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Review

Strategic anion templation

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Contents

Abstract

This review provides first a brief overview of the general field of templation, with particular emphasis placed on previous uses of strategies utilising anion templation effects in the construction of sophisticated interweaved motifs. It focuses on the development and exploitation of a new anion templation strategy which utilises the properties of discrete halide anions to direct the formation of a range of novel architectures, including orthogonal complex, [2]-pseudorotaxane, [2]-rotaxane and [2]-catenane derivatives. These derivatives have been shown to exhibit novel anion binding behaviour which is dependent on their interlocked nature, a feature which has further been exploited by the incorporation of signalling groups to sense the anion binding event.

Keywords: Anions; Templation; Interpenetrated structures; Pseudorotaxanes; Rotaxanes; Catenanes

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1. Introduction

The field of anion coordination chemistry has grown rapidly over recent years, inspired by the manifold and previously under-appreciated roles that these negatively charged species play in a range of biological, environmental, and chemical processes [1]. A variety of synthetic inorganic and organic systems capable of the binding and sensing of anionic substrates have been reported, wherein the substrate–host binding interaction may be affected variously by electrostatic, hydrogen bonding and Lewis–acidic interactions, or a combination thereof [2–6]. However, the role of anionic substrates for the templation of chemical processes, in an analogous manner to that commonly utilised for their cationic congeners, has received comparably little attention [7–9]. This is partially a natural result of the still emerging nature of the anion coordination field, and also a consequence of the properties of anionic substrates themselves, which, due to their varying

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geometries, low charge/radius ratios and pH dependence do not initially appear as ideal templating motifs. Where anions have been shown to play a role, the templation is often serendipitous, rather than a direct result of strategic design.

Within this review, however, it will be shown that the calculated use of anions as templating agents for the formation of a wide range of inorganic and organic architectures is a highly effective strategy, and can be favourably compared to previous methods using cationic and neutral templating agents. In particular, the use of anion templation for the formation of sophisticated interpenetrated motifs will be explored, with emphasis placed on the recently developed use of halide anion recognition for the formation of new architectures that demonstrate properties dependent on the nature of the template.

2. Precedent for templation in architecture formation

The rational design and exploitation of templation phenomena in general has attracted a huge amount of interest, due to the high level of functionality and novelty that can be achieved in the systems thereby generated. The templating interaction may be mediated by any of the commonly used supramolecular interactions, and has been diversely achieved by cationic, neutral and anionic substrates [10–13]. A brief overview of some of the successes of templation by cationic and neutral species will be discussed below, followed by a more in depth consideration of the uses of anionic templation. Special emphasis is placed on the use of templation techniques to form interpenetrated structures.

The formation of interlocked species represents a particularly formidable challenge. These systems present huge opportunities for future innovation, due to their high degree of functionality and unique topological nature, which opens up the possibility for new molecular machine, computing, sensing or materials behaviour [14,15]. Previous statistical approaches to the formation of catenanes [16] and rotaxanes [17] were plagued by extremely low yields and difficulty of purification. However, by unlocking the potential of the template effect, the synthesis of a range of novel, interpenetrated structures has been achieved [18–20]. Due to the special challenges involved in forming these structures, the following will focus particularly on the successes of templation methods in generating sophisticated architectures.

2.1. Templation by cationic and neutral substrates

The role of metal cations as directing agents in a variety of syntheses has been well documented. This led to the coining of the term ‘template effect’ [21,22], and since the pioneering work of Busch it has been exploited in the construction of a huge volume of structures, including macrocycles [23–25], cages [26–28], ladders [29], and networks [30]. Unsurprisingly, given these successful applications of cationic templation methodologies, they have received considerable attention for the construction of sophisticated interweaved motifs, some of which are considered in more detail below.

The use of discrete metal cation templates in the formation of interlocked species is elegantly illustrated by the work of Sauvage and co-workers. Using a copper(I) phenanthroline precursor **1**, wherein the two ligands were arranged orthogonally by the tetrahedral metal geometry (Fig. 1), the formation of a [2]-catenane **2** was shown to take place in 27% yield [31]. Removal of the copper(I) template proved possible, leaving the interlocked nature of the catenane structure intact. This approach has been extensively elaborated to furnish a number of [*n*]-catenane and rotaxane derivatives, which furthermore have been shown to display molecular machine like behaviour [32–35]. Similar copper-based templation strategies have been utilised by other groups to form a range of new motifs [36,37], while recent work with square planar Pd(II) templating centres has also allowed the construction of interlocked molecules (e.g. **3**) [38]. The use of metals with six-coordinate octahedral geometries has been exploited somewhat less than for tetrahedral systems [39–41], although examples such as **4** illustrate the potential for these species to direct catenane assembly [42].

There are many other illustrations of the importance of metal ions in interlocked structure synthesis [43,44]. For example, the group of Fujita have demonstrated that [3] catenane **5** formation may be favoured by thermodynamic rearrangement of the parent metallomacrocycle species [45], while Beer and co-workers found that the formation of [2]-catenane derivatives based on dithiocarbamate ligands was dependent on mixed-metal charge–transfer interactions (e.g. Cu(II)/Cu(III) in **6**) [46]. Furthermore, in an impressive recent example, Zn(II) cations have been found to template the formation of highly complex Borromean ring compounds, e.g. **7** [47].

The use of templating organic cations has also been extensively investigated. For example, a combination of electrostatic, π-stacking and charge–transfer interactions has been widely exploited by the group of Stoddart in the formation of interlocked species, in an approach based on interaction of a paraquat unit with electron rich aromatic-ether species [48]. This strategy has been utilised to form the eye-catching ‘Olympiadane’ (**8**) [49], as well as manifold other systems [50–53] (Fig. 2).

A combination of hydrogen bonding and electrostatic interactions has also widely been exploited by the group of Stoddart and co-workers [54,55] and others [56–58] to form a vast catalogue of interlocked species. The strategy relies on the threading of difunctionalised ammonium derivatives through crown ether wheels [59]. Recently, it has been employed in the generation of a new [4]-rotaxane derivative (**9**) [60], among others, under thermodynamic control.

Templation processes based on neutral recognition processes have also been exploited extensively in organic synthesis [11]. Hydrogen bonding in particular has been utilised for interlocked molecule formation. For example, since the formation of a [2]-catenane (**10**) by Hunter [61], the use of complementary amide and urea hydrogen bonding interactions has been exploited to form not only a range of molecular entanglements [62–65], but also new derivatives which demonstrate molecular machine behaviour, such as **11** which undergoes light induced shuttling of the threaded ring [66].

A recent example of the formation of pseudorotaxanes through H-bond mediated second sphere metal coordination has been provided by Wisner and co-workers [67]. Templa-

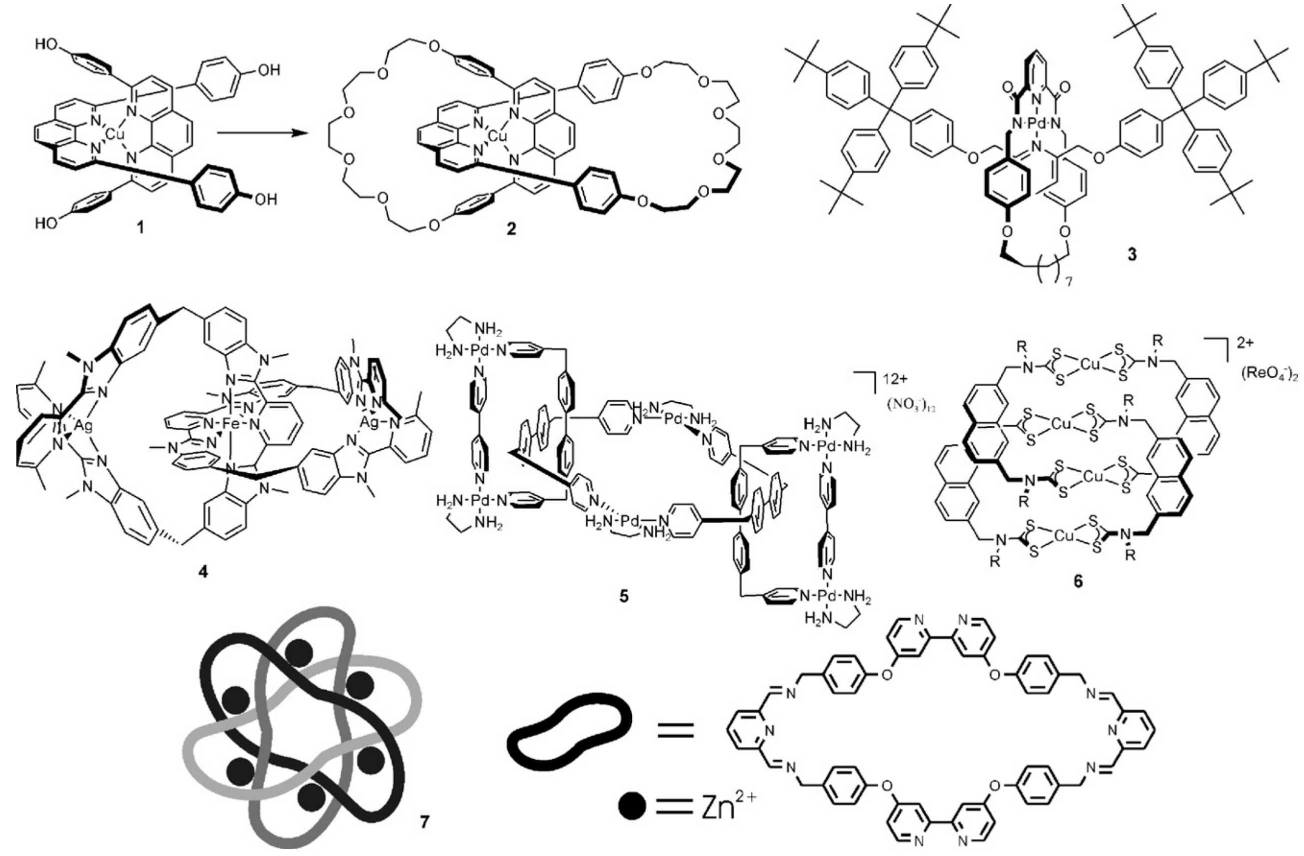


Fig. 1. Assembly of interlocked motifs by transition metals.

tion occurs through hydrogen bonding of the amide units of a macrocyclic wheel to the coordinated chloride units of a palladium-centred thread, with the threading assembly process further directed by the square planar coordination of the palladium metal centre to give the pseudorotaxane **12** (Fig. 3).

Other systems reliant on neutral templation events include those based solely on neutral donor–acceptor π-stacking interactions (e.g. **13**) [68] and those whereby the threading process is aided by a solvophobic interaction, such as in the threading of cyclodextrin units onto a molecule containing, for example, cyanine dye units (**14**) [69]. Impressively, the result of this encapsulation is to improve the photostability and fluorescence properties of the system.

There is thus an extensive precedent for the use of templating strategies in the formation of interpenetrated molecules. Despite the elucidation, as briefly summarised above, of numerous templation strategies involving electrostatic, coordinative, hydrogen bonding, and π-stacking interactions for neutral and cationic substrates, the premeditated use of these interactions for anion templation has received much less close attention.

