

Concept transfer from the life sciences into materials science

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Abstract: The use of self-assembly processes, which are presided over by noncovalent bonding interactions, has led to the construction of a variety of mechanically-entwined and interlocked entities — namely, the so-called pseudorotaxanes, rotaxanes and catenanes — of nanometre size. Although these superstructures and structures are entirely unnatural in their forms, they have been constructed utilising approaches akin to those occurring in nature.

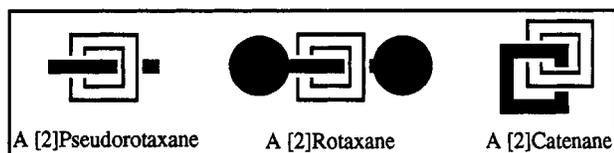
INTRODUCTION

In recent years, the rigidly-defined boundaries which once separated the chemical and life sciences, have become decidedly less visible. Increasingly, there has been considerably more interplay between laboratories in terms of *commodity transfer* — of, for example, chemical compounds and materials, and of equipment and experimental techniques — and *concept transfer* — that is, adapting and applying the recognition processes [1], employed by living systems in achieving their forms and fulfilling their functions, to the construction of chemical systems with well-defined forms and prescribed functions at a supramolecular [2], as well as a molecular, level [3]. However, the activity of concept transfer is one that has been far less developed and exploited than the practice of commodity transfer. Ironically, much of what passes as ‘natural products chemistry’ bears little resemblance to the processes which operate in the living world. For instance, the laboratory syntheses of natural products or the industrial preparation of biologically-active substances are usually performed using unnatural reagents, catalysts and solvents, and employing multistep syntheses relying upon protecting group strategies. By contrast, the methods used by nature for the preparation of its compounds and complexes are conceptually much different. Nature relies on the use of weak, noncovalent bonding interactions in recognition processes we refer to as self-assembly and self-organisation [1,3]. These weak interactions not only lead to the formation of living cells and help to sustain their functions, but they also preside over the formation of covalent bonds in reactions catalysed by enzymes.

The physical sciences are very much concerned today with the fabrication of nanostructures [4]. The approach of the physical scientist towards the creation of nanostructures is one of microfabrication using techniques such as photolithography [5]. There is a growing realisation that such approaches are becoming limited in their practicality as far as producing nanoscopically-sized entities is concerned [6]. For example, the current limit in resolution of a well-defined microfabricated structure is of the order of 10–100 nm [3]. The chemist, on the other hand, is well adapted to working with precise control of the shape and form of structures that are much smaller in size. However, in order to produce nanosystems chemically that are capable of exhibiting functions, the chemist has to enter the domain of the nanometre-sized world. Since the control over the form of molecules of such size is difficult, a new conceptual approach to make them is necessary. It is here where chemist can learn a lesson from the life sciences and utilise the noncovalent bond as a tool for the construction of well-defined mesomolecular superstructures in addition to highly organised molecular assemblies. And so, chemists must continue to learn about the recognition processes

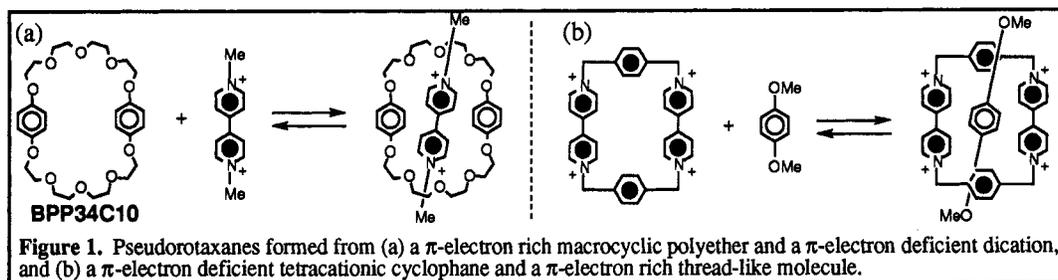
used in the natural world, such as self-assembly, self-organisation and self-replication, and then apply their knowledge towards the construction of supramolecular arrays and molecular assemblies from 'intelligent' atomic, molecular and ionic building blocks [7].

Our own approach to this field of investigation has been to study 'intelligent' subunits — molecules and ions — which contain the correct stereoelectronic information necessary to define good molecular recognition within a superstructure. Over the last decade, we have uncovered two versatile self-assembling systems which produce entwined and entangled supramolecular arrays (*e.g.* pseudorotaxanes) and interlocked molecular assemblies, such as rotaxanes and catenanes [8]. These entities are of considerable interest for us to study because, not only do they have considerable aesthetic appeal, but their degrees of entanglement and interlocking also make them candidates for the study of prototypical molecular-based switching devices. Additionally, they are extremely difficult entities to construct employing the techniques of traditional synthetic chemistry. As such, they have become particularly attractive targets to prepare using the self-assembly paradigm.

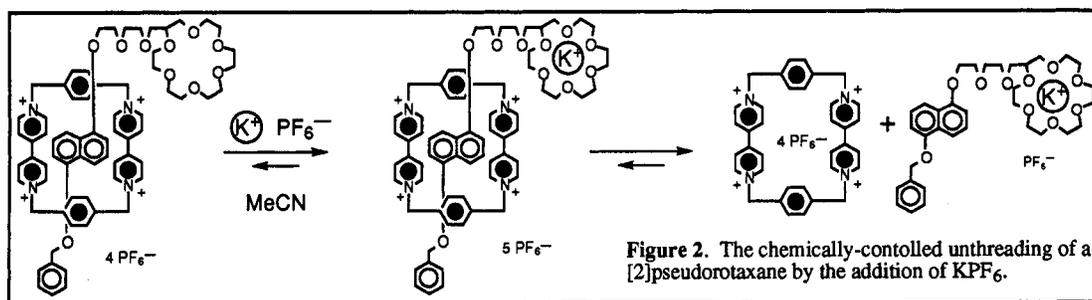


DONOR-ACCEPTOR COMPLEXES

The observation [9] that π -electron deficient bipyridinium (and related) dications form complexes with pseudorotaxane-like geometries in solution and in the solid state with π -electron rich macrocyclic polyethers, such as bis-*p*-phenylene[34]crown-10 (BPP34C10), led to the discovery [10] that the roles of the host and guest may be reversed, such that the π -electron rich and π -electron deficient units be incorporated in the thread-like and macrocyclic components, respectively, with the overall geometry of a pseudorotaxane being retained (Figure 1). These pseudorotaxanes are stabilised predominantly by charge



transfer, π - π stacking, [C-H... π] and hydrogen bonding interactions. The presence of charge transfer bands in their UV-VIS spectra imparts interesting photochemical properties upon these systems. For instance, [2]pseudorotaxanes constitute part of a simple molecular 'machine' in which threading and dethreading of the complex may be controlled by a photochemically-driven redox process [11]. Another photochromic switching device has been realised [12] in which the unthreading of a pseudorotaxane is



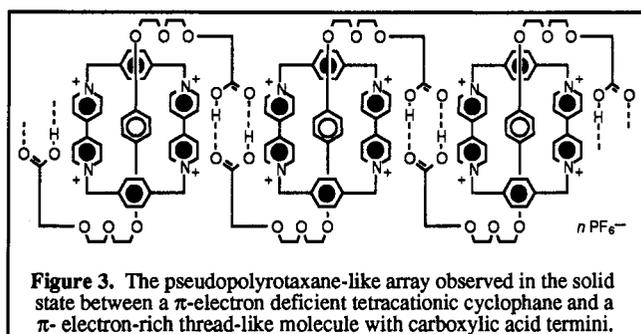


Figure 3. The pseudopolyrotaxane-like array observed in the solid state between a π -electron deficient tetracationic cyclophane and a π -electron-rich thread-like molecule with carboxylic acid termini.

