REVIEW

Synthetic receptors

James H. Hartley, Tony D. James† and Christopher J. Ward

School of Chemistry, University of Birmingham, Edgbaston, Birmingham, UK B15 2TT. E-mail: jameshartley@hotmail.com; t.d.james@bham.ac.uk; chrisward77@hotmail.com

Received (in Cambridge, UK) 20th June 2000
First published as an Advance Article on the web 13th September 2000

Covering: January 1995 to February 2000. Previous review: *Contemp. Org. Synth.*, 1997, **4**, 61.

† Present address: Department of Chemistry, University of Bath, Bath, UK BA2 7AY. E-mail: T.D.James@Bath.ac.uk

1 Introduction

"*Supramolecular chemistry embodies the creative power of chemistry. By its very essence, by its ability to create and through the beauty of its objects, chemistry is an art as well as a science. Indeed, it fashions entire new worlds that do not exist before they are shaped by the hand of the chemist, just as matter, shaped by the hand of the sculptor, becomes a work of art.*" These words from Jean-Marie Lehn[1] seem particularly apt for a review of this type.

The purpose of this article is to review developments in host–guest systems, over the period of January 1995 to February 2000, inclusive. The article is complementary to the coverage of similar compilations by Perry and Kilburn published in 1997.[2] Attention is focused on the wide range of recognition events possible through the rational design and synthesis of artificial receptors. As is common, the review is divided into sections by receptor-type. However, due to the increasing fusion and unification occurring in this field of research, categorisation can be somewhat subjective.

Even a comprehensive review of this area cannot hope to cover all the literature over the last five years within the limited time and space considerations. We have chosen to detail a representative sample of work from the English language literature highlighting new developments in receptor technology based on discrete molecular entities. Relevant literature was obtained using the Bath Information and Data Services (BIDS) Science Citation Index. The final list of references was compiled by visual inspection of pertinent content. Any authors whose work, although relevant, does not appear here must accept our apologies. Unfortunately we have had to omit some excellent work based on dendrimer,[3–8] monolayer,[9–15] porphyrin,[16–18] steroidal[19] and fullerene chemistry,[20] so the reader is referred to some appropriate recent articles.

2 Cyclodextrins

The naturally occurring cyclodextrins (CDs) were the first receptor molecules whose binding properties towards organic molecules were recognised and extensively studied.[13,21–32] CDs are cyclic oligosaccharides consisting of α-1,4-linked D-(+)-glucopyranose units. The most important members of this class consist of 6 (α-CD), 7 (β-CD), or 8 (γ-CD). The cyclic array of saccharides produces a hydrophobic cavity, generally described as a truncated cone. The primary alcohols are located around the narrow rim and the secondary alcohols around the wider rim as shown in Fig. 1.

DOI: 10.1039/a909641h

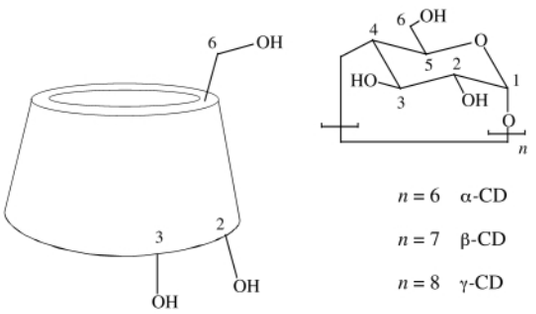


Fig. 1

2.1 Simple receptors

The hydrophobic cavity makes CDs particularly good hosts for hydrophobic organic molecules in water. Synthetic modifications of cyclodextrins are possible at the primary alcohol on the narrow rim and the two secondary alcohols on the wider rim. Such modifications can be used to control the selectivity of CD towards guests. Parker *et al*. have developed CD systems for creatinine,[33] Kean *et al*. have synthesised receptors for carboxylic acids,[34] Yoshida and Ichikawa have prepared molecules selective for anilinonaphthalenesulfonate anions,[35] and Smith and Cotner have constructed CDs able to discriminate phosphotyrosine.[36] The inherent asymmetry of the CD allows for chiral recognition.[37,38] Kano and Liu and co-workers[39,40] in particular have developed systems for the chiral recognition of α-amino acids.

2.2 Lariat-type receptors

An interesting class of CD receptor has been developed with covalently attached groups. When these lariat-type CDs are placed in water the covalently linked group becomes encapsulated by the CD. The lariat or covalently linked guest can then be displaced selectively by other guests when they are added to the system (Fig. 2).

Such systems have been developed by Liu *et al*. using L-tryptophan and organoselenium lariats for chiral aliphatic alcohols.[41,42] Ueno and co-workers have used biotin-appended dansyl lariats for the selective recognition of bile acids.[43]

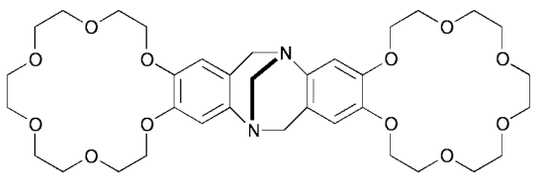
A large number of lariated systems for α-amino acids have been studied by Inoue and co-workers.[44,45] Lariat CDs have also been used by Reetz as ligands in supramolecular rhodium catalysis,[46] and by Easton and co-workers in the control of 1,3-cycloaddition reactions.[47]

2.3 Dimeric receptor systems

Selective host molecules have also been obtained by linking two CDs. Woggon and co-workers have prepared CD dimers selective for β,β-carotene.[48] Dimeric systems have been shown by Breslow *et al*. to be selective for aromatic guests.[49] Reinhoudt and co-workers have obtained selective hosts by linking CDs with other receptors such as calixarenes.[50]

3 Crown ethers, aza crowns and related macrocycles

Crown ethers are possibly the most widely used family of host compounds in supramolecular chemistry. Pedersen's discovery of the macrocyclic polyethers has laid the foundation for an exhaustive study of their ability to act as receptors for cations, neutral and anionic species.[51] This account covers a selection of oxygen and nitrogen containing macrocyclic receptors, but does not include crown-type systems utilised in rotaxane-like assemblies.



1

3.1 Crown ethers

A number of research groups have incorporated a Tröger's Base motif into crown-based receptors.[52,53] Wärnmark and co-workers have employed a condensation reaction to synthesise the C_2 symmetric bis(18-crown-6) analogue **1**, which binds heptane-1,7-diylbis(ammonium chloride) most strongly from a series of achiral primary diammonium salts.[53] Prevot-Halter and Weiss have also looked at a system to bind diammonium species.[54] A crown-ether substituted catecholate organised around a *cis*-MoO_2 core showed complexation to numerous alkyl diammoniums. Shephard *et al*. have synthesised redox-active cluster compounds by the direct reaction of aryl crown ethers with a hexaruthenium carbido cluster, which display host–guest behaviour with Na^+ and NH_4^+.[55]

Stoddart and co-workers have reported hydrogen-bonded complexes of aromatic crown ethers with (anthracen-9-yl)-methylammonium derivatives.[56] Results show that as a consequence of the hydrogen bond driven recognition process, the anthracene chromophoric unit interacts with the aromatic units of the crown ethers. Upon guest interaction, some of the complexes show complete fluorescence quenching—the basis of a potential supramolecular switching system. A ditopic molecule consisting of crown ether and nickel azamacrocycle units has also shown promise as a switch-like system.[57]

Much attention has been paid to the use of crown ethers in biological environments. Fyles and Zeng have reported that the release of liposome entrapped carboxyfluorescein is switched 'on' *via* molecular recognition of barium ions by a bis(crown ether carboxylate) bola-amphiphile **2**.[58] Barboiu *et al*. have

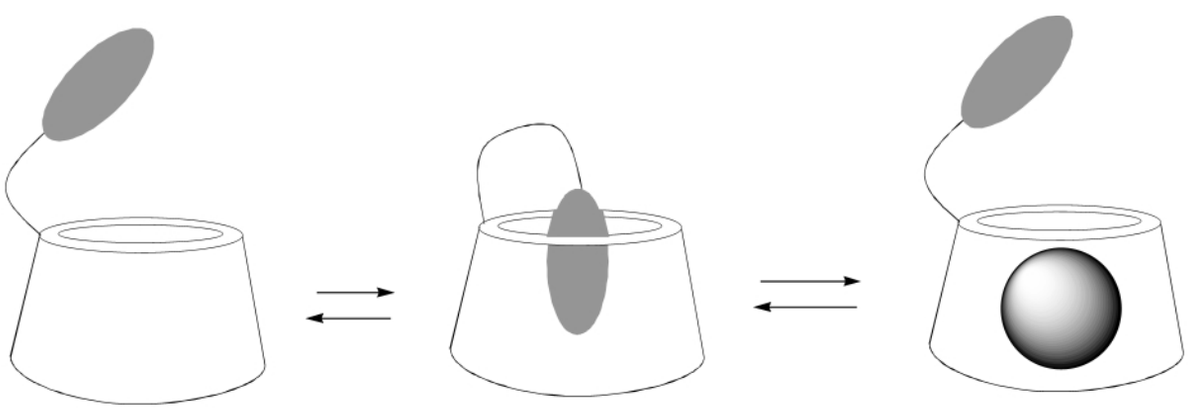
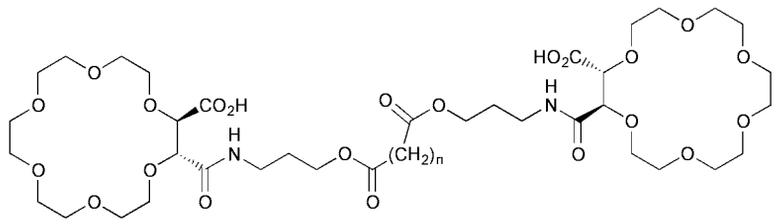


Fig. 2



2

prepared a series of supramolecular complexes of the ammonium salt of a crown ether with different natural and non-natural amino acids (*e.g.* L-phenylalanine, L-leucine).[59] The new complexes act as very efficient activators of the zinc enzyme carbonic anhydrase (isozymes I and II). Significant effort has been devoted to developing receptors for sequence-selective recognition of peptide side-chains.[60,61] Hossain and Schneider's systems utilising an 18-crown-6-ether and a peralkylammonium group (Fig. 3), bind peptides in water with moderate selectivity.[60] Voyer *et al.* have designed some bis-crown ether modified peptides which selectively complex Cs^+ and linear α,ω-diammonium alkanes using the simultaneous action of the two distant crown ethers.[62] Complexation of Cs^+ was shown to induce a specific conformational change in the backbone of one of the peptides.

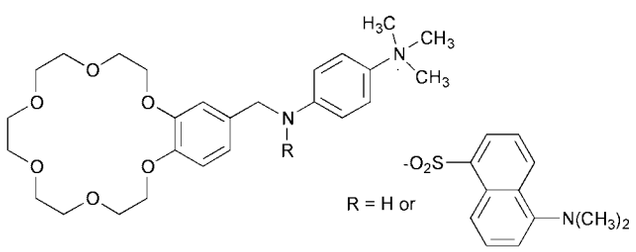
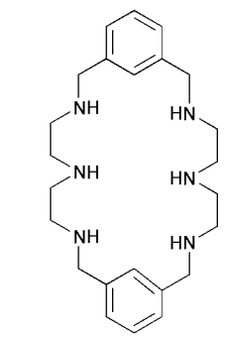


Fig. 3

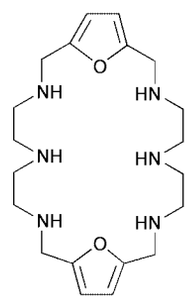
3.2 Aza crowns and other related macrocycles

Hexaaza macrocyclic ligands have been particularly well studied.[63–68] The protonated hexaaza macrocyclic ligands **3** and **4** selectively bind nucleosides such as AMP, ADP and ATP; rate enhancement of ATP hydrolysis was also observed. Copper(II) complexes of the hexaaza macrocyclic ligands and their host–guest interactions with various phosphate anions were also investigated. Lehn and co-workers have synthesised a macrocyclic polyamine based polyphosphate receptor bearing two acridine units **5**.[69] It uses electrostatic and stacking interactions for the binding of nucleotide polyphosphates and for the recognition of ATP and NADPH, and can be used as an *in vitro* fluorescent probe for ATP. Further work on receptors for nucleotide anions has been performed by Bazzicalupi *et al.*[70] Phenanthroline containing macrocycles bind diphosphate, triphosphate, ATP and ADP at neutral or slightly acidic pH, giving 1 : 1 complexes. Sessler and Kral have utilised sapphyrin-based systems to recognise phosphates and carboxylates.[71–73] Lehn and co-workers have also studied the binding of malonate ions to polyammonium macrocycles and shown that this greatly enhances the H/D exchange at the CH_2 group.[74]

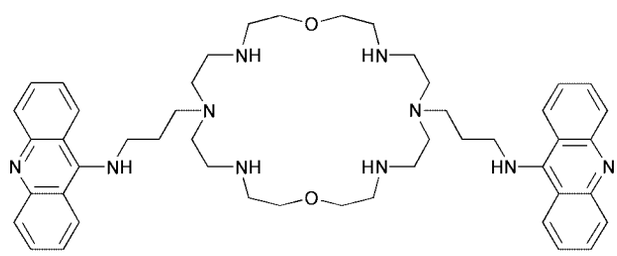
The study of cationic binding to crowns continues to receive widespread attention. Boens and co-workers have described new, versatile routes for the synthesis of 4-substituted pyridino crown ethers and 4,4′-substituted dipyridino crowns **7**, **8** and **9**.[75] The aryl thiophene fluorophore has been used to study the binding of monovalent cations, where selectivity is shown for K^+. Costa *et al.* have synthesised methylpyridine derivatives of 14-membered tetraaza macrocycles and determined their stability constants with a variety of transition metal ions.[76]



3



4



5

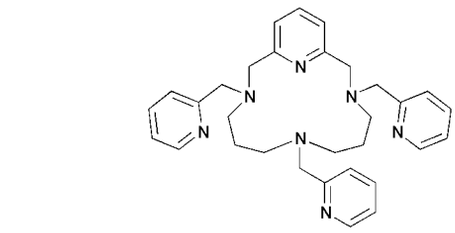
Compound **6** shows remarkable selectivity for Cd^{2+}, making it especially useful for systems that remove this toxic metal from the environment. Alkaline earth and rare earth metal cations have been complexed by novel spironaphthoxazine compounds appended with aza-15-crown-5 ether fragments.[77] Some 2-aminothiophenol based cyclic receptors, **10** and **11**, showing high selectivities for Ag^+ over other metal ions have been synthesised by Kumar *et al.*[78] Ranganathan *et al.* have constructed a series of adamantane-containing macrocycles that possess high efficiency in transporting Na^+, Ca^{2+} and Mg^{2+} ions across model membranes.[79] Gunnlaugsson *et al.* have reported the terbium(III) complex of **12** as acting as a molecular logic gate.[80] Receptors for the bipyridinium ions paraquat and diquat ‡ consisting of porphyrins with over-arching dibenzo-crown ether straps have been described by Gunter *et al.*[81]

4 Calix[*n*]arenes, resorcin[*n*]arenes and cavitands

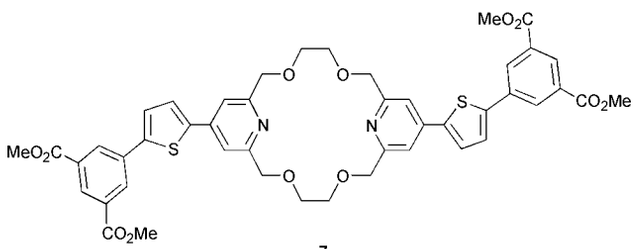
The term calix[*n*]arene indicates the class of phenolic metacyclophanes derived from the condensation of phenols and aldehydes. Because of their easy large-scale preparation, distinctive concave molecular architecture, tuneable size of inner cavity and excellent capability of derivatisation, calix[*n*]arenes, resorcin[*n*]arenes and cavitands have emerged as very attractive building blocks for supramolecular chemistry.[82] In this review, the conventional nomenclature for the phenolic hydroxy group side of calix[*n*]arenes as the lower rim will be followed.

Wieser *et al.* have published an exhaustive review of calix[*n*]arenes containing transition metals in a variety of binding

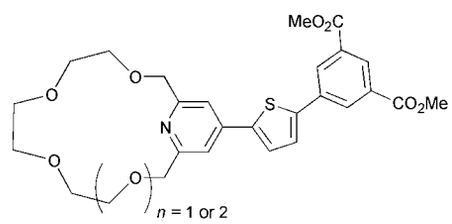
‡ The IUPAC names for paraquat and diquat are 1,1′-dimethyl-4,4′-bipyridinium and 6,7-dihydrodipyrido[1,2-*a*:2′,1′-*c*]pyrazinediium, respectively.



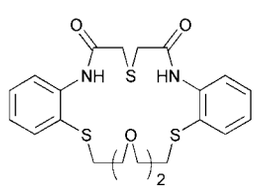
6



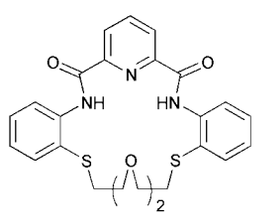
7



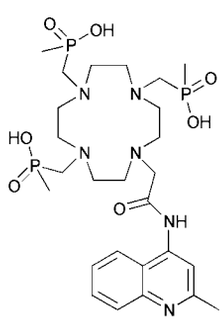
8 and 9



10



11



12

modes.[83] Lhoták and Shinkai have reviewed a selection of calix[*n*]arene systems utilising cation-π interactions.[84] Calix[*n*]-arenes represent interesting compounds exhibiting enhanced cation-π interactions, because of the preorganisation of their 'concentrated' core of aromatic units.

4.1 Cation receptors

Ungaro *et al*. have developed dialkoxycalix[4]arene-crown-5 conformers fixed in the 1,3-alternate structure that show a very high potassium ion selectivity.[85] The corresponding crown-6 derivatives have large Cs^+/Na^+ selectivities. Four mixed calix-[4]arene amides have been synthesised by Arnaud-Neu *et al*.[86] High complexation selectivities for Sr^{2+} and Ca^{2+} over Na^+ were achieved for a mixed primary/tertiary derivative **13**. Continuing their work on cation recognition, Arnaud-Neu *et al*. have recently reported the synthesis of two pentamethyl ester derivatives of the *p*-benzyl- and *p*-*tert*-octylcalix[5]arenes (Fig. 4).[87] Liquid–liquid extraction studies have shown that these ligands display high selectivity within the alkali metal cation series. Beer's group has designed a calix[4]arene-based tubular receptor **14** possessing an eight-coordinate binding site displaying a remarkable affinity for K^+ over any other alkali metal.[88] These so-called calix[4]tubes show potential as a new class of membrane-spanning compounds.