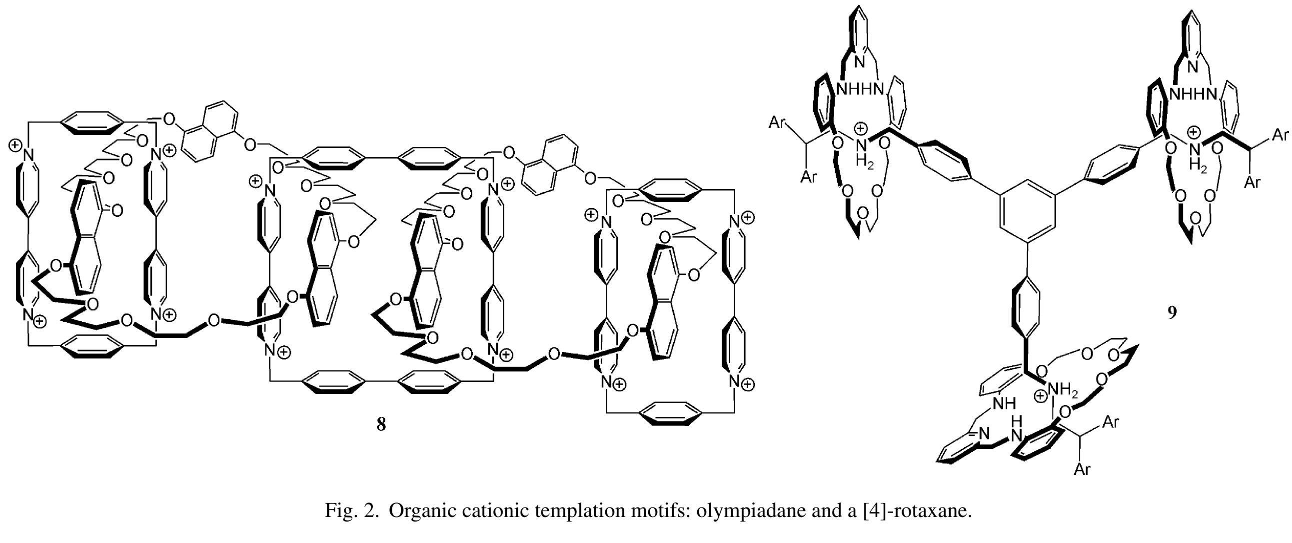


Fig. 2. Organic cationic templation motifs: olympiadane and a [4]-rotaxane.

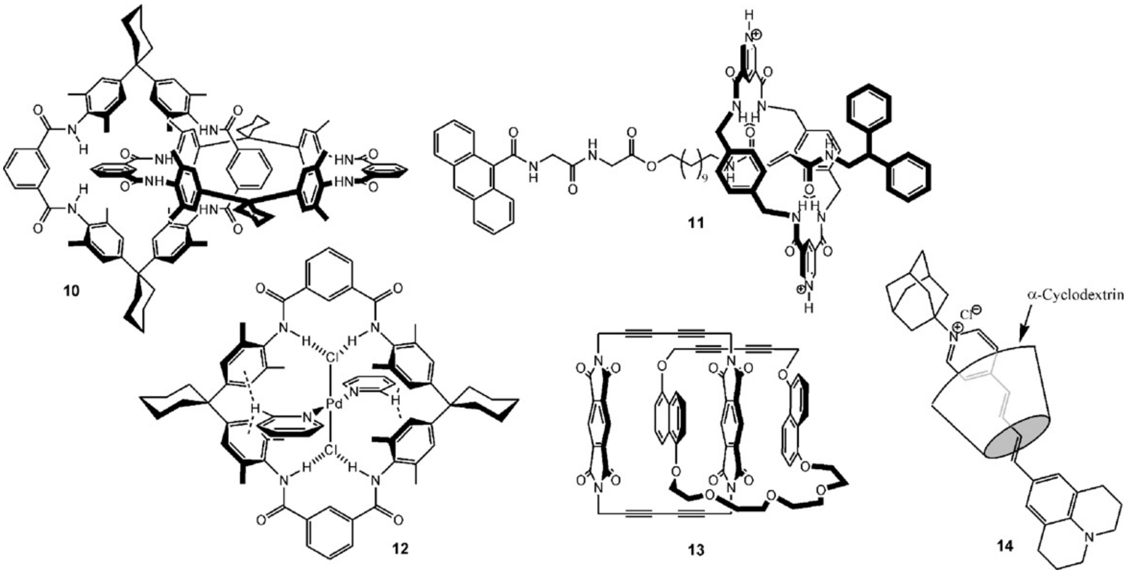


Fig. 3. Neutral templation motifs.

2.2. Templation by anionic substrates

With the emergence of the anion recognition and sensing field, the study of anion templation has received increasing attention [7–9]. It is perhaps surprising to find that of the numerous examples of anionic templation in the literature, only a few rely on a rational design process. Although the formations of an impressive range of structures have been shown to depend on the influence of an anionic template, this lack of design compares unfavourably with the numerous elegant examples encountered in templation processes mediated by neutral and cationic substrates. A survey of some of the more salient examples of both rational and fortuitous anion templation follows.

A number of metal-directed coordination assemblies have been shown to rely on an anion templating influence in their construction. For example, the formation of the elegant circular helicate structure **15** has been shown to depend on the presence of a chloride template, while in the presence of sulphate anion only the related hexanuclear derivative was observed [70,71]. Further studies on this system revealed that the template operated by a thermodynamic size-fit with the resulting macrocyclic cavity [72]. Other inorganic motifs, including macrocycles [73,74], cages [75–77], nanotubes [78], polymers [79] and networks [80], have been found to be similarly reliant on the presence of variety of anionic templates to adopt the observed structures, some of which are detailed below (Fig. 4).

An appreciation of the role of anion templation has revealed considerable potential for the use of these substrates as directing agents in metallomacrocycle formation. In pioneering work, Hawthorne and co-workers showed that the formation of the mercurocarborand system **16** was dependent on the presence of a suitable halide anion template [81,82]. In a more recent example, the group of Dunbar demonstrated that the presence of small anions such as tetrafluoroborate favoured the formation of molecular squares (e.g. **17**) whereas the larger SbF_6^- species favoured the formation of a molecular pentagon [83].

The role of anion templates in metallocage complex formation has similarly been exploited. For example, anion geometry

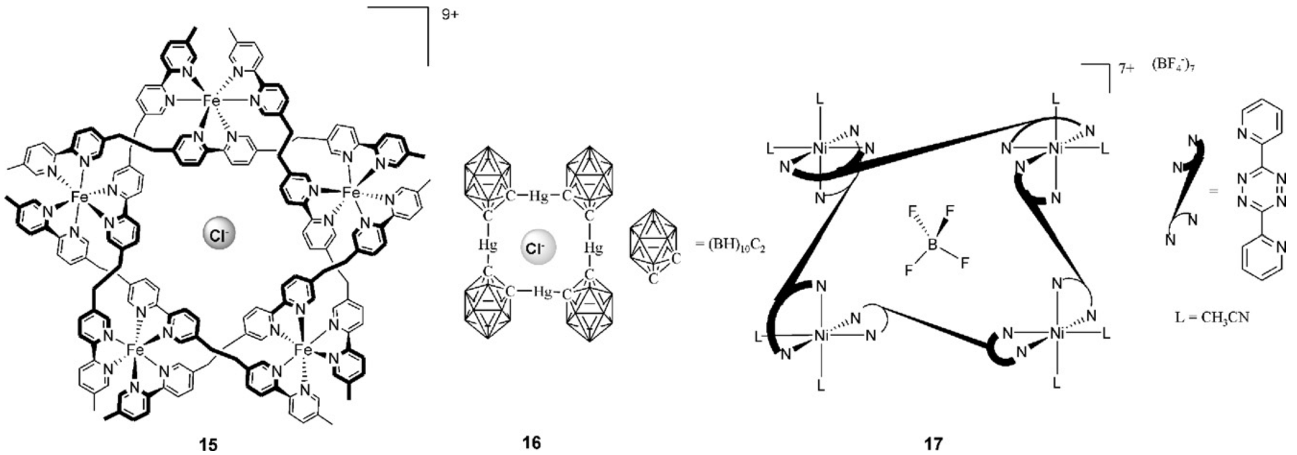


Fig. 4. Anion templated metallahelices and metallomacrocycles.

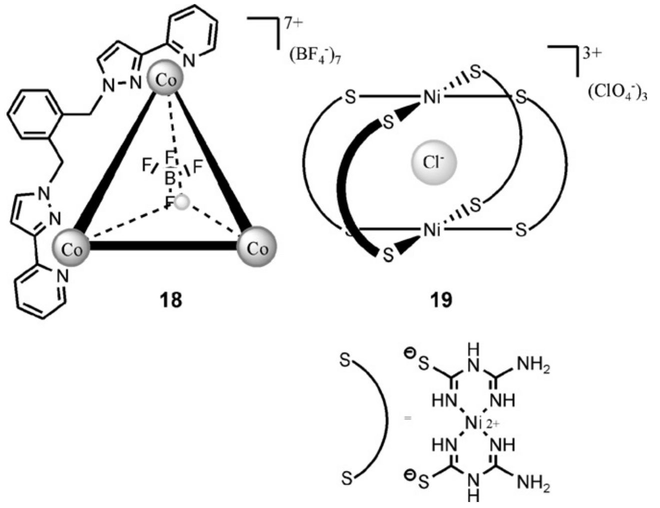


Fig. 5. Anion templated metallocages. In **18**, one of the ligands resides on each edge.

and size has been used by Ward and co-workers to direct the formation of a range of M_4L_6 cages [84,85], such as **18**, through a combination of electrostatic and hydrogen bonding interactions with tetrahedral templates such as BF_4^- and ClO_4^- [86]. Furthermore, Vilar and co-workers have developed a colorimetric sensor which relies on an anion-templation event [87]. The Ni(II) and Pd(II) cage systems **19** will only form in the presence of a chloride or bromide template, with chloride being the most effective, with the effect mediated by a combination of electrostatic and hydrogen bond interactions with the ligand. Because of the intense colour change observed on formation of these metallocages, it was proposed that the system could act as a sensor for the templating ion, which, allowing time for the self-assembling mixture to equilibrate, was demonstrated (Fig. 5).

In an interesting recent development, Schalley and co-workers have demonstrated the ability of surface-confined chloride ions to impose long-range order on a deposited monolayer of the metallomacrocycles **20** [88]. Chloride anions were adsorbed onto a positively charged copper electrode, then exposed to **20**. It was found that, under ideal deposition conditions, a two-dimensional ordered pattern was obtained, whereas adsorption of **20** to a graphite surface without the templating chloride resulted in a surface with different patterning. This was attributed to the directing role of the well-ordered surface bound chloride anions (Fig. 6).

The syntheses of a number of organic-based systems have also been shown to depend critically on the presence of a templating anion [89,90]. The synthesis of macrocycle **21** was shown by Sessler and co-workers to depend on the presence of nitrate anions, in the form of nitric acid [91], while related recent work by the same group has demonstrated the importance of anions in determining related polypyrrolic macrocycle product distributions [92]. Furthermore, Alcade and co-workers have evaluated the nature of the chloride template effect in the synthesis of dicationic imidazoliophanes (**22**), wherein the presence of chloride can lead to an increase in the reaction rate and yield [93]. This effect arises due to the stabilisation of the reaction transition state by the anion, through a combination of electrostatic and hydrogen bonding interactions.

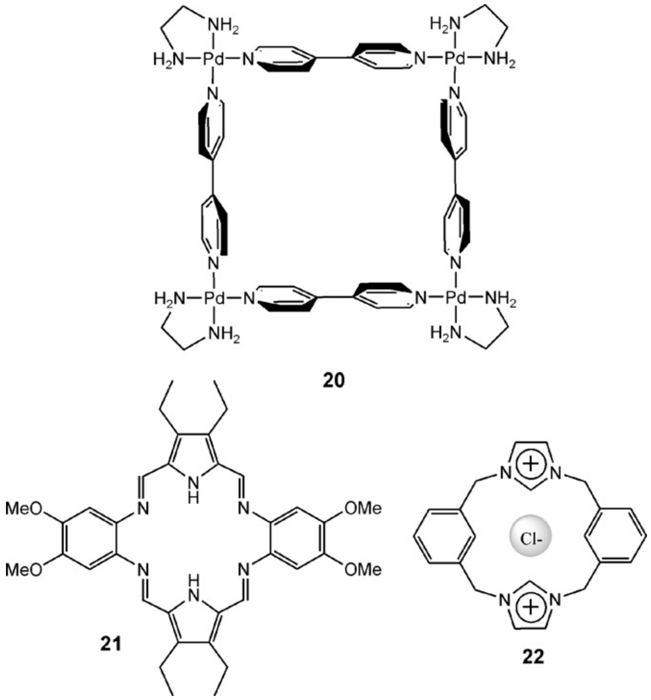


Fig. 6. Macrocycles exploiting anion templation.

