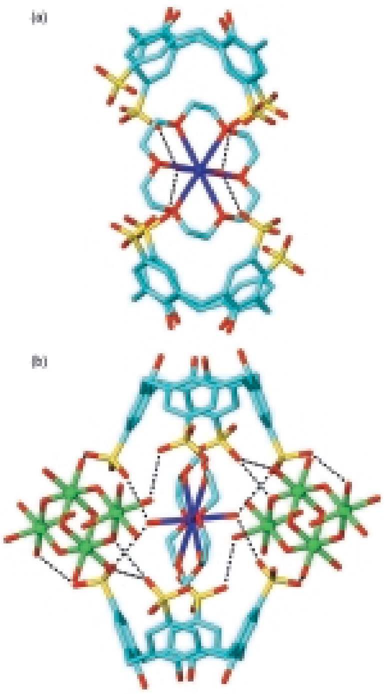


Fig. 4 (a) The superanion capsule X^{7-} + H, where $X = \{Na^+\subset(18\text{-crown-6})(OH_2)_2\}\subset\{(p\text{-sulfonatocalix[4]arene}(4-))_2\}$ taken from the crystal structure of $[Cr_4(OH)_6(H_2O)_{12}][X + H^+]$; (b) hydrogen bonding interactions (shown as dashed lines) between the superanion and $[Cr_4(OH)_6(H_2O)_{12}]$ tetramers.[25]

notably hydrogen bonding between the coordinated water ligands and sulfonate groups of the calixarenes. They have alternating hydrophilic and hydrophobic character in the direction of the principal axis, and this Jovian arrangement relates to how the anions pack in the solid state which appears to be driven by π stacking between aromatic rings of adjacent superanions. In the complex $[Cr_4(OH)_6(H_2O)_{12}][X + H^+]$ the cyclic Cr^{3+} tetranuclear cation sits at the periphery of the hydrophilic sulfonate equator of the superanion (Fig. 4), as would be expected on electrostatic considerations, with each cation forming hydrogen bonding interactions with two superanions. The cyclic structure of the cation is similar to that proposed on the basis of solution studies, however the proposed μ_3-OH[24] is not evident, although the crystallisation process may result in isomerisation of other tetranuclear species. In the structures containing the di- and tri-nuclear Cr^{3+} polynuclear cations the cations are severely disordered over several sites but nevertheless their connectivity was established with a high level of confidence. The calixarenes within $[Cr_4(OH)_6(H_2O)_{12}][X + H^+]$ form an up–down bilayer arrangement [25] similar to those found in previous studies of sulfonated calix[4]arenes (Fig. 3),[14–19] however with a slipped relative displacement between layers to create a capsule assembly. The trinuclear and dinuclear Cr^{3+} containing complexes (which are essentially isostructural) form a more irregular highly distorted bilayer arrangement with rotation of some of the calixarenes (Fig. 5) relative to those in Fig. 3.[25]

The polynuclear cations may be initially acting as a clamp for the two calixarenes of each superanion in building up the supramolecular array, and in this context we note that the Cr^{3+} polynuclear cations can irreversibly be leached out of the crystalline hydrated complexes of the di- and tri-nuclear cations on treatment with aqueous $HClO_4$, leaving a white crystalline powder. The same conditions for the complex of the tetranuclear species results in dissolution and solvation of the complex.[25] Mononuclear $[Cr(H_2O)_6]^{3+}$ forms a complex with the superanion at a lower pH of 1, presumably with a higher degree of protonation of the superanion capsule.[28] At higher pH the lower charge on the mononuclear cation (3+ *cf.* 4+, 5+ and 6+ for polynuclear species) is likely to be insufficient to compensate for the electrostatic repulsion between the calixarenes within the superanions.

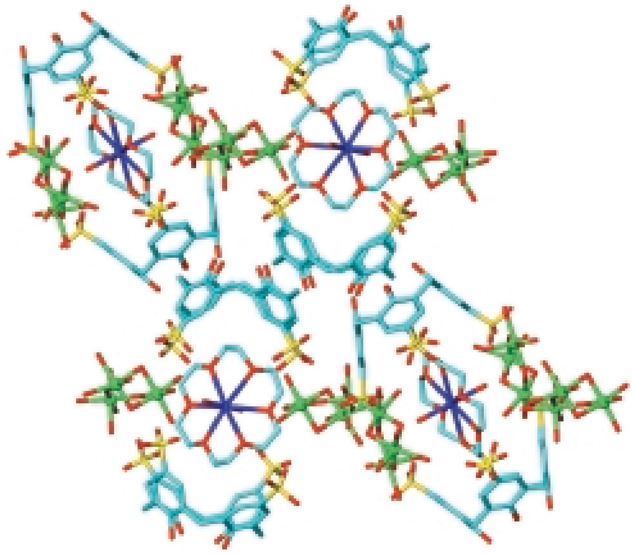
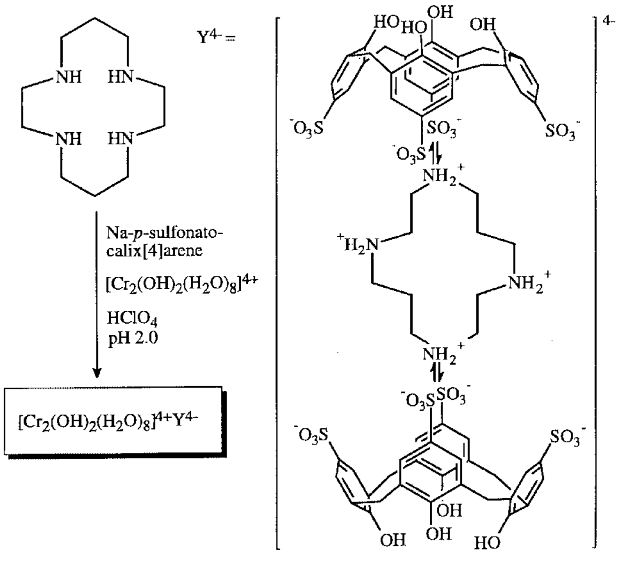