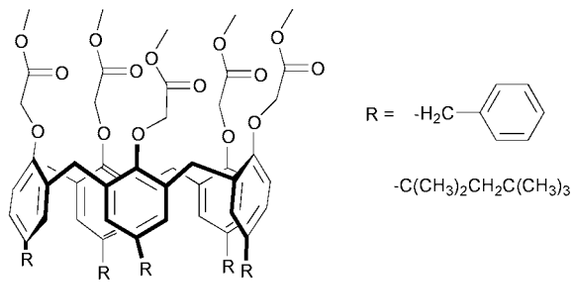
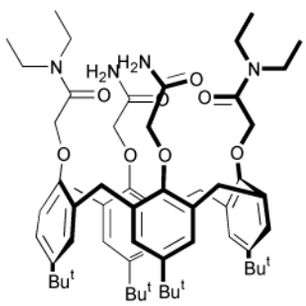
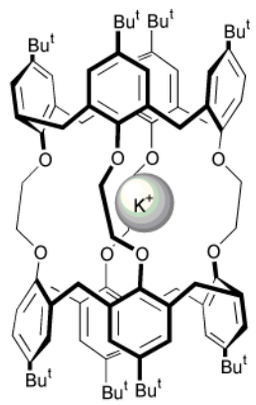


Fig. 4



13

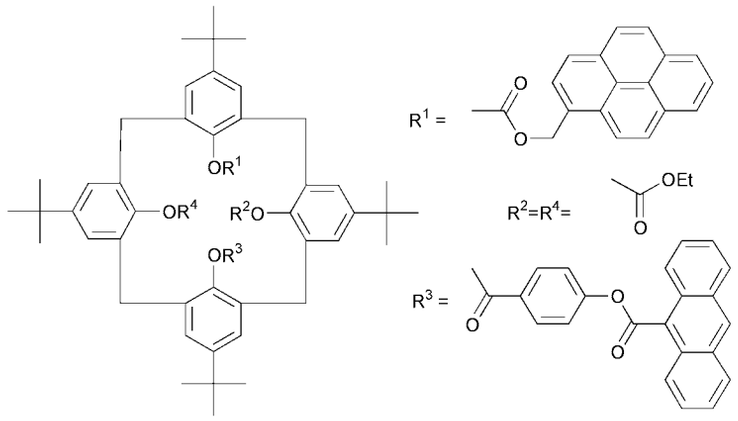


14

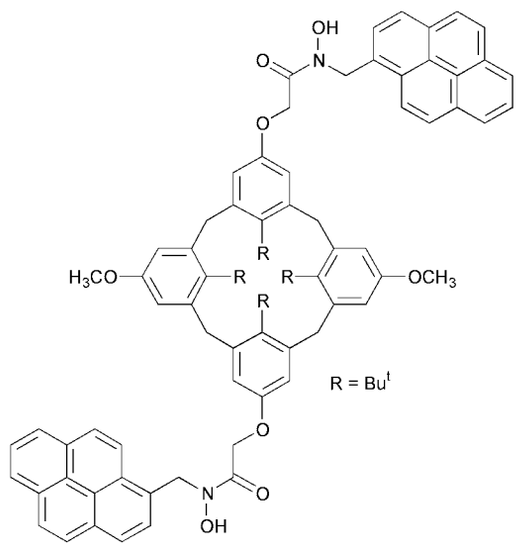
A sensor for Na^+ based on intramolecular fluorescence energy transfer has been developed by Jin.[89] The calix[4]arene-derived molecule, **15**, has pyrene and anthroyloxy moieties at the lower rim, as a donor and as an acceptor respectively. Bodenant *et al*. have reported another fluorescent calix[4]arene-based receptor, **16**, which incorporates two pyrenyl and two hydroxamic acid functionalities.[90] The fluorescence intensity was shown to be sensitive to proton concentration and the presence of transition metal ions. Addition of Cu^{2+} and Ni^{2+} induced a dramatic quenching of fluorescence. Nishimura's group has synthesised a group of chiral calix[4]arenes.[91] These show strong 1:1 complex formation with (*R*)-(+)-α-phenylethylammonium picrate.

4.2 Anion receptors

The vast majority of calix[*n*]arene anion receptors have relied upon functionalising the upper or lower rims with cationic moieties. A typical example of this is Schneider's aminocalix-[*n*]arenes (Fig. 5).[92] Calix[*n*]arenes with (trimethylammonium)-methyl groups at the phenyl rings in the upper rim were prepared and association constants with various mono-nucleotides determined. Complexation free energies (ΔG) increased from AMP, ADP to ATP in all cases. The ligands also show a preference for DNA rather than RNA, so may hold promise for biomedical applications. Beer and co-workers have prepared lower rim substituted calix[4]arene bis-pyridinium receptors and a novel lower rim bridged calix[4]arene pyridinium receptor (Fig. 6).[93] The bis-pyridinium species, **L1** and **L2**, complex $H_2PO_4^-$, Cl^-, Br^- and HSO_4^- anions with $L:2X^-$ stoichiometry, with **L1** showing a preference for $H_2PO_4^-$. Conversely, **L3** forms 1:1 stoichiometric complexes with Cl^- and Br^-.



15



16

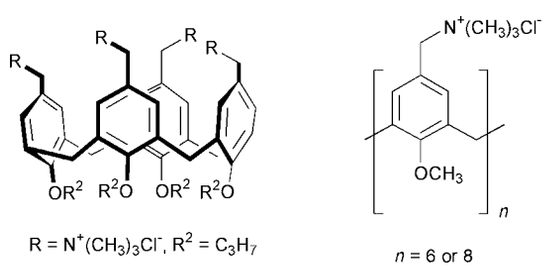


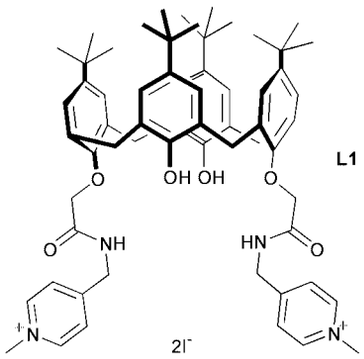
Fig. 5

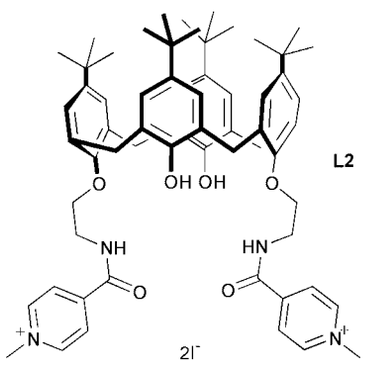
Staffilani *et al*. have synthesised a range of bi- and tetra-metalated macrocyclic complexes based upon calix[4]arene derivatives (Fig. 7 shows an example).[94] The presence of the transition metal centres enhances the acidity of the hydroxy functionalities at the calix[*n*]arene lower rim. The host–guest behaviour of the calix[*n*]arene is dramatically altered such that anionic species (*e.g.* BF_4^-, HSO_4^-, SO_4^{2-}, I^-) are included in the molecular cavity. Niikura and Anslyn have used an azacalix[4]-arene, **17**, with its cationic and hydrophobic cavity, as a useful receptor for anionic guests, such as inositol triphosphate.[95] Modulation in the fluorescence intensity of fluorescent competition binding assay probes was observed upon replacement of the probes with anions in the cavity. An interesting variation on the calix[*n*]arene anion binding theme is Lippert's Pt metal analogue of calix[4]arene **18**.[96] When protonated, the open 'molecular box' can act as a host for organic anions (*e.g.* sulfonates) in water.

4.3 Neutral species receptors

In continuation of their work on calix[4]arenes, Ungaro *et al*. have synthesised rigid cone calix[4]arene derivatives with bridges at the lower and upper rim that are able to complex small organic molecules with acidic CH groups.[85] More recent work from the same group has involved the development of synthetic routes to link L-alanine based units to the upper rim of calix[4]arenes locked in the cone conformation.[97] The amino acid groups could help in recognition processes as seen in many natural systems. Shinkai and Ikeda have developed calix[6]-arenes containing *N*,*N*-dialkylaniline and *m*-phenylenediamine units which complex [60]fullerene through π–π interactions. This and other related work has been recently reviewed.[98] Pinalli *et al*. have reported the preparation and chemical-sensor properties of a new class of cavitands (Fig. 8) designed to detect alcohol vapours by mass-sensitive transducers.[99] The receptors are capable of two synergistic interactions; hydrogen bonding with the P=O group and CH–π interactions in the π-basic cavity. Kubo has introduced indoaniline type chromogens into the upper rim of 1,1′-binaphthyl-derived calix[4]crowns.[100] These receptors (Fig. 9) are capable of translating chiral recognition events into colour changes. Calix[4]pyrroles **19** that bind neutral substrates (mainly solvents, *e.g.* methanol, DMF) both in solution and the solid state have been developed by Sessler and co-workers.[101] These are readily made by acid-catalysed condensation of pyrrole with symmetrical ketones.

Hamilton and colleagues have prepared a family of synthetic receptors for protein surface recognition.[102] The design





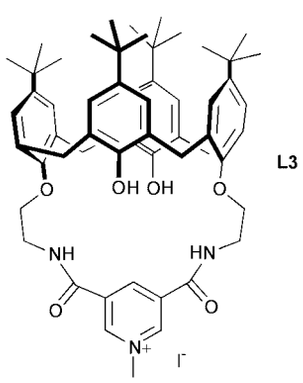


Fig. 6

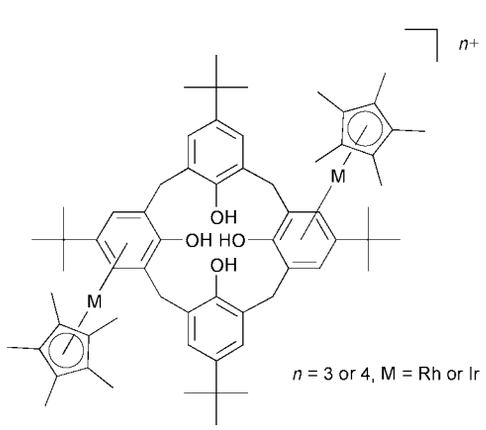


Fig. 7

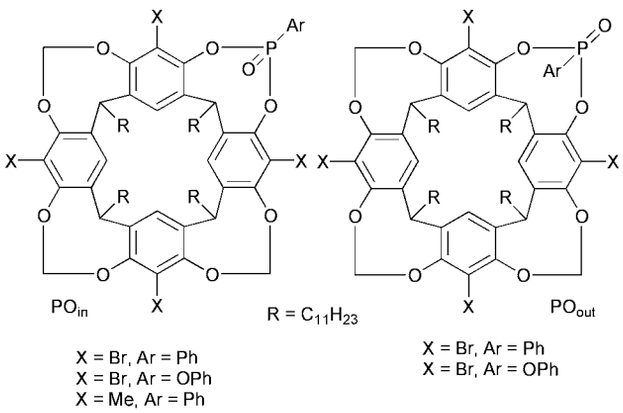


Fig. 8

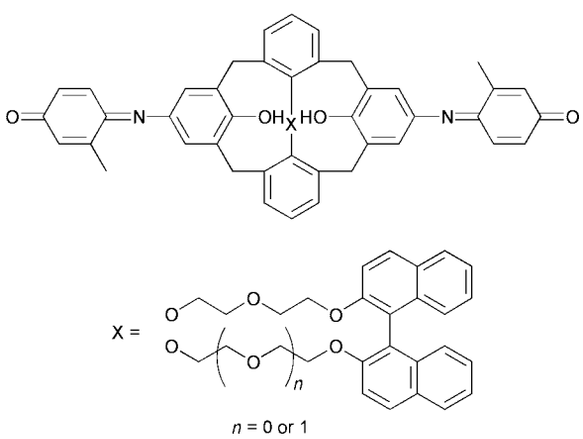
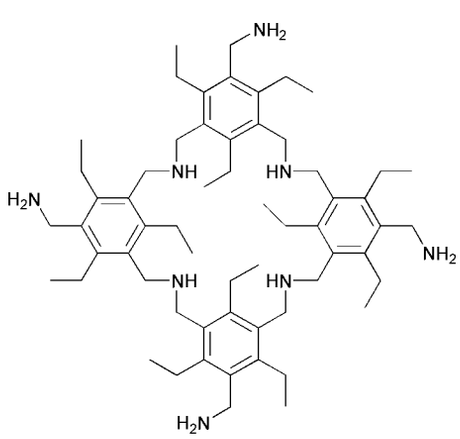
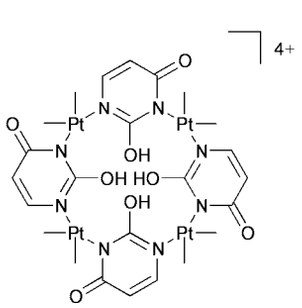


Fig. 9



17



18

incorporates four peptide loops arrayed around a central calix-[4]arene core (Fig. 10). By varying the sequence of the loop regions a range of differently functionalised receptor surfaces approximately 450 Å^2 in area can be prepared. From this family, potent inhibitors of chymotrypsin have been identified that function by binding to the protein surface.

A number of resorcin[*n*]arene-based systems have been used for neutral species recognition. Reinhoudt and co-workers have investigated the interaction of optically labelled saccharides with resorcin[4]arenes as synthetic saccharide receptors (Fig. 11).[103] Complexation of merocyanine labelled glucose,

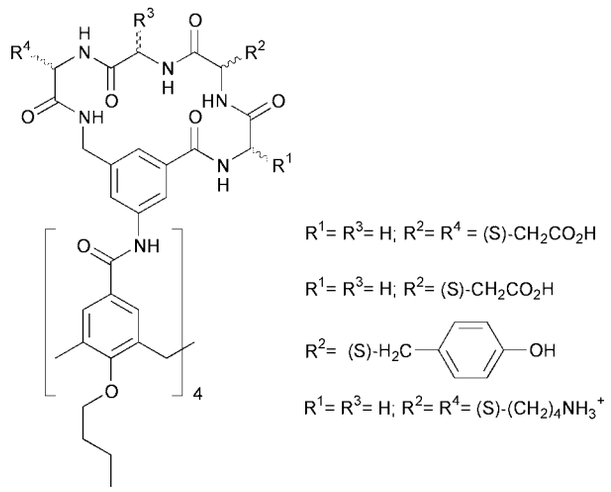


Fig. 10

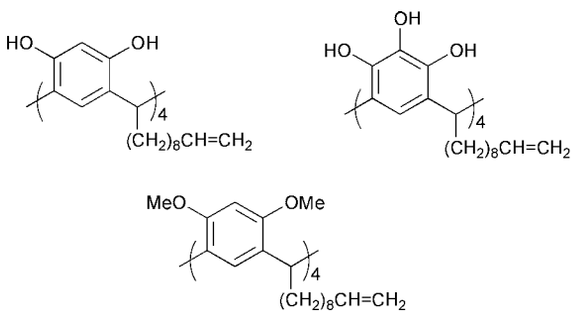
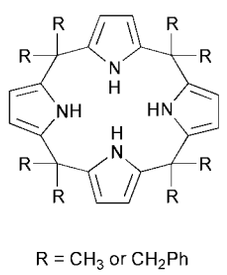


Fig. 11

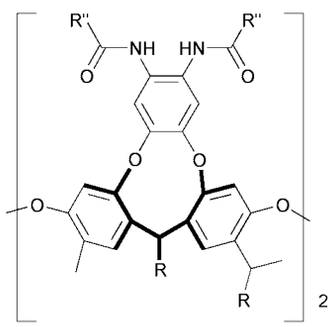


19

galactose and ribose was optically detected, with a modest selectivity towards the labelled glucose. A novel class of resorcin[*n*]arene-based cavitands (Fig. 12) that fold into a deep (8 × 10 Å dimensions) open-ended cavity by means of intramolecular hydrogen bonds have been synthesised by Rebek Jr and co-workers.[104] Self-folding is reversibly controlled by solvent and temperature. ^{1}H NMR demonstrated complexation of the cavitands with organic molecules such as adamantanes, lactams and cyclohexane derivatives. Exchange between complexed and free guest species is slow on the NMR time-scale. It is proposed that hydrogen bonding is responsible for this feature.

4.4 Extension of the calix[*n*]arene cavity

The group of Reinhoudt has carried out much work in the linking of medium-sized building blocks to calix[*n*]arene systems. The combination of upper rim 1,3-functionalised calix[4]arenes with bridged and di-bridged resorcin[*n*]arenes yields both 1 : 1 and 2 : 1 calix-resorcin[*n*]arenes.[105] This has provided the synthetic methodology for a new class of potential receptor molecules with large concave surfaces. Indeed, one such receptor composed of two calix[4]arene fragments and one bridging cavitand, has been shown to complex the steroid prednisolone-21-acetate in apolar solvents.[106] Synthesis of receptor molecules *via* a combination of calix[4]- and calix[6]arenes with other medium-sized building blocks, including cyclodextrins (Fig. 13), porphyrins and cyclotriveratrylene, has also been described.[107,108] Crown[*n*]cavitands have been synthesised by alkylation of tetrahydroxycavitands with polyethyleneglycol ditosylates.[109] The combination of 1,2-crown[6]cavitands with calix[4]arenes or resorcin[4]arenes resulted in potential receptor molecules with large hydrophobic surfaces. More recent work has focused on non-covalent assemblies to calix[*n*]arenes.[110] Calix[4]arenes diametrically substituted at the upper rim with two melamine units (Fig. 14) spontaneously form well-defined box-like assemblies in the presence of two equivalents of 5,5-diethylbarbituric acid. These molecular box assemblies consist of nine different components and are held together by 36



R = C_9H_{19}, R'' = n-C_7H_{15}
R = C_9H_{19}, R'' = cyclo-C_6H_{11}
R = C_9H_{19}, R'' = CH_2Cl
R = $C_{11}H_{23}$, R'' = n-C_7H_{15}
R = $C_{11}H_{23}$, R'' = cyclo-C_6H_{11}

