Interlocked host rotaxane and catenane structures for sensing charged guest species *via* optical and electrochemical methodologies†

Michał J. Chmielewski,‡ Jason J. Davis* and Paul D. Beer*

Received 16th October 2008, Accepted 18th November 2008
First published as an Advance Article on the web 10th December 2008
DOI: 10.1039/b818351a

The potential of interlocked host rotaxane and catenane structures as innovative optical and electrochemical sensors is highlighted. Interlocked structures can be engineered to bind specific guests within the topologically constrained three dimensional cavities created during their template-driven syntheses. This binding ability, when coupled to the signal transduction capabilities associated with appended reporter groups and their dynamic structures, make catenanes and rotaxanes highly promising candidates for the development of molecular sensors. With the ultimate challenge of fabricating highly selective anion sensing configurations, a three-staged strategy has been followed. First, we developed a general anion templation methodology for the construction of a variety of interpenetrated and interlocked molecular structures. [2]Rotaxanes and [2]catenanes synthesised using this novel protocol show, after template removal, favourable selective anion binding characteristics distinct from their separate components. At the second stage, the incorporation of redox- and photo-active groups into these interlocked frameworks converts them into electrochemical/optical molecular sensors. In the final third stage, the confinement of interlocked anion receptors at surfaces results in the fabrication of devices exhibiting highly selective binding and electrochemical and/or optical sensing behaviour.

1. Introduction

Interlocked molecules such as catenanes and rotaxanes have captured chemists' imagination due to their unique dynamic behaviour and non-trivial topology.[1] Intense recent research has been focused 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 nanotechnology.[2,3] Despite this huge interest, the potential of these molecules in molecular recognition and in particular sensing has been largely overlooked, even though their unique, topologically constrained three dimensional cavities have exceptional promise in chemical sensor technological applications. In addition there is also the possibility of exploiting the dynamics of interlocked molecular systems as a means of functional sensor response.

It is the objective of this article to highlight these new host–guest sensor aspects of catenane and rotaxane chemistry which are only now beginning to emerge and attract attention. This article will review briefly rare examples of interlocked host systems specifically designed to recognise guest species and then focus on our own research accomplishments in the construction of rotaxanes and catenanes for anion sensory applications.

2. Interlocked host systems for cation and neutral guest recognition

Guest binding is often used to control conformation and dynamics of interlocked molecules. Although in principle this dynamic behaviour may be exploited for potential sensing applications, there are very few examples of rotaxanes and catenanes that have been designed explicitly as molecular sensors. To the best of our knowledge, of the rare examples reported to date, nearly all are concerned with cation and neutral guest recognition. Nevertheless, even these few examples already demonstrate an impressive range of possible architectures, functions and properties offered by interlocked receptors.

Both [1], [2] and [3]rotaxanes were used as molecular sensors for alkali metal cations. Hiratani and co-workers[4] used a self-threading molecule ([1]rotaxane) to create a small, three-dimensional cavity between (covalently linked) axle and wheel for selective binding of Li^+ (Fig. 1). A built-in signalling mechanism based on energy transfer from naphthalene antennas in the wheel to the anthracene emitter in the thread was able to signal lithium binding by fluorescence enhancement.

With the aim of creating a binding site suitable for the much larger Cs^+ cation, two crown ether-type wheels were threaded onto the same axle ([3]rotaxane)[5] (Fig. 2). The formation of a sandwich type complex with caesium in CD_2Cl_2:CD_3CN (9:1) solution was signalled by a similar fluorescence enhancement mechanism as in the previous example.

In a recent paper, Chiu and co-workers[6] described a [2]rotaxane able to bind metal cations in a cavity formed between the oligo(ethylene glycol) chain of a wheel and the bipyridyl moiety of a thread (Fig. 3). The proof-of-principle sensing of physiologically

---

Chemistry Research Laboratory, Department of Chemistry, University of Oxford, Mansfield Road, Oxford, UK OX1 3TA. E-mail: jason.davis@chem.ox.ac.uk, paul.beer@chem.ox.ac.uk; Fax: 44 01865 272690; Tel: 44 01865 272600

† Dedicated to Professor Seiji Shinkai on the occasion of his 65th birthday.
‡ Present address: ISIS, ULP, Rue Gaspard Monge, Strasbourg, France.

Michał J. Chmielewski

Michał Chmielewski gained his PhD from the Institute of Organic Chemistry of the Polish Academy of Sciences under the supervision of Prof. J. Jurczak. From 2006 to 2007 he was an EPSRC Postdoctoral Fellow in the group of Prof. P. Beer at Oxford University. Since 2007 he has been a Marie Curie Postdoctoral Fellow in the laboratory of Prof. J.-M. Lehn at the Université Louis Pasteur.

Jason J. Davis

Jason Davis obtained a PhD in 1998 from the Inorganic Chemistry Laboratory, University of Oxford and was awarded a Royal Society University Research Fellowship in 1999. He was made a University Lecturer and Official Student and Tutor in Chemistry at Christ Church in 2003. His work has focused on the molecular and nanometre-scale construction and analysis of bioinorganic, sensory, electronic and optical systems.

Paul D. Beer

Paul Beer gained a PhD from King's College, London in 1982. After a Royal Society European postdoctoral fellowship with Professor J.-M. Lehn, Strasbourg, and a demonstratorship at the University of Exeter, he took up a Lectureship at the University of Birmingham in 1984. In 1990 he moved to the Inorganic Chemistry Laboratory, University of Oxford and became a Professor of Chemistry in 1998. His research interests cover many areas of coordination and supramolecular chemistry.

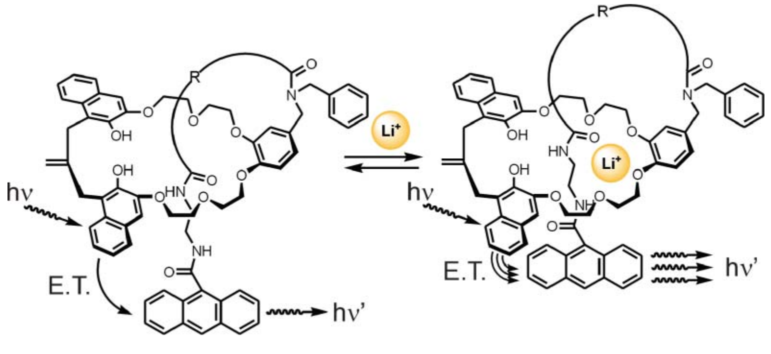


Fig. 1

important ions (Li^+, Na^+, K^+, Mg^{2+}, Ca^{2+}) in CD_3CN was demonstrated using ^1H NMR spectroscopy, taking advantage of the fact that each metal complex gives distinct signals in the respective ^1H NMR spectrum.