Fig. 5 Packing of superanions and partially occupied, disordered trimeric cations in $[Cr_3(OH)_4(H_2O)_{10}]_2[X_3 + 11H^+]$, showing the distorted bilayer arrangement of the calixarenes.[25]

The tetraprotonated form of cyclam (= 1,4,8,11-tetraazacyclotetradecane), $[H_4(cyclam)]^{4+}$, Fig. 1, adopts an *exodentate* conformation[29] which, like 18-crown-6, has complementarity of size and curvature with that of the cavity of *p*-sulfonatocalix[4]arene, along with hydrogen bonding possibilities. At pH 2 these components assemble with the dinuclear Cr^{3+} aqua ion, crystallising as $[Cr_2(OH)_2(H_2O)_8]^{4+}[H_4(cyclam)]^{4+}\subset\{(p\text{-sulfonatocalix[4]arene}(4-))_2\}]^{4-}$ as the hexahydrate, Scheme 2.[30] The new ionic capsule has a central tetraprotonated cyclam shrouded by two *p*-sulfonatocalix[4]arenes associated through numerous hydrogen bonding interactions as well as electrostatics. The extra charge on the core relative to the superanions containing a crown ether, with or without a metal ion (see below), reduces the need for protonation of the sulfonate groups to overcome the electrostatic repulsion between the calixarenes. Indeed the charge on the Cr^{3+} counter cation, 4+, is the opposite to that of the capsule assembly, 4−, without any protonation. Thus the ratio of *exo*-capsule cations to capsules is 1 : 1 which contrasts with 2 : 3 for the crown ether analogue (see



Scheme 2

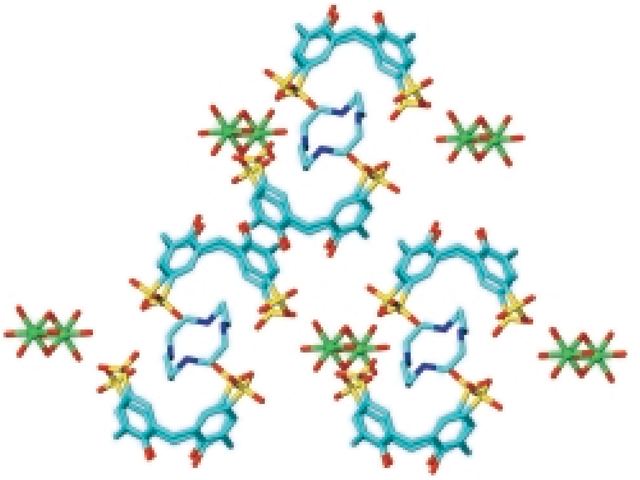


Fig. 6 Crystal structure of $[Cr_2(OH)_2(H_2O)_8][H_4(cyclam)]\subset\{(p$-sulfonatocalix[4]arene$(4-))_2\}]\cdot 6H_2O$ (waters and hydrogens omitted for clarity) showing packing of superanion capsules with a bilayer arrangement of calixarenes and $[Cr_2(OH)_2(H_2O)_8]^{4+}$ cations situated at the hydrophilic equator of the capsules.[30]

above). Nevertheless the dinuclear Rh^{3+} cation forms a 1 : 1 complex with the X^{7-} (see below).[31]

The cyclam containing capsule is not as symmetrical as those containing the crown ether, Fig. 6,[30] with the two calixarene bowls offset relative to each other, which maximises hydrogen bonding interactions between the components. The overall lattice has the up–down bilayer structure often encountered in sulfonated calix[4]arene structures.[14–19] The dinuclear chromium cations are well defined and fully ordered unlike in the above crown ether capsule example, and are located at the hydrophilic equator of the superanions, Fig. 6. We note that the same tetraprotonated form of cyclam has been used as a template in crystal engineering studies, as has the *endodentate* diprotonated form, which forms polymeric arrays with a variety of anions.[29,32]

2.2 Rhodium(III) ions

The Russian doll superanion approach to crystallising large cations has also been rewarding in identifying new polynuclear rhodium(III) aqua cations, notably $[Rh_3(\mu\text{-}OH)_4(H_2O)_{10}]^{5+}$ and $[Rh_4(\mu\text{-}OH)_6(H_2O)_{12}]^{6+}$,[31] as well as crystallising the previously reported dinuclear cation $[Rh_2(\mu\text{-}OH)_2(H_2O)_8]^{4+}$.[26,31,33] Solutions of pure dinuclear rhodium(III) cation $[Rh_2(\mu\text{-}OH)_2(H_2O)_8]^{4+}$ with crown ether and sulfonated calixarene at low pH give a 1 : 1 ratio of the rhodium(III) cation to capsule, with composition $[Rh_2(\mu\text{-}OH)_2(H_2O)_8][X + 3H^+]\cdot 11.5H_2O$ Scheme 1.[31] The 1 : 1 ratio of cation to capsule is surprisingly different to that of the Cr^{3+} crown ether analogue, but the same as that of the cyclam containing capsule, despite the smaller charge of the core moiety in this case. Three of the total of eight sulfonate groups of the superanion capsule are required to be protonated to achieve overall charge balance. The overall structure takes on the familiar up–down bilayer arrangement of calixarenes, Fig. 3.[31] The structure of $[Rh_2(\mu\text{-}OH)_2(H_2O)_8][X + 3H^+]\cdot 11.5H_2O$ is not isostructural with, or extensively disordered as in, the chromium(III) analogue,[25] where the cations are disordered over several sites within the unit cell (see above). These differences may relate to the larger size of the cation in the present case and/or different polarisation effects.

Complex mixtures of polynuclear Rh^{3+} aqua ions in perchloric acid, formed by treating aqueous Rh^{3+} solutions with sodium hydroxide at pH 13 then acidifying with perchloric acid, contain mononuclear, dinuclear, trinuclear and higher oligomer cations.[26,34] Remarkably, on the addition of sodium *p*-sulfonatocalix[4]arene and 18-crown-6 at pH 2, selective retrieval of the tri- and tetra-nuclear Rh^{3+} species in a single 1 : 1 co-crystallised phase results. This is a hydrate salt with overall composition $[Rh_3(\mu\text{-}OH)_4(H_2O)_{10}][Rh_4(\mu\text{-}OH)_6(H_2O)_{12}][2X + 3H^+][Na(H_2O)(ClO_4)]_2\cdot 27H_2O$.[31] The tri- and tetra-nuclear Rh^{3+} cations both have a cyclic structure with μ-hydroxide and terminal water ligands, Scheme 1. This complex has an additional coordination of an *exo*-capsule Na^+ by the calixarenes, but despite this the overall arrangement of superanions is in the up–down bilayer structure. The ability to co-crystallise two large polynuclear aqua cations, $[Rh_3(\mu\text{-}OH)_4(H_2O)_{10}]^{5+}$ and $[Rh_4(\mu\text{-}OH)_6(H_2O)_{12}]^{6+}$, in the same solid is without precedent. Moreover, of these two cations, only the trinuclear one has been studied with its existence in solution postulated on the basis of NMR experiments,[34] and there is considerable uncertainty in the nature of higher nuclearity species. At pH 0.35 an otherwise identical reaction mixture leads to the selective retrieval of the tetranuclear Rh^{3+} cation in the complex $[Rh_4(\mu\text{-}OH)_6(H_2O)_{12}][X + \{X - 2H_2O\} + 8H^+]\cdot 33H_2O$. The richness of the chemistry in this area manifests itself now in the presence of two types of capsule which reflects further the versatility of the parent superanion X^{7-} which is present in the structure along with its dehydrated form where the two sodium bound water molecules have been replaced by oxygen centres of calixarene sulfonate groups, Scheme 1. This structure takes on a distorted up–down bilayer structure, Fig. 7, presumably because of the less symmetrical shape of the superanion devoid of the *trans*-water molecules around the central sodium ion.[31] The Na–OS distance of 2.319(9) Å requires that one sulfonate group from each of the calixarene subunits is pulled in towards the Na^+ perturbing the usual head-to-head arrangement of calixarenes, leaving the superanion open at each side, Fig. 7.

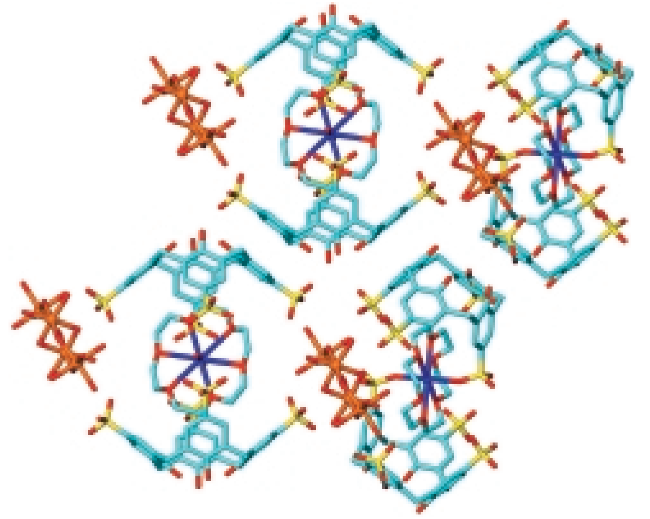


Fig. 7 Crystal packing of $[Rh_4(\mu\text{-}OH)_6(H_2O)_{12}][X + \{X - 2H_2O\} + 8H^+]\cdot 33H_2O$ (waters and hydrogens omitted). The two types of superanion X^{7-} and the dehydrated $\{X - 2H_2O\}^{7-}$ are shown and it is evident that the SO–Na–OS bonding of $\{X - 2H_2O\}^{7-}$ skews the structure from the usual head-to-head arrangement of calixarenes.[31]

Despite a static disorder of trinuclear species $[Rh_3(\mu\text{-}OH)_4(H_2O)_{10}]^{5+}$ over an inversion centre the atom connectivity is well defined,[31] and the μ-OH bridged cyclic structure is isostructural with that of the Cr^{3+} analogue,[25] but this is at odds with the assigned linear structure based on ^{103}Rh NMR studies. However, the NMR data showing two resonances in a 1 : 2 ratio are consistent with the triangular structure.[34] The structure of the tetranuclear $[Rh_4(\mu\text{-}OH)_6(H_2O)_{12}]^{6+}$ cation is the same in both structures,[31] and isostructural with the Cr^{3+} analogue (above).[25] Interestingly the structure of the superanion X^{7-} in the mixed Rh^{3+} cation complex is slightly different to that of other systems,[25,35] with the central Na^+ coordinating to only five of the six crown ether oxygens at Na–O distances from 2.55(1) to 2.740(9) Å as well as two *trans* water molecules.[31]

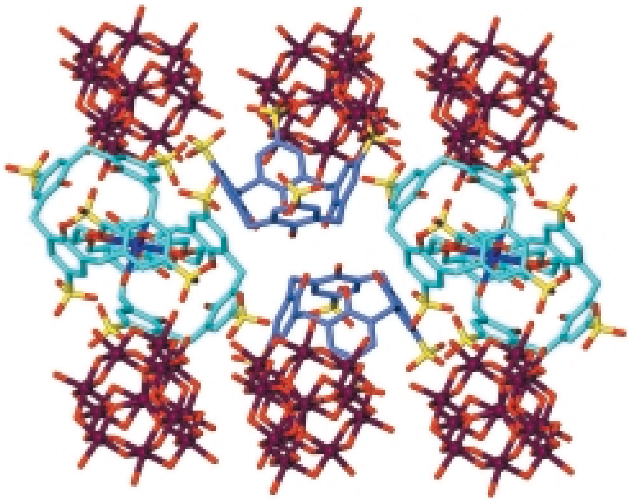


Fig. 8 Packing of the major structural components in $[Al_{13}O_4(OH)_{24}(H_2O)_{12}]\{X + (H)_w\}_{0.5}\{(p\text{-sulfonatocalix[4]arene}(4-))(H^+)_y\}(H_2O)_{29}$ (water molecules and hydrogens are not shown for clarity). Chains of Keggin ions (in red) are shown running across the page, chains of superanions come out of the page. Water bearing calixarenes not involved in capsule formation are highlighted in darker blue.[35]

The complex $[Rh_4(\mu\text{-}OH)_6(H_2O)_{12}][X + \{X - 2H_2O\} + 8H^+]\cdot 33H_2O$ has a 1 : 1 : 1 ratio of tetranuclear cation, superanion X^{7-} and dehydrated superanion $\{X - 2H_2O\}^{7-}$ as well as 33 solvent water molecules in the unit cell, and requires a total of eight sulfonate groups to be protonated for charge balance. The higher ratio of capsules to cations in this structure relative to that of the above structures is consistent with complex formation from a more acidic solution, pH 0.35. Each tetranuclear cation forms hydrogen bonding interactions to the sulfonate groups of four superanions; two X^{7-} capsules positioned opposite each other across the cation, and two $\{X - 2H_2O\}^{7-}$ superanions, at O···O separations of 2.61 to 2.79 Å. Each superanion, whether X^{7-} or $\{X - 2H_2O\}^{7-}$, hydrogen bonds to two tetranuclear cations, extending into a two dimensional rectangular grid array. The nature of the species present in solution for Rh^{3+} polynuclear species interacting with crown ether and sulfonated calixarene is yet to be realised, and indeed has proved a difficult task for all such systems to date.

2.3 Aluminium(III) Keggin ion

In extending this work to larger cations, the labile main group Keggin ion $[Al_{13}O_4(OH)_{24}(H_2O)_{12}]^{7+}$ was targeted, and it can selectively be precipitated in the presence of the crown ether and sulfonated calixarene.[35] This ion has been the subject of numerous ^{27}Al NMR studies[36–40] and a preliminary crystal structure determination of the sulfate or selenate salts.[41] It crystallises within the complex $[Al_{13}O_4(OH)_{24}(H_2O)_{12}]\{Na(18\text{-crown-}6)(OH_2)_2(p\text{-sulfonatocalix[4]arene})_2(H^+)_w\}_{0.5}{}^{x-}\{(p\text{-sulfonatocalix[4]arene}(4-))(H^+)_y\}^{x-}(H_2O)_{29}$, from aqueous solutions of $AlCl_3$ treated with NaOH to pH 4.5 where there are significant quantities of $[Al(H_2O)_6]^{3+}$ and $[Al_{13}O_4(OH)_{24}(H_2O)_{12}]^{7+}$ and minor amounts of higher oligomers, the quantities of which vary with aging time,[36] then the addition of the crown ether and sodium salt of the sulfonated calix[4]arene, Scheme 1.[35]

The crystal structure of this complex features three distinct elements; the cationic Keggin ion $[Al_{13}O_4(OH)_{24}(H_2O)_{12}]^{7+}$, a water bearing calixarene and a superanion capsule $\{X(H^+)_w\}^{x-}$, along with numerous water molecules, Fig. 8. One sulfonate group of each of the calixarenes of the ionic capsule or one sulfonate group of the other calixarene is required to be protonated to achieve overall charge balance. The structure is held together by a complicated array of hydrogen bonds complemented by additional supramolecular interactions such as π stacking and electrostatics.

The superanion capsule is similar to those found in the Cr^{3+} and one of the Rh^{3+} complexes, with a bi-capped hexagonal central sodium ion core bound by 18-crown-6 and two *trans*-water molecules. The superanions run in chains and the overall arrangement is distinctly different to the above structures, with no resemblance of the up–down bilayer structure because of the incorporation of an additional calixarene in the lattice (Fig. 8).

The aluminium(III) Keggin ion is an Al_{13} cluster made up of discrete aluminium–oxygen groups where twelve AlO_6 octahedra are joined together by means of common edges and the central tetrahedron of oxygen atoms contains the 4-coordinate aluminium atom, AlO_4. The Keggin ions run in hydrogen bonded chains perpendicular to the hydrogen bonded chains of superanions with hydrogen bonded inter-Keggin contacts (O···O 2.70 to 2.85 Å). The Keggin ion to superanion ratio is 2 : 1, with the Keggin ions positioned at both the periphery of the hydrophilic sulfonate equator of the globular superanion, and at the outer edges of the sulfonates, thus overcoming electrostatic repulsion between the calixarene. The presence of both the superanion and a calixarene in the solid state structure implies that a delicately balanced equilibrium between the superanion and water containing calixarene may exist in solution, as shown in Scheme 1.

The additional calixarene that is not part of a capsule has water in the cavity with the closest interactions consistent with O–H···π hydrogen bonding, with closest contacts to opposite aromatic rings within the calixarene. This imbedded water molecule shows additional hydrogen bonding interactions to two other water molecules. The calixarene–water complex species is similar to that reported in sodium(calix[4]arene sulfonate)–water (4/1/13.5)[20] with aromatic π hydrogen bonding to a water molecule in the cavity which also hydrogen bonds to two additional water molecules.

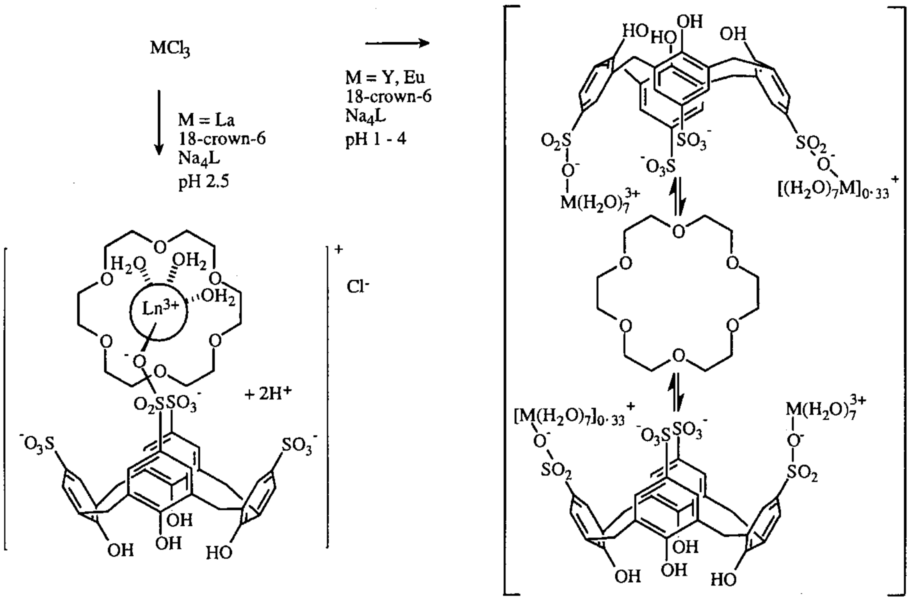
3 Lanthanide(III) systems

3.1 Capsule structural types

Replacing polynuclear cations by lanthanides or rare earths in combinatorial experiments leads to several types of self assembly structures, Scheme 3.[42–44] One of these is a new type of capsule, another is a ferris wheel cation with just one calixarene associated with each crown ether (see below), or a combination of both structural types, depending on the relative sizes of the lanthanides. The chemistry is also distinctly different in that the lanthanides are directly bound *via* oxygen coordination to one or two sulfonate groups of the calixarenes. The new type of capsule is found in the complexes, $[\{18\text{-crown-}6\}\subset\{(M(H_2O)_7{}^{3+})_{1.33}(p\text{-sulfonatocalix[4]arene}(4-))\}_2]$, M = Y^{3+} or Eu^{3+}.[42] These complexes crystallise from an aqueous solution of sodium *p*-sulfonatocalix[4]arene, 18-crown-6, yttrium(III) or europium(III) chloride, and hydrochloric acid as the tetrahydrate at a pH between 1.0 and 4.0, with no solid complex formation outside of this pH regime.

In these structures the rare earth cations coordinate to the 1,3-sulfonate groups of the calixarene with two calixarene subunits encapsulating an 18-crown-6 molecule. Surprisingly the 18-crown-6 is devoid of Na^+, unlike in several of the above capsules, and also devoid of Y^{3+} or Eu^{3+}, but it is noteworthy that these smaller lanthanide ions are not well suited to interact with this crown ether.[45] For larger lanthanides, seemingly the perched 'ferris wheel' structure $[\{La^{3+}\subset(18\text{-crown-}6)(OH_2)_3\}\cap\{(p\text{-sulfonatocalix[4]arene}(4-) + 2H^+)\}]^{+}$[43] is favoured (see below).

In the Y^{3+}/Eu^{3+} capsule structures an up–down bilayer arrangement of calixarenes is formed where there are two types of lanthanide metal centre, Fig. 9.[43] Both coordinate to seven water molecules and one sulfonato group of the calixarene which are involved in RSO–Y–HOH···OSR hydrogen bonding leading to the dimerisation of calixarene sub-units in two



Scheme 3

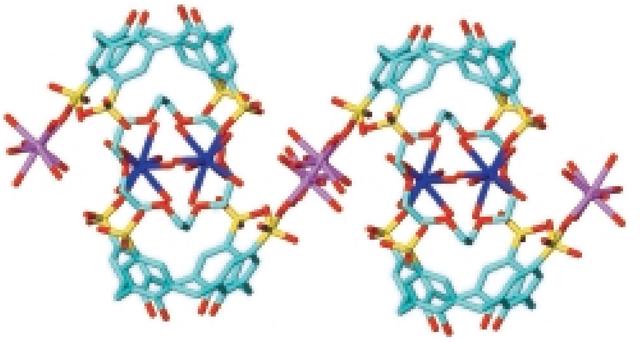
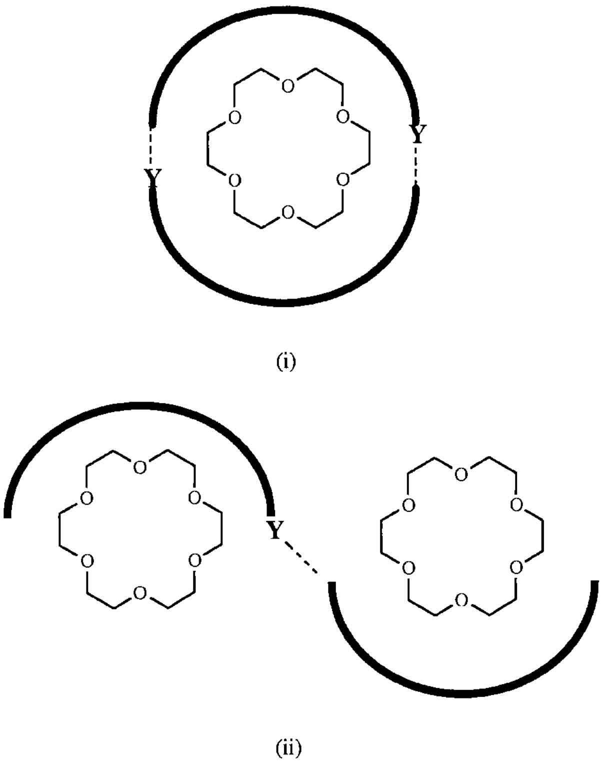


Fig. 9 Capsule formation in the complex [{18-crown-6}⊂{(Y(H$_2$O)$_7$)$_{1.33}$(*p*-sulfonatocalix[4]arene(4−))}$_2$] (from the crystal structure). There are two types of [Y(H$_2$O)$_7$]$^{3+}$ moiety, one with the Y shown in dark blue is fully ordered and positioned towards the centre of the capsule, the other, with the Y centre in pink, is disordered with a 1/3 occupancy and points away from the capsule core. Eu^{3+} forms an isostructural complex.[42]



(i)

(ii)

Fig. 10 Schematic representation of the hydrogen bonding modes of the capsules found in the complex [{18-crown-6}⊂{(M(H$_2$O)$_7$)$_{1.33}$-(*p*-sulfonatocalix[4]arene(4−))}$_2$], M = Y or Eu (see Fig. 9): (i) the intracapsule Y–OH$_2$ ··· O–S hydrogen bonding of the fully occupied M positions, (ii) the intercapsule S-type Y–OH$_2$ ··· O–S hydrogen bonding of the partially occupied M positions.

distinct modes, shown schematically in Fig. 10. One of these modes involves a head-to-head dimerisation of the calixarenes to form a capsule. The other mode forms an S-type motif and involves the partially occupied M(H$_2$O)$_7$ disordered over two adjacent sites with 1/3 occupancy each. The crown ether core molecule is involved in hydrogen bonding and presumably this results in a significant distortion from its usual 'crown' shape due to *exo*-crown ether cavity hydrogen bonding.

In the absence of crown ether, Ln^{3+} (Ln = Yb or Eu) can form complexes with *p*-sulfonatocalix[4]arene with the metal centre also bound to one sulfonato group. Some of these form slipped capsules with water or other solvent molecules in the cavities of the calixarenes,[44] but for others, different structural types are formed,[46] including nanotubes and vesicles in the presence of pyridine *N*-oxide.[14]

3.2 Ferris wheel structural types

For the larger La^{3+} ion a cationic supermolecule results, [{La^{3+}⊂(18-crown-6)(OH$_2$)$_3$}⊂{(*p*-sulfonatocalix[4]arene(4−) + 2H$^+$)}]$^+$, which is isolated over a narrow pH regime 2.5–3.0, as a chloride salt, Scheme 3.[43] The lanthanum is ten-coordinate with the crown ether, the calixarene (*via* one sulfonate group) and three water molecules acting as ligands. The three water molecules are *trans* to the sulfonate group. The crown ether resides in the cavity of the calixarene as a perched structure akin to a 'ferris wheel' with the axis about the La–OS bond, Fig. 11.[43] A similar structure results from a solution prepared using lanthanum tris(trifluoromethanesulfonate) nonahydrate rather than a chloride, at pH 2.5.[43]

This ferris wheel assembly has a single positive charge and hence two of the sulfonate groups are protonated. Formation of the capsule X^{7-} and its partially protonated forms are precluded in this system by (i) the lanthanum ions effectively competing with sodium to form the central cationic core, demanding a different coordination environment, and/or (ii) the trivalent positive charge of the metal ion being insufficient to overcome the electrostatic repulsion between two calixarenes in any ionic capsule (at least for the pH of the solutions where crystallisation occurs). It is noteworthy that this structure like the Keggin ion structure does not conform to an up–down bilayer array of the calixarenes. Interestingly the intermediate sized lanthanide cerium forms a complex comprised of (a) a capsule which is of different type again with a cerium in the crown ether and attached to two sulfonate groups, one from each of the calixarenes, (b) a 'ferris wheel' type structure, and (c) two other cerium centres. This result suggests that other structures are likely, which may depend on subtle changes in the size of the lanthanide ion, and this has implications in using superanion chemistry in separating the lanthanide cations.

4 Other related systems

The concept of preparing superanions with *exo*-cavity organic cations, too large to be incorporated in the capsule, has been realised with the synthesis of $[H_4TMTAA]_2[X + 3H^+]$, Scheme 4, Fig. 12.[47] Taking the same organic cation, and replacing the crown ether with 2-hydroxybenzimidazole, gives a capsule with the same *exo*-cations but with two π-stacked benzimidazolium cations which are hydrogen bonded to the calixarenes. From here the formations of analogous capsules with biologically important molecules such as histidine and tyrosine is a possibility. In this context we note that Coleman and co-workers have recently reported the structure of L-lysine with sulfonated calix[4]arene which has an up–down bilayer structure.[15]

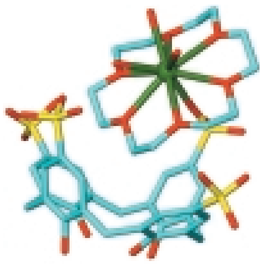


Fig. 11 The 'ferris wheel' assembly $[\{La\subset(18\text{-crown-}6)(OH_2)_3\}\cap\{(p\text{-sulfonatocalix[4]arene}(4-) + 2H^+)\}]^+$; hydrated crystals are isolated as the chloride salt.[43]

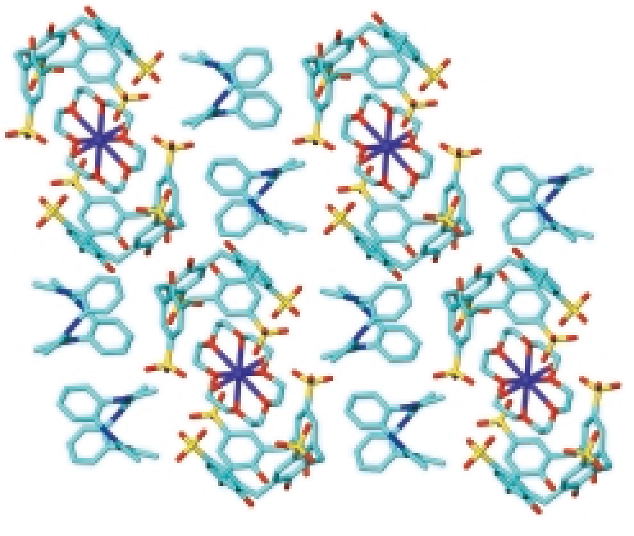


Fig. 12 Superanion capsule with *exo*-cavity organic cation. The crystal structure of $[H_4TMTAA]_2[X + 3H^+]\cdot xH_2O$ (see text). Solvent water has been omitted for clarity.[47]

We plan to develop analogous superanion capsule chemistry for sulfonated calix[5]arene which also favours a cone conformation, and the ensuing capsules will have considerably greater internal volumes for binding larger molecules. Interestingly we have found that a molecular capsule comprised of two calix[5]arene sulfonic acid molecules encapsulating two sulfuric acid molecules as a hitherto unknown hydrogen bonded dimer crystallises from sulfuric acid.[48] The supermolecule here is $[(H_2SO_4)_2\subset(\text{calix[5]arenesulfonic acid})_2]$, Fig. 13.[48] The structure is notably different from that of the corresponding Na^+ salt where the calixarenes do not form molecular capsules.[49,50] This is in direct contrast to the only other structurally authenticated calixarene sulfonic acid, calix[6]arene sulfonic acid–water (1/23), which is isostructural with its corresponding Na^+ salt and has the calix[6]arene in a double partial cone conformation effectively excluding the possibility of capsule formation.[51] It is likely that the larger calix[5]arene has greater flexibility, being able to form a flattened, slipped structure, or an expanded structure able to encapsulate larger molecules, beyond the crown ether in the above calix[4]arene studies.[25,31,35] This may include C_{60} noting that two linked calix[5]arenes can encapsulate the fullerene,[52] and there is therefore the possibility of water solubilisation of the fullerene at least at low pH to overcome any electrostatic repulsion between ionised calixarene sulfonic acid molecules in the capsule.

5 Future prospects

The self assembly of superanion capsules, and also the ferris wheel cation for some of the lanthanides, relies on the formation of a large number of supramolecular interactions which interplay in concert. The lead compounds authenticated thus far show a remarkably diverse range of structural types possible using simple synthons, water as a benign solvent, and rapid, high throughput reaction optimisation techniques. New directions include (a) the confinement of other cations in the core of the superanion assembly, (b) the binding of organic molecules in the core, which will encompass biologically important molecules, (c) the binding and stabilisation of large, highly charged *exo*-capsule cations in general, (d) the formation of ionic capsules based on >2 calixarenes shrouding large cations,

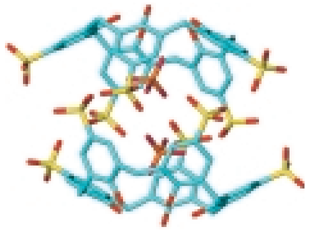
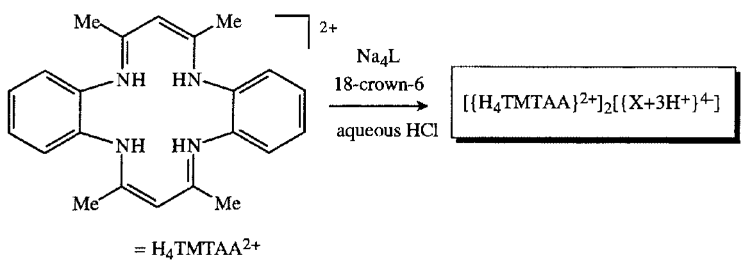


Fig. 13 The flattened capsule structure of $[(H_2SO_4)_2\subset(\text{calix[5]arene sulfonic acid})_2]$. The encapsulated sulfuric acid dimer is highlighted in orange/dark red.[48]



Scheme 4

an objective achieved by MacGillivray and Atwood for a neutral resorcinarene,[4] and (e) constructing mesoporous materials and template imprinting associated with leaching of *exo*-cavity components from the supramolecular structures.

The crystallisation of polynuclear aqua ions alone has been a challenging problem. The superanion approach is a new general method for the structural characterisation of polynuclear metal ions present in aqueous systems. The crystallisation process may, however, perturb the structure present in solution, and clearly a challenge is to establish the nexus between species present in solution and the solid state, and the hierarchy of the interacting components prior to crystallisation. Understanding the hydrolytic polymerisation reactions of metal ions in solution is of fundamental importance and such reactions occur widely in biological systems, industrial processes and natural waters. One of the earlier supramolecular methods of crystallising polynuclear cations involved the use of aromatic sulfonates as counter ions. This relies on the formation of layers of aqua cations and water molecules stabilised in a hydrogen bonded network by layers of sulfonate anions, and more recently by the inclusion of crown ether molecules in this network.[53,54] However, this approach has had limited success for some oxo- and hydroxo-bridged binuclear aqua ions including $[Cr_2(\mu\text{-}OH)_2(H_2O)_8]^{4+}$,[53,54] $[Rh_2(\mu\text{-}OH)_2(H_2O)_8]^{4+}$,[26] $[CrRh(\mu\text{-}OH)_2(H_2O)_8]^{4+}$,[27] and a molybdenum(IV) trinuclear species.[55]

Incorporating crown ether or its metal complexes or tetraprotonated cyclam in the core of the capsules allows access to capsules of different charge for particular pH regimes. The ambivalent nature of the capsule X^{7-} *versus* $\{X - 2H_2O\}^{7-}$ also highlights the complexity in studying these systems, introducing another structural assembly parameter. The lanthanide chemistry is complex and the binding of the metal centres to sulfonate groups also introduces another assembly process, beyond those for the transition metal complexes to date.

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