Fig. 12

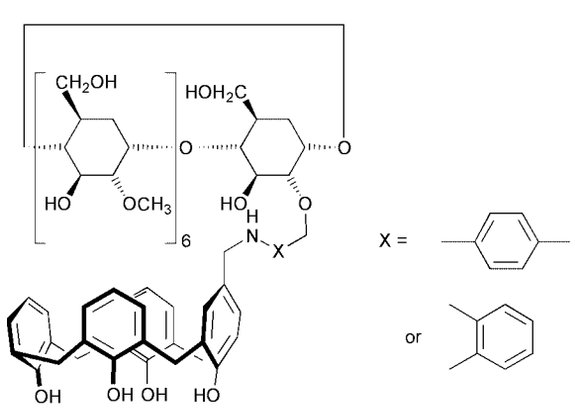


Fig. 13

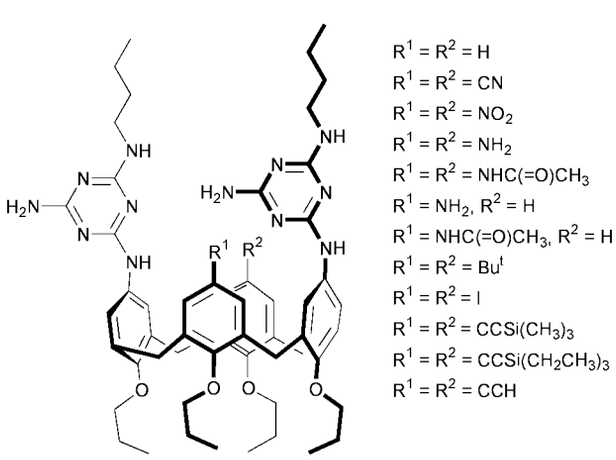
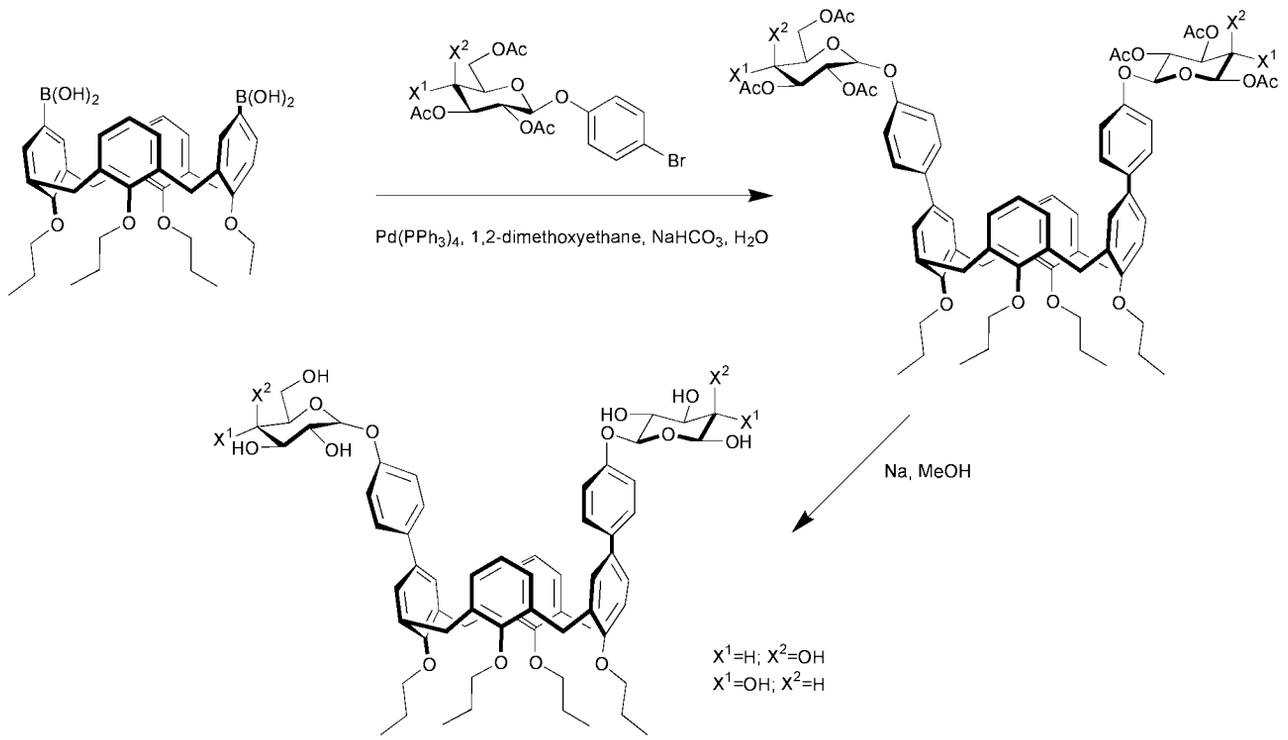
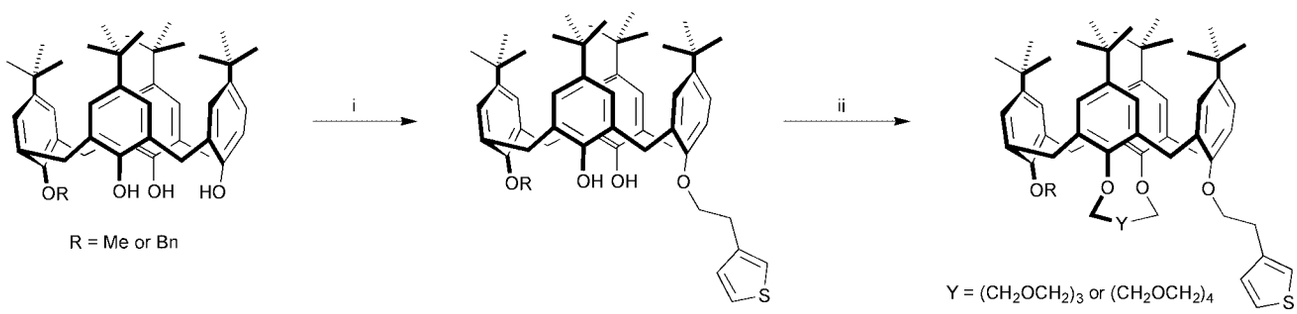


Fig. 14



Scheme 1



Scheme 2 *Reagents and conditions*: (i) 2-(3-thienyl)ethanol tosylate, K_2CO_3, MeCN, reflux; (ii) $TsOCH_2YCH_2OTs$, Cs_2CO_3, MeCN, reflux.

hydrogen bonds. Kobayashi and co-workers have very recently reported a similar concept with cavitands.[111]

Continuing the theme of enlarging the cavity of calix[*n*]-arenes, MacGillivray and Atwood have extended the cavity of a resorcin[*n*]arene by adding four pyridine molecules that participate in hydrogen bonding to the phenolic moieties.[112] Included solvent then acts as a guest. The Suzuki reaction has been used by Félix *et al*. to couple *p*-bromophenyl glycosides to boronic acid derivatives of *n*-propoxy-calix[4]arene in a 'one-pot' synthesis (Scheme 1).[113] These carbohydrate containing calix[*n*]-arenes with deepened cavities may provide a new class of molecular vectors. Ferguson *et al*. have reported synthetic protocols towards novel thienyl-calix[4]crown building blocks (Scheme 2).[114] Their aim is to graft the 1,3-bridged calix[4]arene crown ether units to polythiophenes, in order to create new classes of molecular sensors for alkali metal ions.

5 Cyclophanes

"*Cyclophanes represent* the *central class of synthetic receptors in molecular recognition. All types of substrates… have been complexed by tailor-made cyclophanes. In these association processes, all known modes of intermolecular binding interactions have been used.*" These words, written by François Diederich in 1990,[115] give an indication of the progress and scale of this area of research. In a general review of this type we cannot describe the majority of research over the past six years, so the reader is instead directed to excellent recent reviews.[21,22,116–124]

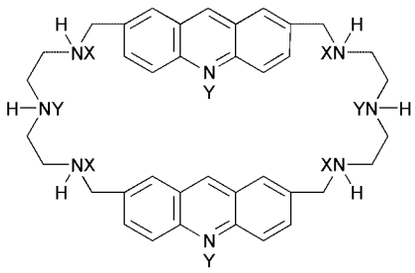
5.1 Acridine-based receptors

The group of Lehn continues to produce many contributions to this fascinating field of research. Lehn and co-workers have been looking at the molecular recognition of a variety of charged and neutral guests using receptors based on bisacridine units.[125,126] His group synthesised a cyclophane host **20** which displayed recognition phenomena with nucleosides and nucleotides.[125] It was shown that the number of charges carried by the substrates strongly influenced the association constant. This points towards the electrostatic attraction predominating in the receptor–substrate association. Hydrophobic effects are also of great importance—purine derivatives are bound nearly 200 times more strongly than pyrimidines.

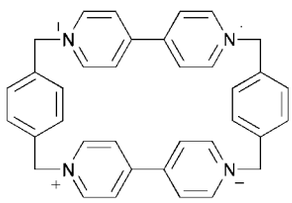
Lehn and co-workers have studied similar cyclophanes[126] that have displayed molecular recognition of azobenzene dicarboxylates. The stability constants of these complexes depend on substitution pattern and *cis*, *trans* configuration. He has also reported related cyclophanes based on phenanthridine units.[127]

5.2 Cyclobis(paraquat-*p*-phenylene)-based receptors

Since its synthesis in 1988 Stoddart's "Blue-Box"—cyclobis-



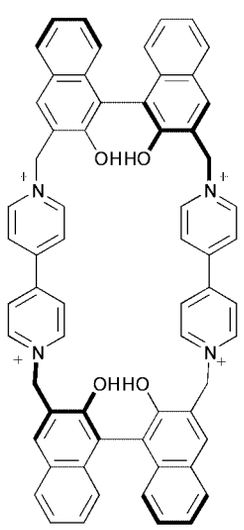
20



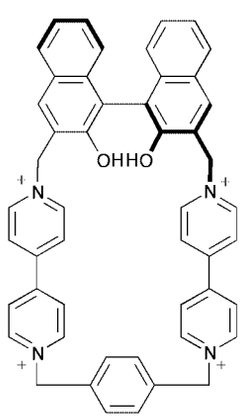
21

(paraquat-*p*-phenylene) **21**—and its derivatives have received intense study (for an excellent overview, the reader is referred to Stoddart and Philp's review of self-assembly in natural and unnatural systems[128]). An improved synthesis of **21** has been reported by Stoddart and co-workers[129] and its binding properties have been evaluated with phenyl glycopyranoside,[130] where the β-anomer was bound 0.6 kcal mol^{-1} more strongly than the α-anomer. Recent work[131,132] has investigated the effect of side arm length and structure of *p*-substituted phenyl derivatives on their binding to **21**. This has shown that the aromatic core, whilst essential in placing the guest in the host cavity, is not responsible for an appreciable amount of binding in the system studied. In fact, the ether oxygen atoms in the side arms bind to the exterior of the cyclophane, providing the majority of the observed association.

Stoddart and co-workers have elaborated **21** by exchanging the *p*-phenylene spacer groups with 3,3′-linked-2,2′-dihydroxy-1,1′-binaphthyl spacers to form **22** and **23**.[133] This binaphthyl group is a very popular chiral spacer with C_2 symmetry. The binding studies show a nearly eight-fold preference for L-enantiomers over D-enantiomers for π-electron-rich amino acids and indicate that **22** and **23** have potential uses in resolving racemic substrates containing π-electron-rich aromatic rings, and could also act as asymmetric catalysts of appropriate reactions.

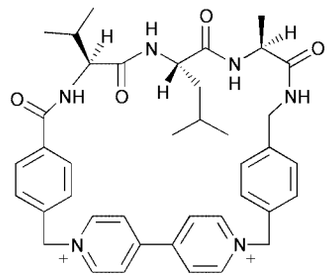


22



23

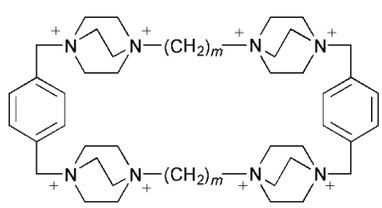
Chiral molecular recognition is also displayed in **24**, designed by Mallouk *et al.*[134] Here one of the paraquat moieties has been substituted for a tripeptide, (*S*)-Val-Leu-Ala. This cyclophane binds (*R*)-DOPA 13 times more strongly than (*S*)-DOPA [DOPA = 3-(3,4-dihydroxyphenyl)-L-alanine] and could lead the way for combinatorial methods of synthesis and screening, not unlike the methods used by Fessmann and Kilburn[135] (mentioned in the Clefts section of this review). Another closely related compound has been synthesised and assessed by Mallouk and co-workers.[136]



24

Smith and co-workers. have designed a receptor for paraquat and related systems.[137] This cyclophane incorporates boronic acid moieties (described in detail later in this review) which complex to the charged nitrogen atoms of paraquat to give modest association constants.

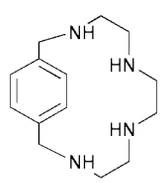
The usual binding mode for the "blue-box" is for the guest to reside within the cyclophane. However this is not always the case with related compounds, and Menger and Catlin showed with **25** that ATP and other anionic guests rely on ion-exchange to provide the binding interaction.[138] Although Job plots showed the formation of a 1 : 1 complex in solution, this did not necessarily mean the formation of an inclusion complex. An investigation of the crystal structure clearly shows a clathrate-type interaction with the guest residing external to the cavity.



25

5.3 Biomimetic receptors

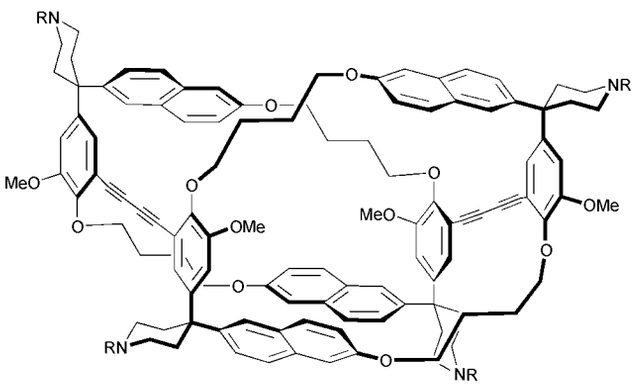
The modelling of active sites in enzymes has application in many areas of science. Investigations into the active site of carbonic anhydrase have been carried out using polyaza[*n*]paracyclophanes such as **26**.[139] When complexed to zinc, its catalytic activity in the hydrolysis of *p*-nitrophenyl acetate has been measured. It was found that small modifications (replacing a secondary amine with a tertiary species) had large effects on the overall catalytic activity.



26

Steroid-binding proteins contain deep hydrophobic cavities defined by aromatic amino-acid side chains which encapsulate steroid molecules. This has been modelled by the group of

Diederich who synthesised tricyclic cyclophane receptor **27** to study the effect of cavity depth on receptor selectivity.[140] It was found that an increase in depth of 2 Å (from 11 Å to 13 Å) increased the steroid encapsulation with a gain in binding free energy of 0.9 kcal mol^{-1} in deuterated methanol. The development of steroid receptors could lead to a new class of pharmacological agent.[19]



27

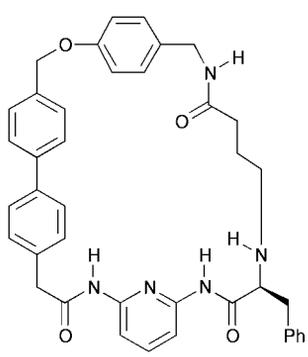
Diederich has also described the synthesis of a receptor which mimics the vancomycin carboxylate binding site.[141] These cyclophanes contain open, preorganised cavities of sufficient size to incorporate small aliphatic residues, but ^{1}H NMR studies indicate that complexation occurs outside of the cavity, presumably due to the high entropic cost of fully desolvating the anionic centres in the receptors.

5.4 Aza-cyclophanes

A range of aza-cyclophanes have been synthesised and their binding and basicity properties studied.[142–144] It has been shown that cyclophanes of this type can bind nucleotides with very respectable stability constants. Ragunathan and Schneider have also investigated aza-cyclophanes' binding properties with nucleotides.[145]

5.5 Peptide receptors

Kilburn *et al*. have been examining receptors designed to bind to peptidic guests with a carboxylic acid terminus.[135,146,147] Whilst the acyclic receptors[135] are dealt with elsewhere in this review, macrocyclic receptor **28** is also worthy of mention.[147]



28

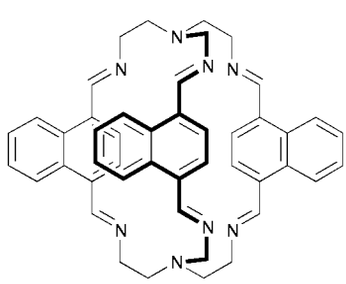
Compound **28** binds a range of *N*-benzyloxycarbonyl (*N*-Cbz) protected dipeptides in chloroform-d_1 with association constants of 3.0×10^2–3.6×10^3 M^{-1}. The best binding was realised with *N*-Cbz-β-alanyl-L-aniline and indicates that in addition to a strong interaction between the carboxylic acid and the diamidopyridine unit, hydrogen bonding interactions between the guest backbone and the receptor amide side wall are feasible. Other peptide receptors synthesised recently have come from the Still lab.[61,148–151]

6 Molecular containers

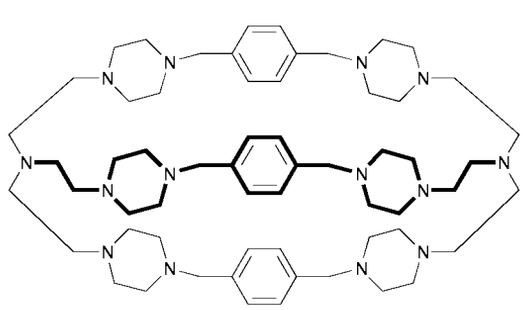
Nature's selective binding sites are often characterised by a large degree of encapsulation of the targeted substrate. Total encapsulation of guest species within a cavity of a synthetic host molecule is thus an important goal for many supramolecular chemists.[152,153] Such systems have potential applications in separations, catalysis, sensors and drug delivery. This section discusses such 'container'-like structures, including cryptand and cage-based molecules, which totally or partially surround a guest.

6.1 Cation encapsulation

The synthesis of a hexaimino cryptand containing two tris(2-aminoethyl)amine moieties bridged by three naphthylene groups, **29**, has been undertaken by Tsubomura and co-workers.[154] Ag^+ and Cu^+ cryptates of the ligand were also prepared which show conformational changes about the imino-bonds from the original cryptand. Bencini *et al*. have developed a large cavity reinforced cryptand, **30**, composed of two polyamine moieties connected *via* three *p*-xylene bridges.[155,156] The macrobicycle forms stable mono- and di-copper(II) species and, when fully protonated, behaves as a selective receptor for naphthalene disulfonate anions in aqueous solution. Graf *et al*. synthesised the pseudocryptand (**X** in Fig. 15) combining a [2.2] macrocyclic core of a [2.2.2] cryptand with two bidentate dianionic catecholate units.[157] The binding of boron by both catecholate moieties leads to a borate ester (**Y** in Fig. 15), creating a preorganised cavity bearing a negative charge, which can then strongly complex alkali metal cations to form a neutral complex (**Z** in Fig. 15). A more exotic example of cation recognition is provided by Raymond and co-workers' self-assembled gallium metal cluster containing (dihydroxybenzamido)-naphthalene groups, which selectively encapsulates aqueous cationic ammonium species.[158] The group of Kim and co-workers has reported a "molecular bowl" based on caesium ion complexed cucurbituril, in which inclusion of a guest molecule can be reversibly controlled by the acidity of the medium.[159] A dye labelled and conformationally restricted podand ionophore was prepared and screened for peptide binding by Burger and Still.[150] It was found to bind unhindered cationic peptides containing arginines or *N*-terminal glycines. It also selectively bound a single tripeptide (L-Arg-L-Phe-D-Asp).



29



30

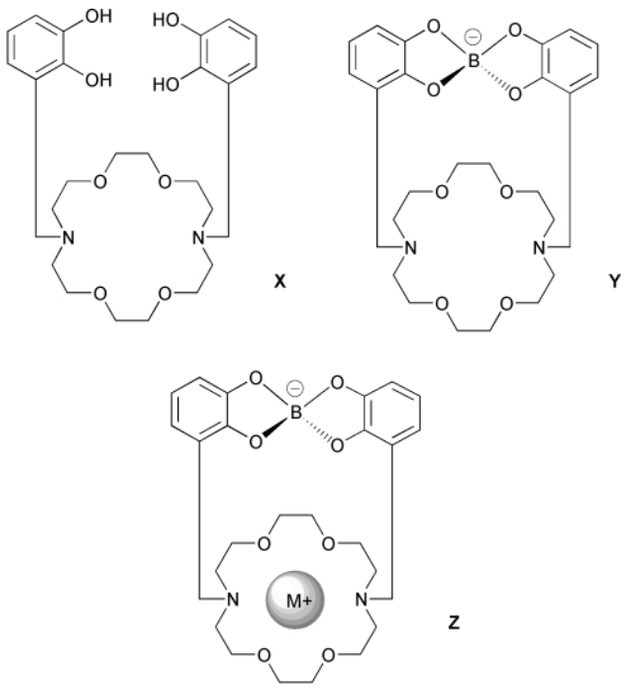
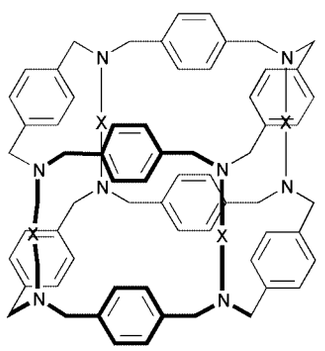


Fig. 15

6.2 Anion encapsulation

A number of small review articles describing synthetic anion receptors have lately been published.[160–162] Nitrate ions have been detected using an ensemble of a synthetic receptor **31** and colorimetric dyes as indicators.[163] Anslyn and co-workers' receptor forms 1 : 1 complexes with anionic dyes such as Methyl Red in organic solvents. Adding nitrate ions perturbs the equilibrium between the dye and receptor, resulting in the formation of a receptor–nitrate complex. Displacement of the dye causes large absorbance changes due to alteration of the microenvironment of the chromophore. Cattani and Schmidtchen have designed a zwitterionic compound built on a tetrahedral macrocyclic core, by attachment of anionic tetraphenylborate moieties to a parent macrotricyclic amine **32**.[164] The betainic product was shown to form inclusion complexes with chloride and bromide anions. Tanaka *et al*. have been interested in introducing dipeptide moieties into the bridging segments of cage-type cyclophanes.[165,166] These novel cyclophanes were constructed with two rigid macrocyclic skeletons, tetraaza[3.3.3.3]paracyclophanes, and four bridging segments composed of either β-L-aspartyl-L-aspartyl or β-D-aspartyl-D-aspartyl residues (Fig. 16). Fluorescent guests, such as 8-anilinonaphthalene-1-sulfonate, were shown to be incorporated into the host cavity. Chiral host–guest interactions between the host and pamoic acid (a hydrophobic guest) were also observed. Holman *et al*. have prepared a series of π-metalated cyclotriveratrylenes (CTV).[167] Treatment of ruthenium and iridium organometallic species with the bowl-shaped macrocycle CTV, results in the formation of mono-, di-, and trimetallic CTV complexes. The CTV hosts display inclusion of both anionic and neutral guests within the bowl-shaped cavity. The unique inclusion phenomenon of anionic species, such as BF_4^- and $CF_3SO_3^-$, within the aromatic cavity is explained by the withdrawal of π-electron density by the transition metal centres.