Rotaxanes and catenanes can be readily desymmetrised to create topologicaly chiral receptors. In a recent example, Kameta *et al.*[7] constructed a chiral [2]rotaxane from an achiral, asymmetric, wheel and thread (Fig. 4). In chloroform solution, this novel receptor was able to sense the chirality of phenylalaninol by changes in fluorescence of the attached fluorophores, while it showed no interaction with other amino acid derivatives such as alaninol, prolinol and tryptophanol.

It is worth noting that more than one binding cavity can be fashioned even within a simple [2]rotaxane framework. The simultaneous binding of two or more guests may lead to interesting phenomena such as cooperativity and allosteric regulation, which in turn can be utilised, for example, to improve the selectivity of a receptor. Highly cooperative binding of two Li^+ cations

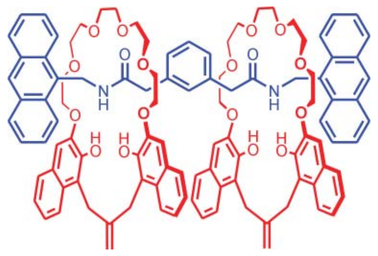


Fig. 2

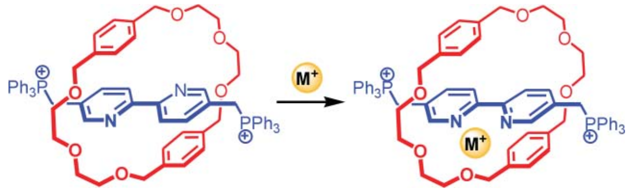


Fig. 3

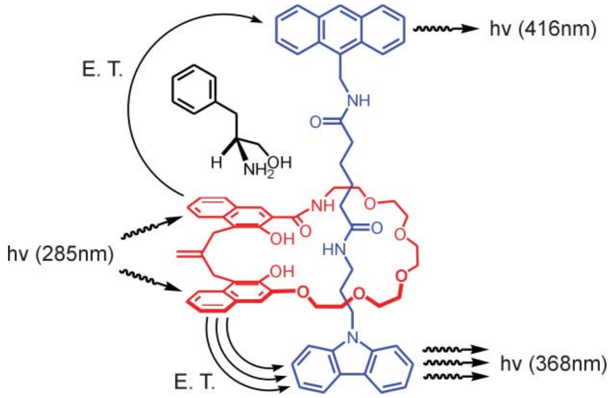


Fig. 4

on opposite sides of a [2]pseudorotaxane thread was discovered serendipitously by Sanders and co-workers[8] (Fig. 5). Interestingly, lithium binding strengthens charge transfer interactions between wheel and thread with concomitant visible colour change. This phenomenon was utilised to achieve switching in a bistable rotaxane[9] and to template catenane synthesis;[8] however, applications in sensing are yet to be demonstrated.

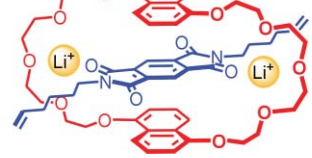


Fig. 5

Another unique feature of rotaxane architecture is the dynamic mobility of the wheel component along the axle axis. In a recent paper, Sauvage and co-workers[10] used this shuttling mobility to construct an adaptable receptor in which the distance between two binding sites (zinc porphyrins) attached to the wheels of a [3]rotaxane may vary over a wide range (from ~10 to ~80 Å) in order to adapt to substrates (bis-pyridyls) of various lengths (Fig. 6). The length of the binding site can be controlled by fixing the wheels to the axle by copper(I) coordination.

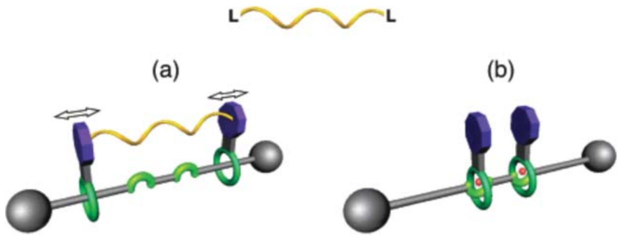


Fig. 6

A similar tweezer-like porphyrin [3]rotaxane host designed to bind fullerenes was reported by Morin and co-workers[11] (Fig. 7). Despite its high conformational flexibility, this host binds fullerenes with an efficiency comparable to those based on a calix[4]arene scaffold. However, the host's inherent flexibility was deemed to be responsible for its relatively low selectivity factors between C_{60} and higher fullerenes.

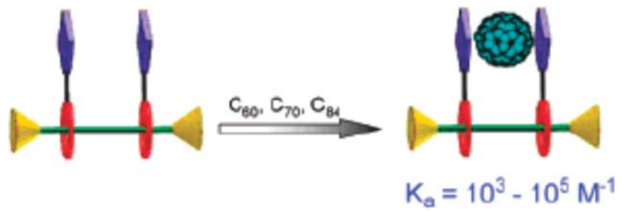


Fig. 7

The sliding motion of a wheel was also found to play an important role in rotaxane-mediated transport of charged guests (fluoresceinated peptides) through an apolar membrane.[12] By altering its conformation, the transporter rotaxane behaves like a molecular chameleon—it adapts to changes in environment while passing through a cell membrane (Fig. 8).

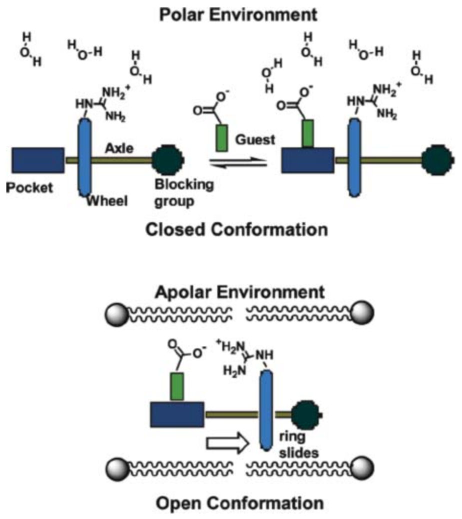


Fig. 8

It is noteworthy that in the above three examples the rotaxane is used as a mobile scaffold onto which anchoring groups can be attached and that the cavities between the wheels and the thread do not participate in guest binding. This approach, pioneered and consequently developed by Smithrud and co-workers,[12–14] allows for binding of larger guest species. In a very recent example, Hayashida and Uchiyama[15] arranged four anionic resorcinarenes around a cyclophane-type rotaxane wheel to achieve strong and selective binding of histones (small, positively charged peptides). Fluorescent tags attached to the rotaxane axle allowed for histone detection by fluorescence enhancement and also by a FRET mechanism (Fig. 9).