controlled by the addition of metal ions which bind selectively with a macrocyclic polyether incorporated at the end of a thread-like component, thus facilitating expulsion of the thread from the bead as a result of electrostatic repulsions (Figure 2). The predictability and reliability of the formation of pseudorotaxanes upon mixing the requisite modules makes this donor-acceptor system a useful supramolecular synthon for the construction of highly ordered supramolecular arrays. Furthermore, mixing recognition motifs — by using the donor-acceptor synthon in conjunction with the carboxylic acid dimer synthon — results [13] in the formation of hydrogen-bonded pseudopolyrotaxane arrays such as $[A \cdot B^{4+}]_n$ in the solid state (Figure 3).

The fact that these systems form thermodynamically stable pseudorotaxane-like complexes may be exploited in the construction of mechanically-interlocked analogues, such as rotaxanes and catenanes [8]. Three

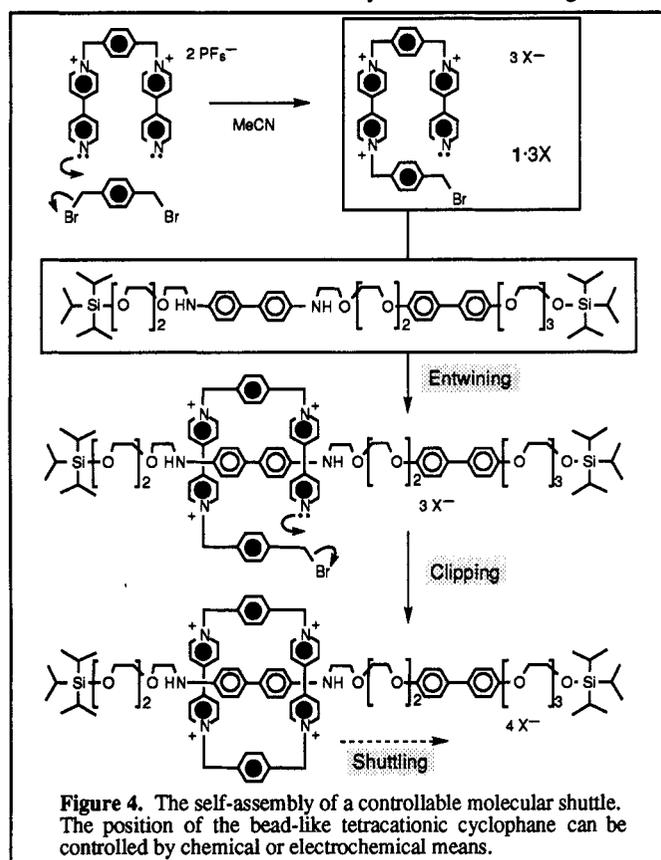
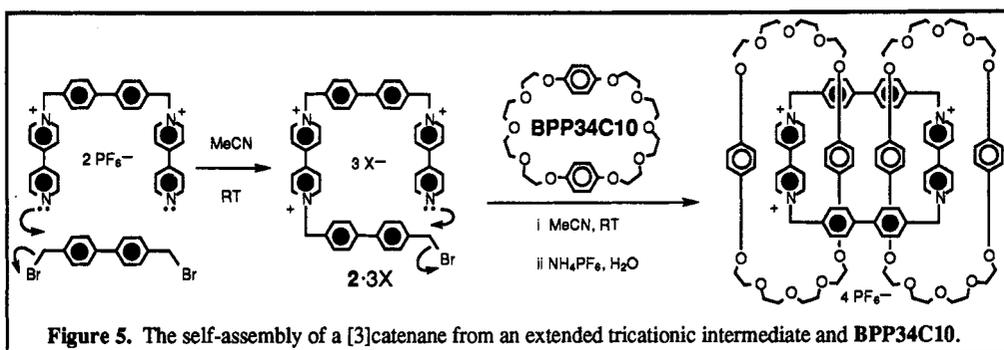


Figure 4. The self-assembly of a controllable molecular shuttle. The position of the bead-like tetracationic cyclophane can be controlled by chemical or electrochemical means.

successful approaches to rotaxanes have been uncovered — namely, threading-followed-by-stoppering, clipping and slipping. These approaches have been reviewed extensively elsewhere [14]. A particularly versatile approach is the clipping method in which a tricationic intermediate 1^{3+} undergoes cyclisation to a tetracationic cyclophane about the electron-rich rod of the dumbbell-shaped component. These approaches have led to the formation of a range of rotaxanes, including some in which the bead-like component shuttles between 'stations' contained along the rod of the dumbbell-shaped component [15]. If designed correctly, the shuttling properties — such as the preferred site of occupancy of the bead — may be controlled by external stimuli. For instance, a controllable molecular shuttle (Figure 4) has been described in which the location of tetracationic 'bead' may be controlled by either electrochemical or chemical means. As such, this molecular shuttle constitutes a simple binary switch, which may be capable of storing information at a molecular level [16].

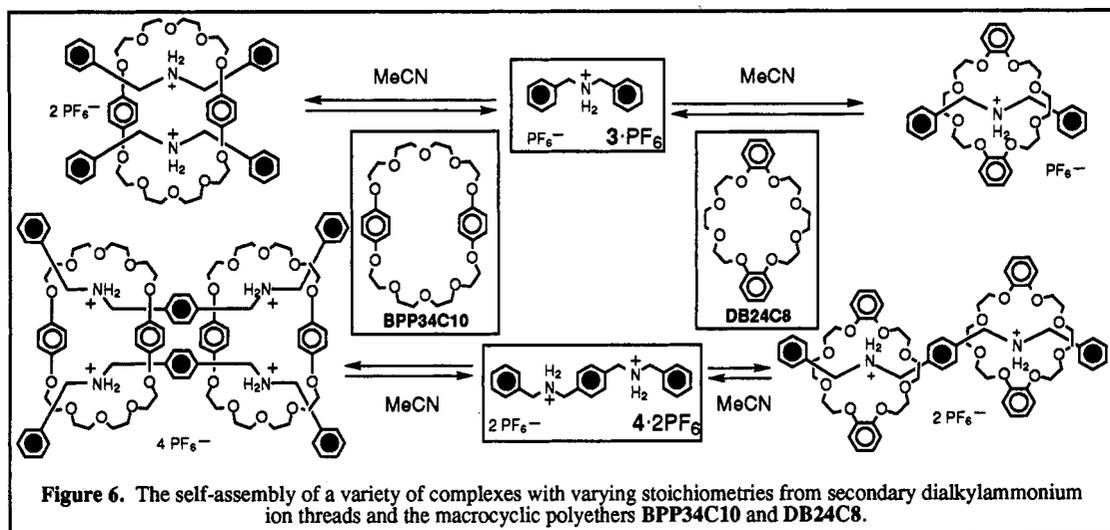
[*n*]Catenanes are molecules comprised of *n* interlocked rings [8]. An extremely effective synthetic route to [2]catenanes is one in which the clipping approach is utilised, such that a tricationic-intermediate (*e.g.* 1^{3+}) is allowed to cyclise about a π -electron rich unit of a macrocyclic polyether, such as **BPP34C10**. In this manner, a wide range of catenated structures have been prepared in which the effects on the efficiency of self-assembly and translational isomerism of different recognition units within the two components have been examined [17]. [3]Catenanes may also be prepared (Figure 5) using the self-assembly paradigm. Quite remarkably, a good yield of a [3]catenane is obtained [18] when the enlarged tricationic intermediate 2^{3+} is cyclised in the presence of **BPP34C10**. A linear [5]catenane — dubbed Olymriadane — has been

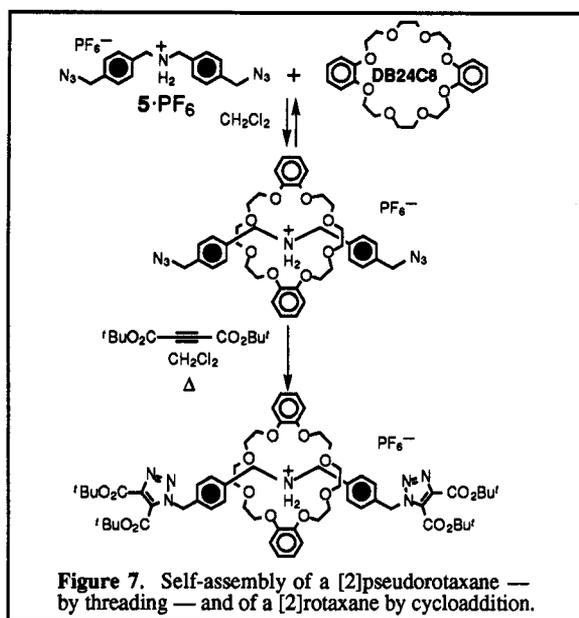


self-assembled [19] from a similar [3]catenane intermediate (containing a larger macrocyclic polyether incorporating dioxynaphthalene units as the π -electron rich recognition units) by the clipping on of a further two small tetracationic cyclophanes. Coincidentally, the solid state structure of Olympiadane was solved during the period of the 1996 Olympic Games. It adopts an extended conformation akin to that of the Olympic symbol [20]. Linear [n]catenanes are interesting molecules for the construction of polymeric structures incorporating mechanical bonds within their polymer chains [21]. Other prototypes of polymers with noncovalently-linked components are bis[2]rotaxanes and bis[2]catenanes, which have also been prepared by clipping processes [22].

HYDROGEN BONDED COMPLEXES

A more recent discovery has been the realisation [23] that secondary dialkylammonium salts — such as dibenzylammonium hexafluorophosphate ($3 \cdot \text{PF}_6$) and dibenzyl-*p*-xylyldiammonium bishexafluorophosphate ($4 \cdot 2\text{PF}_6$) — and suitably-sized macrocyclic polyethers — such as dibenzo[24]crown-8 (**DB24C8**) and **BPP34C10** — self-assemble in solution and in the solid state to produce superstructures with pseudorotaxane-like geometries, stabilised primarily by $[\text{N}^+-\text{H}\cdots\text{O}]$ hydrogen bonding interactions (Figure 6). In fact, this supramolecular system is extremely versatile in producing complexes with quite diverse stoichiometries and geometries, *e.g.* the cationic thread-like ions 3^+ and 4^+ are capable of being encircled by one and two crown ethers respectively, and the crown ethers **DB24C8** and **BPP34C10** are capable of including one or two dialkylammonium ions within their cavities, respectively. As such, complexes of the pseudorotaxane-type have been characterised having 1:1, 1:2, 2:2 and 2:1 stoichiometries (host:guest) [24]. This system must rank as one of the simplest self-assembling systems for the construction of complexes with pseudorotaxane-like geometries based, as it happens, on the interactions between NH_2^+ centres and oligoethyleneglycol chains [25].

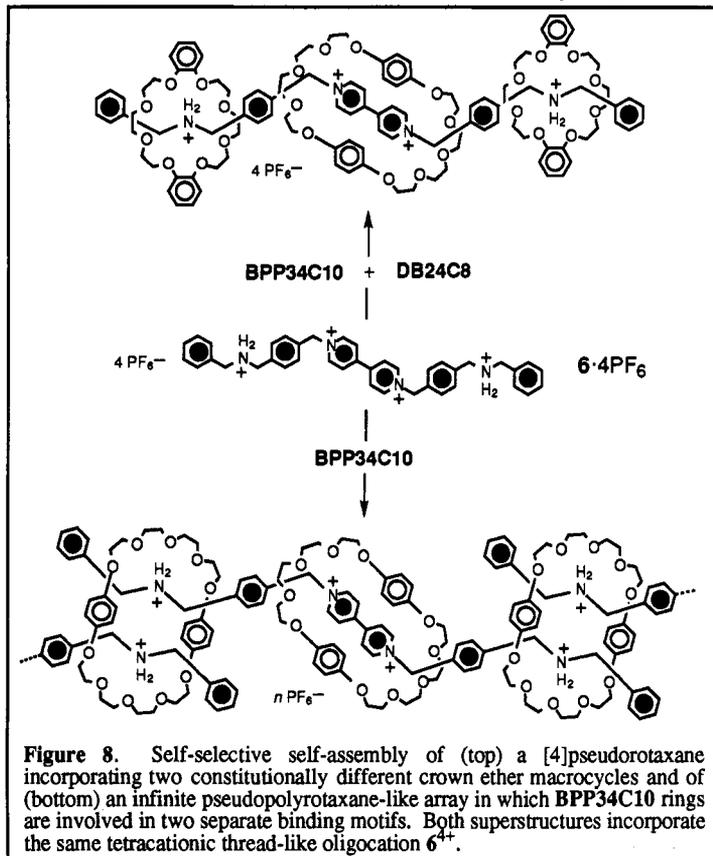




Rotaxanes may also be constructed around this new self-assembling system [25,26]. On account of the acidity of the NH_2^+ centres — and the desire not to deprotonate them in the process of forming the rotaxanes — we have utilised [26] a threading-followed-by-stoppering approach in which suitably terminally-functionalised dialkylammonium salts (e.g. $5 \cdot \text{PF}_6^-$) are first complexed with crown ethers to form pseudorotaxane-like intermediates which are then stoppered subsequently as a result of two dipolar cycloadditions (Figure 7). In this manner, both [2]- and [3]rotaxanes may be self-assembled. Moreover, the stabilising interactions, which hold these complexes and molecules together, may be disrupted by changes in pH. Thus, simply altering the pH of the medium provides a useful means of controlling the rates and preferred sites of occupancy in switches and shuttles based upon these systems.

COMBINING THE RECOGNITION MOTIFS — SELF-SELECTIVE BINDING

Naturally, we became intrigued to investigate whether or not we could combine the two recognition motifs described in the previous two sections to self-assemble superstructures with pseudorotaxane geometries in which each of the recognition motifs acts in a self-selective manner. As a first model target, we prepared [27] the tetracationic thread-like salt $6 \cdot 4\text{PF}_6^-$ (Figure 8) which contains a central bipyridinium dicationic core and terminal dibenzylammonium moieties. Upon crystallisation with **BPP34C10**, a complex forms with an empirical 2:1 (host:guest) stoichiometry in which the bipyridinium dicationic unit is threaded through one macrocyclic polyether and pairs of dibenzylammonium units are doubly-inserted through the other.



However, the pairs of NH_2^+ centres come from separate thread-like tetracations and, as a result, the superstructure formed by these self-assembly processes has the overall structure of a pseudopolyrotaxane-like one-dimensional array. On the other hand, crystallisation of $6 \cdot 4\text{PF}_6^-$ with a mixture of **BPP34C10** and **DB24C8** produces a [4]pseudorotaxane in which the terminal NH_2^+ units are encircled by **DB24C8** rings and the central bipyridinium moiety by a **BPP34C10** macrocycle. As such, this very simple self-assembling system displays self-selective binding of its respective recognition motifs. This

finding augers well for the construction of mechanically-interlocked analogues capable of being controlled by pH changes and by redox processes at the NH_2^+ centres and bipyridinium binding sites, respectively.

CONCLUSIONS AND REFLECTIONS

We have developed two versatile self-assembling recognition systems which are relatively simple with respect to the constitutions of their components. Although, the superstructures which they generate are quite complex and intricate, they are formed with a large degree of control and reliability. As discussed in the last example in this short review, we are now able to incorporate facets of both of these motifs into the same supramolecular systems and so construct superstructures in which the individual components self-assemble predictably. Since the two systems display quite different physical properties (e.g. the first is redox active, the second is pH dependent) we should be able to construct functioning molecular assemblies and supramolecular arrays in which the independent functions may be controlled by more than one external stimulus.

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