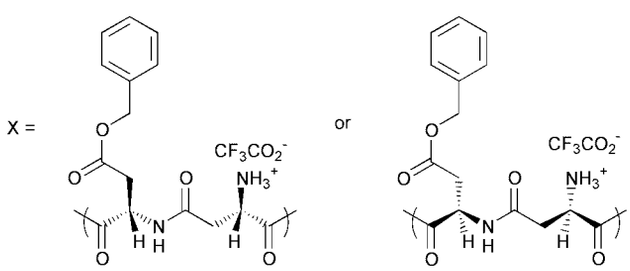
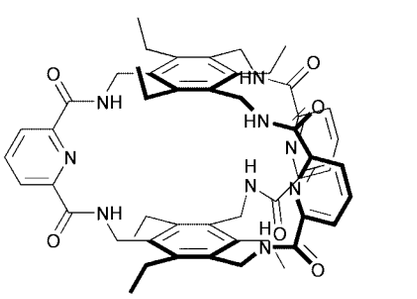


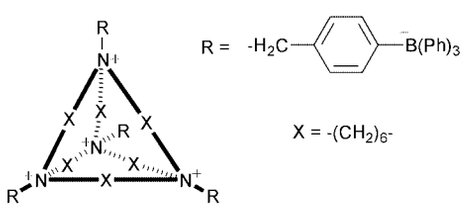
Fig. 16

6.3 Neutral molecule encapsulation

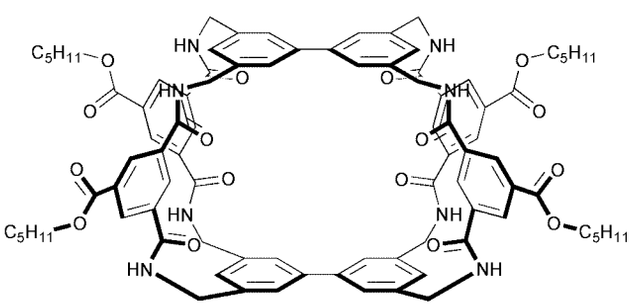
A novel carbohydrate receptor from Davis and Wareham, **33**, was inspired by carbohydrate-binding proteins, which commonly place aromatic surfaces against patches of carbohydrate CH groups while accepting the hydroxy groups into networks of hydrogen bonds.[168] The receptor shows unusual levels of affinity and selectivity to octyl pyranosides in chloroform even in the presence of 8% methanol-d_3. Davis and co-workers have also developed "cholaphanes" for binding carbohydrates in nonpolar media.[169] The cholic acid steroid-derived macrocyclic hosts feature substantial cavities with inward-directed hydroxy



31

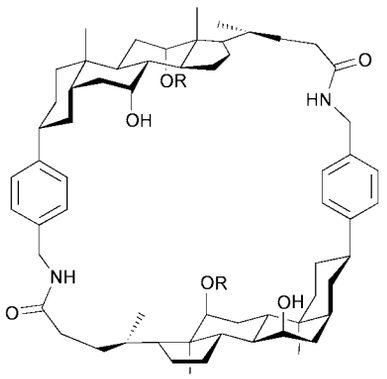


32

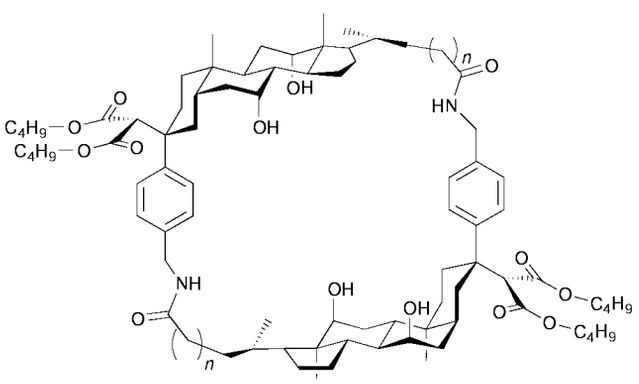


33

groups (Fig. 17). Another type of carbohydrate receptor is Penadés' "glycophanes", cyclodextrin-cyclophane hybrids,[170] which bind a series of 4-nitrophenyl glycosides in a stable and stereoselective manner. Aoyama and co-workers have reported the synthesis of a number of sugar clusters constructed from a macrocyclic skeleton and four carbohydrate branches.[171] The clusters containing maltose or maltotriose residues were found to bind the lectin concanavaline A.



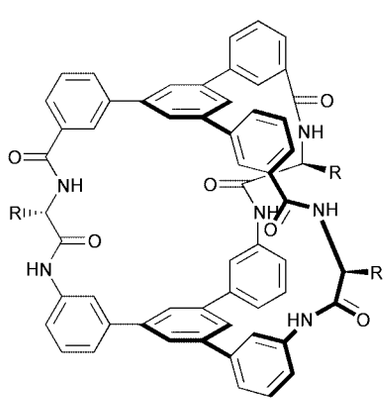
R = H or CH_2Ph



n = 0, 1 or 2

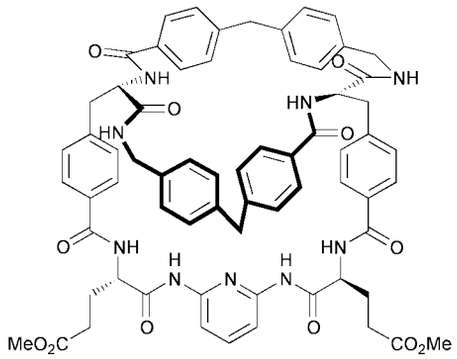
Fig. 17

Kilburn *et al*. have prepared a bowl-shaped macrobicyclic receptor, **34**, which is selective for dipeptides derived from two α-amino acids, and is a particularly strong receptor for Cbz-L-Ala-L-Ala-OH. Chiral C_3-symmetric, cage-like receptors with convergent, helically oriented amide hydrogen bonding sites have been synthesised by Diederich and co-workers (Fig. 18).[172] They were found to complex *N*-protected amino acid derivatives and, in particular, dicarboxylic acids in non-competitive solvents. Enantioselectivity is observed in the binding of *N*-

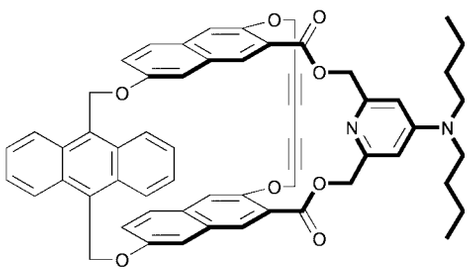


R = $CH_2CH(CH_3)_2$ or CH_2Ph

Fig. 18



34



35

Cbz-Glu. Cloninger and Whitlock have reported the synthesis and complexation behaviour of a receptor containing an anthracene unit that is capable of forming multiple edge–face interactions to large aromatic guests.[173] The host, **35**, binds bicyclic aromatic guests such as 6-nitro-2-naphthol, a serotin-mimic and a stilbene derivative with high affinity. Neugebauer and Knoche have studied the reaction of cucurbituril with 4-amino-4′-nitroazobenzene (DO3) and 4,4′-diaminoazobenzene (Diam) in aqueous HCl.[174] The formation of 1:1 host–guest complexes is observed. Kräutler has described the efficient synthesis of a porphyrinoid container molecule, "calix-porphyrin", from anthracene and studied its ability to bind a selection of amines.[175]

7 Clefts

This section consists of compounds whose molecular shape is reminiscent of a cleft, clip, pair of tweezers or any other related shape of compounds where the receptor partially but not fully surrounds the guest molecule. Recent reviews in this area have come from Diederich and co-workers,[176] Bishop[177] and Bell *et al*.[178]

7.1 Ferrocene-based neutral molecule receptor

An interesting "ball-bearing" system has been designed by Gokel and co-workers using the central iron atom as the flexible element in the receptor system.[179] The design schematic, shown in Fig. 19, paved the way for a large range of related compounds to be synthesised. A general synthetic pathway is shown (Scheme 3) which affords the target receptors in good to excellent yields. Binding constants, determined using dynamic ^{1}H NMR methods, are quoted between 10^2–10^4 M^{-1} in chloroform-d_1 or THF-d_8, depending on the basicities and sizes of substrates. The "ball-bearing" feature of the cleft allows conformational reorganisation during complexation. This feature has been taken advantage of recently by Inouye *et al*. who have designed a ferrocene-based receptor for nucleobases.[180]

7.2 Guanadine-based clips

Nolte and co-workers have studied a variety of molecular clips based around a guanidine core.[181–183] These have included phenyl[181] (Fig. 20) and naphthyl[182,183] (Fig. 21) side walls.

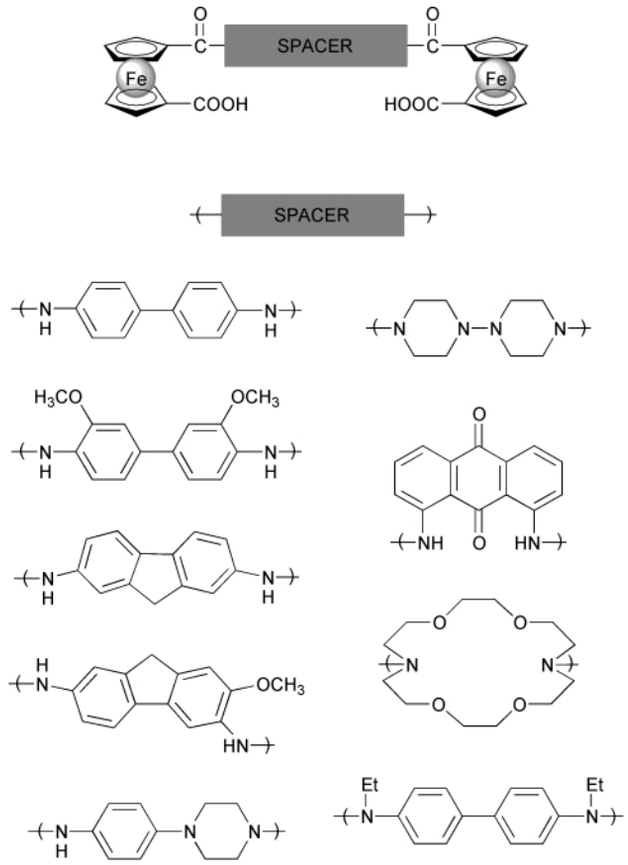
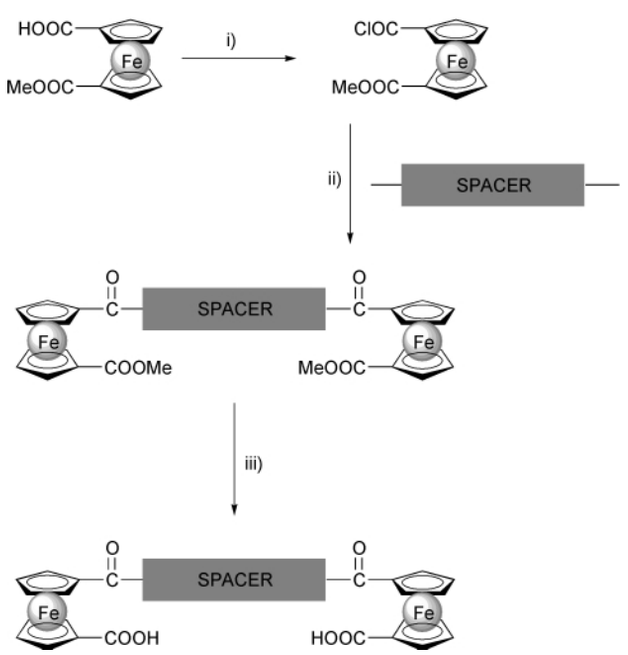


Fig. 19



Scheme 3 *Reaction conditions and yields*: i) $(COCl)_2$, pyridine–CH_2Cl_2, 4 h, rt, 88%; ii) Et_3N, CH_2Cl_2, 4 h, rt, 60%; iii) LiOH, 10% $NaOH_{(aq)}$, DME, 12 h, reflux, 93%.

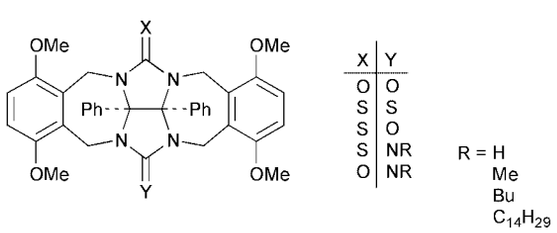


Fig. 20

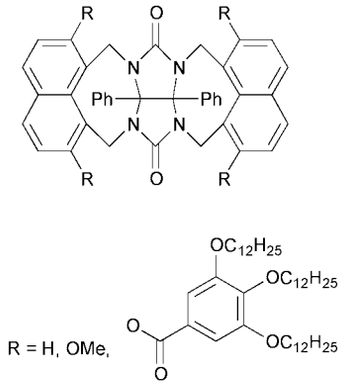


Fig. 21

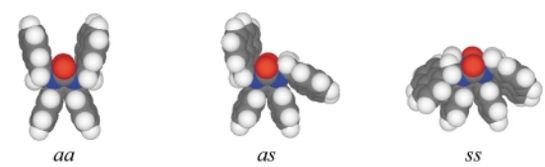


Fig. 22

The naphthyl derivatives have been shown to exist in three different conformations (Fig. 22), designated *aa*, *as* and *ss*. These interconvert on the NMR time-scale but it is only the minor conformer *aa* which binds aromatic guests. Indeed, *as* and *ss* conformers disappear completely in the presence of excess guest molecules.

These clips bind aromatic guests by π–π interactions as shown in the crystal structure of a complex of nitrobenzene with the naphthalene derivative shown in Fig. 21 (R = OMe).[183]

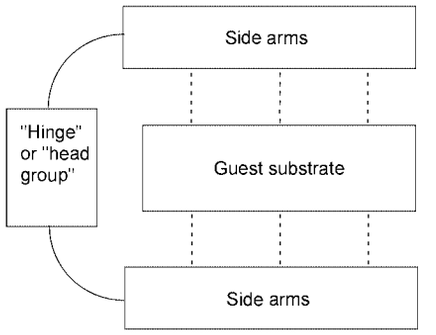
7.3 Natural product receptors

Moran and co-workers have developed a receptor for tartaric acid derivatives based on a spirobifluorene spacer.[184] This receptor, containing two chromenone-benzoxazole binding arms, successfully discriminated L- and D-tartaric acid derivatives, with differences in binding constants as large as 37 fold.

Two other examples both take advantage of combinatorial chemistry techniques, but from different perspectives. Liskamp and co-workers have synthesised several tweezers based on peptidosulfonamide peptidomimetics[185] and then tested them against a library of ~25000 tripeptides to generate hits. They found one receptor which showed high selectivity for a small number of deprotected tripeptides. Fessmann and Kilburn have reversed this methodology and designed a receptor library to detect a specific tripeptide guest.[135] The design principles are shown in Fig. 23—two side arms connected by a hinge will complex a suitable guest. If the guest is known to have a carboxylic acid head group, this can be targeted by incorporating a carboxylic acid binding site (CBS) into the hinge part of the receptor.

Using this approach, Fessmann and Kilburn synthesised a small library of receptors with a diamidopyridine head unit and tetrapeptide side arms. The most common successful receptor sequence was subsequently resynthesised *via* solid-phase synthesis. This receptor had the tetrapeptide side-arms Phe-Val-Leu-Trp. Fluorimetric binding studies on this compound with dansyl-L-Glu(OBu′)-L-Ser(OBu′)-L-Val-OH in DMSO–$CHCl_3$ (2:98) revealed the formation of a 1:1 complex with an association constant of 2.6×10^5 M^{-1}. Torneiro and Still describe receptors which bind certain peptides sequence-selectively in water[151] and speculate on the possibility of combinatorial libraries of receptor molecules, which two years later has been realised by Kilburn.

Carbohydrate recognition and binding is complicated by the formation of intramolecular hydrogen bonds and by



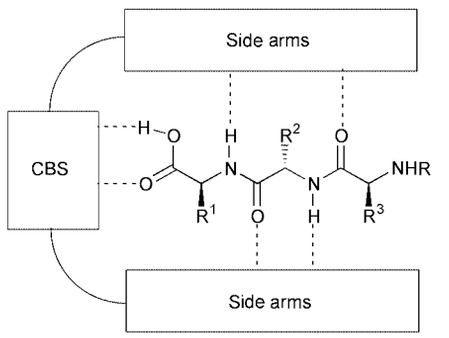


Fig. 23

solvation.[186] de Mendoza and co-workers have designed a cleft based on a flexible steroid framework designed to probe the binding behaviour of D-glucuronic acid metabolites.[187] This exhibits moderate binding in competitive solvents but the steroid framework does not significantly increase the binding, compared to the model compound. However, he predicts a more rigid framework would produce better binding.

Schrader has made progress towards the binding of small biologically important molecules with his bisphosphonate based receptors.[188–192] Those containing a xylene core with one or two pendent phosphonate moieties (Fig. 24) display significant binding to 1,2- and 1,3-amino alcohols[188,190] and amino sugars,[191] whilst receptors with a biaryl core are large enough to bind alkylguanidinium species.[189] The xylene system relies on hydrogen-bonding between the phosphonates and the amine protons (Fig. 25) and forms 1:1 complexes with binding constants greater than 10^4 M^{-1} in many cases.