Anions have also been widely observed to influence the structures of supramolecular assemblies in the solid state [94,95]. For example, Gale and co-workers demonstrated the formation of a fluoride templated double helix (**23**) [96], which depended strongly on the geometry of the templating anion, while Lee and co-workers showed that a strong directing influence was exerted by the counteranion on the secondary structure of a coordination polymer, with smaller anions forcing the adoption of a helical structure, whereas successively larger anions favour the formation of dimeric cycle and lamellar derivatives [97] (Fig. 7).

While there is therefore a relatively large volume of examples of the uses of anion templation for the formation of non-interpenetrated inorganic and organic systems, the use of anions

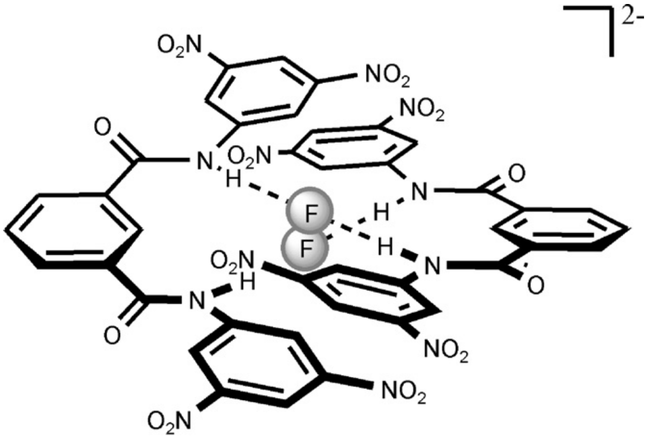
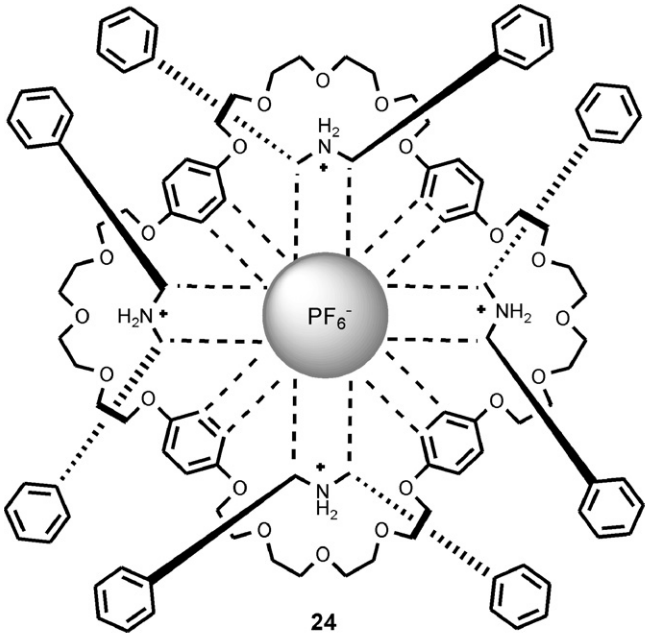


Fig. 7. Anion directed assembly: Gale's double helix.



24

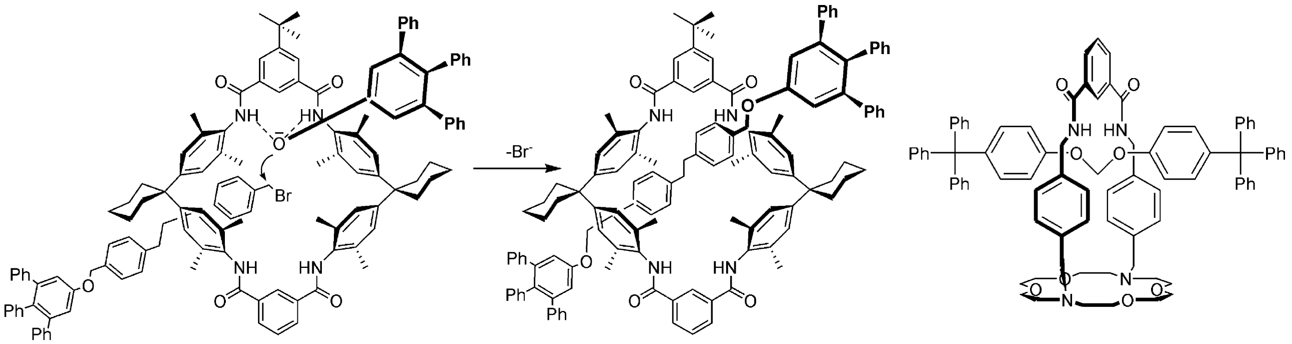
Fig. 8. Stoddart's [5]-pseudorotaxane.

for the formation of more complex architectures has received precious little attention. However, where a deliberate anion-template strategy has been adopted, a large degree of success has been achieved.

In an extension of the bisammonium salt based threading process mentioned above, Stoddart and co-workers demonstrated the dependence of [5]-pseudorotaxane formation on the presence of the hexafluorophosphate anion (**24**) [98]. This templating event is thought to depend critically on the geometry and size of the PF_6^- species, which mediates the threading process through a combination of electrostatic and hydrogen bonding interactions. The same group has demonstrated that this anion has a directing influence in the formation of a variety of similar structures [99] (Fig. 8).

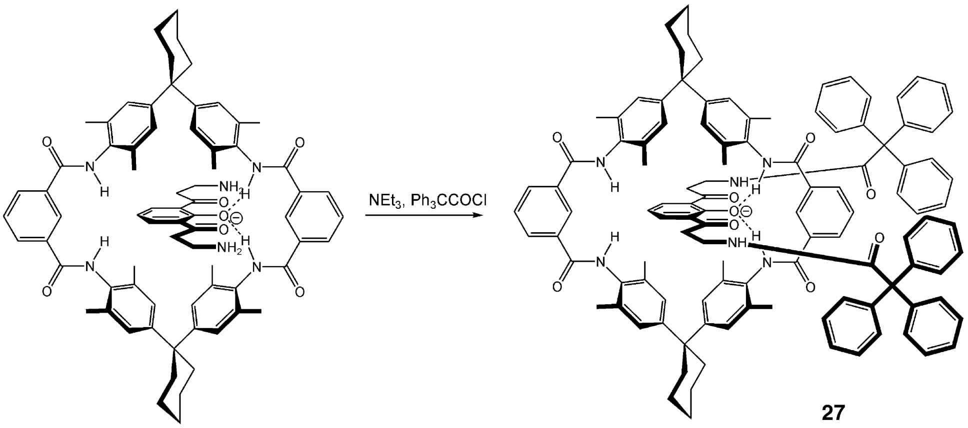
An elegant anion-mediated synthetic route to a range of rotaxane systems has been developed by Vögtle and co-workers (Scheme 1) [100]. In this methodology, a bulky phenolate unit is complexed by a tetralactam wheel, which provides considerable shielding to the complexed phenolate unit. The phenolate may react with a suitable acyl chloride or electrophile to leave an interlocked [2]-rotaxane species **25**. This process opens the possibility to the formation of a range of interlocked derivatives, although the template itself is completely consumed during reaction. Smith and co-workers have further exploited this technique to produce interlocked systems based on an ion-pair recognising motif as the 'wheel' unit (e.g. **26**) [101].

In a related approach, the group of Schalley has demonstrated the feasibility of phenoxide templation for [2]-rotaxane synthesis (Scheme 2) [102,103]. As in the previously detailed approach, the phenoxide unit is bound by a suitable hydrogen bond donating wheel, then stoppered to form a rotaxane species



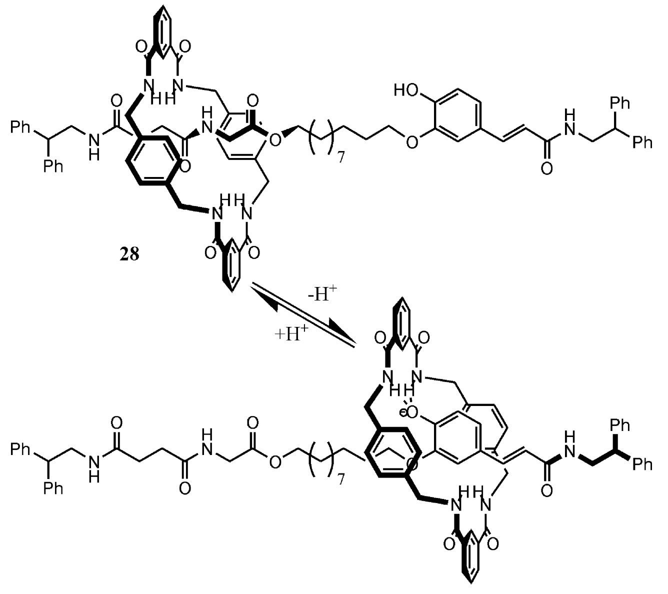
25 **26**

Scheme 1. Vögtle's templated rotaxane assembly, and Smith's rotaxane system.



27

Scheme 2. Schalley's phenoxide rotaxane synthesis.

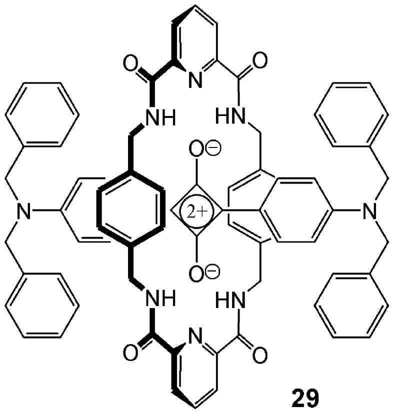


Scheme 3. Leigh's phenoxide pH shuttler.

(**27**). The crucial difference in this case is that the phenoxide template remains present in the product, which suggests a role for the anion other than just being a template. This possibility has been exploited by Keaveney and Leigh, who demonstrated that the [2]-rotaxane **28**, which was formed by neutral hydrogen-bond templation methods, could be induced to undergo shuttling of the wheel component by deprotonation of the phenolate unit (Scheme 3) [104]. This pH dependent process occurs due to the better hydrogen bonding ability of the phenoxide anion compared to the neutral amide station.

The potential for anion templation to lead to materials with new properties has been investigated by Smith and co-workers [105]. They demonstrated the encapsulation of a squaraine dye into a new [2]-rotaxane structure **29**, using a hydrogen bond mediated encirclement methodology previously mentioned. In this system, the assembly of the wheel component is directed by the squaraine oxygen units, which can be thought of as anionic so as to allow aromaticity at the cyclobutadienyl core of the thread. The resulting dye system has a stability which is greatly increased compared to the unencircled thread, due to the inhibition of aggregation processes [106]. This impressive application of anion templation suggests a much wider role for this methodology for the generation of functional materials than has been thus far exploited (Fig. 9).

A large number of examples of anion templation effects, therefore, have been shown to exist, although the rational design of these effects and their application in the formation of new interlocked architectures seems thus far somewhat underexploited. Where they have been investigated, however, strategic approaches to anion templation have resulted in molecules of novel functionality, topology and potential application. A striking omission, however, in the development of this field thus far is the utilisation of discrete anions as templates in a manner consistent with that pioneered for metal cations by Sauvage (Section 2.1). An account of the design, development and exploitation of such a strategy constitutes the remainder of this review.



29

Fig. 9. Smith's rotaxinated squaraine dye.

3. Orthogonal complexes and pseudorotaxanes: Demonstrating the potential for a new strategy for interpenetrated architecture formation

The use of discrete anions as templates for interpenetrated architecture formation, in a manner consistent with that so successfully exploited by Sauvage and others, should prove possible via an analogous tetrahedral complex assembly process (Fig. 10) [32]. When using anions to direct such an assembly, however, the inherently lower charge/radius ratios and lack of strong coordinative directionality compared to transition metals present immediate difficulties. Therefore, careful consideration of the design of such a system is needed, as detailed below.

3.1. Anion templated orthogonal complexes

In order to facilitate the preparation of orthogonal complexes with pseudotetrahedral geometry based on anion complexation, as outlined above, it was necessary to both identify, and investigate the binding properties of, suitable anion binding fragments for templation. A search of the literature revealed potentially appropriate isophthalamide fragments used by Crabtree and co-workers [107], which in non-competitive solvents were demonstrated to have selectivity for chloride anions, over bromide and iodide [108]. The receptors were not notably preorganised, with intramolecular hydrogen bonding favouring a syn-anti conformation, but on binding an anion, the molecule **29** rearranged to provide a convergent hydrogen bonding array (Fig. 11). However, the binding stoichiometry of the analogous dihexyl system N1 (Fig. 12) with halide anions was found to be 1:1 in all solvent systems studied, which was unsuitable for the formation of orthogonal complexes, wherein two fragments must surround

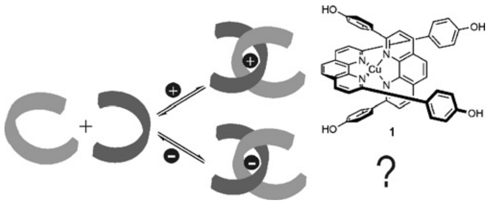


Fig. 10. Discrete anion templation through pseudotetrahedral intermediates.

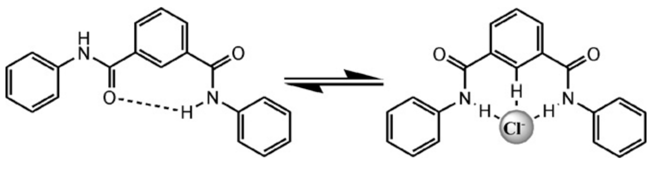


Fig. 11. Crabtree's isophthalamide binding fragments.

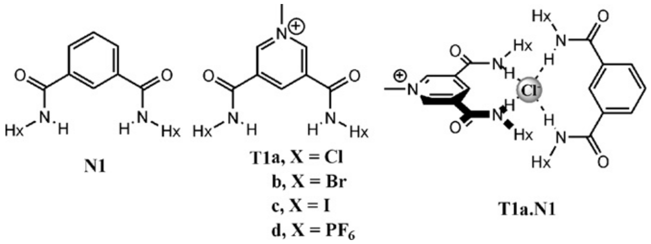


Fig. 12. Fragments N1 and T1, and the orthogonal complex T1a.N1.

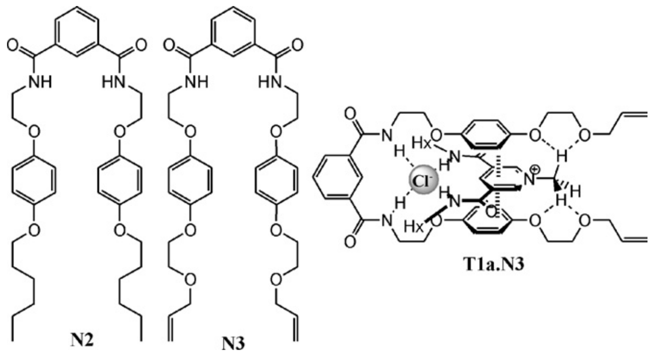


Fig. 13. Increasing second sphere coordination interactions: N2, N3 and T1a.N3.

the templating anion. In order to circumvent this problem, a tightly associated pyridinium chloride ion-paired species T1 was designed [109]. In this system, halide anions are tightly associated with the anion binding cleft by a combination of electrostatic and hydrogen bonding interactions. This is a very strong interaction, with K_{ass} for chloride in acetone-d_6 of $>10^5$. Importantly, it was found that the coordination sphere of the associated halide anion was unsaturated, which allowed the further association of a neutral dihexyl isophthalamide species in acetone-d_6 to the vacant meridian, with a K_{ass} of 100 M^{-1} for the complex T1a.N1, as determined by ^1H NMR titration. This result implied the existence of the desired tetrahedral anion-templated orthogonal complex (Fig. 12), with the efficacy of the assembly process depending on the anion. No association was observed when a non-coordinating anion such as hexafluorophosphate (T1d) was used.

The design of this first generation of orthogonal assemblies could be improved by incorporating features in the neutral component that favoured second-sphere coordination of the chloride anion [110]. Thus, from the simple dihexyl system N1, already discussed, significant enhancements in the association of the ion-paired and neutral components could be achieved by incorporating first electron rich π-stacking hydroquinone components (N2), then extra hydrogen-bond accepting ether oxygen units (N3), which were designed to allow N^+Me-O hydrogen bonding interactions to occur (Fig. 13). The success of this strategy is borne out by the ^1H NMR derived association constants in CD_2Cl_2 (Table 1). A significant enhancement of the association event was observed, with evidence for the presence of π-stacking interactions being gleaned from the occurrence of small upfield shifts in the signals arising from the hydroquinone protons; the observed shift is larger for the association of ligand N3 than N2 with the ion-pair T1, thus suggesting that the terminal ether oxygens do indeed aid the assembly process by improving the hydroquinone ring orientation. Further evidence for the existence of π-stacking in the complexes derived from N2 and N3 with T1 can be inferred from observing the UV–vis absorption spectra of the mixtures. A charge transfer absorption at ∼380 nm is seen in dichloromethane, resulting in a pale yellow colouration of the complex solution. No such absorption is seen for the assembly T1a.N1, and the absorption for the complex T1a.N3 is considerably stronger than that for T1a.N2, providing further evidence that the assembly process is stronger in this system. Again, there was no evidence for association in CD_2Cl_2 when the pyridinium ion-pair included a non-coordinating anion, hexafluorophosphate, which demonstrates that these extra coordination interactions are secondary to the anion-recognition event in driving the assembly process.

Table 1
^1H NMR derived association constants and free energies of complexation for the interaction of different neutral fragments with T1a in CD_2Cl_2 at 298K

	N1	N2	N3
K_{ass} (M^{-1})	25	50	260
$-\Delta G$ (kJ mol^{-1})	8	9.7	13.8

These interactions were further exploited in the related demonstration of orthogonal complex formation for podand-imidazolium assemblies (Fig. 14) [111]. In this case, the ion-pair was provided by the imidazolium-based threads T2–T4, whilst the neutral component consisted of the bis-urea podand species N4. This species incorporates the anion binding (urea), electron-rich aromatic and ether oxygen units previously detailed for N3. The formation of the orthogonal complex T2a.N4 in $CDCl_3$ could be inferred from the chemical shifts of the protons involved, and through ROESY experiments which demon-

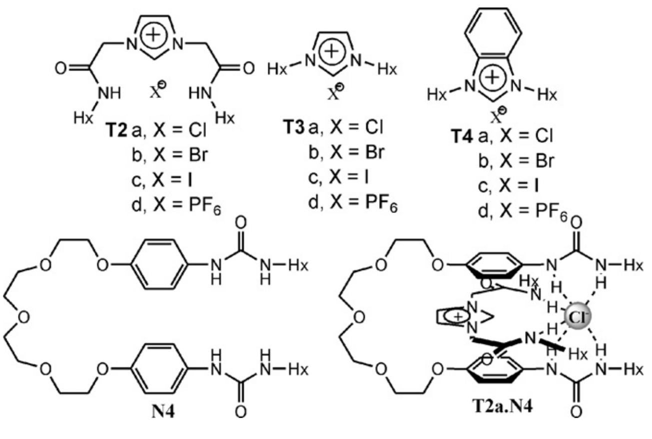


Fig. 14. Threads T2–T4, neutral species N4, and the orthogonal complex T2a.N4.

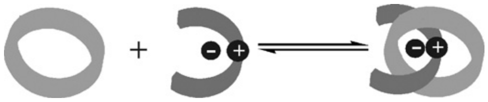


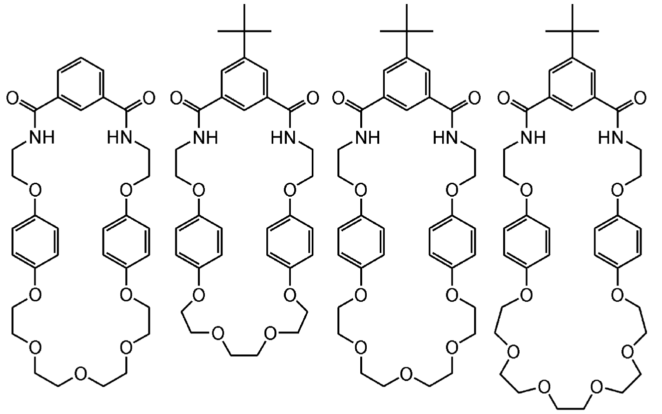
Fig. 15. Anion templated pseudorotaxane formation.

strated coupling interactions between the aromatic protons of the species N4 and those of the thread (T2a). It was again found that the association process depended strongly on the nature of the anion template, with chloride providing the strongest association constants, and hexafluorophosphate leading to no appreciable perturbations in the ^{1}H NMR spectra of the species involved.

3.2. Anion templated pseudorotaxane formation

Having demonstrated the potential for anions to direct the formation of orthogonal complexes, it was desirable to use this new methodology for the formation of threaded species, namely pseudorotaxanes (Fig. 15). This necessitated the design and synthesis of new macrocyclic ligands M1–M4 (Fig. 16), which contained the design features already found to be of paramount importance in orthogonal complex assembly. The utilisation of anion recognition coupled with the secondary interactions provided by the π-stacking hydroquinone rings and the hydrogen bond donating ether loop should, it was postulated, lead to pseudorotaxane formation. The assembly process could also be assisted by the incorporation of these motifs into a macrocycle due to preorganisation effects.

In an analogous manner to that outlined above, the association of the ion pair species T1a with the macrocycle M1 was shown [109]. Pseudorotaxane formation could be inferred from the results of ^{1}H NMR spectroscopic titrations in acetone-d_6. It was found that, in the presence of a suitable anion template, threading could indeed be said to occur. Initially, this was inferred from the changes in chemical shift observed (Fig. 17). The peaks corresponding to the amide and isophthalyl protons of the macrocycle M1 were observed to shift downfield, indicating binding of the anion through hydrogen bonding. Simultaneous upfield shifts in the amide and pyridyl protons of the thread T1a indicated that the thread–anion interaction was somewhat weakened, implying competitive coordination of the anion template. Further support for pseudorotaxane formation could be gleaned from a consideration of the protons involved in secondary interactions during threading. Of specific interest were the changes in chemical shift of the signals arising from the thread pyridinium protons and the macrocycle hydroquinone protons. Both sets of signals demonstrated significant upfield shifts consistent with the formation of a pseudorotaxane species wherein π–π stacking is in operation. Furthermore, the emergence of a charge transfer band in the UV–vis spectrum of T1a.M1 was observed in acetone, where no such band exists in either of the free components. As with orthogonal complex formation, this observation was consistent with the existence of a π-stacked species. Importantly, the nature of the anion template controlled the degree of pseudorotaxane formation in acetone-d_6 (Table 2), with the most efficient template proving to be chloride (T1a), as expected, with only very weak association observed for the non-coordinating hexafluorophosphate (T1d). Unambiguous evidence for the existence of the interlocked species in the solid state was provided by the single crystal X-ray structure of the supermolecule T1a.M1, in which the pyridinium ring resides between the macrocycle hydroquinone units, the chloride is coordinated by both anion binding fragments, and the expected CH–O hydrogen bond interactions are observed (Fig. 18).



M1 M2 M3 M4

Fig. 16. New macrocycles M1–M4.

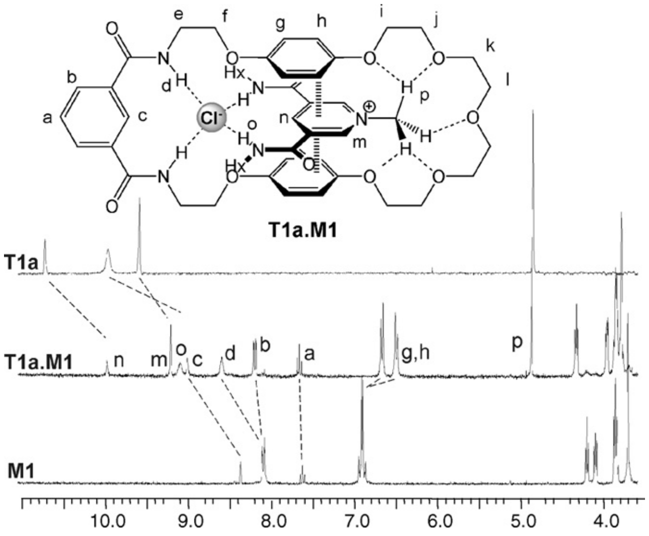


Fig. 17. ^{1}H NMR shift changes on T1a.M1 [2]-pseudorotaxane formation in acetone-d_6 at 298 K.

The formation of a large variety of pseudorotaxane species based on combinations of different macrocyclic and thread units proved possible in acetone [112,113]. The key differences

Table 2
^{1}H NMR derived association constants and free energies of complexation for the interaction T1 with M1 in acetone-d_6 at 298 K

Complex	K_{ass} (M^{-1})	$-\Delta G$ (kJ mol^{-1})
T1a.M1	2400	19.3
T1b.M1	700	16.2
T1c.M1	65	10.3
T1d.M1	35	8.8

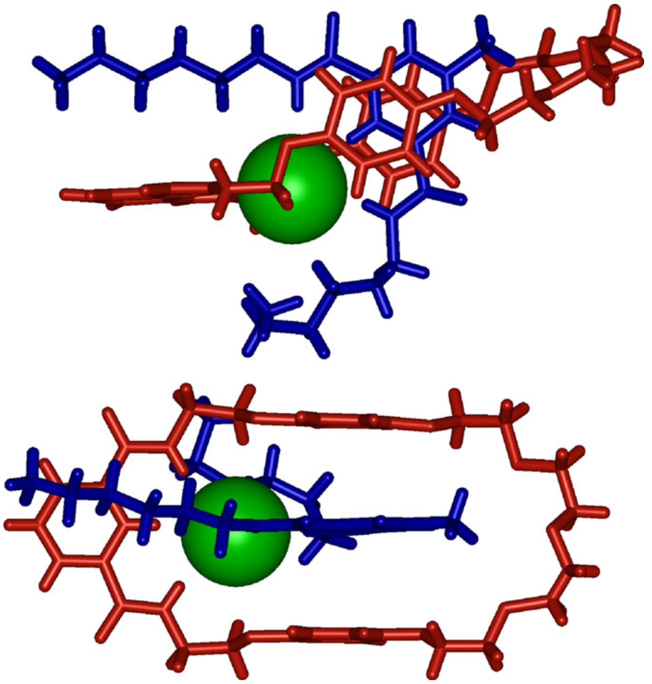
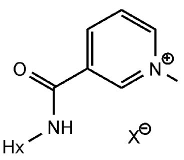


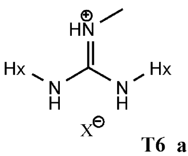
Fig. 18. Two views of the single X-ray crystal structure of T1a.M1. Chloride is represented as a space-filling sphere. Reprinted with permission from Ref. [109]. Copyright Wiley-VCH, 2001.

between the macrocycles M2–M4 lie in the differing polyether chain lengths. A range of possible thread systems were demonstrated to undergo threading into these macrocycles. These threads included pyridinium (T1), imidazolium (T3), benzimidazolium (T4), nicotinamide (T5) and guanidinium (T6) based systems (Fig. 19). Once again, the threading event was found to depend strongly on the anion template – with the association constants of pseudorotaxane formation increasing in the order $Cl^- > Br^- > I^-$. Little or no evidence of threading was observed when the thread counterion was hexafluorophosphate.

There were also found to be significant differences in the stability constants of threading dependent on the macrocycle ring size. This observation is consistent with the importance of the second-sphere coordination interactions outlined above. For example, in the cases of the pyridinium and nicotinamide-based thread systems (Fig. 20), the chloride-templated pseudorotaxane stability constants in acetone-d_6 were found to vary with macrocycle size in the order M4 < M3 < M2 (Table 3). This may readily be explained by the fact that the entropy deficit associated with pseudorotaxane formation for the larger systems will be greater. These inferences were confirmed by the results of isothermal calorimetry experiments, which show that the formation of pseudorotaxanes T1a.M2 and T1a.M3 was enthalpically driven, with the latter system being more enthalpically favoured and entropically disfavoured. This second observation is consistent with the loss of more degrees of freedom in the larger macrocycle.

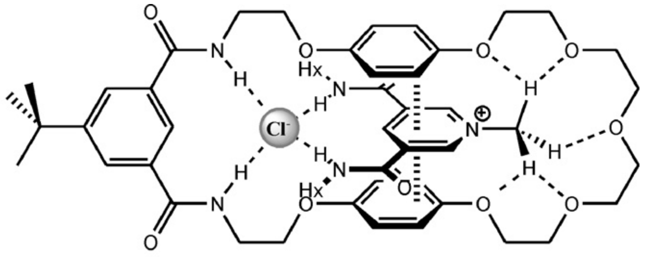


T5a, X = Cl
b, X = Br
c, X = I
d, X = PF_6

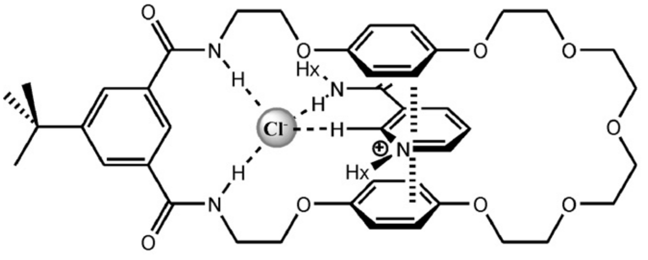


T6 a, X = Cl
b, X = Br
c, X = I
d, X = PF_6

Fig. 19. Threads T5 and T6.



T1a.M3



T5a.M3

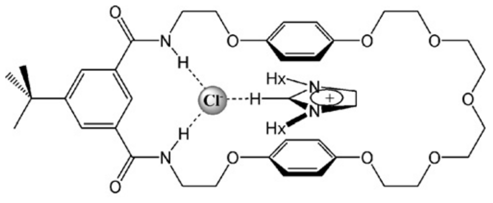
Fig. 20. Pyridinium- and nicotinamide-based pseudorotaxanes.

There are also salient trends in the pseudorotaxane stability constants for differing thread systems, which arise due to a combination of the strength of thread-anion pairing and second-sphere coordination interactions. For example, the pyridinium threads T1a and T1b form stronger complexes than their nicotinamide (T5) analogues in acetone-d_6, due to the presence of secondary N^+-CH_3· · ·polyether oxygen stabilising interactions. This illustrates the importance of these interactions in assisting the anion templation event. A consideration of the trends in the stability constants of the other thread systems (T3, T4 and T6) is complicated by the weaker anion-thread ion-pair association constants inherent in these systems (Figs. 21 and 22). Unlike the nicotinamide and pyridinium systems, the templating anion is not so strongly associated with these threads in the solvent of interest (For T3d K_{ass} for chloride association is 2000 M^{-1} in acetone-d_6), due to their diminished hydrogen bond donating ability. The macrocycles could therefore compete for the anion, and a more detailed consideration of the solution equilibria was

Table 3
^1H NMR derived association constants (K_{ass}, M^{-1}) for pseudorotaxane formation for a range of macrocycles and strongly ion-paired threads, in acetone-d_6 at 298 K

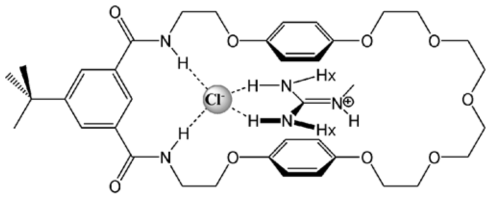
	T1			T5		
	T1a	T1b	T1c	T5a	T5b	T5c
M2	9500	610	40	1900	200	65
M3	2400	700	65	950	240	40
M4	980	120	40	320	180	50

No interaction was observed for T1d or T5d with any macrocycle.



T3a.M3

Fig. 21. Imidazolium-based pseudorotaxane formation.



T6a.M3

Fig. 22. Uronium-based pseudorotaxane formation.

Table 4

^{1}H NMR derived association constants (K_{ipc}, M^{-1}) for pseudorotaxane formation for a range of macrocycles and weakly ion-paired threads, in acetone-d$_6$ at 298 K

	T3			T4		
	T3a	T3b	T3c	T4a	T4b	T4c
M2	400	190	10	320	240	80
M3	500	300	10	250	230	90
M4	230	10	10	200	110	10

The values quoted are corrected so as to allow for competing anion sequestration. No interaction was observed for T3d or T4d with any macrocycle.

therefore necessary, to reflect the fact that a considerable amount of ‘free’ anion is present during any threading experiment – it was not suitable to presume that the thread would ‘follow’ the templating anion into the macrocyclic cavity. An analysis of the concentration dependence of the association process and monitoring of the hydroquinone perturbations of the macrocycle ring gave corrected acetone-d$_6$ association constants which were a measure only of the threading event (Table 4), and not of anion sequestration by the macrocyclic species. The resulting stability constant values for T3 and T4 indicate that the threading event is significantly less favoured than for T1 or T5, due to a combination of their reduced affinity for the anionic template and reduced second-sphere interactions, the latter of which also explains the relative invariance of association strength of T3-4 with macrocycle ring size. It is also notable that the benzimidazolium thread T4 associates more weakly than does T3, due to either less effective secondary stabilising interactions, or a greater entropic deficit on binding.

Evidence for the threading of the guanidinium systems T6 through M2–M4 could not be inferred directly from the observed ^{1}H NMR shifts in acetone-d$_6$ on mixing thread and macrocycle; instead NOE experiments were utilised to demonstrate a strong coupling interaction between the macrocyclic hydroquinone protons and the guanidinium *N*-methyl and NHCH$_2$ protons, suggesting that the thread was indeed residing in the cavity (Fig. 22).

It furthermore proved possible to grow X-ray diffraction grade single crystals of a number of these assemblies, namely T1a.M2, T1a.M4, T1b.M2 and T5a.M3 (Fig. 23). In each case, the supermolecule was shown to adopt the desired threaded geometry, with the anion residing in the binding cleft of both the

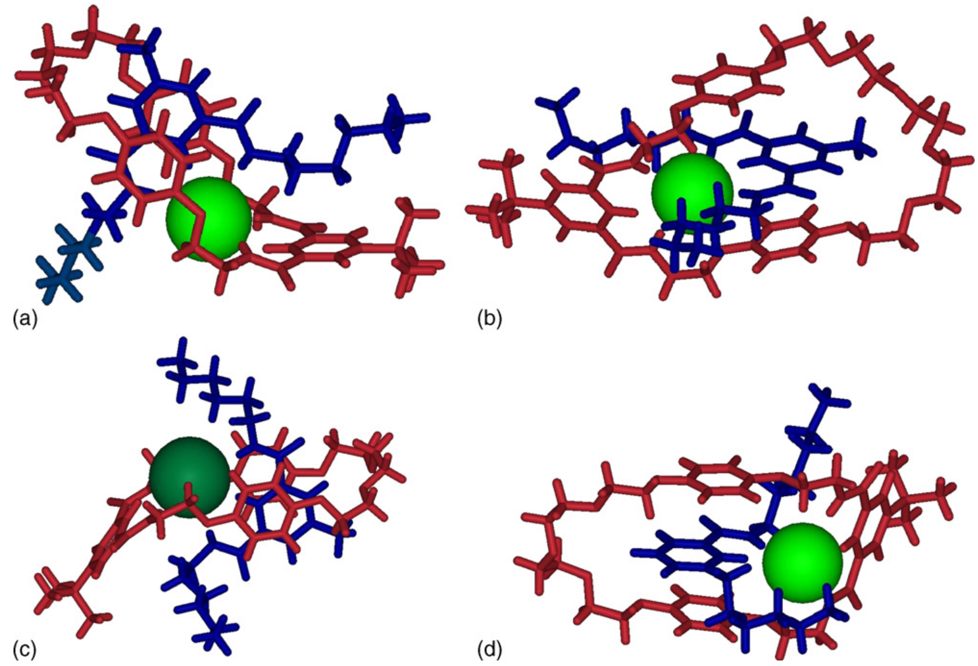


Fig. 23. Single X-ray-crystal structures of [2]-pseudorotaxanes. (a) T1a.M2, (b) T1a.M4, (c) T1b.M2, and (d) T5a.M3. Templating halide anions are represented as a green space-filling sphere, the macrocycle is red and the thread blue in each case. Reprinted with permission from Ref. [113]. Copyright 2005 American Chemical Society.

thread and macrocycle, and the cationic thread component penetrating the macrocycle. Although the exact geometries of the anion and thread differ from structure to structure, the expected hydrogen bond and π–π stacking interactions are observed for all systems.

The potential for a new discrete anion-templation methodology to provide a pathway to orthogonal complex and pseudorotaxane systems was thus established, through the demonstration of threading in a wide range of systems, using a variety of techniques. It was highly desirable, however, to extend this methodology towards more practical applications, both in its exploitation for the formation of mechanically interlocked architectures such as catenanes and rotaxanes, and the generation of systems with novel behaviours which could be mediated by the nature of the anion template.

4. Exploitation of anion templation: Formation of mechanically interlocked species

Having demonstrated the feasibility of using anions to direct the assembly of orthogonal complexes and pseudorotaxanes, it was hoped that the same methodology would prove readily applicable to the synthesis of permanently interlocked rotaxane and catenane species. As mentioned earlier, anionic substrates have received little attention as potential templates in the formation of interlocked molecules, due to their varying geometries, low charge/radius ratios and pH dependence.

Three main strategies can be envisaged for the template-directed formation of a [2]-rotaxane (Fig. 24). In the first 'stoppering' strategy, rotaxane synthesis may be effected by attachment of a suitable bulky group to the thread termini of a intermediate pseudorotaxane system [114,115]. In the second, the rotaxane derivative is formed by the 'clipping' of one component of a tetrahedral complex around another, which has the bulky end groups already in place [116,117]. Finally, rotaxane formation may be encouraged by a 'slippage' stratagem, whereby the stoppered thread and macrocycle are mixed in situ, then heated to encourage the force the sterically unfavourable formation of a rotaxane [118,119]. All three methods have been widely used previously, but for synthetic reasons the clipping strategy was preferred in this case.

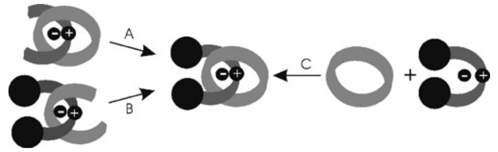
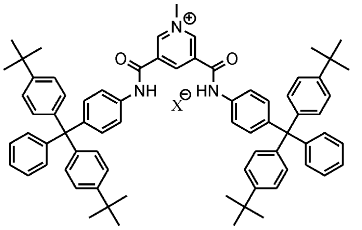


Fig. 24. Different approaches to [2]-rotaxane synthesis: (A) stoppering; (B) clipping; (C) slippage.



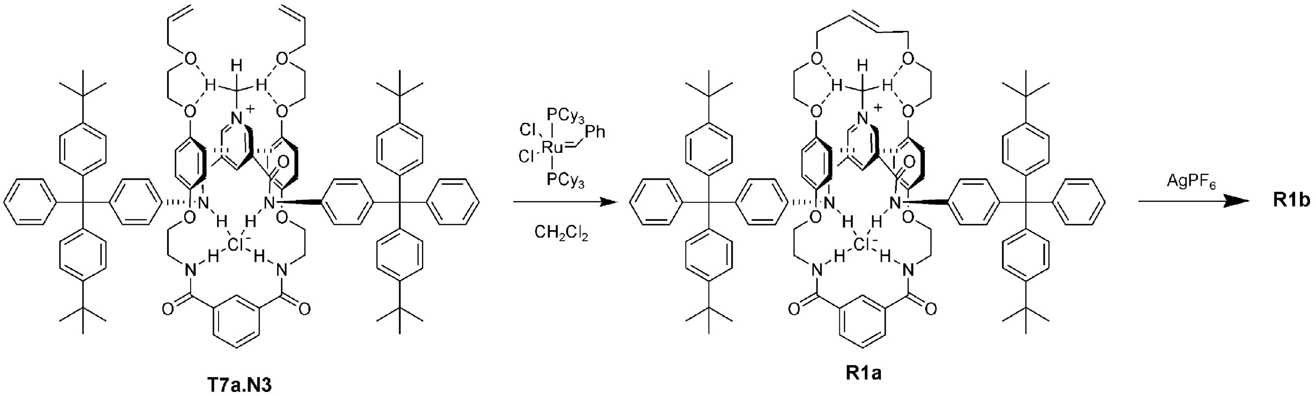
T7a, X = Cl
b, X = Br
c, X = I
d, X = PF_6

Fig. 25. Dumbbell shaped ion-paired thread T7.

Two key adaptations of the existing components were necessary in order to allow the formation of new [2]-rotaxane systems [110]. The neutral system N3 was, as detailed above, shown to form complexes with the thread T1, with the association depending on the nature of the anion template, as well as being enhanced by the presence of both the electron rich, π-stacking capable, hydroquinone rings and the hydrogen bond accepting ether oxygen units, due to second sphere coordination of the thread ion pair. A further design feature of N3, not mentioned above, is the inclusion of terminal allyl moieties which, under Grubbs' catalysed ring closing metathesis conditions [120], should close to give macrocyclic species. When a suitable ion-paired thread is bound by N3, it was postulated that this ring closure process would lead to a new rotaxane species.

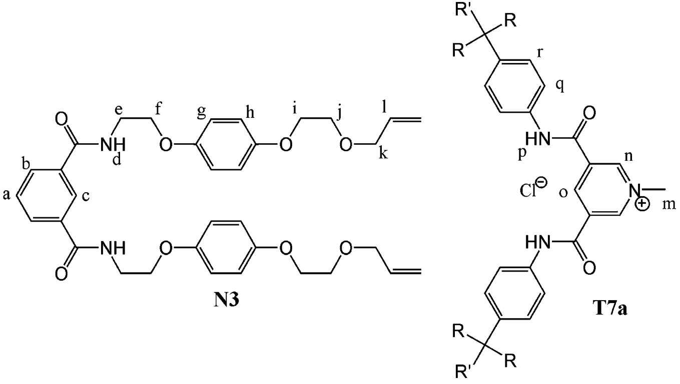
It was therefore also necessary to design a new thread system which incorporated both the strongly associated pyridinium ion-pair unit, but also bulky stoppering groups to prevent dethreading; if the macrocycle is capable of 'slipping' off of the thread then the species would not be a rotaxane, but a pseudorotaxane (although the distinction between the two is often far from clear [121]). To this end, the dumbbell-shaped thread T7 was designed and synthesised (Fig. 25).

The association of T7a and N3 to form the supermolecule T7a.N3 occurred by analogy with the formation of the species T1a.N3 outlined in the previous section (Scheme 4). It is



Scheme 4. Formation of [2]-rotaxane R1 by an anion-directed ring closing metathesis procedure.

Table 5
Important differences in the ^{1}H NMR spectra of T7a, N3 and R1a in $CDCl_3$ at 298 K, indicating the interlocked nature of the [2]-rotaxane product



	a	b	c	d	g, h	l
N3	7.47	7.91	8.20	6.90	6.82	5.92 (m)
R1a	7.16	8.00	8.89	9.14	6.40/6.18	6.02
$\Delta\delta$ (ppm)	−0.31	0.09	0.69	2.24	−0.42/−0.64	0.10

	m	n	o	p	q
T7a	3.79	8.77	10.65	10.92	7.80
R1a	4.37	8.55	9.66	10.31	7.78
$\Delta\delta$ (ppm)	0.58	−0.22	−0.99	−0.61	−0.02

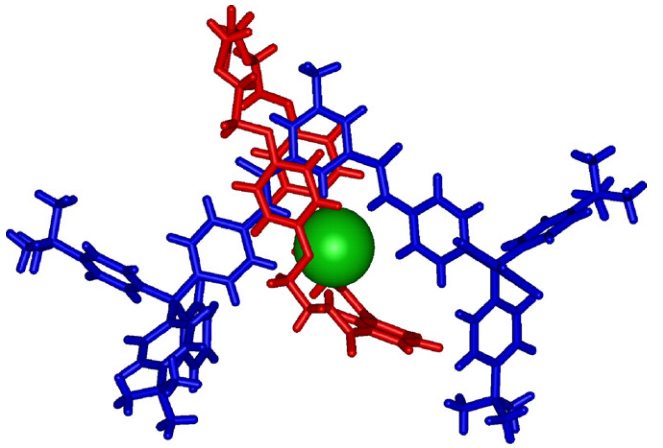


Fig. 26. Single crystal X-ray structure of [2]-rotaxane R1a. Chloride is represented as a space-filling sphere. Reprinted with permission from Ref. [110]. Copyright 2002 American Chemical Society.

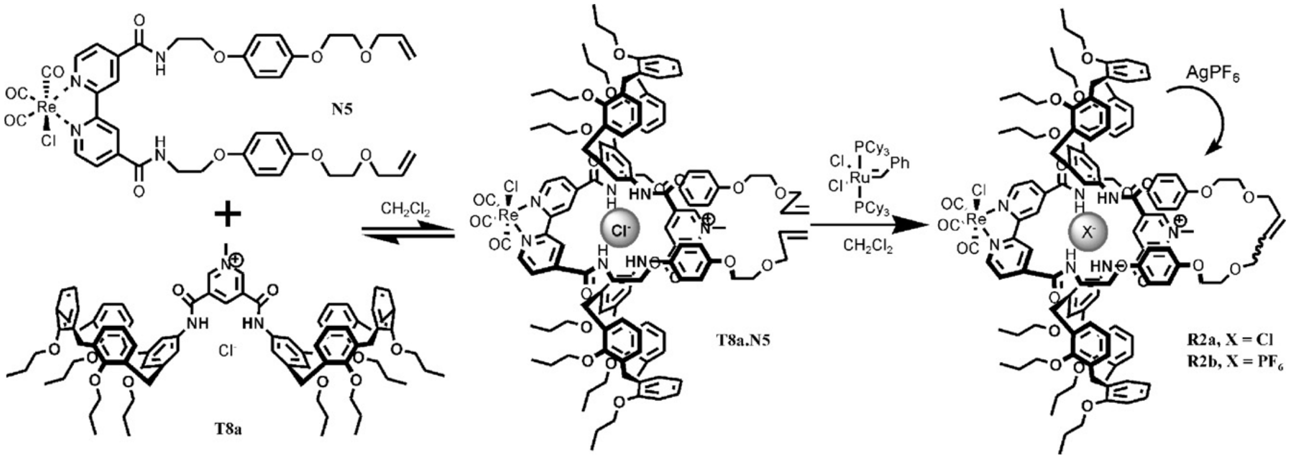
noteworthy in this case that the second sphere coordination interactions which lent greater stability to the complex T1a.N3 here, as well as supporting the primary chloride recognition process, facilitate the ring closure process around the ion pair by directing the allyl-terminated arms into close proximity. The application of Grubbs ring closing metathesis conditions, in CH_2Cl_2, to the complex T7a.N3 did indeed give the expected [2]-rotaxane product R1a in 47% yield. Only the *trans* isomer was detected, presumably as a result of the reaction proceeding under thermodynamic control. Vitally, the success of the rotaxane assembly process depended entirely on the nature of the anionic template. For the pyridinium threads T7b-d, when the counterion was bromide, iodide or hexafluorophosphate, no [2]-rotaxane product was observed to form whatsoever, presumably due to the diminished affinity of N3 for these thread systems. These crucial observations underline the importance of the anion template in effecting interlocked molecule formation.

The nature of the interlocked species could be inferred from several important observations. Inspection of the ^{1}H NMR spectra of the interlocked and 'free' species in $CDCl_3$ reveals similar differences to those seen for orthogonal complex and pseudorotaxane species (Table 5). The amide and their mutually ortho aromatic protons of the macrocyclic species are shifted considerably downfield, indicating coordination of the anionic substrate – this observation is reinforced by similar upfield shifts in the amide and *para*-pyridinium protons of the thread species, due to polarisation of the chloride anion as a result of its binding to the macrocycle. Furthermore, there are considerable upfield shifts in both the macrocycle hydroquinone and thread *ortho*-pyridinium protons, indicative of extensive π-stacking in R1a. Finally, the presence of C–H···O interactions between the methyl group of the pyridinium thread and the ether units of the macrocycle are supported by the downfield shift of the thread methyl protons.

Further evidence for the interlocked nature of the rotaxane species could be gained from the solid state. The single crystal X-ray structure of R1a revealed the macrocycle encircling the thread ion-pair to give the [2]-rotaxane species (Fig. 26). This crystal structure reveals the coordination of the chloride anion by both the thread and the macrocycle, as expected, although the macrocycle is fairly distorted. The structure also provides evidence for the existence of the π-stacking and hydrogen bonding interactions outlined above.

As a key measure of success for this anion template strategy, it should prove possible to remove the template to leave the assembled rotaxane species entirely intact. This proved possible, with the replacement of the chloride anion with hexafluorophosphate providing the new rotaxane species R1b, the interlocked nature of which could be inferred from its ^{1}H NMR spectrum, with for example the π-stacking interactions consistent with the thread residing in the macrocycle still present. This underlined the success of the chloride templating strategy, as the new species R1b could not be synthesised directly from T7d and N3, and thus should, by analogy with the pseudorotaxane systems, just fall apart, but is prevented from doing so by the bulky stopper groups. Thus it seemed that a general strategy for chloride anion templation of new interlocked species had been developed.

The successful synthesis of a further [2]-rotaxane system incorporating a luminescent rhenium bipyridyl fragment provided further evidence for the use of chloride templation for the formation of new architectures [122]. This necessitated the synthesis of both a new neutral macrocycle precursor N5 and a calixarene-stoppered thread ion pair T8a (Scheme 5). These extremely bulky stopper groups were required due to the large nature of the macrocyclic derivative produced, as a result of the bipyridyl spacer fragment. The supermolecule species T8a.N5 was shown to exist in $CDCl_3$ solution by methods similar to those outlined previously. Grubbs' catalysed ring closing metathesis carried out on this supermolecule intermediate in CH_2Cl_2 solution gave the [2]rotaxane species R2a in 21% yield. The



Scheme 5. Anion-templated synthesis of [2]-rotaxane R2.

interlocked nature of this system could be inferred from comparison of the ^{1}H NMR spectra of R2a, T8, N5, and T8a.N5 in $CDCl_3$. Interestingly, the ^{13}C and ^{1}H NMR signals arising from the calyx[4]arene units demonstrated that the two stoppers are magnetically inequivalent in the rotaxane species, whereas they are not in the orthogonal complex. The cause of this phenomenon is presumably the twisting of the macrocycle induced by the bipyridyl fragment. Once again, exchange of the chloride anion of R2a for hexafluorophosphate using $AgPF_6$ to give R2b leaves the rotaxane assembly intact. The synthesis of R2 provided further support for the general applicability of this anion templation methodology.

A slight modulation of the synthetic strategy employed for rotaxane formation suggests the possibility for the formation of [2]- and higher order catenane species [123]. If, rather than 'clipping' an orthogonal complex, a pseudorotaxane supermolecule intermediate is utilised, then the species resulting would be a catenane (Fig. 27) [124]. This required the synthesis of the new thread molecule T9a, which was designed to complement the binding sites of macrocycle M1, with the usual tight ion-pair, π-stacking and hydrogen bonding capabilities, as well as allyl termini capable of ring closing metathesis. Assembly of

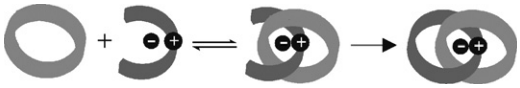
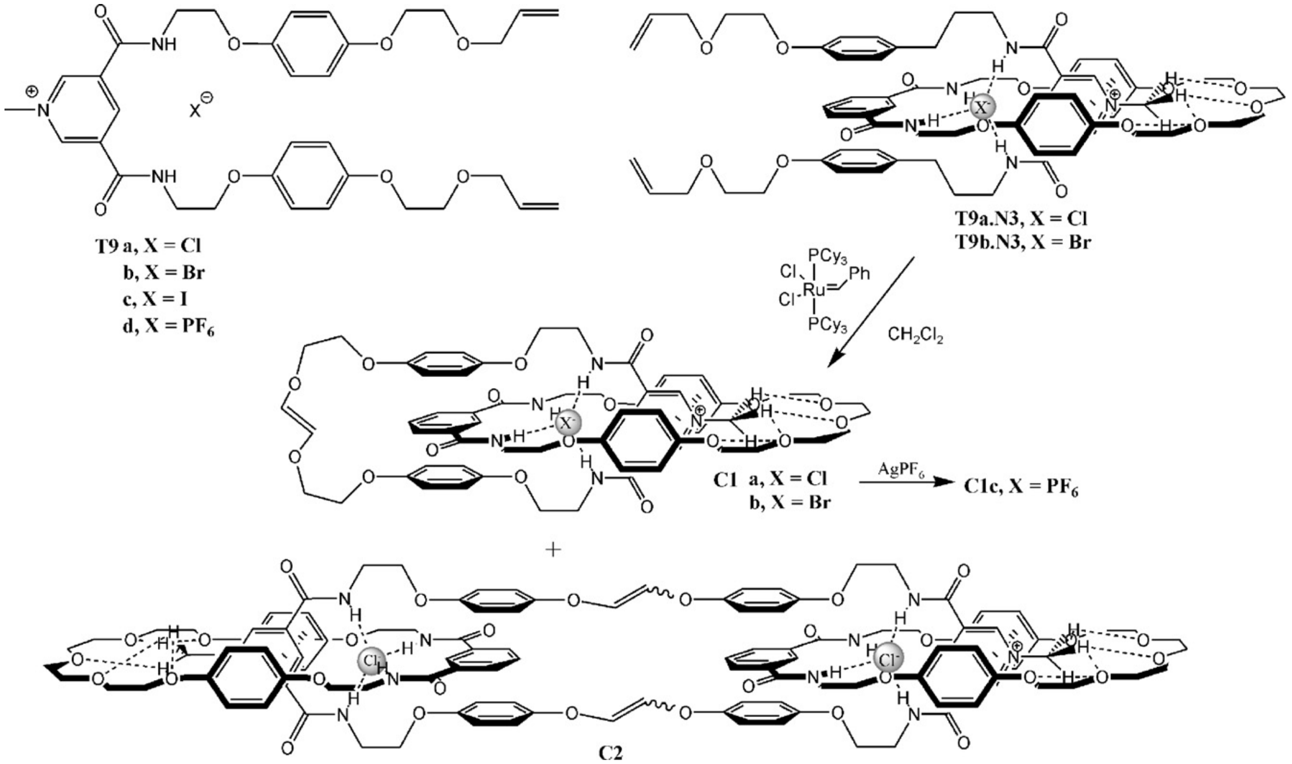


Fig. 27. Anion templated synthesis of [2]-catenane.



Scheme 6. Anion templated synthesis of [2]- and [3]-catenane species C1 and C2.

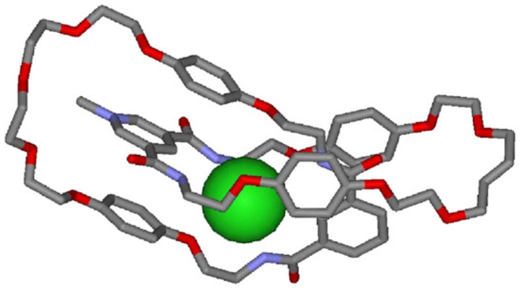


Fig. 28. Single crystal X-ray structure of the [2]-catenane C1a. Chloride is represented as a space-filling sphere. Hydrogens have been omitted for clarity. Reprinted with permission from Ref. [124]. Copyright 2004 American Chemical Society.

the pseudorotaxane T9a.M1 in CH_2Cl_2, followed by Grubbs catalysed ring closing metathesis, gave not only the expected [2]-catenane species C1a in 45% yield, but also the [3]-catenane C2 in <5% yield. No catenane product was isolated when the templating ion was iodide (T9c), or hexafluorophosphate (T9d), and only a very small yield (6%) of catenane C1b could be prepared from the assembly of T9b and M1 (Scheme 6). This once again highlights the crucial importance of the templating anion in the assembly process. Furthermore, as with the [2]-rotaxane species R1 and R2, replacement of the chloride anion of C1a with hexafluorophosphate proved possible, with the [2]-catenane C1c retaining the structure of the original templated motif.

Evidence for the existence of these catenanes could be obtained from studies in solution and the solid state. The interactions in these systems are directly analogous to those in the [2]-rotaxanes considered above, and corresponding evidence for catenane formation and structure can be taken from the ^1H NMR spectra. The structures of C1a and C1b are very similar, indicating that the catenane structure is almost invariant with different counterions. Furthermore, the single crystal X-ray structure of C1a was determined, proving the interpenetrated nature of the structure, the presence of the anion in the binding clefts of both macrocycles, and secondary π-stacking and hydrogen bonding interactions (Fig. 28).

It was thus demonstrated that the ability of anions to template supermolecule formation, such as orthogonal complexes and pseudorotaxanes, could be utilised through a clipping methodology to form new permanently interlocked molecules, such as rotaxane and catenane species. The interlocked nature of these species could be inferred from both solution and solid state studies. It was further hoped that these new, anion templated structures would exhibit properties that were dependent on the nature of the anion template.

5. Exploitation of anion templation: Interlocked architectures for selective sensing and binding applications

The development of novel units for the selective binding and sensing of substrates has received a great deal of attention in past years. Recent efforts focused particularly on the development of new anion binding motifs have yielded a variety of systems suitable for a wide range of applications [2–6]. It was hoped that these new interlocked species could further add to this panoply of receptors, with the particular benefit that the binding properties would be significantly mediated by the nature of the anionic template, and to incorporate suitable sensing functionality for anion and thread detection.

5.1. Formation of unique binding pockets in interlocked molecules

A key motivation for the formation of the new rotaxane and catenane derivatives R1 and C1 (Section 4) was the possibility of generating new architectures which derived a functionality dependent on the anion templation event, which was furthermore independent of either of the non-interlocked precursors. It was expected that the cavities resulting in these molecules, on chloride template removal, would retain their preference for the chloride anion. As explained above, removal of the chloride template to form the new systems C1c and R1b proved possible, whilst leaving the interlocked structure of the system intact.

A series of ^1H NMR titration experiments were therefore conducted in order to investigate the postulated anion binding properties of these systems, and to compare their behaviour with those of the 'free' threads, T7d and T9d [110,124]. In a 1:1 mixture of $CDCl_3$ and CD_3OD, it was found that these threads demonstrated an anion binding selectivity trend based primarily on the oxobasicity of the anions (Table 6). Thus, T7d bound anions with association constants in the order $AcO^- \gg H_2PO_4^- > Cl^-$. Similarly, T9d demonstrated strong binding for both AcO^- and $H_2PO_4^-$, but a weaker affinity for chloride. However, both of the interlocked systems C1c and R1b demonstrate a reversal in these anion binding affinites; that is, they bound with a selectivity trend $Cl^- > H_2PO_4^- > AcO^-$ in the same solvent mixture. This dramatic alteration in the binding properties is thought to be a result of the formation of a unique hydrogen bond donating pocket by the diamide clefts of the cation and macrocycle in the interlocked systems C1c and R1b, defined by the topology of these systems. The formation of this pocket favours the complexation of the chloride anion, which is of complementary size and shape, and disfavours the binding of larger anions. These larger anions must either force a conformational change to the superstructure, or interact peripherally, to bind. In either of these cases, it is unlikely that the

Table 6
^1H NMR derived association constants (M^{-1}) for various anions with threads T7d and T1d, rotaxane R1b, and catenane C1c

Anion	Receptor			
	T7d	R1b	T9d	C1c
Cl^-	$K_{11} = 125$	$K_{11} = 1130$	$K_{11} = 230$	$K_{11} = 730$
$H_2PO_4^-$	$K_{11} = 260$	$K_{11} = 300$	$K_{11} = 1360$ $K_{12} = 370$	$K_{11} = 480$ $K_{12} = 520$
AcO^-	$K_{11} = 22000$ $K_{12} = 140$	$K_{11} = 100$ $K_{12} = 40$	$K_{11} = 1500$ $K_{12} = 345$	$K_{11} = 230$

Solvent—1:1 $CD_3OD:CDCl_3$.

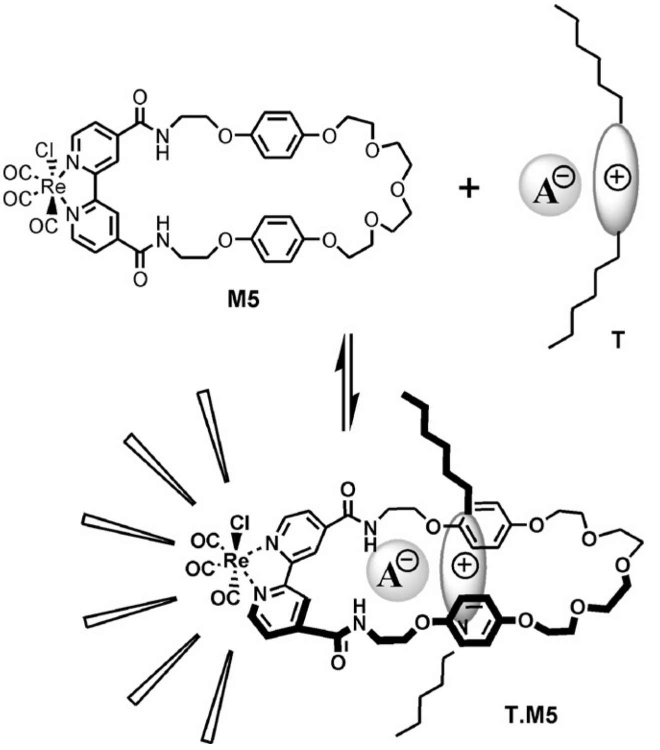
anion would be able to access the full complement of hydrogen bond donating groups available.

It therefore appeared that this anion template strategy did indeed provide a route to systems with new functionality, which depended largely on the nature of the template used. The unique nature of the binding site of these new catenane and rotaxane systems stemmed from the provision of an enclosed hydrogen bond donating pocket, which is complementary to anions similar to the original template, but inaccessible to other species.

5.2. Incorporation of luminescent sensing fragments to detect pseudorotaxane formation and rotaxane anion binding

There has been much recent interest in the efficient signalling of anion recognition events by optical and electrochemical means [125]. These sensing systems employ signalling moieties that partly make up, or lie in close proximity to, the anion binding sensor such that the recognition event perturbs the optical or electrochemical properties of the active subunit. Surprisingly, the exploration of interlocked architectures as scaffolds for anion sensing remains rather unexplored. Through the incorporation of a suitable luminescent anion sensing fragment, the optical sensing of pseudorotaxane formation could be achieved (Scheme 7). Furthermore, this sensing fragment could be incorporated into related anion-templated rotaxane systems in order to signal the unique binding properties of the resulting three-dimensional cavity.

The rhenium-bipyridyl functionality of macrocycle M5 was designed to provide an optical signal for anion binding and thus, when the anion was paired to a suitable thread, for pseudorotaxane formation [126]. This rhenium based fragment has previously been reported to provide a reporter group for anion sensing [127]. M5 was shown by ^{1}H NMR studies in acetone-d_6 to bind halide anions in the expected basicity trend, that is $Cl^- > Br^- > I^-$, with no affinity for PF_6^-. This trend is borne out in the strength of association with T1a-d in acetone d_6, again demonstrated by ^{1}H NMR titration experiments, showing that the strength of pseudorotaxane formation was controlled by the affinity of M5 for the thread counteranion (Table 7). The ^{1}H NMR spectrum of T1a.M5 illustrates the expected primary and secondary interactions of M5 with T1a, as detailed in Section 2. M5 was also demonstrated to undergo threading with T3-5a, with strong complexes forming in all cases in acetone-d_6 solution.



Scheme 7. Luminescent response to pseudorotaxane formation by M5.

Table 7
^{1}H NMR derived association constants (M^{-1}) for the interaction of T1 with M5 in acetone-d_6 at 298 K

	T1a	T1b	T1c	T1d
M5	1500	1200	140	0

Further evidence for the interpenetrated nature of the supermolecule T1a.M5 was attained from the single crystal X-ray structure (Fig. 29), which shows the interlocked nature of the components in which the macrocycle encircles the ion-pair, as well as the occupation by the chloride anion of the resulting hydrogen bond-donating pocket.It furthermore proved possible to signal the threading process by monitoring the ^{3}MLCT luminescent emission band of M5 on the addition of threads T1a and T3-5a in acetone. As was hoped, there was a significant enhancement in the emission observed on pseudorotaxane formation (Fig. 30), probably due to an increased rigidity of the macrocyclic receptor, and thus a disfavouring of the non-radiative decay processes [128]. Thus the optical sensing of interpenetrated architecture formation had been achieved.

Having demonstrated the utility of luminescent fragments for the signalling of the interpenetration process, it was desired to use this property to signal the anion-binding event in an interlocked structure, and thus to further probe the nature of the unique hydrogen bond donating pocket formed on architecture formation. To this end, the previously detailed rotaxane system R2b was prepared (Scheme 5) [122]. As in the similar

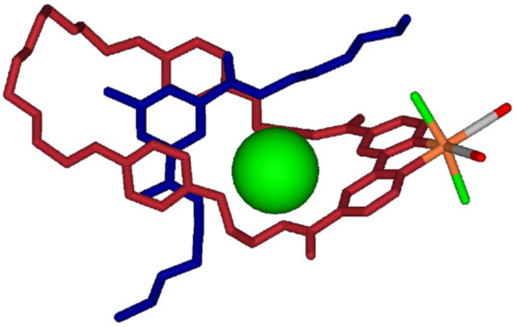


Fig. 29. Single X-ray crystal structure of T1a.M5. Hydrogens have been omitted for clarity. Reprinted from Ref. [126].

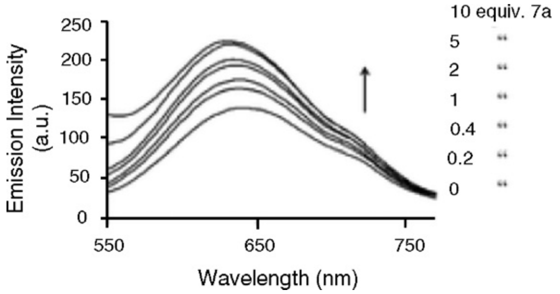
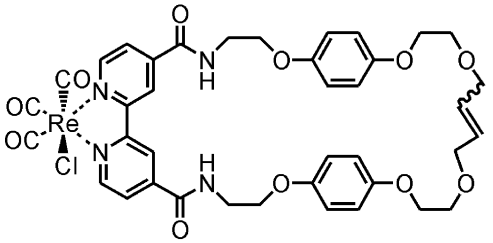


Fig. 30. Enhancement of ^{3}MLCT luminescent emission band of M5 on addition of T1a, in acetone at 298 K. Reprinted from Ref. [126].



M6

Fig. 31. Rhenium containing macrocycle M6.

species R1, this system has an encircled hydrogen bond donating pocket, with the key additional feature of a luminescent sensing fragment. The binding properties of R2b could then be compared, utilising fluorescent spectroscopy techniques, to those of the 'free' rhenium-containing rotaxane precursors N5 and M6 (Fig. 31).

Although ^{1}H NMR titration methods proved that R2b interacted strongly with chloride anions in acetone-d_6, the complexity of the spectra under study prevented accurate stability constant determination due to overlapping peaks. Luminescence spectroscopy, however, provided a readily accessible tool for the measurement of anion binding. The addition of Cl^-, NO_3^- and HSO_4^- anions to acetone solutions of N5, M6 and R2b demonstrated that all three systems sensed the presence of anions by an enhancement in their ^{3}MLCT emission intensities (Fig. 32), which is due again to a rigidification of the receptors interfering with the non-radiative decay pathways [128]. Luminescence titration experiments in acetone with these anionic substrates indicated that the components M6 and N5 demonstrated strong chloride selectivity, but that the rotaxane R2b exhibited a preference for hydrogensulphate binding (Table 8). This was attributed to the provision of a topologically complementary anion binding site for tetrahedral hydrogensulphate by the anion binding pocket of the rotaxane.

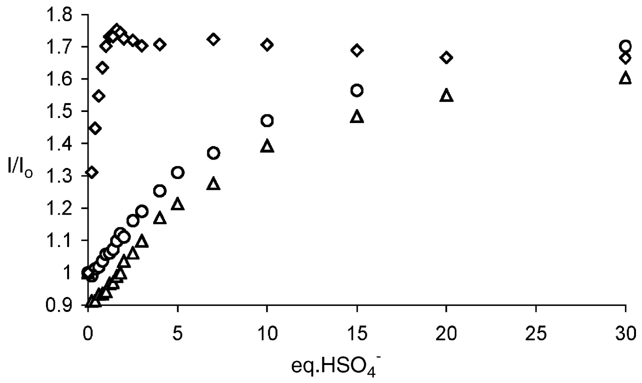


Fig. 32. Enhancement of ^{3}MLCT luminescent emission bands of N5, M6 and R2b on addition of TBAHSO$_4$, in acetone at 298 K. $\lambda_{exc} = 390$ nm. ○: N5; △: M6; ◇: R2b. Reprinted from Ref. [122].

Table 8
Luminescence spectroscopy derived association constants (M^{-1}) for various anions with neutral fragment N5, macrocycle M6 and rotaxane R2b

	Cl^-	HSO_4^-	NO_3^-
N5	3.1×10^5	3.5×10^3	1.8×10^3
M6	8.7×10^4	4.7×10^3	3.9×10^3
R2b	1.8×10^3	$>10^6$	5.1×10^4

Solvent: acetone.

Thus it has been shown that, through the incorporation of a suitable signalling unit, the distinctive anion binding properties of the anion-templated hydrogen bond donating pockets of the [2]-rotaxane R2b may be readily detected by optical means. It was furthermore shown that sensing fragments can be used to indicate the formation of interpenetrated superstructures. These observations hint at a much more general applicability for signalling motifs in interlocked architectures, both as a measure of interpenetration and as sensing units to indicate the unique binding properties of the resulting architectures.

6. Conclusions and future perspectives

This review has discussed the recent evolution of anion templation methodologies for the preparation of a range of novel systems. In particular, it has focused on the design and development of a discrete anion templation strategy for the fabrication of interpenetrated structures, based primarily on halide anion recognition coupled with ion-pairing. This strategy represents a generally applicable method for the preparation of a wide range of architectures, including orthogonal molecular assemblies, pseudorotaxanes, rotaxanes, and catenanes, in which the nature of anionic template is critical. Furthermore, it provides a route to structures wherein the recognition and sensing properties depend on the nature of the original anionic template, due to the formation of a topologically unique, three dimensional anion binding cleft in the novel interlocked structure.

The potential for designed anion templation in both inorganic and organic synthesis remains largely untapped, however, particularly in comparison to the myriad systems synthesised by cationic and neutral templation strategies. As a greater understanding not only of the templation properties, but also of the recognition and sensing, of anionic substrates continues to emerge, there seems to be little barrier to vastly extending the contribution of the anion template to the synthesis of highly complex molecular systems, including those exhibiting sensing and molecular machine-like behaviour.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.ccr.2006.04.018.

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