This freedom of motion of mechanically bound components of rotaxanes and catenanes, which is a very attractive feature for signal transduction and signalling, certainly contradicts the classic Cram's requirement[16] for a well preorganised, rigid receptor. In fact, guest binding usually freezes the intramolecular dynamics, which leads to some energetic penalty (estimated as being not very high[17]). However, according to a new, interesting concept from Smithrud and co-workers, the rotaxane wheel can be incorporated within a host to produce a favorable entropy term for molecular association, arising through a release of the wheel upon guest binding.[18]

Rotaxane receptors have been also integrated into conducting polymer frameworks to produce sensory devices. In a pioneering paper, Swager and co-workers[19,20] exploited Sauvage's copper(I) templation methodology to create a thiophene functionalised rotaxane which was electropolymerised to give a conducting polymetallorotaxane (Fig. 10). This polymer was shown to reversibly bind zinc and copper ions and signal their presence by both electrochemical and optical means.

The potential of catenanes as highly effective receptors was spectacularly demonstrated by Sanders and co-workers[21] in the following "objective" experiment. The researchers allowed a guest to choose its favourite host from a dynamic combinatorial library of interconverting ligands. The library was prepared from a reversibly binding building block which oligomerised to form a mixture of macrocycles of various sizes. Addition of a target guest—acetylcholine, $Me_3N^+CH_2CH_2OC(=O)Me$—drove the equilibrium mixture towards the selection of the best receptor, which, unexpectedly, turned out to be a [2]catenane consisting of two interlocked macrocyclic trimers (Fig. 11). This highly "improbable" hexameric structure was amplified owing to its much stronger association with the acetylcholine template in comparison with competing macrocyclic receptors.

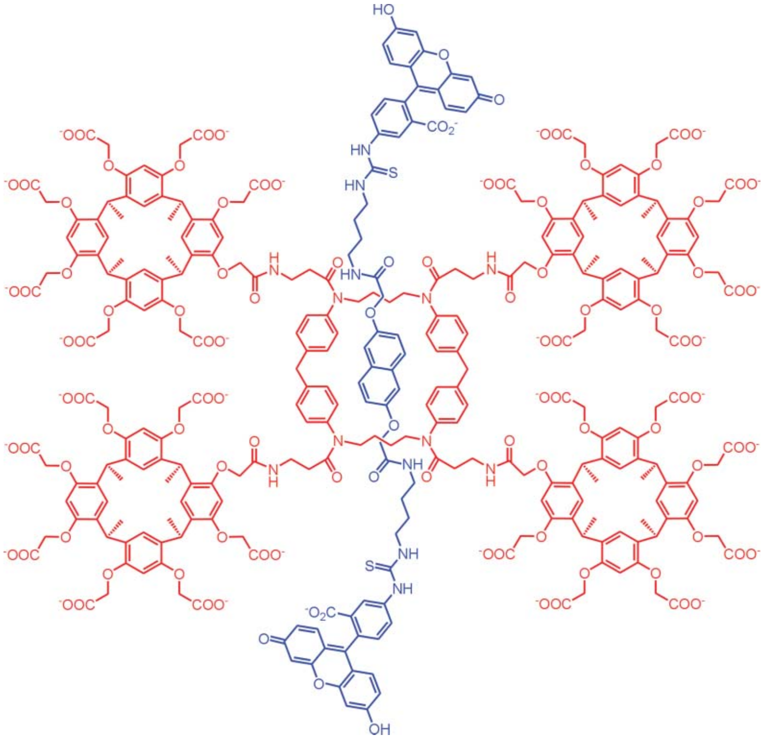


Fig. 9

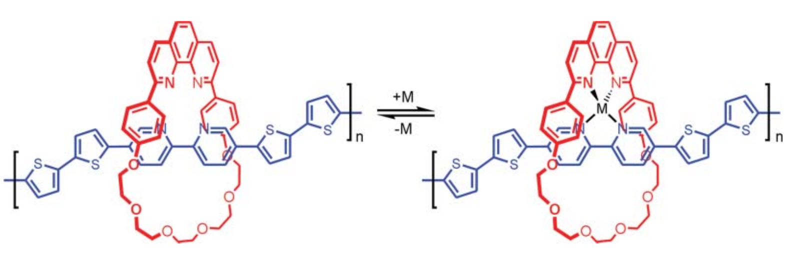


Fig. 10

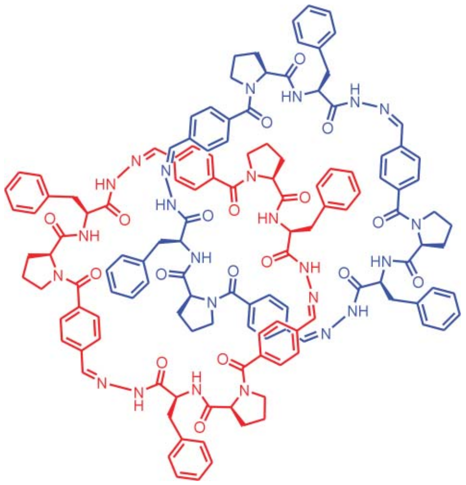


Fig. 11

3. Anion templation strategy for interpenetrative/interlocked synthesis

Whereas the above examples concern binding of cationic and neutral guests, it can be argued that the real challenge of recognising anionic guests selectively necessitates the construction of intricate interlocked receptors. Anions present a particular challenge for molecular receptors due to their low charge densities (in comparison to isoelectronic cations), weakly pronounced coordination preferences, high hydration energies and pH dependence.[22–25] Therefore simple hydrogen bond donating acyclic clefts and macrocycles, which dominate the current landscape of anion receptors, often suffer from poor selectivities and are unable to bind anions in protic solvents. Examples from Nature,[26–29] where strong and highly selective binding of sulfate and phosphate anions in water is achieved by a network of hydrogen bonds deeply buried inside specific proteins, suggest that, despite synthetic difficulties, the design of elaborate three dimensional receptors is required to fully encapsulate anions for high affinity binding. An innovative way towards the goal of constructing such target receptors is through threading of a one-dimensional, acyclic receptor through the annulus of a two dimensional, macrocyclic receptor, thus creating a three dimensional cavity for anion recognition. Such a design has a number of potential advantages which include: (i) orthogonal disposition of the two binding units, which is difficult to achieve by other means; (ii) lower risk of slow exchange kinetics owing to a less rigid, mechanically bonded structure than that of covalently linked polycyclic cage compounds and (iii) a number of potential mechanisms of signal transduction, based on guest induced changes in co-conformation or in mutual interactions between interlocked components. Thus we believe that the development of such innovative receptors for anion recognition is particularly worthwhile.

The first interlocked receptor for anions was described in 1998 by the groups of Sessler and Vögtle.[30] Their bipyrrole amide-based catenane was found to strongly and selectively bind various anions in tetrachloroethane inside the binding pocket of approximate tetragonal symmetry formed by its two wheels (Fig. 12).

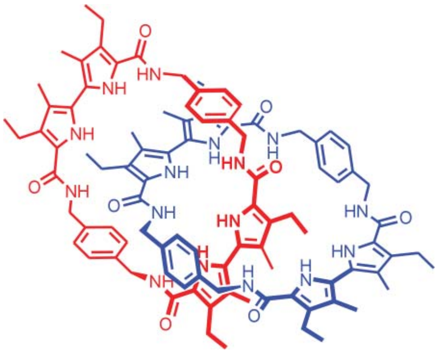


Fig. 12

For example, the catenane's affinity for chloride was much higher than for fluoride in opposition to what might be expected on the basis of their relative charge densities and basicities. Significantly, the binding ability of the catenane was much stronger than of its acyclic analogue. Unfortunately, this catenane could be obtained in just 4% yield and attempts to improve the yield by anion templation were unsuccessful.

Incorporation of porphyrin rings into rotaxane and catenane structures provides them with a multitude of physicochemical properties which may be exploited for optical and electrochemical sensing. Gunter and co-workers[31] used isophthalamide strapped porphyrins as components of interlocked structures with potential anion sensing capabilities (Fig. 13). Preliminary anion binding studies confirmed chloride binding by such pseudorotaxane and rotaxane structures.

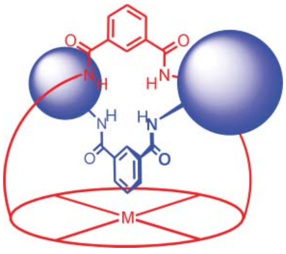
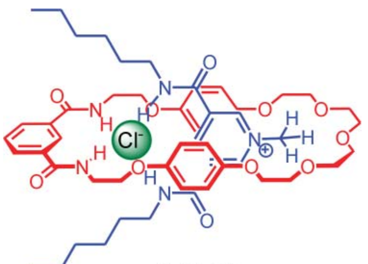


Fig. 13

Despite the very promising early precedent by Sessler and Vögtle, further developement of interlocked receptors for anions was hampered by the lack of efficient synthetic methods. With the ultimate objective of constructing novel anion sensing systems with increasingly superior binding characteristics, we set ourselves the challenge to rationally develop an anion templated synthesis[32,33] of mechanically interlocked supramolecular assemblies such as rotaxanes and catenanes.

Over the past few years, we have developed a general anion templation methodology for the synthesis of interpenetrated structures.[34–37] The basic design principles of this approach are illustrated in Fig. 14. The templating chloride anion is strongly associated with the potential pyridinium cationic threading component **2**$^+$ but, importantly, its coordination sphere remains unsaturated. This permits subsequent anion binding by the isophthalamide macrocyclic ligand **1**, which results in interpenetration of the ion-paired threading component through the annulus of the macrocycle. Anion binding, the major driving force of the assembly process, is reinforced here by the built-in complementary



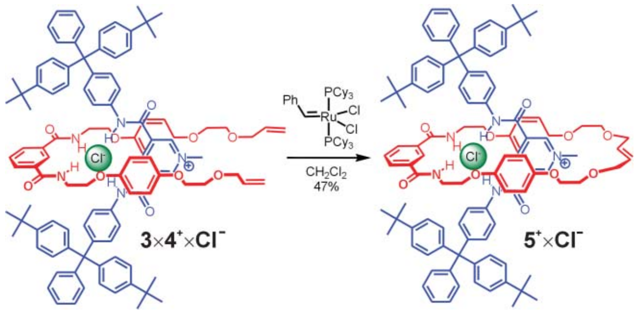
$1 \times 2^+ \times Cl^-$

Fig. 14

supramolecular interactions (π–π stacking and CH–O hydrogen bonds) between the macrocycle and thread.[38]

This templation strategy works very well in non-competitive solvent media (typically CH_2Cl_2, $CHCl_3$, acetone) as illustrated by the chloride-directed assembly of a series of pseudorotaxanes containing pyridinium, pyridinium nicotinamide, imidazolium, benzimidazolium and guanidinium threading components and various macrocyclic ligands.[39]

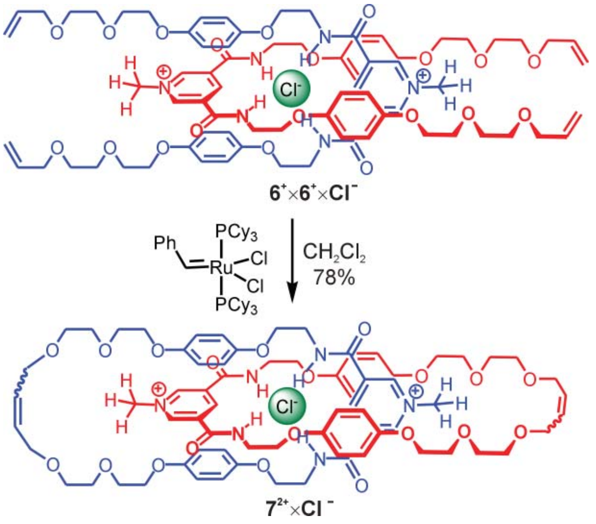
Moreover, the basic recognition motif sustains substitution of the macrocycle by its acyclic U-shaped precursor, that allows for the synthesis of a range of rotaxanes[40,41] and catenanes[42] by a clipping method templated by chloride (Scheme 1).



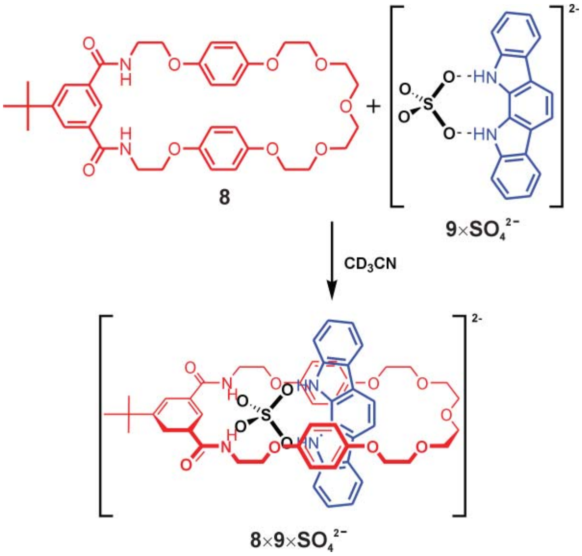
Scheme 1

The power of this methodology was recently demonstrated by a double clipping, one-pot synthesis of [2]catenanes in very high yields with chloride and sulfate anion templates (Scheme 2).[43,44] Importantly, these are the first direct anionic analogs (with reversed polarity) of Sauvage's[45] seminal metal-directed catenane synthesis directed by a pseudotetrahedral copper(I) bis(1,10-phenol-phenanthroline) complex.

Very recently we have also demonstrated that the scope of the anion-driven threading methodology is not limited to cationic threads. Pseudorotaxane formation from a neutral indolocarbazole threading component **9** and isophthalamide macrocycle **8** was achieved using a particularly powerful template, a doubly charged sulfate anion (Scheme 3).[46] As indolocarbazoles are known to sense anions by changes in their strong fluorescence,[47] this finding opens the door to interpenetrated fluorescent anion sensors.



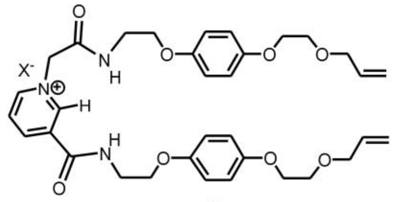
Scheme 2



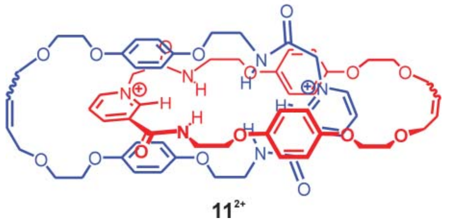
Scheme 3

Although anion templated synthesis of interlocked structures is still in its infancy, it has already demonstrated its value and given us access to various interlocked anion receptors. Removal of the anion template from these compounds leads to novel receptor behaviour not present in the separate components. For example, exchange of the chloride template in $\mathbf{5}^+Cl^-$ for the non-coordinating hexafluorophosphate anion yields [2]rotaxane $\mathbf{5}^+PF_6^-$, which binds anions strongly even in a very competitive protic solvent mixture d_4-methanol:$CDCl_3$ (1:1) with a remarkable reversal of selectivity with respect to the pyridinium thread (the macrocycle itself does not bind anions in this solvent system). Thus, whilst the thread binds anions according to their hydrogen bond accepting ability ($K_{(Cl^-)} = 125 M^{-1}$, $K_{(H2PO4^-)} = 260$, $K_{11(AcO^-)} = 22000\ M^{-1}$, $K_{12(AcO^-)} = 140\ M^{-1}$), the rotaxane has a notable preference for chloride ($K_{(Cl^-)} = 1130\ M^{-1}$) over dihydrogenphosphate ($K_{(H2PO4^-)} = 300\ M^{-1}$) and acetate ($K_{11(AcO^-)} = 100\ M^{-1}$, $K_{12(AcO^-)} = 40\ M^{-1}$). This is postulated to be the result of a high degree of complementarity of the unique hydrogen bonding pocket of the rotaxane, formed by orthogonal clefts of the thread and macrocycle, to the guest chloride anion. The complexation of larger anions would result in the significant, unfavourable distortion of the binding cavity and thus reduction of complex stability.

Similarly, catenane $11^{2+}(PF_6^-)_2$ (Fig. 15) studied in the same solvent mixture (d_4-methanol:$CDCl_3$ = 1:1), strongly and selectively binds its own template, sulfate anion, in preference to chloride, bromide and acetate, where the latter two anions are very weakly bound ($K(SO_4^{2-}) = 2200\ M^{-1}$, $K(Cl^-) = 780\ M^{-1}$, $K(Br^-) = 55\ M^{-1}$, $K(AcO^-)$—no binding). In stark contrast, the U-shaped acyclic catenane precursor $\mathbf{10}^+PF_6^-$ forms the strongest complex with acetate, followed by sulfate, chloride and bromide ($K(SO_4^{2-}) = 1120\ M^{-1}$, $K(Cl^-) = 100 M^{-1}$, $K(Br^-)$—no binding, $K(AcO^-) = 1850\ M^{-1}$).[44]



$\mathbf{10^+X^-}$



$\mathbf{11^{2+}}$

Fig. 15

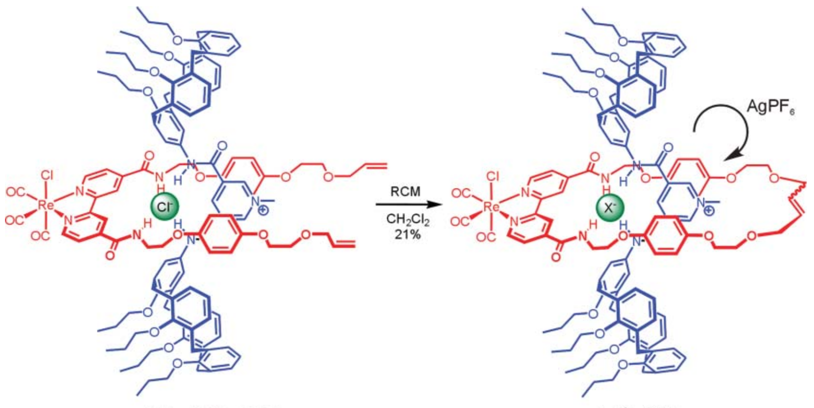
4. Anion sensing by interpenetrative/interlocked systems

Thus far it has been shown that the unique interlocked binding domain topology lends anion-templated rotaxanes and catenanes interesting anion binding characteristics distinct from their 'parent' species. The observed increase in binding strength coupled with reversal of selectivity makes these interlocked structures of great interest in the molecular sensing arena. In order to apply these receptors to anion sensing, it is necessary to equip them with reporter groups able to signal the recognition event by electrochemical and/or spectroscopic means. The above described advances in templation methodology have made the synthesis of such sophisticated structures feasible.

Our first photo-active anion sensing rotaxane[48,49] was based on a luminescent rhenium(I) bipyridyl probe being incorporated into a macrocyclic wheel (Scheme 4). The chloride salt $\mathbf{14}^+Cl^-$ was prepared in 21% yield *via* ring clipping of the neutral rhenium(I) bipyridyl-containing precursor **12** around the pyridinium-chloride thread $\mathbf{13}^+Cl^-$; the bulky calix[4]arene stopper groups were necessary to prevent dethreading of the larger macrocycle.

As before, replacement of the chloride template with hexafluorophosphate anion gave [2]rotaxane sensor $\mathbf{14}^+PF_6^-$. The addition of TBA anion salts to a solution of $\mathbf{14}^+PF_6^-$ in acetone induced an enhancement in the ^{3}MLCT emission band intensity of the rotaxane receptor. Titration experiments demonstrated that the rotaxane selectively binds hydrogensulfate ($K_a > 10^6\ M^{-1}$) over nitrate and chloride, which contrasts with the properties of the free wheel, which is selective for chloride ($K_a = 8.7 \times 10^4\ M^{-1}$). Hydrogensulfate selective receptors are rare, because this anion is a particularly poor hydrogen bond acceptor. This example illustrates that an anion templation approach may be used to synthesise molecular sensors selective for anions different from the template.

The above rotaxane sensor utilises a common sensing mechanism based on electronic communication between anion and reporter group. However, rotaxane and catenane based receptors offer some potential means of signal transduction that are unique to interlocked structures, based on the mutual relationships between the mechanically bound subunits. For example, anion binding may amplify/reduce interactions between thread and macrocycle and, as a consequence, alter their spectroscopic or electrochemical properties. Alternatively, anions may induce co-conformational changes, such as shuttling of the macrocycle along the thread, which could also translate into an observable signal. Although basic mechanisms underlying the signal generation in the above examples are well developed to study, for example, molecular switches or machine-like behaviour of interlocked molecules, their application to molecular sensing is underexplored, due to the lack of guest binding cavities in previously described catenanes and rotaxanes.

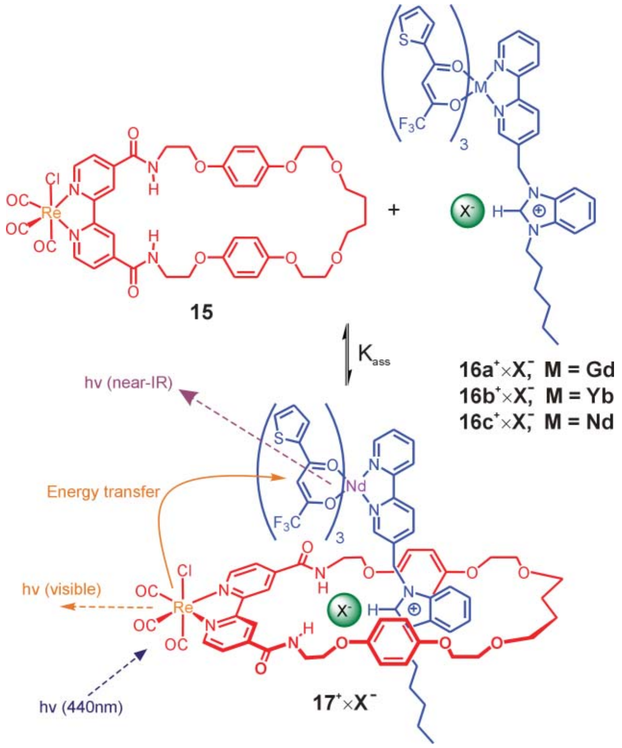


$\mathbf{12 \times 13^+ \times Cl^-}$ $\mathbf{14^+ \times X^-}$

Scheme 4

As a prototype sensing system illustrating this paradigm, we designed a pseudorotaxane with a through space communication between thread and macrocycle components, which may be influenced by anion binding.[50]

The mechanism used to accomplish this was photoinduced energy transfer between a rhenium(I) bipyridyl sensitizer incorporated in the macrocycle **15** and a luminescent lanthanide complex appended to one terminus of the benzimidazolium threads **16**$^+$ (Scheme 5).



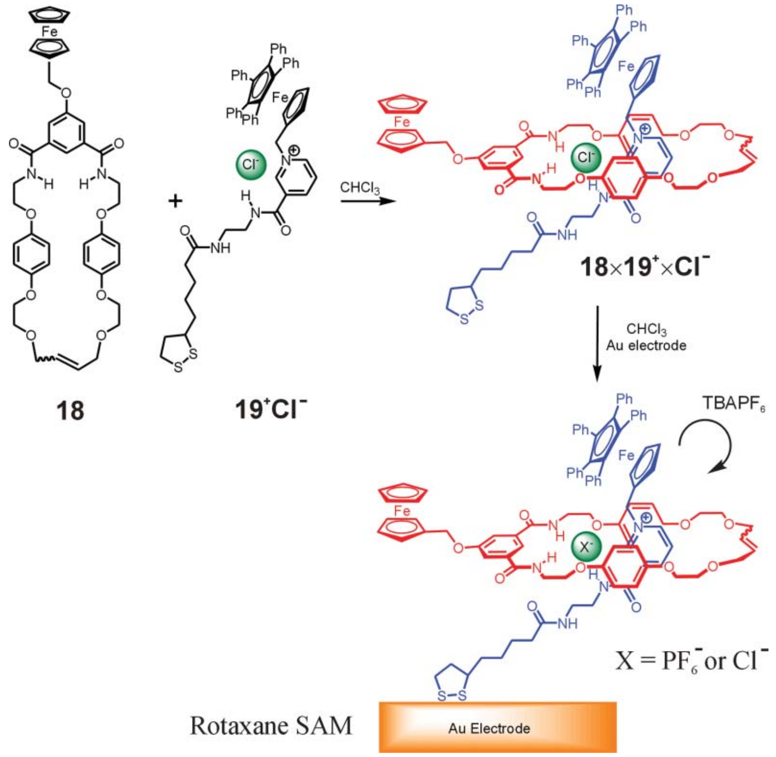
Scheme 5

Addition of chloride ion pair threads containing no lanthanide emitter, or a lanthanide not suitable for energy transfer such as gadolinium (**16a**$^+$), to the rhenium macrocycle **15** resulted in an enhancement of rhenium ^{3}MLCT luminescent emission, as observed in **12**·and **14**$^+$$PF_6^-$ above. In contrast, however, for threads containing a suitable lanthanide metal such as neodymium or ytterbium, no such enhancement was observed on pseudorotaxane formation; indeed for the neodymium thread **16c**$^+$ a significant quenching of the rhenium-centered luminescence was observed. Furthermore, the evolution of new near-infrared (NIR) emission bands consistent with lanthanide metal emission was observed due to energy transfer between the ^{3}MLCT excited state of the rhenium(I) bipyridyl centre and the lanthanide complex. As such, an energy transfer process is highly dependent on the distance between the two metal centres, the appearance of NIR luminescence indicates the proximity between the stopper and macrocycle, and hence pseudorotaxane formation, which, in turn, takes place only in the presence of specific anions. Thus, the same principle may be used for anion sensing and, for example, to monitor anion-induced shuttling of the macrocycle along the thread in a prototype molecular machine-like device based on an anion recognition process.

5. Surface confined interlocked host systems for sensing applications

Though solution phase studies have resolved cation, pH and light triggered molecular motion in interlocked structures, such as those described above, it is the controlled interfacing of these molecules with solid electroactive or optically transparent surfaces that will lie central to proposed applications in sensing or data storage. From a host–guest sensing perspective, the advantages of tethering the former to a transducing surface (such as that presented by an electrode) are considerable. In addition to the possibility of generating a robust and renewable host surface capable of operation in a variety of fluid media (static or flowing), there exists considerable evidence that the thermodynamics of host–guest association are favoured at such interfaces.[51–53]

Although there have been several reported examples of the covalent attachment of interlocked molecular systems to solid surfaces,[54] such as silicates or gold,[55–60] until our recent report of an anion templated surface assembly of a redox-active sensory rotaxane,[61] there existed no precedent for use of any surface assembled interlocked structure for chemical sensing applications. We have also recently been able to demonstrate the surface chemisorption of disulfide appended indolocarbazole axles on gold electrodes and, by means of surface plasmon resonance (monitoring threading associated changes in surface refractive index), the sulfate anion templated threading of appropriate macrocycles over these in the formation of surface confined pseudorotaxanes.[46] In such configurations, the supporting gold surface acts as a stopper. If the axle terminus is also stoppered then a surface confined rotaxane results.[61] In appending redox active moieties to the axle or macrocycle (or both), additional surface characterisation routes become accessible and, additionally, one may envisage the establishment of redox switchable binding and/or motion within the interlocked structure. Guest binding characteristics can also be analysed electrochemically. We have utilised the formation of self-assembled monolayers (SAMs) of a redox-active bis-ferrocene functionalized pseudorotaxane **18** × **19**$^+$ × Cl^- at gold surfaces, as an example (Scheme 6). The presence of two different redox-active centres on the thread and on the macrocycle in this case study enabled independent monitoring of axle and macrocycle on the electrode surface. The replacement of the chloride template with hexafluorophosphate proved possible without disrupting the interlocked nature of the surface assembled rotaxanes. The anion binding properties of this redox-active rotaxane-SAM could be probed through an examination of analyte induced perturbation of the two redox waves of the system; proximal anion binding should be accompanied by a cathodic shift due to electrostatic stabilization of the oxidized ferrocene unit. In acetonitrile solutions, the ferrocene unit of the rotaxane macrocycle was shown to demonstrate a selective voltammetric response to chloride ($\Delta E \sim 40$ mV), even in the presence of a hundredfold excess of competing anion such as dihydrogenphosphate. This contrasts sharply to the solution responses of the free thread **19**$^+$$PF_6^-$ and macrocycle **18**, which demonstrate small cathodic shifts in the presence of halides and basic oxyanions, except for **18** with dihydrogenphosphate ($\Delta E \sim 45$ mV) and hydrogensulfate ($\Delta E \sim 15$ mV) and provides a nice example of the change in selectivity induced by the mutual interpenetration of two components. It also further demonstrates the ability of this templation methodology



Scheme 6

to generate potentially sophisticated surface-confined interlocked host systems capable of directly transducing target anion presence.

6. Conclusions

In this article we have demonstrated that appropriately designed interlocked host molecules containing unique three dimensional cavities can be engineered to selectively bind specific guest species. The potential superior level of molecular recognition and binding affinity as compared to two dimensional cyclic systems, together with signal transduction capabilities associated with the incorporation of reporter groups and their mechanically bonded dynamic structures, make interlocked receptors very promising candidates for the development of molecular sensors. Indeed as a consequence of the recent progress made in template synthetic methodologies, the application of rotaxane and catenane chemistry to molecular recognition and sensing is only now starting to be realized.

The choice of such intricate receptor architecture is particularly well justified when challenging guests are targeted, as is the case with anions. We set ourselves a strategic goal to construct highly selective optical and/or electrochemical anion sensors based on catenane or rotaxane molecular frameworks. With this long-term goal in mind, we first developed a general anion templation methodology for the construction of a variety of interlocked host structures and showed that the resulting [2]rotaxanes and [2]catenanes exhibit, after template removal, highly selective anion binding characteristics distinct from their separate components. Next, we incorporated photo-active groups into these interlocked frameworks and demonstrated their ability to selectively sense anions *via* optical responses. The ultimate challenge of fabricating these systems on surfaces to construct robust anion sensory devices has only recently been approached for the first time. As a 'proof of principle', this has resulted in the successful fabrication of a redox-active rotaxane SAM-modified gold electrode acting as a selective electrochemical sensor for chloride anions.

Although this area of interlocked host–guest chemistry research is still in its infancy, the examples described in this article clearly demonstrate the real exciting potential redox- and photo-active rotaxane and catenane based systems have as future innovative optical and electrochemical sensors of practical utility.

Notes and references

1 *Molecular Catenanes, Rotaxanes and Knots. A Journey Through the World of Molecular Topology*, C. Dietrich-Buchecker and J. P. Sauvage, eds., Wiley-VCH, Weinheim, Germany, 1999.
2 V. Balzani, M. Venturi and A. Credi, *Molecular Devices and Machines. A Journey into the Nano World*, Wiley-VCH, Weinheim, Germany, 2003.
3 E. R. Kay, D. A. Leigh and F. Zerbetto, *Angew. Chem. Int. Ed.*, 2007, **46**, 72–191.
4 K. Hiratani, M. Kaneyama, Y. Nagawa, E. Koyama and M. Kanesato, *J. Am. Chem. Soc.*, 2004, **126**, 13568–13569.
5 Y. Nagawa, J. Suga, K. Hiratani, E. Koyama and M. Kanesato, *Chem. Commun.*, 2005, 749–751.
6 N. C. Chen, P. Y. Huang, C. C. Lai, Y. H. Liu, Y. Wang, S. M. Peng and S. H. Chiu, *Chem. Commun.*, 2007, 4122–4124.
7 N. Kameta, Y. Nagawa, M. Karikomi and K. Hiratani, *Chem. Commun.*, 2006, 3714–3716.
8 G. Kaiser, T. Jarrosson, S. Otto, Y. F. Ng, A. D. Bond and J. K. M. Sanders, *Angew. Chem. Int. Ed.*, 2004, **43**, 1959–1962.
9 S. A. Vignon, T. Jarrosson, T. Iijima, H. R. Tseng, J. K. M. Sanders and J. F. Stoddart, *J. Am. Chem. Soc.*, 2004, **126**, 9884–9885.
10 J. Frey, C. Tock, J. P. Collin, V. Heitz and J. P. Sauvage, *J. Am. Chem. Soc.*, 2008, **130**, 4592–4593.
11 J. S. Marois, K. Cantin, A. Desmarais and J. F. Morin, *Org. Lett.*, 2008, **10**, 33–36.

12 X. F. Bao, I. Isaacsohn, A. F. Drew and D. B. Smithrud, *J. Am. Chem. Soc.*, 2006, **128**, 12229–12238.
13 I. Smukste, B. E. House and D. B. Smithrud, *J. Org. Chem.*, 2003, **68**, 2559–2571.
14 J. Zhu, B. E. House, E. Fleck, I. Isaacsohn, A. F. Drew and D. B. Smithrud, *Bioorg. Med. Chem. Lett.*, 2007, **17**, 5058–5062.
15 O. Hayashida and M. Uchiyama, *Org. Biomol. Chem.*, 2008, **6**, 3166–3170.
16 D. J. Cram, *Angew. Chem. Int. Ed.*, 1986, **25**, 1039–1057.
17 F. Eblinger and H. J. Schneider, *Angew. Chem. Int. Ed.*, 1998, **37**, 826–829.
18 J. Zhu and D. B. Smithrud, *Org. Biomol. Chem.*, 2007, **5**, 2992–2999.
19 S. S. Zhu, P. J. Carroll and T. M. Swager, *J. Am. Chem. Soc.*, 1996, **118**, 8713–8714.
20 S. S. Zhu and T. M. Swager, *J. Am. Chem. Soc.*, 1997, **119**, 12568–12577.
21 R. T. S. Lam, A. Belenguer, S. L. Roberts, C. Naumann, T. Jarrosson, S. Otto and J. K. M. Sanders, *Science*, 2005, **308**, 667–669.
22 *Supramolecular Chemistry of Anions*, A. Bianchi, K. Bowman-James and E. García-España, eds., Wiley-VCH, New York, 1997.
23 J. L. Sessler, P. A. Gale and W.-S. Cho, *Anion Receptor Chemistry*, RSC, Cambridge, 2006.
24 Anion Sensing, *Topics in Current Chemistry,*ed. I. Stibor, 2005, **255**.
25 Recognition of Anions, *Structure & Bonding,*ed. R. Vilar, 2008, **129**.
26 J. W. Pflugrath and F. A. Quiocho, *Nature*, 1985, **314**, 257–260.
27 H. Luecke and F. A. Quiocho, *Nature*, 1990, **347**, 402–406.
28 J. J. He and F. A. Quiocho, *Science*, 1991, **251**, 1479.
29 Z. F. Kanyo and D. W. Christianson, *J. Biol. Chem.*, 1991, **266**, 4264–4268.
30 A. Andrievsky, F. Ahuis, J. L. Sessler, F. Vogtle, D. Gudat and M. Moini, *J. Am. Chem. Soc.*, 1998, **120**, 9712–9713.
31 M. J. Gunter, S. M. Farquhar and K. M. Mullen, *New J. Chem.*, 2004, **28**, 1443–1449.
32 R. Vilar, *Angew. Chem. Int. Ed.*, 2003, **42**, 1460–1477.
33 R. Vilar, *Eur. J. Inorg. Chem.*, 2008, 357–367.
34 M. J. Chmielewski and P. D. Beer, in *Organic Nanostructures*, ed. J. L. Atwood and J. W. Steed, Wiley-VCH, 2008.
35 M. D. Lankshear and P. D. Beer, *Acc. Chem. Res.*, 2007, **40**, 657–668.
36 M. D. Lankshear and P. D. Beer, *Coord. Chem. Rev.*, 2006, **250**, 3142–3160.
37 P. D. Beer, M. R. Sambrook and D. Curiel, *Chem. Commun.*, 2006, 2105–2117.
38 J. A. Wisner, P. D. Beer and M. G. B. Drew, *Angew. Chem. Int. Ed.*, 2001, **40**, 3606–3609.
39 M. R. Sambrook, P. D. Beer, J. A. Wisner, R. L. Paul, A. R. Cowley, F. Szemes and M. G. B. Drew, *J. Am. Chem. Soc.*, 2005, **127**, 2292–2302.
40 J. A. Wisner, P. D. Beer, M. G. B. Drew and M. R. Sambrook, *J. Am. Chem. Soc.*, 2002, **124**, 12469–12476.
41 M. R. Sambrook, P. D. Beer, M. D. Lankshear, R. F. Ludlow and J. A. Wisner, *Org. Biomol. Chem.*, 2006, **4**, 1529–1538.
42 M. R. Sambrook, P. D. Beer, J. A. Wisner, R. L. Paul and A. R. Cowley, *J. Am. Chem. Soc.*, 2004, **126**, 15364–15365.
43 K. Y. Ng, A. R. Cowley and P. D. Beer, *Chem. Commun.*, 2006, 3676–3678.
44 B. Huang, S. M. Santos, V. Felix and P. D. Beer, *Chem. Commun.*, 2008, 4610–4612.
45 C. O. Dietrich-Buchecker, J. P. Sauvage and J. M. Kern, *J. Am. Chem. Soc.*, 1984, **106**, 3043–3045.
46 M. J. Chmielewski, L. Zhao, A. Brown, D. Curiel, M. R. Sambrook, A. L. Thompson, S. M. Santos, V. Felix, J. J. Davis and P. D. Beer, *Chem. Commun.*, 2008, 3154–3156.
47 D. Curiel, A. Cowley and P. D. Beer, *Chem. Commun.*, 2005, 236–238.
48 D. Curiel, P. D. Beer, R. L. Paul, A. Cowley, M. R. Sambrook and F. Szemes, *Chem. Commun.*, 2004, 1162–1163.
49 D. Curiel and P. D. Beer, *Chem. Commun.*, 2005, 1909–1911.
50 M. R. Sambrook, D. Curiel, E. J. Hayes, P. D. Beer, S. J. A. Pope and S. Faulkner, *New J. Chem.*, 2006, **30**, 1133–1136.
51 S. Zhang, C. M. Cardona and L. Echegoyen, *Chem. Commun.*, 2006, 4461–4473.
52 P. D. Beer, J. J. Davis, D. A. Drillsma-Milgrom and F. Szemes, *Chem. Commun.*, 2002, 1716–1717.
53 J. J. Davis and P. D. Beer, *The Encyclopedia of Nanoscience and Nanotechnology*, Marcel Dekker, 2004, pp. 2477-2492.
54 V. Balzani, A. Credi and M. Venturi, *ChemPhysChem*, 2008, **9**, 202–220.
55 S. Chia, J. Cao, J. F. Stoddart and J. I. Zink, *Angew. Chem. Int. Ed.*, 2001, **40**, 2447–2451.
56 F. Cecchet, P. Rudolf, S. Rapino, M. Margotti, F. Paolucci, J. Baggerman, A. M. Brouwer, E. R. Kay, J. K. Y. Wong and D. A. Leigh, *J. Phys. Chem. B*, 2004, **108**, 15192–15199.
57 L. Raehm, J.-M. Kern, J.-P. Sauvage, C. Hamann, S. Palacin and J.-P. Bourgoin, *Chem. Eur. J.*, 2002, **8**, 2153.
58 N. Weber, C. Hamann, J. Kern and J. Sauvage, *Inorg. Chem.*, 2003, **42**, 6780–6792.
59 K. Kim, W. S. Jeon, J. K. Kang, J. W. Lee, S. Y. Jon and T. Kim, *Angew. Chem. Int. Ed*, 2003, **42**, 2293–2296.
60 E. Katz, O. Lioubashevsky and I. Willner, *J. Am. Chem. Soc.*, 2004, **126**, 15520–15532.
61 S. R. Bayly, T. M. Gray, M. J. Chmielewski, J. J. Davis and P. D. Beer, *Chem. Commun.*, 2007, 2234–2236.