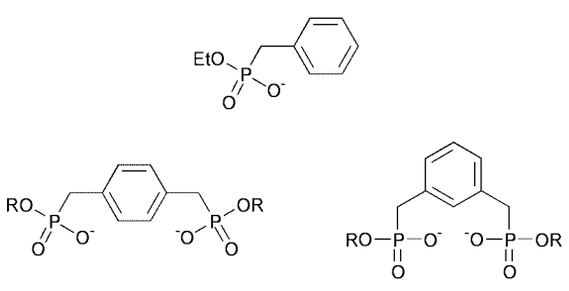


Fig. 24

The alkylguanidinium receptor also relies on the phosphonate–amine interaction and gives 1:1 complexes with binding constants of approximately 3×10^5 M^{-1} in DMSO. Recently, binding of arginine in water has been reported,[193] with binding constants of 1.1×10^3 M^{-1}.

Phosphate binding proteins are important receptors for active transport systems in cells. Two recent examples of neutral phosphate receptors[194,195] use thiourea derivatives as hydrogen-bond donors. Umezawa and co-workers' receptor[195] has a binding constant in DMSO of 1.95×10^5 M^{-1} compared to 1.08×10^5 M^{-1} in DMF for Wu and co-workers' receptor.[194]

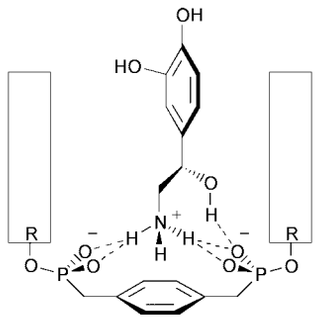


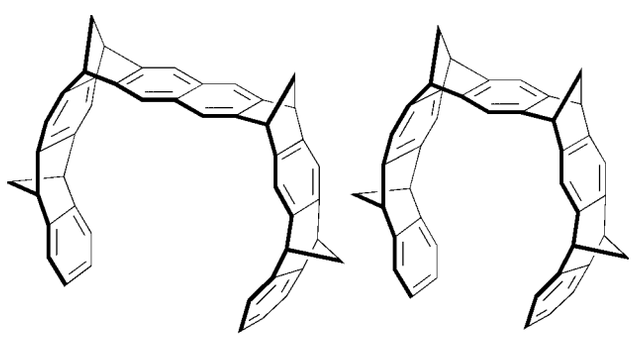
Fig. 25

Costa and co-workers have synthesised several squaramido-based receptors for the binding of tetraalkylammonium compounds.[196,197] Initially binding was studied by ^{1}H NMR techniques but a recent modification to the receptor[197] has added a fluorescent moiety to one of the arms, leading to binding being followed by quenching of fluorescence.

Other examples of molecular recognition of biologically important molecules include clefts for dicarboxylic acids,[198] adenine[199] and the synthesis of transacylase mimics.[200]

7.4 Molecular tweezers

Whilst a number of receptors can lay claim to being molecular tweezers, those designed by the group of Klärner *et al.* are beautiful recent examples.[201,202] Synthesised by repetitive Diels–Alder cyclisation reactions (an example is shown in Scheme 4) these molecules (**36** and **37**) bind a wide range of electron-deficient aromatic and aliphatic substrates within an electron-rich preorganised cavity.



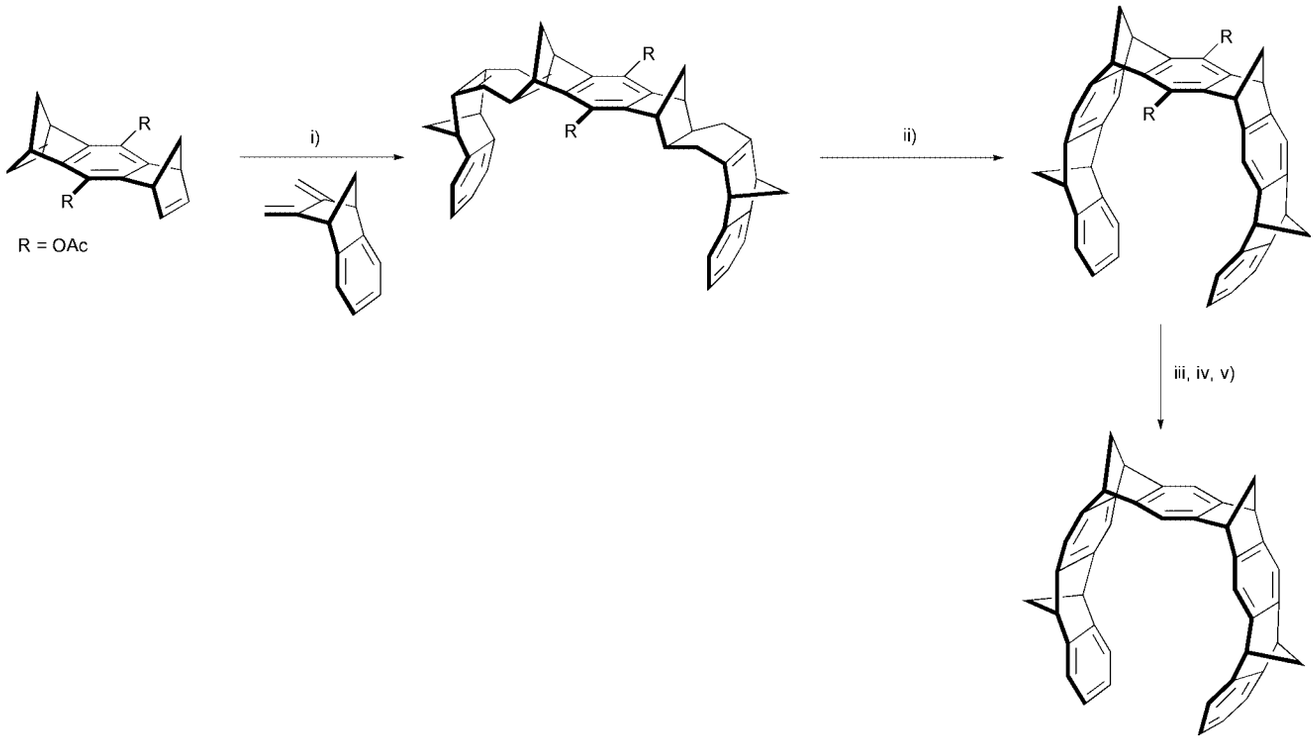
36 **37**

7.5 1,1′-Binaphthalene-based receptors

Diederich and co-workers have investigated clefts based on the chiral 1,1′-binaphthalene spacer.[116,203,204] These form complexes with a variety of *N*-Cbz derivatives of excitatory amino acids. Enantioselectivity is improved by introducing functionality at the 7,7′-positions of the 1,1′-binaphthalene spacer[116] or locking the dihedral angle θ either by bridging the 2,2′-positions or by attaching sterically demanding substituents to these positions (Fig. 26).[204] Diederich and co-workers have since extended this work[203] by synthesising ditopic macrocyclic 1,1′-binaphthalene based receptors which demonstrate negative cooperativity between the two binding sites, *i.e.* the first binding event unfavourably affects the second.

8 Hydrogen-bonding receptors

Hydrogen-bonding is an incredibly important supramolecular force. Life as we know it would, quite literally, not be possible without this interaction. The reader is directed to articles cited elsewhere in this review for a discussion of hydrogen-bonding with regard to individual applications. Within this section we



Scheme 4 *Reaction conditions and yields*: i) $(C_2H_5)_3N$ (catalytic amount), toluene, 160 °C, 5 d, 71%; ii) DDQ, toluene, 110 °C, 2 h, 83%; iii) $LiAlH_4$, tetrahydrofuran, 60 °C, 5 h, 98%; iv) Tf_2O, pyridine, 20 °C, 20 h, 98%; v) $PdCl_2(PPh_3)_2$, 1,3-bis(diphenylphosphine)propane, dimethylformamide–NBu_3–HCO_2H, 100 °C, 90 h, 82%.

investigate hydrogen-bonding systems not considered elsewhere for reasons of classification.

8.1 Theoretical investigations

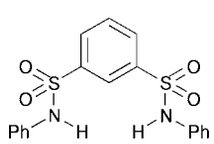
Progress has been made towards a quantification of the importance and strength of hydrogen-bonding interactions. Lüning and Kühl investigated systems containing arrangements of four adjacent hydrogen-bond donors and acceptors.[205] The association constants are assessed experimentally and found to agree with the values calculated from increments. This incremental approach for the prediction of hydrogen-bond associations was described by Sartorius and Schneider who proposed two simple free energy increments which successfully describe a large range of experimental association constants.[206]

Hunter and co-workers have investigated intermolecular edge-to-face aromatic interactions using a chemical double mutant cycle,[207–210] an approach originally developed by Fersht and Serrano for quantifying side chain–side chain interactions in proteins.[211] A hydrogen-bonded complex including an aromatic edge-to-face interaction has been synthesised. By systematically varying the receptor and the guest molecules it is possible to quantify the aromatic interaction. The cooperative nature of hydrogen-bonding is emphasised with his investigation of ternary mixtures.[212] The formation of a small hydrogen-bond network polarises the hydrogen-bonding groups of the molecules in question, increasing the strength of the individual hydrogen-bonding interactions. He has also developed software for calculating complexation-induced changes in ^1H NMR chemical shift for hydrogen-bonded complexes.[213] This software can be used to determine supramolecular structures in solution.

8.2 Replication and catalysis

The recognition of small molecules through hydrogen-bonding interactions is an important field of research. In particular, the ability of hydrogen-bond donors to stabilise developing charge on reaction intermediates has been exploited to devise enzyme mimics. Hamilton and co-workers have devised a synthetic host containing an "oxyanion hole" which can be viewed as a mimic of many protease enzymes. In their work[214] they demonstrate that this methodology can result in rate acceleration of the Michael addition of a thiol to a maleimide bound to a hydrogen-bonding receptor, by stabilising the developing negative charge on the oxyanion intermediate (Fig. 27).

A similar approach has been taken by Crabtree and co-workers with their receptor **38** which catalyses aldehyde imination, again by stabilising the developing oxyanion intermediate.[215,216] A rate increase of more than six-fold is reported.



38

More complex receptors have been designed for the acceleration and/or stereocontrol of a Diels–Alder cycloaddition reaction between a furan and a maleimide. Philp and co-workers have shown[217] that the formation of intramolecular hydrogen-bonds in the cycloadducts is the key to understanding the origin of the acceleration and stereocontrol of the reaction. Rebek Jr and co-workers have designed synthetic templates for adenine derivatives.[218] The product of the templated reaction (an amide) is itself a template for the formation of the original template. This "reciprocal template effect" should not be confused with self-replication, where there is only one final product, the template itself. Self-replicating systems will not be discussed here as a detailed review has appeared recently in the literature.[219]

8.3 Natural product receptors

8.3.1 Amino acid receptors

Wills and co-workers have described the synthesis and binding properties of a number of chiral receptors for amino acids.[220,221] These receptors, synthesised by a sequence of *ortho*-lithiation

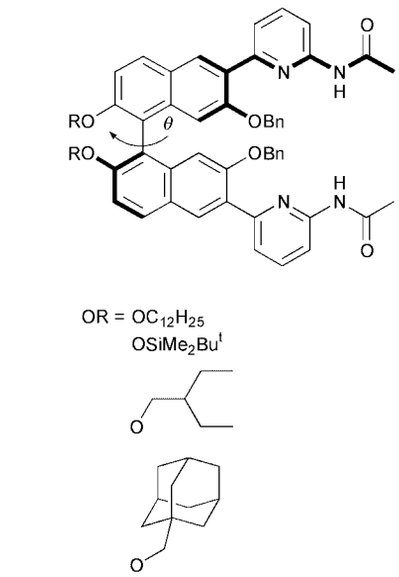
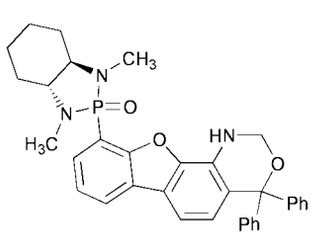


Fig. 26

reactions with chirality introduced late in the synthesis, were shown to bind *N*-Boc protected amino acids with binding constants in the region of 10^{-3} M^{-1}. One receptor, **39**, displayed enantioselective binding to aniline derivatives with 40% ee.



39

8.3.2 Carboxylic acid receptors

Goswami *et al.* underline the importance of multiple hydrogen-bonding interactions in the design of successful receptors within their paper describing two flexible hosts for carboxylic acids.[222] One can form two hydrogen-bonds with the carboxylic

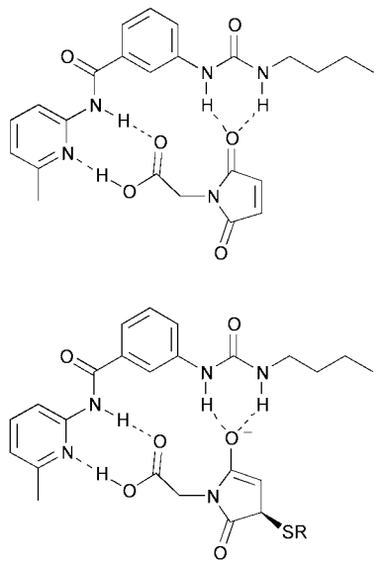
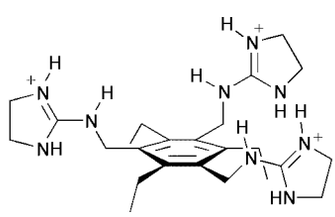


Fig. 27

acid guest whilst the other can form three. The receptor with three H-bonding sites displays the higher association constants with a range of acids, including the drug molecule ibuprofen.

Another synthetic receptor for carboxylic acid-containing biomolecules is described by Anslyn and co-workers. Their receptor for citrate[223] (a tricarboxylic acid) displays the power of preorganisation in the rational design of host molecules. In highly competitive media, **40** displayed selectivity for citrate over a number of other carboxylates with a binding constant of 6.9×10^3 M^{-1}. The importance of the guanidinium groups for recognition was determined by the use of control compounds. The authors concluded that when extensive hydrogen-bonding is involved in the host–guest complex, guanidinium groups are better receptors than ammonium ions in water.



40

Lactic acid carbamoyl derivatives can be chirally discriminated by a group of receptors developed by Moran and co-workers. These receptors (Fig. 28), based on a chromenone-benzoxazole framework, display K_{rel} (defined as K_{SS}/K_{RS}) values

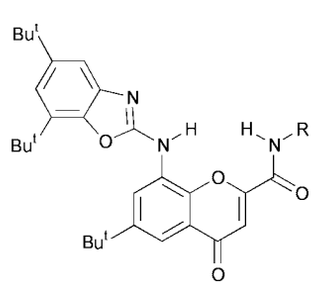
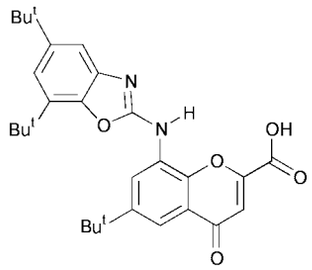


Fig. 28

of between 1.2 and 9.0, depending on the aminoethanol employed in the synthesis from chromenone carboxylic acid **41**.[224]



41

A chiral receptor molecule for carboxylates and diketones has also been developed by Schuster and Göbel.[225] This has three convergent hydrogen-bond donors and, although binding constants are not quoted, complexation is observed by the appearance of a broad CD band, indicating chiral perturbation of the diketone chromophore.

Hughes and Smith have also investigated the binding of carboxylic acids with a range of related synthetic receptors.[226] He found that an internal Lewis acid as in the pinacol-protected boronic acid (Fig. 29) enhances acetate binding 20 fold compared to the non-boronic acid derivative.

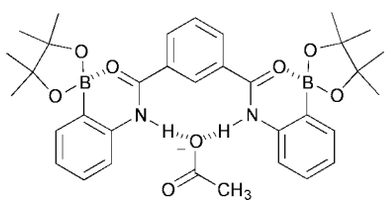
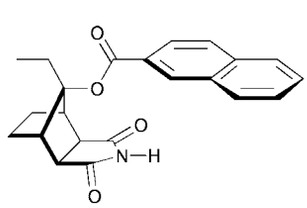


Fig. 29

8.3.3 Heterocycle receptors

Two examples demonstrate the scope available to the synthetic chemist for binding these common types of biomolecules. The first is the binding of creatinine, a blood metabolite of considerable importance in clinical chemistry. This has been achieved by Bell and co-workers using highly preorganised, polyheterocyclic receptors.[227] These receptors contained chromophores to enable binding constants to be investigated by UV–visible spectroscopy. The authors are unable to provide quantitative association constants, but binding is clearly observed by quenching of absorption on addition of creatinine.

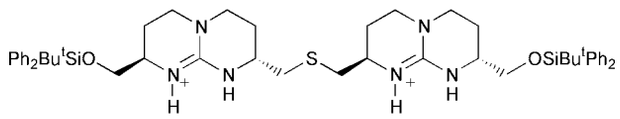
The second example comes from Lonergan and Deslongchamps who describe the synthesis of molecular scaffolds which can be converted into simple receptors, **42**, for 9-butyladenine.[228] These compounds combine hydrogen-bonding with π–π stacking interactions to form complexes with modest association constants. The role of aryl interactions is not quantified, but seemed to follow the Hunter–Sanders electrostatic model for π-stacking interactions.[229]



42

8.3.4 Peptide receptors

de Mendoza and Hamilton and co-workers have approached the binding of peptide surfaces by designing hydrogen-bonding receptors which recognise specific peptide sequences and stabilise α-helices.[230–232] In the first example, aspartate residues are targeted by **43**,[232,233] based around two guanidinium recognition sites linked by a sulfide bridge. Binding constants of the order of 10^5 M^{-1} are achieved with successful stabilisation of the peptide strand.



43

In the second example, Hamilton and co-workers again target aspartate residues, now separated by a variable number of alanine or glutamine residues.[231] The receptors are again based around guanidinium groups, this time separated by a rigid bicyclo[3.3.0]octane spacer. Their results indicate that the bicyclooctane spacer serves as a rigid scaffold that preorganises the guanidinium groups in a complementary manner to a specific aspartate arrangement in the peptide strand.

Hunter and co-workers have synthesised two cyclic dipeptide receptors (Fig. 30).[234,235] These amide macrocycles are highly preorganised and rely on both hydrogen-bonding and CH–π bonding interaction to complex their guests. One of these macrocycles has been analysed using in-house software to investigate its solid-state *vs.* ^{1}H NMR structure.[213]

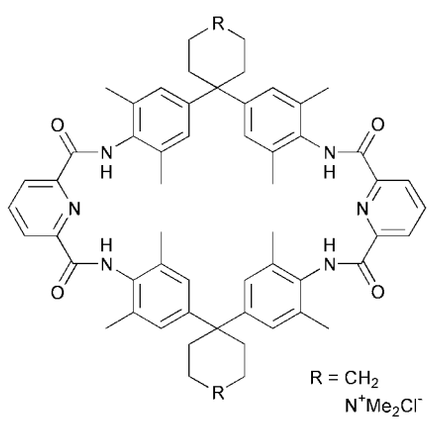


Fig. 30

9 Self-assembling receptors

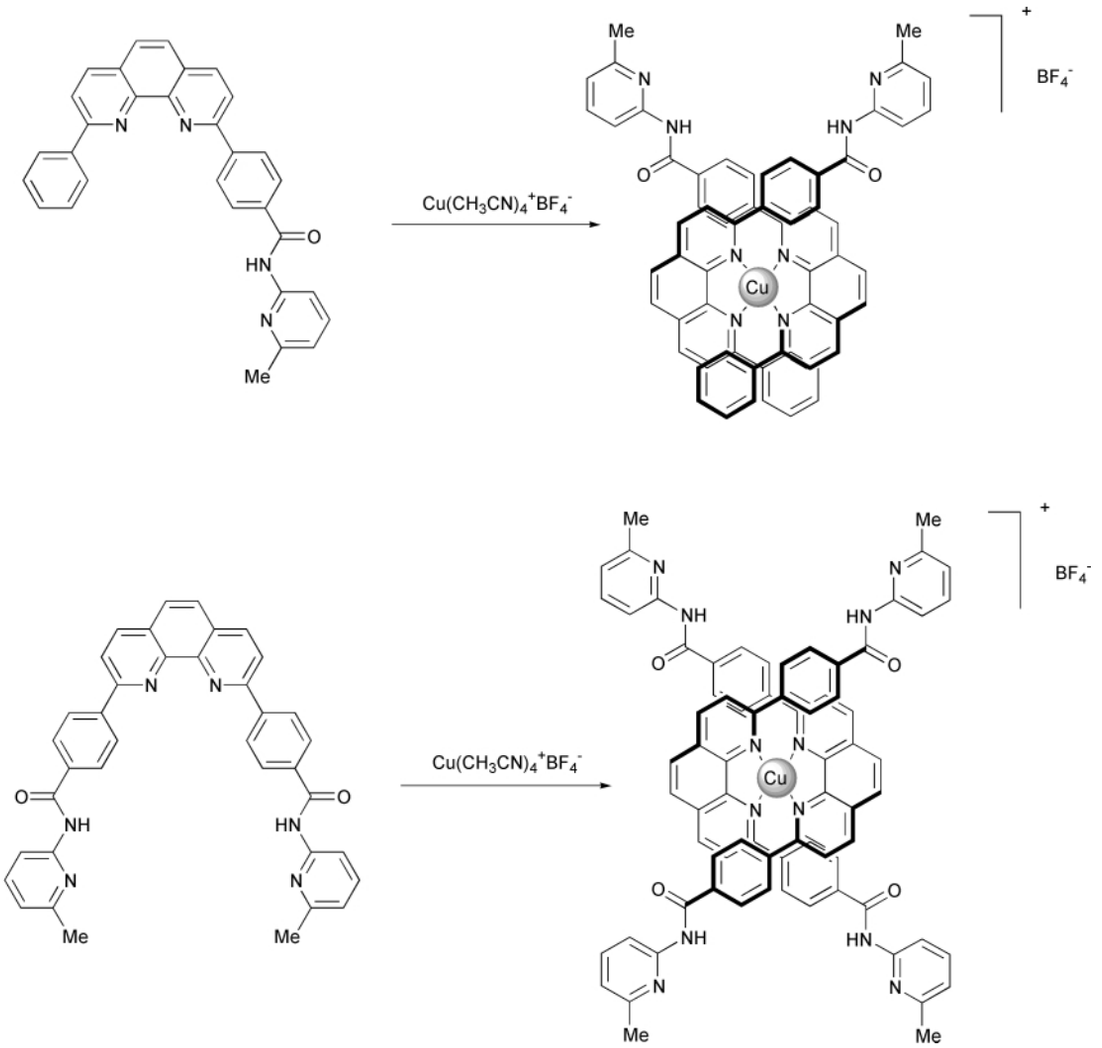
Self-assembled systems are probably the most thoroughly reviewed area within our remit.[128,236–238] To try and avoid repetition, catenane and rotaxane systems are omitted. Self-assembly is defined here as two or more separate molecules coming together to form the active receptor.

9.1 Metal-directed self-assembled receptors

Ligands assembled around metal ions can form successful synthetic receptors (for recent reviews see Fujita and Ogura[239–241]). An early example of this comes from the Hamilton group.[242] Here they design a receptor for dicarboxylic acids based around a 1,10-phenanthroline unit. On adding a Cu(I) salt the monomer self-assembles to form a dimer (Scheme 5).

These dimers bind dicarboxylic acids across the two strands with binding constants of 0.5–8.0 × 10^4 M^{-1} depending on the specific acid studied. Interestingly a colour change occurs on binding, leading to the possibility of chromogenic chemoselective sensors for biologically important dicarboxylic acids, such as glutamic acid.

Another example of this technique is provided by Schwabacher *et al.*[243] Their system is dimerised by the addition of Zn(II) to form a receptor selective for various 1- and



Scheme 5

2-substituted naphthalene guests. Prevot-Halter and Weiss[54] have reported receptors for dicarboxylates and diammoniums by assembling two half-receptors around a *cis*-MoO_2 core to form complexes with log *K* values of 3.5–5.2.

Piguet and co-workers have used lanthanide ions to template a synthetic receptor selective for Ln(III) ions,[244] whilst Laschat and co-workers have used metal templating to tailor the final conformation of their receptor molecules.[245] Rhodium has been used as the directing agent by Fish and co-workers in the construction of receptors for a wide range of amino acids and carboxylic acids.[246] They incorporate nucleobase, nucleoside and nucleotide moieties in the host framework to attempt to model the interactions between DNA–RNA molecules and their binding proteins.

Other work in this area includes a platinum-linked porphyrin trimer which acts as a receptor for the octahedral aluminium tris[3-(4-pyridyl)acetylacetonate],[247] iron based receptors for tetrafluoroborate ions,[248] and rhenium based receptors for porphyrins.[249] Raymond and co-workers have described how host–guest interactions can alter the topology of the self-assembled host. Their helical receptor is transformed into a tetrahedron on the addition of Me_4N^+.[250]

9.2 Dimeric hydrogen-bonded receptors

Since Rebek Jr and co-workers' "Tennis Ball" dimer was reported[238,251,252] there has been a large number of dimers synthesised, using hydrogen-bonding to self-assemble the monomeric sub-units which bind a range of guests.[253] Recent examples include the discovery that solvent molecules can template the self-assembly of hydrogen-bonded capsules—different solvents can lead to different final isomeric structures.[254] This can be compared to the work of Laschat and co-workers.[245] discussed in the preceding section.

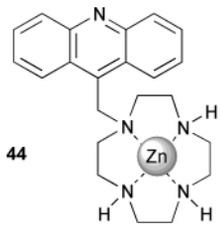
Dimers based on calixarenes are by far the most common. Work by de Mendoza and co-workers has shown a variety of dimeric species is possible, the most recent examples being formed by calix[4]- and calix[6]arenes containing urea substituents at the upper ring.[255–257] Other recent work, from the group of Rebek Jr, has looked at the modification of reactivity of guests enclosed within self-assembled molecular capsules.[258] Here, aromatic amides of varying lengths are utilised as "molecular rulers" to estimate the internal cavity of the capsule. Dibenzoyl peroxide is readily enclosed within the capsule and is unable to act in its usual oxidative manner towards diphenyl carbazide or triphenylphosphine. Receptors based on this technology have potential in catalysis and drug-delivery systems.

9.3 Other self-assembled receptors

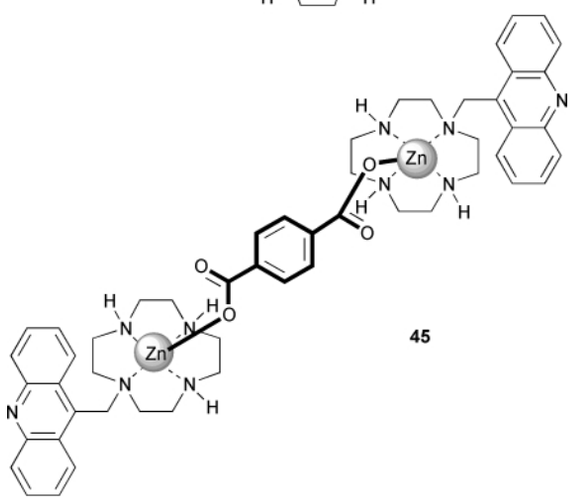
Stoddart and co-workers have described a [3]catenane which exhibits binding of bipyridinium-based guests.[259] The guest resides within the central ring. A lovely example of a hydrogen-bonded network exhibiting receptor characteristics is supplied by Pedireddi *et al*. They describe[260] the self-organisation of 3,5-dinitro-4-methylbenzoic acid into discrete hexamers which then bind 2,6-dimethylnaphthalene.

Formation of a host–guest complex can be the basis for a separation technique. This has been utilised by Kimura *et al*.

in the design of **44**.[261] This molecule selectively separates terephthalate from its isomers phthalate and isophthalate by first forming the 2:1 complex **45**, and then an insoluble self-assembled aggregate.



44

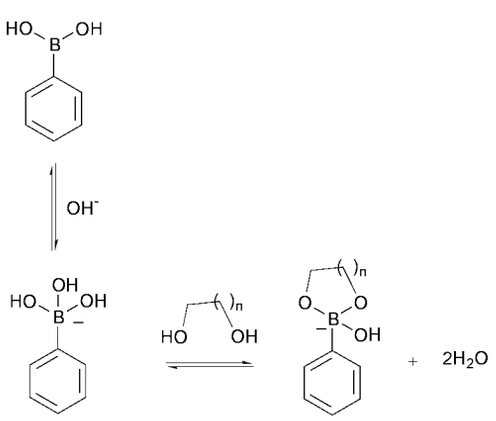


45

10 Boronic acids

Boronic acids offer themselves as one potential functional mimic of natural systems. Boronic acids rapidly and reversibly form cyclic esters with diols albeit in basic aqueous media as shown in Scheme 6. Many synthetic systems that attempt to mimic natural systems have employed hydrogen bonding as the main binding force. Such systems have met with great success in non-hydrogen-bonding solvents, which are non-competitive with the guest for the binding pocket. In contrast natural systems have evolved to function in water, a very competitive solvent. Synthetic hydrogen-bonding systems may yet evolve and make a successful transition into water.[186] But, if the transition can not be made, all is not lost; synthetic systems need not be structural mimics of natural systems.

Some excellent reviews exist in the literature covering the use of boronic acids in supramolecular chemistry.[262–266] This section will overlap with some examples in the reviews but will in general present only the newer developments in the field.



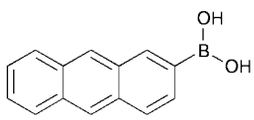
Scheme 6

10.1 Fluorescent saccharide receptors

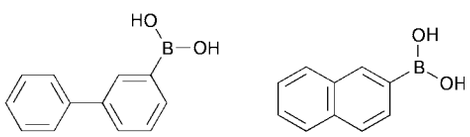
10.1.1 Fluorescent saccharide PET receptors

The area of saccharide PET sensors has been covered in the earlier reviews.[263–266] However it is worth introducing the basic systems and describing how the area is currently expanding. Photoinduced electron transfer (PET) has been widely used as the preferred tool in fluorescent sensor design for atomic and molecular species.[267–272] PET sensors generally consist of a fluorophore and a receptor linked by a short spacer. The changes in oxidation/reduction potential of the receptor upon guest binding can alter the PET process creating changes in fluorescence.

The first fluorescence PET sensors for saccharides were based on fluorophore boronic acids. Yoon and Czarnik showed that 2-anthrylboronic acid[273] **46** could be used to detect saccharides. However, the fluorescence change was small [I (in the presence of saccharide)/I_o (in the absence of saccharide) = *ca.* 0.7]. The pK_a of the fluorophore boronic acids is shifted by saccharide present in the medium. The extent of the effect is in line with the inherent selectivity of phenylboronic acid.[274] The PET from the boronate anion is believed to be the source of the fluorescence quenching. Although, 2-anthrylboronic acid displays only a small fluorescence change Suenaga *et al.* have screened eight aromatic boronic acids[275,276] and determined that **47** and **48** are more suitable candidates for saccharide detection.



46

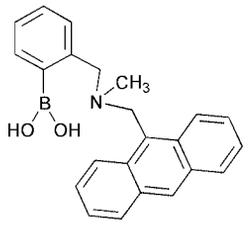


47 **48**

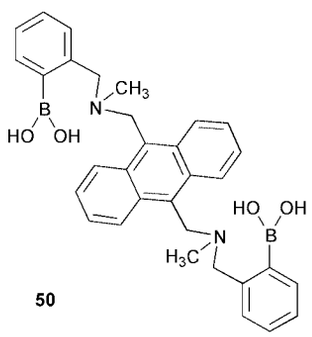
With the system outlined above facile boronic acid saccharide complexation only occurs at the high pH required to create a boronate anion. To overcome these disadvantages molecular fluorescence sensors which contain a boronic acid group and an amine group were developed. The boronic acid group is required to bind with and capture sugar molecules in water. The amine group plays two roles in the system. (1) For biological systems the physiological pH is neutral. Boronic acids with a neighbouring amine can bind with sugars at neutral pH, but, simple boronic acids can only bind with sugars at a high pH. (2) The fluorescence intensity is controlled by the amine. With no sugar the "free" amine reduces the intensity of the fluorescence (quenching by photoinduced electron transfer). This is the 'off' state of the fluorescent sensor. When sugar is added the amine becomes "bound" to the boron centre. The boron bound amine cannot quench the fluorescence and hence a strong fluorescence is observed. This is the "on" state of the fluorescent sensor. The system described above illustrates the basic concept of an "off–on" fluorescent sensor for sugars.

James *et al.* prepared the first fluorescent PET system for saccharides ("off–on"). This simple monoboronic acid system[277] **49** shows a selectivity order, which is inherent to all monoboronic acids[274] (D-fructose selectivity).

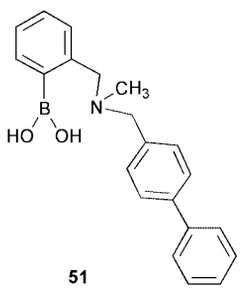
The simple "off–on" PET system was improved with the introduction of a second boronic acid group **50**.[278] Due to fortuitous spacing of the boronic acid groups the diboronic acid was selective for D-glucose over other monosaccharides. Norrild and co-workers have carried out a more detailed investigation of this system in order to confirm the structure of



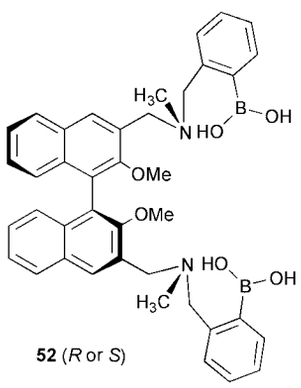
49



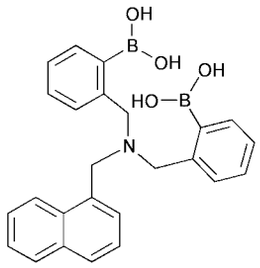
50



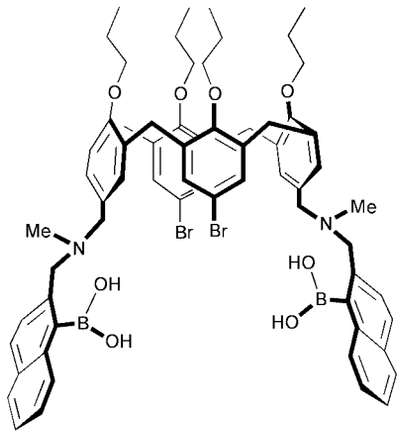
51



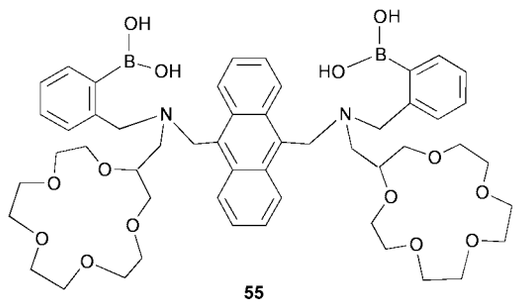
52 (*R* or *S*)



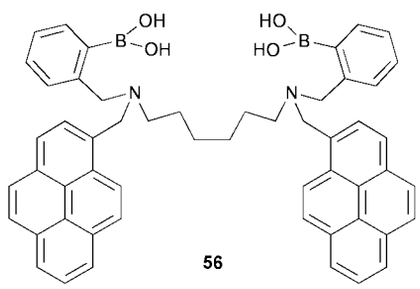
53



54



55



56

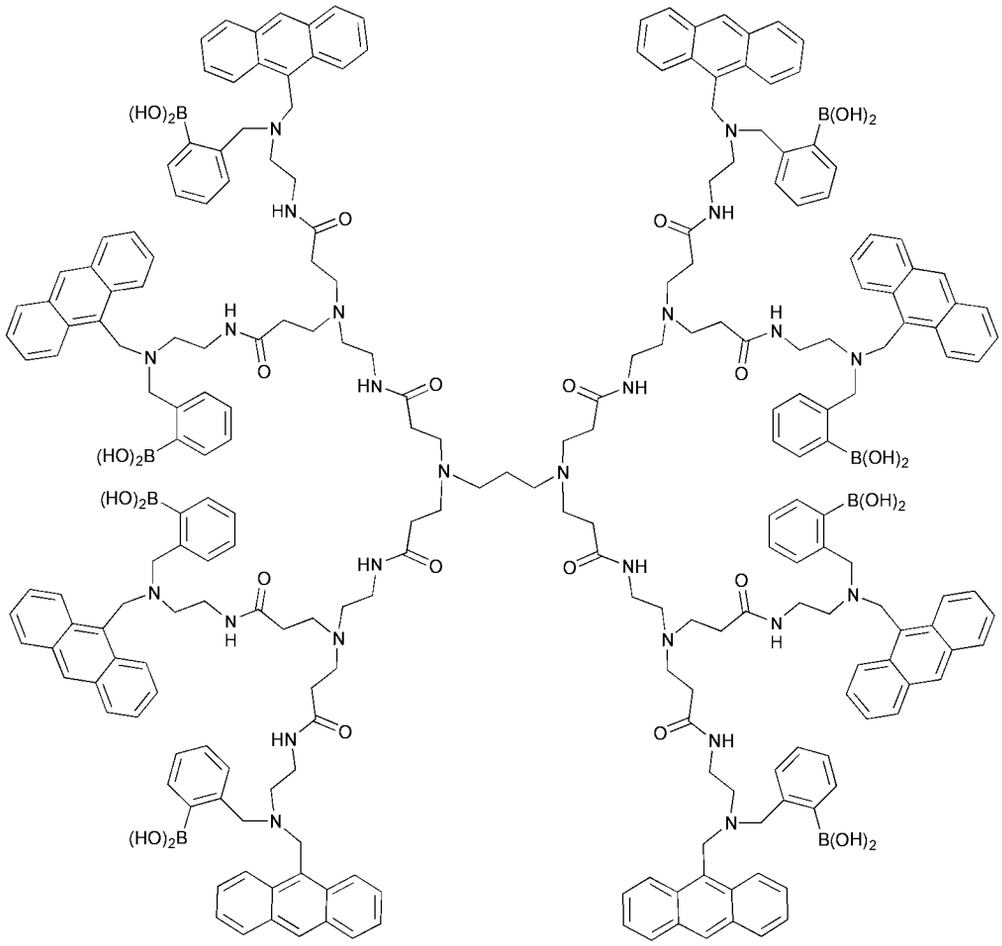
the bound glucose.[279] Norrild and co-workers were interested in the system since the ^{1}H NMR reported by Shinkai indicated that D-glucose bound to the receptor in its pyranose form. Norrild with Eggert had previously shown that simple boronic acids selectively bind with the furanose form of D-glucose.[280] From ^{1}H NMR observations it was concluded that the diboronic acid initially binds with the pyranose form of D-glucose, and over time the bound glucose converts to the furanose form. The Norrild experiments were carried out using 1 : 1 D-glucose and diboronic acid, whereas the fluorescence titrations reported by Shinkai range from 10–100 fold excess of D-glucose. Therefore, in the D-glucose fluorescence titrations it is possible that the furanose form will be replaced by a new molecule of the pyranose form as it forms (water at 31 °C contains 0.14% of D-glucose as the furanose form).

Cooper and James have shown that simple monoboronic acids **51** can selectively signal the furanose form of saccharides.[281] Shinkai and co-workers have prepared a diboronic acid **52** (*R* or *S*) capable of chiral recognition.[282]

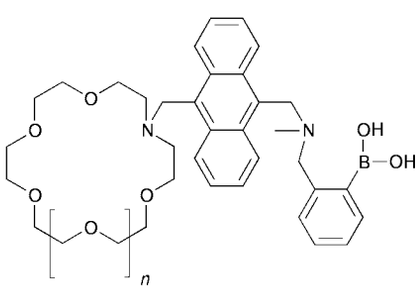
James *et al.* have prepared a diboronic acid with a smaller bite angle **53** which is selective for small saccharides such as D-sorbitol.[283] Linnane *et al.* have used the calixarene framework **54** as a core on which to develop novel saccharide selective systems.[284] Calixarenes have also been used by Lu *et al.*[285] in the allosteric system of Ohseto *et al.*,[286] and the luminescent system of Matsumoto *et al.*[287] James and Shinkai have also prepared an allosteric diboronic acid, **55**, where formation of a metal crown sandwich causes the release of bound saccharide.[288] The allosteric concept was also applied in the two dimensional PET sensor **56**. With the two dimensional system, the amount of eximer can be directly correlated with the amount of non-cyclic saccharide complex formed.[289] Shinkai and co-workers have also prepared a dendritic boronic acid **57**, which shows enhanced binding affinities but the selectivity amongst the monosaccharides is reduced.[290]

More recently the boronic acid PET system has been used in combination with other binding sites. Cooper and James have developed a D-glucosamine selective fluorescent system **58** and **59** based on a boronic acid and aza crown ether[291,292] at about the same time Shinkai and co-workers developed a D-glucuronic acid selective fluorescent system **60** based on a boronic acid and metal chelate.[293,294]

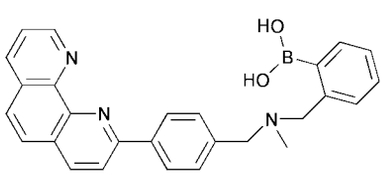
Shinkai and co-workers have recently introduced a new twist with the development of a novel "on–off" PET system **61**.[295] In this system steric crowding on saccharide binding breaks the B–N bond found in the receptor.



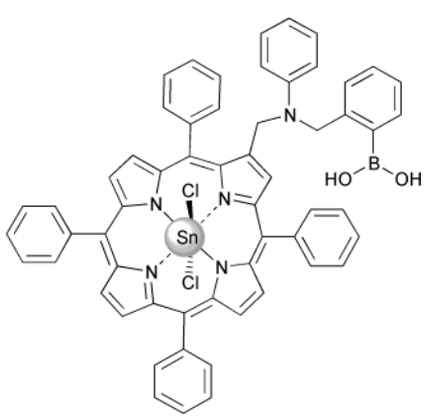
57



58 (*n*=0) and **59** (*n*=1)



60



61

10.1.2 Other fluorescent saccharide receptors

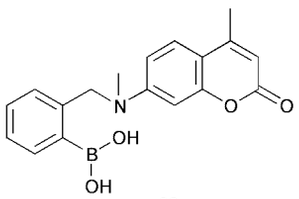
The amino coumarine boronic acid **62** prepared by Sandanayake *et al.*[296] is an example of an internal charge transfer (ICT) chromophore. Here both fluorescence intensity and wavelength are affected since the nitrogen is directly connected with the chromophore. Sadly, this system shows only a small shift in intensity and wavelength.

Molecular rigidification has been used by Takeuchi *et al.*[297] to generate a fluorescence increase with cyanine diboronic acid **63** on saccharide binding. Rigidification has also been used with a diboronic acid appended binaphthyl **64** to develop a chiral discriminating system.[298]

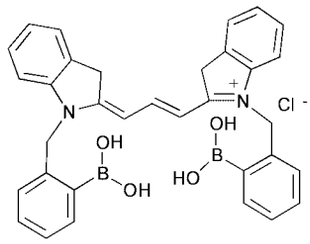
Norrild and co-workers have developed an interesting diboronic acid system **65**.[299] The system works by reducing the quenching ability of the pyridine groups on saccharide binding.

10.2 Colorimetric saccharide receptors

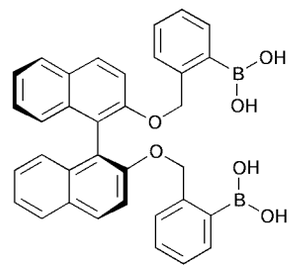
A fairly recent development has been the study of the effect of saccharides on the colour of dyes containing boronic acid functionality. Boronic acid azo-dyes have been known for over forty years where they were used for investigations in the treatment of cancer by a technique called boron neutron capture therapy (BNCT).[300,301] However, it has only been in the 1990's that



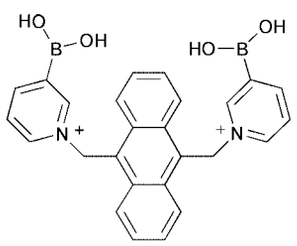
62



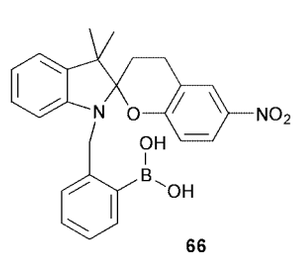
63



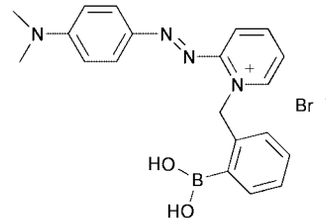
64 (*R*)



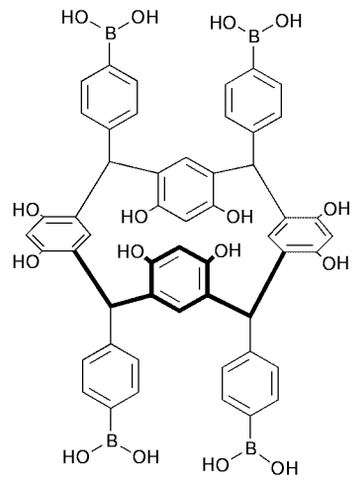
65



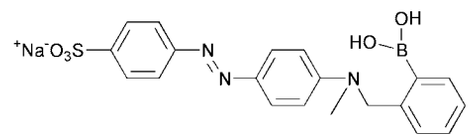
66



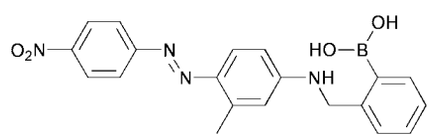
67



68



69



70

related dyes and their interaction with saccharides have been studied. Russell[302] has synthesised a boronic acid azo-dye from *m*-aminophenylboronic acid which was found to be sensitive to a selection of saccharides.

Shinmori *et al*. have shown that boronic acid appended spirobenzopyrans **66** undergo changes in the absorption spectra.[303] The added saccharides change the merocyanine to spiropyran equilibrium position and hence colour of the system. Takeuchi *et al*. have prepared boronic acid dye **67**, which undergoes an absorption spectral change on addition of nucleosides.[304] The boronic acid binds with the ribose and the dimethylaminophenylazo moiety can stack with the adenine of the nucleoside. Strongin and co-workers have prepared a tetraboronic resorcinarene for the visual sensing of saccharides **68**. However, for a colour change to be observed the saccharide must be heated (90 °C) in DMSO.[305]

In 1994 Sandanayake and Shinkai reported a synthetic molecular colour sensor for saccharides.[306] The designed molecular internal charge transfer (ICT) sensor, dye molecule **69**, was based on the intramolecular interaction between the tertiary amine and the boronic acid group. The electron-rich amine creates a basic environment around the electron-deficient boron centre, which has the effect of inducing the boronic acid–saccharide interaction and reducing the working pH of the sensor. Electronic changes associated with this decrease in the pK_a of the boronic acid moiety on saccharide complexation, were shown to be transmitted to the neighbouring amine. This creates a spectral change in the connected ICT chromophore, which can be detected spectrophotometrically. The main drawback of this system is the relatively small shifts in the absorption bands of the chromophore upon saccharide binding.

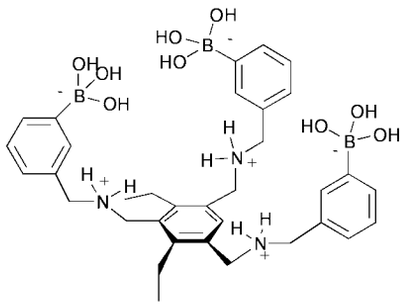
Ward *et al*. have recently developed a diazo-dye system which shows a large visible colour change from purple to red on saccharide binding.[307] The azo dye **70** is purple in colour at pH 11.32. When saccharides bind with **70** the anilinic proton becomes acidic and can be deprotonated to give the red colour.

Anslyn and co-workers have recently reported two very interesting systems based on boronic acid receptors. The Anslyn systems involve a competitive spectrophotometric assay. The first system is a receptor for glucose-6-phosphate **71**.[308] The binding of glucose-6-phosphate is measured through the competitive displacement of 5-carboxyfluorescein **72**. The second system, **73**, is a receptor for tartrate and malate.[309] The binding of tartrate or malate is measured through the competitive displacement of alizarine complexone **74**.

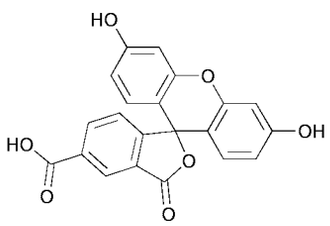
An interesting catalytic system has been developed by Hartley and James.[310] With this system enhanced rates of hydrolysis of the imine bond of **75** and **76** are observed with saccharide binding. The system is not strictly a colour receptor, however the system could be used to measure saccharide concentrations by monitoring the rate of disappearance of the imine signal at 320 nm.

10.3 Porphyrin-based saccharide receptors

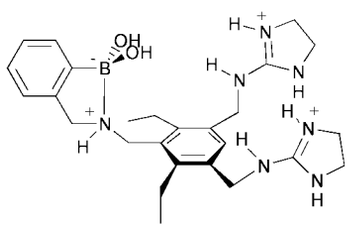
Imada *et al*. have developed a glucose-6-phosphate selective system based on a boronic acid appended metalloporphyrin derivative **77**.[311,312] The two point binding of glucose-6-phosphate creates a rigid complex which gives a strong exciton coupling signal in the CD spectrum. It is believed that the



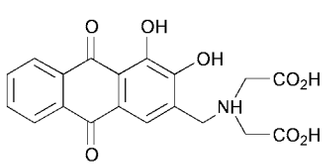
71



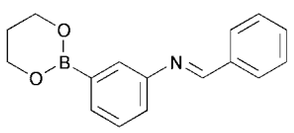
72



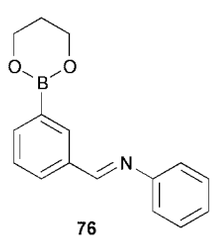
73



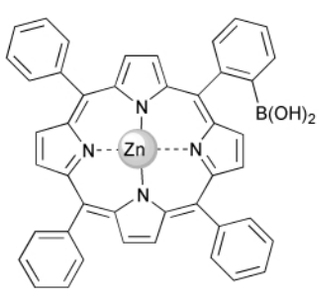
74



75



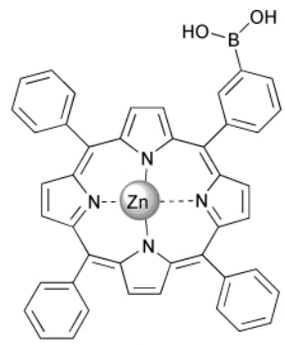
76



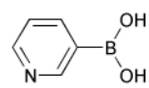
77

strong binding by the primary binding site of glucose (1,2-diol) to the boronic acid followed by the secondary interaction of the phosphate–metal centre results in the high affinity for glucose-6-phosphate.

Takeuchi *et al*. have developed an interesting system consisting of a monoboronic acid zinc porphyrin **78** and monoboronic acid pyridine unit **79**.[313] Self-assembly of the porphyrin and pyridine results in a "diboronic acid". This system is particularly interesting since the synthesis of monoboronic acids is much easier than that of diboronic acids. Modification of each constituent monoboronic acid is therefore much easier than that required in the direct synthesis of a diboronic acid. This system will allow for a large number of structurally similar self-assembled diboronic acids to be investigated with the minimum of synthetic effort.



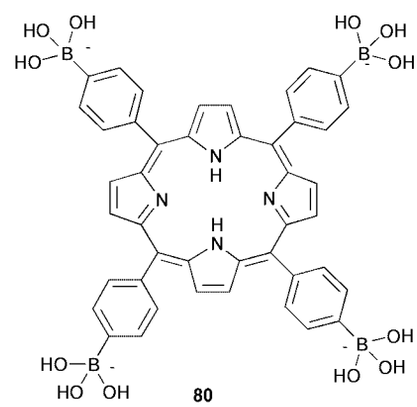
78



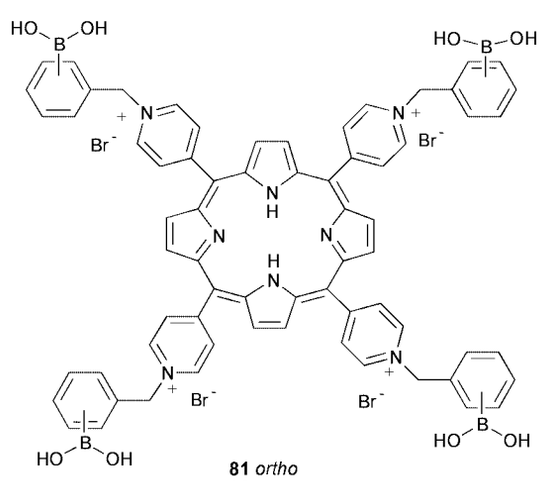
79

A novel porphyrin assembly has been constructed by Sarson *et al*. using **79** and dicatechol porphyrin.[314] Another self-assembled system is the μ-oxodimer of iron porphyrin (Scheme 7).[315,316] This tweezers like molecule shows very high binding with D-glucose and D-galactose.

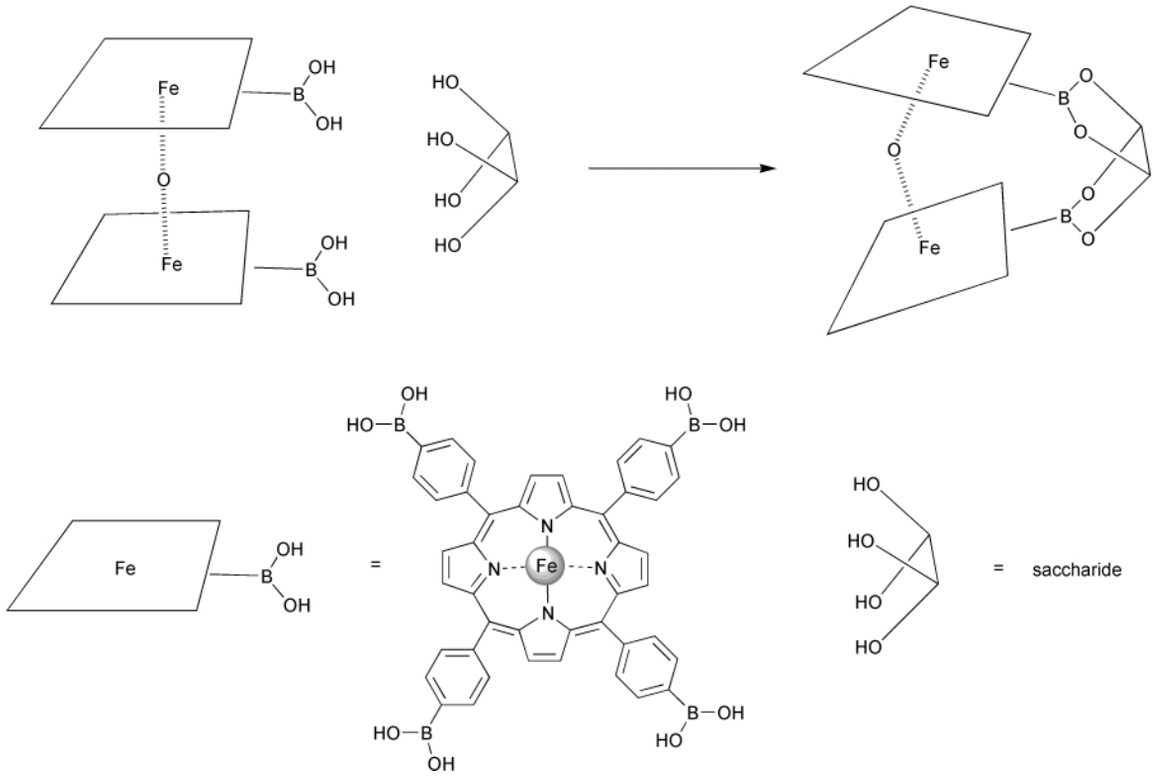
Arimori *et al*. have prepared a novel dimeric system using anionic porphyrin **80** and cationic porphyrins **81** or **82**.[317] The 1 : 1 dimer formed between **80** and **81** or **82** showed selective binding with glucose and xylose. Suenaga *et al*. have also used porphyrin **81** in saccharide controlled intercalation with DNA.[318] With no added saccharide **81** intercalates with DNA



80



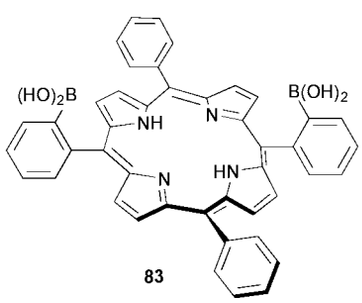
81 *ortho*
82 *meta*



Scheme 7

but when saccharides are added **81** dissociates from DNA. Arimori *et al*. have also used **81** and **82** with 1,5- or 2,6-anthraquinonedisulfonates (ADS) as a competitive system for the fluorescence detection of D-fructose.[319] 1,5- or 2,6-ADS binds with **81** or **82** and quench the fluorescence, addition of D-fructose causes decomplexation and fluorescence recovery.

Kijima *et al*. have also developed a D-lactulose selective system **83** based on a diboronic acid porphyrin.[320] The spacial disposition of the two boronic acids in **83** produces the perfect receptor for the disaccharide D-lactulose.

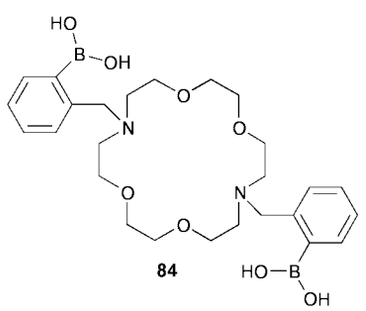


83

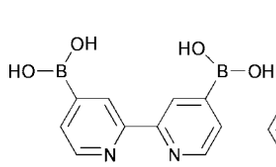
Novel porphyrin dimers have been prepared by Takeuchi *et al*. using monoboronic acid porphyrin and saccharides.[321,322] These systems show saccharide controllable electron-transfer efficiency.

10.4 Metal co-ordinated saccharide receptors

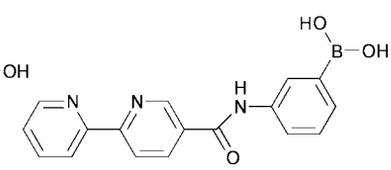
Nakashima and Shinkai have prepared a diaza 18-crown-6 diboronic acid **84**.[323] It was shown that saccharides and calcium ions interact competitively for the receptor. Mizuno *et al*. have prepared a bipyridine (bpy) diboronic acid **85**. The diboronic acid saccharide complex can be used to control the chirality of the cobalt(III) bipyridine complex $[Co^{III}(bpy)_3]^{3+}$.[324,325] Nuding *et al*. have also used saccharides and **86** to transcribe chirality into metal complexes.[326] The helicity of the copper(I) complex of **60** is controlled by added saccharide.[327,328] This system is very



84



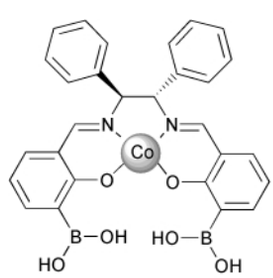
85



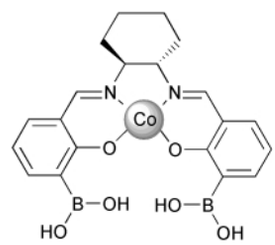
86

similar to that shown in Scheme 5 found in the section on metal-directed self-assembly.

Mizuno *et al*. have used the chiral salen cobalt(II) complexes **87** and **88** for the detection of saccharides.[329] Spectroscopic changes in the metal complexes were used to monitor saccharide complexation. Interestingly **87** showed two-fold selectivity for L-allose over D-allose.

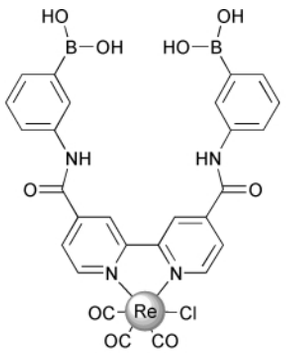


87(*R*)

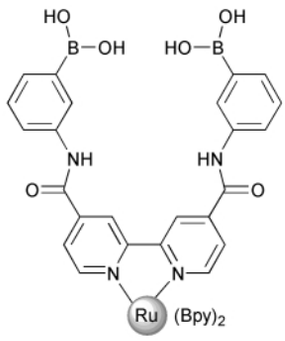


88(*R*)

The rhenium(I) complex **89** has been investigated by Yam and Kai[330] and reinvestigated by Shinkai and co-workers[331] for its potential saccharide sensing properties. Smith and Deetz have investigated the ruthenium(II) complex **90** as a heteroditopic receptor for phosphate and saccharides.[332] It was shown that phosphorylated saccharides display enhanced binding and that binding of saccharides and phosphate ions shows positive cooperativity.



89



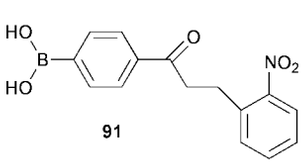
90

10.5 Saccharide transport and extraction

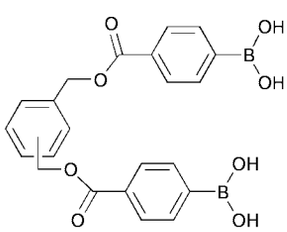
The aim of a saccharide extraction is to selectively bind with a saccharide in water and then be able to move the saccharide into a hydrophobic solvent (membrane). Saccharide transport is very similar to extraction, a saccharide must be bound in water then moved into a hydrophobic membrane. Once in the membrane the saccharide must be transported across the membrane and then released into the water on the other side of the membrane. Although the properties required for a good molecular extractor and transporter are similar, good transporters must balance extraction with release.

Smith and co-workers have investigated the ability of twenty-one monoboronic acids to transport saccharides through lipid bilayers.[333] It was found that lipophilic boronic acids are capable of facilitating the transport of monosaccharides through lipid bilayers, but that disaccharides are not transported. The mechanism of transport requires complexation of the saccharide as the tetrahedral boronate. However, the transported species is the neutral conjugate acid. Smith and co-workers have also investigated selective fructose transport through supported liquid membranes using both mono- and diboronic acids **91**, **92**, **93** and **94**.[334,335] Smith and co-workers have also used a monoboronic acid **95** in combination with a diammonium cation **96** to facilitate the transport of boro-ribonucleoside-5′-phosphates.[336]

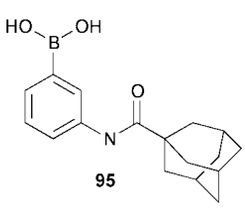
Takeuchi *et al.* have used boronic acids with linked ammonium ions to aid saccharide extraction.[337] Using boronic acids in combination with crown ethers Smith and co-workers have developed a sodium-saccharide co-transporter **97**[338] and facilitated catecholamine transporters **98**, **99** and **100**.[339]



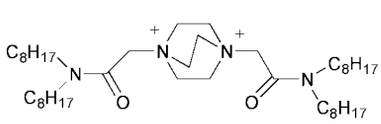
91



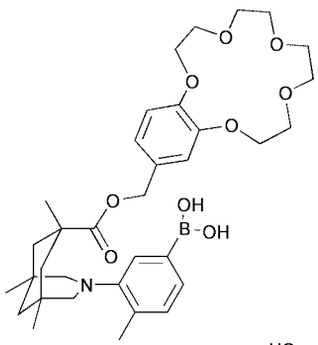
92 *ortho*
93 *meta*
94 *para*



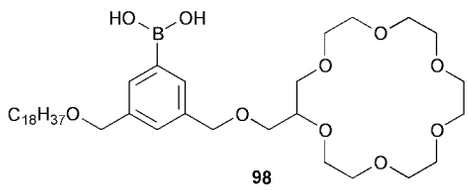
95



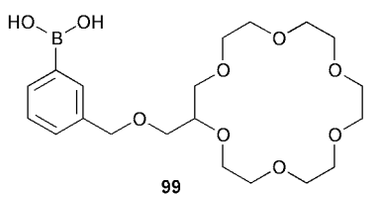
96



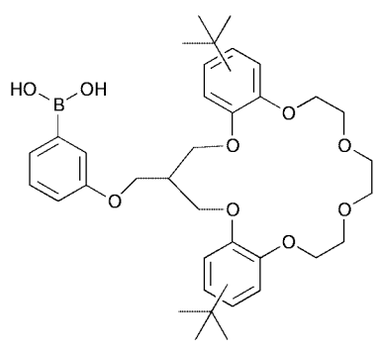
97



98



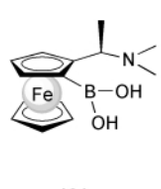
99



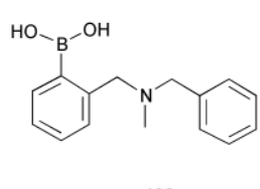
100

10.6 Fluoride receptors

Boronic acids have also been used as anion receptors. The systems are based on the Lewis acid–base interaction between boron and anions. When boron binds with certain anions the hybridisation changes from sp^2 to sp^3.[340,341] Shinkai and co-workers have developed a fluoride receptor based on commercial ferrocene boronic acid, the binding is measured electrochemically[342] or by the colour change of a redox coupled dye molecule.[343] Ori and Shinkai have used ferrocene boronic acid **101**[344] to detect saccharides using the colour change of a redox



101



102

coupled dye molecule. Cooper *et al*. have developed fluorescent fluoride sensors from phenylboronic acid, naphthalene-2-boronic acid, and synthetic receptor **102**.[345] Shiratori *et al*. have used fluoride binding with boron to modulate the electron transfer pathways in zinc porphyrin systems.[346,347]

11 Epilogue

No conclusion can adequately summarise the developments in host–guest systems contained in this review. Host–guest chemistry is still in its infancy, and we are certain that new research will quickly fill the pages of other reviews. Therefore, this should not be a conclusion but rather an introduction.

What we hope is that this review will encourage its readers to go out and solve many of the still unanswered problems of host–guest chemistry. The solution to these problems will require the synthesis of new molecular receptors. These new receptors may belong to one of the receptor-types described within this review, or may be a totally new receptor-type.

As the physicist Richard Feynman said "*What I cannot create I cannot understand*."

The authors wish to thank the Royal Society, the EPSRC, Avecia and the University of Birmingham for their financial support.

12 References

1 J.-M. Lehn, *Supramolecular Chemistry: Concepts and Perspectives*, VCH, Weinheim, 1995.
2 J. J. B. Perry and J. D. Kilburn, *Contemp. Org. Synth.*, 1997, **4**, 61.
3 S. Mattei, P. Wallimann, B. Kenda, W. Amrein and F. Diederich, *Helv. Chim. Acta*, 1997, **80**, 2391.
4 V. V. Narayanan and G. R. Newkome, *Top. Curr. Chem.*, 1998, **197**, 19.
5 G. R. Newkome, *Pure Appl. Chem.*, 1998, **70**, 2337.
6 D. K. Smith, A. Zingg and F. Diederich, *Helv. Chim. Acta*, 1999, **82**, 1225.
7 P. Wallimann, S. Mattei, P. Seiler and F. Diederich, *Helv. Chim. Acta*, 1997, **80**, 2368.
8 F. W. Zeng and S. C. Zimmerman, *Chem. Rev.*, 1997, **97**, 1681.
9 A. R. Bishop and R. G. Nuzzo, *Curr. Opin. Colloid Interface Sci.*, 1996, **1**, 127.
10 A. Ulman, *Chem. Rev.*, 1996, **96**, 1533.
11 T. Wink, S. J. van Zuilen, A. Bult and W. P. van Bennekom, *Analyst* (*London*), 1997, **122**, R43.
12 M. J. Hostetler and R. W. Murray, *Curr. Opin. Colloid Interface Sci.*, 1997, **2**, 42.
13 R. C. Sabapathy, S. Bhattacharyya, W. E. Cleland and C. L. Hussey, *Langmuir*, 1998, **14**, 3797.
14 C. M. Knobler and D. K. Schwartz, *Curr. Opin. Colloid Interface Sci.*, 1999, **4**, 46.
15 C. N. R. Rao, G. U. Kulkarni, P. J. Thomas and P. P. Edwards, *Chem. Soc. Rev.*, 2000, **29**, 27.
16 T. Mizutani, T. Murakami, T. Kurahashi and H. Ogoshi, *J. Org. Chem.*, 1996, **61**, 539.
17 H. Ogoshi, Y. Kuroda, T. Mizutani and T. Hayashi, *Pure Appl. Chem.*, 1996, **68**, 1411.
18 R. Purrello, S. Gurrieri and R. Lauceri, *Coord. Chem. Rev.*, 1999, **192**, 683.
19 P. Wallimann, T. Marti, A. Furer and F. Diederich, *Chem. Rev.*, 1997, **97**, 1567.
20 F. Diederich and M. Gomez-Lopez, *Chem. Soc. Rev.*, 1999, **28**, 263.
21 J. E. Forman, R. E. Barrans and D. A. Dougherty, *J. Am. Chem. Soc.*, 1995, **117**, 9213.
22 G. Gattuso, S. A. Nepogodiev and J. F. Stoddart, *Chem. Rev.*, 1998, **98**, 1919.
23 K. Uekama, F. Hirayama and T. Irie, *Chem. Rev.*, 1998, **98**, 2045.
24 H. J. Schneider, F. Hacket, V. Rudiger and H. Ikeda, *Chem. Rev.*, 1998, **98**, 1755.
25 W. R. Saenger, J. Jacob, K. Gessler, T. Steiner, D. Hoffmann, H. Sanbe, K. Koizumi, S. M. Smith and T. Takaha, *Chem. Rev.*, 1998, **98**, 1787.
26 K. B. Lipkowitz, *Chem. Rev.*, 1998, **98**, 1829.
27 M. V. Rekharsky and Y. Inoue, *Chem. Rev.*, 1998, **98**, 1875.
28 S. A. Nepogodiev and J. F. Stoddart, *Chem. Rev.*, 1998, **98**, 1959.
29 A. R. Khan, P. Forgo, K. J. Stine and V. T. D'Souza, *Chem. Rev.*, 1998, **98**, 1977.
30 R. Breslow and S. D. Dong, *Chem. Rev.*, 1998, **98**, 1997.
31 K. Takahashi, *Chem. Rev.*, 1998, **98**, 2013.
32 A. R. Hedges, *Chem. Rev.*, 1998, **98**, 2035.
33 D. Parker, R. Kataky, P. M. Kelly and S. Palmer, *Pure Appl. Chem.*, 1996, **68**, 1219.
34 S. D. Kean, B. L. May, P. Clements, S. F. Lincoln and C. J. Easton, *J. Chem. Soc.*, *Perkin Trans. 2*, 1999, 1257.
35 N. Ito, N. Yoshida and K. Ichikawa, *J. Chem. Soc.*, *Perkin Trans. 2*, 1996, 965.
36 E. S. Cotner and P. J. Smith, *J. Org. Chem.*, 1998, **63**, 1737.
37 E. Rizzarelli and G. Vecchio, *Coord. Chem. Rev.*, 1999, **188**, 343.
38 K. Kano, *J. Phys. Org. Chem.*, 1997, **10**, 286.
39 T. Kitae, T. Nakayama and K. Kano, *J. Chem. Soc.*, *Perkin Trans. 2*, 1998, 207.
40 Y. Liu, B. H. Han, A. D. Qi and R. T. Chen, *Bioorg. Chem.*, 1997, **25**, 155.
41 Y. Liu, B. H. Han, S. X. Sun, T. Wada and Y. Inoue, *J. Org. Chem.*, 1999, **64**, 1487.
42 Y. Liu, C. C. You, T. Wada and Y. Inoue, *J. Org. Chem.*, 1999, **64**, 3630.
43 T. Ikunaga, H. Ikeda and A. Ueno, *Chem. Eur. J.*, 1999, **5**, 2698.
44 Y. Liu, Y. M. Zhang, A. D. Qi, R. T. Chen, K. Yamamoto, T. Wada and Y. Inoue, *J. Org. Chem.*, 1997, **62**, 1826.
45 Y. Liu, B. H. Han, B. Li, Y. M. Zhang, P. Zhao, Y. T. Chen, T. Wada and Y. Inoue, *J. Org. Chem.*, 1998, **63**, 1444.
46 M. T. Reetz, *J. Heterocycl. Chem.*, 1998, **35**, 1065.
47 A. G. Meyer, C. J. Easton, S. F. Lincoln and G. W. Simpson, *J. Org. Chem.*, 1998, **63**, 9069.
48 R. R. French, J. Wirz and W. D. Woggon, *Helv. Chim. Acta*, 1998, **81**, 1521.
49 R. Breslow, S. Halfon and B. Zhang, *Tetrahedron*, 1995, **51**, 377.
50 J. Bugler, N. Sommerdijk, A. Visser, A. van Hoek, R. J. M. Nolte, J. F. J. Engbersen and D. N. Reinhoudt, *J. Am. Chem. Soc.*, 1999, **121**, 28.
51 G. W. Gokel, *Crown Ethers and Cryptands*, ed. J. F. Stoddart, The Royal Society of Chemistry, Cambridge, 1991.
52 A. Manjula and M. Nagarajan, *Tetrahedron*, 1997, **53**, 11859.
53 A. P. Hansson, P. O. Norrby and K. Wärnmark, *Tetrahedron Lett.*, 1998, **39**, 4565.
54 I. Prevot-Halter and J. Weiss, *New J. Chem.*, 1998, **22**, 869.
55 D. S. Shephard, B. F. G. Johnson, J. Matters and S. Parsons, *J. Chem. Soc.*, *Dalton Trans.*, 1998, 2289.
56 P. R. Ashton, R. Ballardini, V. Balzani, M. Gomez-Lopez, S. E. Lawrence, M. V. Martinez-Diaz, M. Montalti, A. Piersanti, L. Prodi, J. F. Stoddart and D. J. Williams, *J. Am. Chem. Soc.*, 1997, **119**, 10641.
57 E. V. Rybakkimova and Y. D. Lampeka, *Supramol. Chem.*, 1995, **4**, 297.
58 T. M. Fyles and B. Q. Zeng, *Chem. Commun.*, 1996, 2295.
59 M. Barboiu, C. T. Supuran, A. Scozzafava, F. Briganti, C. Luca, G. Popescu, L. Cot and N. Hovnanian, *Liebigs Ann. Chem.*, 1997, 1853.
60 M. A. Hossain and H. J. Schneider, *J. Am. Chem. Soc.*, 1998, **120**, 11208.
61 Y. F. Shao and W. C. Still, *J. Org. Chem.*, 1996, **61**, 6086.
62 N. Voyer, J. Roby, D. Deschenes and J. Bernier, *Supramol. Chem.*, 1995, **5**, 61.
63 Q. Lu, A. E. Martell and R. J. Motekaitis, *Inorg. Chim. Acta*, 1996, **251**, 365.
64 D. A. Nation, A. E. Martell, R. I. Carroll and A. Clearfield, *Inorg. Chem.*, 1996, **35**, 7246.
65 D. A. Nation, J. Reibenspies and A. E. Martell, *Inorg. Chem.*, 1996, **35**, 4597.
66 D. A. Nation, Q. Lu and A. E. Martell, *Inorg. Chim. Acta*, 1997, **263**, 209.
67 T. F. Pauwels, W. Lippens, G. G. Herman and A. M. Goeminne, *Polyhedron*, 1998, **17**, 1715.
68 L. G. Qian, Z. Sun and K. Bowman-James, *Supramol. Chem.*, 1996, **6**, 341.
69 H. Fenniri, M. W. Hosseini and J.-M. Lehn, *Helv. Chim. Acta*, 1997, **80**, 786.
70 C. Bazzicalupi, A. Beconcini, A. Bencini, V. Fusi, C. Giorgi, A. Masotti and B. Valtancoli, *J. Chem. Soc.*, *Perkin Trans. 2*, 1999, 1675.
71 V. Kral and J. L. Sessler, *Tetrahedron*, 1995, **51**, 539.
72 V. Kral, H. Furuta, K. Shreder, V. Lynch and J. L. Sessler, *J. Am. Chem. Soc.*, 1996, **118**, 1595.
73 J. L. Sessler, A. Andrievsky, V. Kral and V. Lynch, *J. Am. Chem. Soc.*, 1997, **119**, 9385.
74 H. Fenniri, J.-M. Lehn and A. Marquis-Rigault, *Angew. Chem., Int. Ed. Engl.*, 1996, **35**, 337.
75 A. Tahri, E. Cielen, K. J. van Aken, G. J. Hoornaert, F. C. de Schryver and N. Boens, *J. Chem. Soc.*, *Perkin Trans. 2*, 1999, 1739.

76 J. Costa, R. Delgado, M. G. B. Drew and V. Felix, *J. Chem. Soc., Dalton Trans.*, 1999, 4331.
77 O. A. Fedorova, S. P. Gromov, Y. V. Pershina, S. S. Sergeev, Y. P. Strokach, V. A. Barachevsky, M. V. Alfimov, G. Pepe, A. Samat and R. Guglielmetti, *J. Chem. Soc., Perkin Trans. 2*, 2000, 563.
78 S. Kumar, V. Bhalla and H. Singh, *Tetrahedron*, 1998, **54**, 5575.
79 D. Ranganathan, V. Haridas, K. P. Madhusudanan, R. Roy, R. Nagaraj and G. B. John, *J. Am. Chem. Soc.*, 1997, **119**, 11578.
80 T. Gunnlaugsson, D. A. MacDonail and D. Parker, *Chem. Commun.*, 2000, 93.
81 M. J. Gunter, T. P. Jeynes, M. R. Johnston, P. Turner and Z. P. Chen, *J. Chem. Soc., Perkin Trans. 1*, 1998, 1945.
82 C. D. Gutsche, *Calixarenes*, ed. J. F. