Sulfate anion templation of macrocycles, capsules, interpenetrated and interlocked structures

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Dedicated to Professor Jean-Pierre Sauvage on the occasion of his 65ᵗʰ birthday.

This review examines the potential of anions, in particular sulfate, to template the formation of complex molecular architectures. Until recently, sulfate has been largely overlooked in this area
10 and the examples described herein demonstrate this anion's versatility in templating the formation of a diverse range of molecular systems including macrocycles, helixes, molecular capsules, interpenetrated and interlocked assemblies such as catenanes. In addition sulfate has been shown to template the formation of interpenetrated structures on a range of solid surfaces including gold, polystyrene beads and silicate nanoparticles, highlighting the potential of this anion in the
15 fabrication of functional sensory devices exhibiting highly selective binding behaviour.

1. Introduction

The concept of using chemical templation to direct the final *shape* or pattern of a given product was pioneered by the work of Busch in the 1960's.[1] Busch defined a chemical template as
20 a species that "organises an assembly of atoms, with respect to one or more geometric loci, in order to achieve a particular linking of atoms".[2] As opposed to a reagent, a template affects only the macroscopic geometry and does not alter the intrinsic chemistry of a system.

25 Metal cations are the dominant inorganic templating agents that have been utilised to increase the yields in macrocycle synthesis. Pioneering work by the groups of Busch, Curtis and Nelson in the 1960s and 70s demonstrated clearly how transition metal ions could be effective in templating the
30 synthesis of a variety of macrocycles (Fig 1.).[1, 3] Alkali metal cations were also shown to template the synthesis of crown ethers as reported by Pedersen in the 1960s.[4]

More recently, by using imaginatively designed polydentate ligands, metal ions (especially transition metal cations) have
35 been employed in the metal-directed assembly of a variety of polymetallic architectures including helicates, cages, lattices, grids, and importantly for the focus of this review, interlocked structures such as rotaxanes and catenanes.[5] Such mechanically bonded systems have captured chemists'
40 imagination due to their unique dynamic behaviour and non-trivial topology. Intense recent research has focussed on the use of external stimuli to control their dynamics and so allow the incorporation of rotaxanes and catenanes into molecular switches and machines, the putative building blocks of
45 nanotechnology.[6] However in spite of this the potential of these interlocked molecules in molecular recognition and sensing has been largely overlooked.[7]

Prior to the concepts of molecular templation and self-assembly, early attempts to synthesise interlocked molecules
50 such as catenanes and rotaxanes were based on a statistical

approach. As such yields of catenanes or rotaxanes using this methodology were very low (<1% in Wasserman's catenane and 6% in Harrison's rotaxane synthesised in higher yields due to repetitive threading and capping processes).[8]

55 **Fig 1.** Busch's seminal example of using nickel (II) cation templation to increase the yields of macrocycles (*A*); and Nelson and co-workers demonstration of the effects the size of the metal cation template has on the final molecular architecture of the macrocyclic product (*B*).

60 One of the most important advances in the synthesis of such intermolecular architectures was Sauvage's use of metal cations to template the formation of a [2]catenane (Scheme 1). Sauvage and co-workers demonstrated that two phenanthroline ligands coordinate to a tetrahedral Cu(I)
65 template in an orthogonal manner. Subsequent simultaneous macrocyclisation of both phenanthroline ligands with polyether chains afforded the first metal cation templated [2]catenane in 27% yield.

70 **Scheme 1.** Sauvage's Cu(I) templated [2]catenane.

Tetrahedral, octahedral, square planar, and linear transition metal stereochemical preferences have all been exploited to assemble interlocked systems.[9] Leigh *et al.* have used metal cation templation between nickel(II), copper(II) or
75 palladium(II) metal ions coordinating an amide macrocycle and a pyridine based thread to template rotaxane formation in high yields. More recently they reported the first example of a two-coordinate gold(I) cation to template the formation of rotaxanes incorporating both a monodentate pyridine
80 macrocycle and a pyridine thread (Fig 2).[10]

Fig 2. Leigh's two-coordinate gold templated rotaxane.

Transition metal cations have also been utilised as interweaving templates in the synthesis of molecular knots.

Sauvage and co-workers demonstrated that their initial studies into the use of copper to template the formation of catenanes could be extended to the synthesis of a Cu (I) templated trefoil knot whereby two copper (I) centres and four phenanthroline ligands are incorporated in the final structure.[11] Another elegant example of the synthesis of molecular knots via metal templation is the construction of a Borromean ring systems by Stoddart *et. al.*. They have exploited the five coordinate geometry of zinc(II) metal cations to template the formation three interwoven macrocycles comprising of he coordination of six endo-diiminopyridyl and six exo-bidentate bipyridyl ligands to the six zinc(II) ions (Fig. 3).[12]

Fig 3. X-ray crystal structures of Sauvage's Cu(I) template trefoil knot *(top)*, and Stoddart's Zn(II) templated Borromean ring system *(bottom)*.

Inspite of the many varied examples of using metal cations to template the formation of elaborate molecular architectures, the area of anion templation is underexploited. This is surprising given the importance of anions in a range of biological, environmental and chemical applications.[13] Anions do however present certain challenges in designing effective receptors due to their low charge-density (as compared to their isoelectronic cationic counterparts), pH dependence, high solvation energies and lack of transition metal ligand field effects.

Many of the early examples of anion templation are serendipitous in nature,[14] whereas the strategic use of anion templation is rare. One of the first examples of the deliberate use of anions for templation purposes was reported by Sessler and co workers in 1992.[15] They showed that the Schiff base condensation reaction between 3,4-diethylpyrrole-2,5-dicarbaldehyde and 4,5-diamino-1,2-dimethoxybenzene afforded macrocycle **1** in quantitative yields when nitric acid was used as the reaction catalyst (Scheme 2). However when HCl was used to catalyse the reaction no macrocycle formed, suggesting that the nitrate anion played a crucial templating role.

Scheme 2. Sessler's nitrate templated pyrrolic macrocycle.

Böhmer and co workers have also used inorganic anions in the templated synthesis of cyclic hexaurea macrocycles (Scheme 3).[16] In the absence of any anionic template, reaction of diamine **2** with the diisocyanate **3** affords predominately the cyclic triurea **4**. However in the presence of chloride the larger [2+2] macrocycle is the major product. X-ray crystallography and ^{1}H NMR revealed that two-chloride ions are simultaneously bound within the hexaurea macrocycle.

Scheme 3. Böhmer and co-workers hexaurea macrocycle templated by two chloride anions

Pioneering work by Luis *et. al.* investigated the use of organic anions, specifically the terephthalate dianion, to template the formation of macrocyclic peptide structures.[17] Reductive amination of the bis-amidoamide **6** with the dialdehyde **7** only resulted in the formation of the [2+2] macrocycle in the presence of one equivalent of the terephthalate dianion (Scheme 4). Inorganic anions such as chloride proved unsuitable in the templation of such macrocycles.

Scheme 4. The terephthalate dianion templated synthesis of Luis *et. al.*'s [2+2] macrocycle.

Amongst the recent examples of programmed anion templation the sulfate anion is only now beginning to be exploited. This is surprising as sulfate has the capability of acting as a potent template not only due to its dinegative charge but also because of its orthogonal tetrahedral coordination preference. Furthermore sulfate has many important biological and environmental applications. [18, 19] For example sulfate is a known contaminant in nuclear waste and drinking water, and thus the design of efficient sulfate selective receptors to aid in the removal of sulfate pollutants is of great interest. The remainder of this review focuses on highlighting the use of sulfate in the templation of macrocycles, capsules, interpenetrated and interlocked structures.

2. Sulfate Templated Macrocycles, Capsules and Interpenetrated and Interlocked Structures

i) Introduction

As mentioned above, sulfate is an attractive anion to use as a potential template due to its orthogonal tetrahedral coordination preference and strong binding capability as a consequence of its dinegative charge. Furthermore sulfate has been shown to have a high coordination number preference with examples in the literature of between four and twelve hydrogen bonds interacting with a single sulfate anion at any one time.[20] These features have enabled sulfate to be used in the templation of a range of molecular architectures from macrocycles, helicates and capsules through to interlocked structures such as catenanes.

ii) Sulfate templated macrocycles and helicates

Although there are examples of receptors capable of binding sulfate both strongly and in some cases selectively, [21] examples of the use of sulfate as a template are rare. The potential for the sulfate dianion to be used as a chemical template was discovered somewhat serendipitously by Lehn and co-workers in the metal-directed assembly field.[22] The complexation of an acyclic tris-bipyridine ligand with various iron(II) salts resulted in the formation of circular helicate structures, the composition of which was found to be dependant on the counter anion of the iron(II) salts. For example when iron chloride was used, a pentametallic circular helicate was isolated, whereas with iron sulfate, a hexametallic circular helicate is produced (Fig. 4)

Fig 4. Lehn *et. al.'s* sulfate templated circular helicate

Work by de Mendoza in 1996 also demonstrated how

counter anions play important roles in templating the formation of higher order assemblies such as helixes. The self assembly of bis- and tetra-kis guanidinium salts into double helical structures was shown to be highly anion dependent (Fig. 5).[23, 24] No higher order self-assembly was observed for the chloride salt of **9** or **10**. However in systems where sulfate was used as the counter anion, two guanidinium molecules were found to orthogonally self-assemble around a single sulfate anion resulting in the formation of a higher order double helix like structure.[23, 24] ROESY NMR spectroscopy was used to confirm intermolecular interactions arising from this helical conformation.

Fig 5. a) Bicyclic bis-guanidinium salts **9** and **10** and tetrakis-guanidinium salt **11**, b) optimised model of a sulfate helicate from (S,S) guanidines. Reproduced with permission.[23]

In a strategic approach, Sessler *et al.* have demonstrated the use of sulfate to template the formation of polypyrrolic macrocycles. Screening of anions showed that the use of HCl or HBr as the reaction catalyst predominantly resulted in the formation of higher oligomers, whereas H_2SO_4 produces the [2+2] macrocycle in 75% yield (Scheme 5).[25, 26] Interestingly, in the presence of dihydrogen phosphate or hydrogen sulfate, over time the [2+2] macrocycle was found to undergo rearrangment to give the corresponding [3+3] analogue.

Likewise Otto and Kubik exploited the sulfate dianion to template the formation of sulfate selective receptors whereby a dynamic combinatorial chemistry approach dramatically improved the receptors selectivity and binding affinity for sulfate.[27] Using conventional synthetic chemistry, the bicyclic receptor **13** and control macrocycle **12** were obtained (Fig. 6).[28] The bicyclic receptor was shown to bind sulfate through a series of six hydrogen bonds between two cyclopeptide rings. Association constants for the binding of sulfate to **13** were determined to be in the order of 2.0 x 10^5 M^{-1} in 2:1 (v/v) acetonitrile/water mixtures.[29]

Scheme 5. Sulfate templated synthesis of a polypyrrolic macrocycle.[26]

By utilising dynamic combinatorial library techniques and the reversible nature of the disulfide bond, Otto and Kubik used sulfate templation to optimise the linking unit in the bicyclic complex to increase the selectivity towards the templating anion. The 'sandwich like' disulfide **14**, which is a poor anion receptor, was mixed with dithiols **a-f** of varying length in the presence of K_2SO_4 and the mixtures were allowed to reached equilibrium. Periodic monitoring of the dynamic combinatorial library by HPLC revealed marked amplification of receptors **15** and **16** indicating that these receptors had a greater affinity for sulfate. Repetition of the same procedure but in the presence of NaCl or KI showed no amplification of these products. Isolation of such receptors by preparative HPLC and subsequent binding studies by isothermal titration microcalorimetry (ITC) revealed that the binding of sulfate to receptors **15** and **16** was a factor of ten times stronger than that of the original dimer **13**.[27]

iii) Sulfate templated capsules

Recently, the use of sulfate to template the formation of molecular capsules incorporating tren-based tris-urea ligands has been reported.[30-34] Initial studies showed that a simple tris(2-aminoethyl)-amine based receptor **17a** strongly coordinated sulfate in highly competitive solvents including DMSO (Fig 7).[33, 34] Molecular modelling studies indicated that sulfate could be encapsulated by two molecules of **17a** with the six urea groups chelating to the dianion.[34]

Functionalisation of **17a** with nitro groups afforded the ligand **17b** which was shown to selectively bind sulfate and phosphate over other oxyanions such as acetate, perchlorate and nitrate. Crystallisation of this ligand in the presence of tetrabutylammonium sulfate resulted in the formation of molecular capsules in which two sulfate molecules bridged by three water molecules are surrounded by two molecules of **17b**.[32]

In a very recent report Custelcean has shown that the incorporation of metal coordinating groups into the TREN framework can lead to sulfate receptors that have the additional potential to act as metal-organic-framework (MOF) linkers. Functionalisation of **17a** with metal coordinating –CN groups afforded the sulfate receptor **17c**.[33] A Job plot monitoring the addition of Ag_2SO_4 into a solution of **17c** indicated a 2:1 ligand to sulfate binding stoichiometry. X-ray crystallography of crystals of **17c** grown in the presence of half an equivalent of Ag_2SO_4 revealed the formation of capsule like structures within the silver coordination polymer in which one sulfate molecule was coordinated between two TREN based ligands stabilised via twelve hydrogen bonds. This is the highest coordination number for sulfate ever reported in the literature. Attempts to crystallise **17c** in the presence of $(Me_4N)_2SO_4$ were unsuccessful indicating that the silver cation plays an important role in stabilising the coordination of sulfate (Fig 7).[33]

The stability of the metal organic frameworks of **17c** was low and thus the functionalisation of TREN with stronger metal chelating groups such as pyridine to yield **18** was investigated. Self assembly of **18** with a variety of metal sulfate salts (including $ZnSO_4$, $CdSO_4$, $CoSO_4$ and $MgSO_4$) again resulted in the formation of one dimensional coordination polymers (Fig 7).[30, 33] Molecular modelling and crystal structures revealed capsule formation in which the sulfate dianion is completely entrapped between two TREN based ligands. Such metal-organic coordination polymers were found to be sulfate selective and were not observed to form in the presence of other anions including F^-, Cl^-, Br^-, I^-, NO_3^-, HCO_3^-, HSO_3^-, ClO_4^-, and $H_2PO_4^-$. This feature allowed the separation of sulfate from nitrate (a significant challenge associated with the cleanup of nuclear waste) by crystallisation even in the presence of up to a 100 fold excess of $NaNO_3$.

Fig 7. Structure of tris(2-aminoethyl)-amine sulfate receptors **17** and **18** *(left)*, and crystal structures of **17b** encapsulating two sulfate dianions

bridged by three water molecules *(top right, **a**)* and crystal structure of **17c** with sulfate encapsulation *via* twelve hydrogen bonds *(bottom right, **b**)*. Figure **a** and **b** are reproduced with permission.[32, 33]

iv) Sulfate templated interpenetrated and interlocked structures

Although many acyclic and macrocyclic two dimensional receptors have shown success in the binding of anions, it can be argued that the challenge of recognising anions selectively in protic solvents, in particular water, necessitates the construction of intricate interlocked receptors.[7] Examples in nature like the sulfate-binding protein suggest that in spite of synthetic challenges, it is the design of sophisticated three dimensional architectures that is needed to fully encapsulate anions, thus creating highly specific anion binding pockets. Indeed the crystal structure of the sulfate-binding protein of Salmonella typhimurium reveals an individual sulfate molecule is completely encapsulated within the core of the protein (7 Å below the surface of the protein) held in place through seven hydrogen bonds with adjacent neutral receptors including five peptide NH groups, one serine OH group and one tryptophan NH (Fig 8).[18, 35]

The highly preorganised, three dimensional cavities afforded by the interlocked nature of catenanes and rotaxanes makes these systems attractive synthetic targets as they have the potential to act as highly selective receptors. Anions bound within the three dimensional cavity are more shielded from the surrounding solvent environment and thus such interlocked host structures may exhibit enhanced anion binding affinities even in competitive solvents. Furthermore if anion templation was used in the construction of such an interlocked host, the selectivity of the final product for the templating anion would be predicted.

Fig 8. Crystal structure of sulfate binding protein.

The ability of anions to template the formation of interpenetrated structures was first demonstrated by Stoddart's example of his [5]- and [6]pseudorotaxane structures incorporating polyether macrocycles and dibenzylammonium threads assembled around an octahedral hexafluorophosphate anion (Fig. 9).[36] The first permanently interlocked system templated by anions was later reported by Vögtle *et. al.*[37] They utilised the strong interaction between a lactam macrocycle and phenoxide half-stoppered thread to initially assemble a pseudorotaxane in organic solvents (Fig 9). Subsequent reaction with a sterically bulky electrophile afforded the [2]rotaxane in 57% yield, however, no anion binding cavity is present in the final rotaxane structure. In a related approach, Schalley and co-workers have exploited the pseudorotaxane assembly between a phenoxide thread and an amide macrocycle followed by stoppering to yield an anion templated [2]rotaxane.[38] Likewise Smith *et. al.* have used the binding of phenoxide anions in the construction of a range of [2]rotaxanes incorporating ion-pair receptors or squaraine dyes.[39] In both of these cases however, the phenoxide anion template remains present in the final rotaxane structure and no interlocked cavity exists for anion recognition purposes.

Fig 9. Stoddart's hexafluorophosphate templated [5]pseudorotaxane (left) and Vögtle's phenoxide templated [2]rotaxane (right).

Inspired by Sauvage's use of copper(I) metal ions to orthogonally assemble two organic ligands and thus template the formation of interweaving structures, Beer and co-workers have undertaken investigations into the viability of using anions as analogous orthogonal templates. Indeed a general method of using anions to template the formation of a range of pseudorotaxanes, rotaxanes and catenanes has been described.[40, 41] This assembly process operates via the coupling of anion recognition with ion-pairing where, in non competitive solvent media, a coordinatively unsaturated chloride anion of a tight ion-pair threading component facilitates the interpenetration of a pyridinium, imidazolium or guanidinium thread through the annulus of an isophthalamide macrocycle. Complementary CH---O hydrogen bonding and π-π stacking reinforces the threading process (Fig 10). This principle has been used to effect in the synthesis of catenanes and rotaxanes incorporating a charged thread and a neutral macrocycle. Furthermore it has been shown that subsequent removal of the anion template results in a cavity that is then selective for the templating anion.

Fig 10. (a) Cartoon representation of anion templated [2]pseudorotaxane assembly *(top)*; Anion templated pseudorotaxane assembly formed between an isophthalamide macrocycle and pyridinium chloride ion pair thread *(bottom)*.[41]

The versatility of this anion templation methodology was further demonstrated by the development of a one-pot double clipping strategy whereby cyclisation via ring closing metathesis of two charged threads self-assembled around a single anion gave the desired catenane in a remarkably high yield (Scheme 6). It is noteworthy that the assembly process has been demonstrated to be anion dependent and only when one of the components is added as a chloride salt and the other as a PF_6 salt is the catenane produced in the highest yield.[42]

Scheme 6. Synthesis of a [2]catenane via a double cyclisation strategy.[42]

Despite the orthogonal binding preference and the potential strong coordination afforded by the sulfate dianion, until recently no examples of using sulfate to strategically template the formation of interpenetrated and interlocked systems such as catenanes have been described. We have very recently reported the first ever catenane synthesised using sulfate anion templation.[43] In an analogous fashion to the chloride templated double clipping strategy discussed above, the sulfate dianion was shown to template the orthogonal assembly of two mono-cationic threads. Double ring closing metathesis of the acyclic bis-vinyl pyridinium nicotinamide sulfate salt afforded the catenane in remarkable yields (80%) (Scheme 7). Analogous ring closing metathesis cyclisation reactions using chloride, bromide or hexafluorophosphate salts of the pyridinium nicotinamide thread failed to produce the desired catenane. As expected, subsequent anion binding studies performed on the hexafluorophosphate salt of the catenane revealed selectivity for the templating sulfate anion

over chloride, bromide and acetate, which is contrary to the anion selectivity properties of the acyclic thread which has a binding preference for acetate.[43]

We have also recently demonstrated that the sulfate anion is capable of templating the formation of interpenetrated assemblies from neutral components.[44] Indolo[2,3-a]carbazoles are attractive anion receptors due to their preorganised hydrogen bond donating pyrrole groups which are known to bind anions strongly.[45] NMR studies indicated that addition of TBA sulfate results in the formation of a 2:1 dimeric structure in which the sulfate dianion is coordinated by two indolocarbazole molecules. X-Ray crystallography confirmed the orthogonal nature of the indolocarbazole:sulfate dimer (Fig 11).[44]

Fig 11. X-Ray crystal structure of the indolocarbazole sulfate homodimer.

Encouraged by the formation of the indolocarbazole homodimer, interpenetration studies to determine whether indolocarbazole could thread through the cavity of an isophthalamide macrocycle in the presence of sulfate were undertaken. ^{1}H NMR was used to monitor pseudorotaxane formation where addition of an equimolar mixture of indolocarbazole **22** and TBA sulfate to a solution of macrocycle **21** resulted in characteristic upfield shifts of the hydroquinone protons of the macrocycle indicating π-stacking with indolocarbazole (Fig 12).[44] Thus even in the absence of any charged electrostatic interactions or favourable π-π stacking effects, sulfate was able to template the interpenetration of these neutral species. This templation effect was also seen with fluoride, however no pseudorotaxane assembly was observed in the presence of chloride or hydrogen sulfate.

Fig 12. The comparison of titration curves obtained by following two signals from hydroquinone protons (HQ1 and HQ2) during ^{1}H NMR titration of an isophthalamide macrocycle **21** with: (TBA)$_2$SO$_4$ (black) and 1:1 mixture of (TBA)$_2$SO$_4$ and indolocarbazole **22** (red). Solvent: acetonitrile-d_3, T=298K.

Solution phase studies of supramolecular systems have given rise to increasingly complex interlocked molecules capable of performing "machine like" operations. However, in order for these systems to be transformed into functional devices, they need to be incorporated into materials or deposited onto surfaces. Sulfate was also used to template pseudorotaxane formation on a range of surfaces including gold, polystyrene beads and silicate nanoparticles.[44, 46] The attachment of indolocarbazole threads to polystyrene beads allows the use of high resolution magic angle spinning (HR MAS) NMR to monitor the anion templated threading process of an isophthalamide macrocycle. Hence a direct comparison of the pseudorotaxane assembly process in both solution and on solid surfaces can be made. Fluorescence spectroscopy was also used to monitor this sulfate templated pseudorotaxane formation in solution, on polystyrene beads and on optically transparent silicate nanoparticles (Fig 13).[46]

Fig. 13. Fluorescence spectra of a) **23** (solid curve) in acetonitrile (4.2×10^{-5} mol L^{-1}) and on the sequential addition of 1 molar equivalence of sulfate (dotted curve) and macrocycle **21** (dashed curve); b) silica nanoparticle surface confined indolocarbazole **24** (solid curve) in acetonitrile (0.05 wt %) and the results of sequential addition of sulfate (dotted curve) and macrocycle 21 (dashed curve), respectively; and c) polystyrene beads confined indolocarbazole **25** (solid curve) and its sequential addition of sulfate (dotted curve) and macrocycle 21 (dashed curve), respectively. Initial peak shape and wavelength differences for **23**, **24** and **25** in the absence of anions and macrocycles are attributed to the combined effects of different conformational freedom/aggregation states of the emitter.

Extension of this work to include electrochemically active surfaces such as gold was also investigated. The indolocarbazole thread was covalently attached to gold surfaces via disulfide linkages, and surface plasmon resonance (SPR) used to monitor sulfate templated pseudorotaxane assembly (see Fig 14).[44] Upon addition of an equimolar solution of macrocycle and sulfate, changes in the surface plasmon resonance was observed, indicating pseudorotaxane formation. No such changes were noted for analogous studies using chloride or hydrogen sulfate. Such comprehensive studies into the assembly of interpenetrated systems on a variety of surfaces (including optically transparent nanoparticles, and electrochemically responsive gold surfaces) are rare.

Figure 14. SPR sensorgram showing the threading of **21** over gold surface confined indolocarbazole on the addition of a 1:1 molar equivalence of the macrocycle and (TBA)$_2$SO$_4$. Physically adsorbed macrocycle can be removed by flushing the surface with acetonitrile solvent to give a stable pseudorotaxane coverage of ~ 30% of axle threading (a). In washing the surface with water approximately 50% of the pseudorotaxanes are triggered to dethread (b).

3. Conclusions

This review examines the potential use of sulfate as a chemical template in the synthesis of complex molecular architectures including macrocycles, helixes, molecular capsules, interpenetrated and interlocked structures such as catenanes. The strong binding, orthogonal tetrahedral coordination preference and high coordination number of the sulfate dianion makes it an attractive choice as a templating reagent. Using a strategic templating approach the groups of de Mendoza, Sessler, and Otto and Kubik have demonstrated that sulfate is effective in the templation of macrocycles and helixes. More recently the higher coordination preference of sulfate was exploited in the construction of molecular capsules whereby two tripodal tren-based tris-urea ligands completely encapsulate a single sulfate dianion stabilised via twelve hydrogen bonds; the highest coordination number for sulfate ever reported.

Anion templation can also be a powerful tool in the

synthesis of interlocked structures such as catenanes and rotaxanes, with the highly preorganised, three dimensional cavity afforded by such structures often proving to be selective for the templating anion. Beer and co-workers have recently reported the first example of employing sulfate to template the synthesis of a pyridinium nicotinamide [2]catenane in excellent yields. As expected the catenane exhibited selectivity for the templating sulfate dianion over other anions such as acetate, and chloride.

In addition sulfate templated pseudorotaxane formation between two neutral components has been demonstrated. In the presence of sulfate, interpenetration of an indolocarbazole thread through the annulus of an isophthalamide macrocycle is observed both in solution and most importantly for the future progression of this field, on a variety of solid surfaces including polystyrene beads, silicate nanoparticles and gold surfaces.

In conclusion, this review clearly highlights the real potential anions, such as sulfate, have in templating the assembly of complex molecular architectures which by appropriate future design may have practical sensing, switching and molecular machine-like nanotechnological applications.

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Notes and references

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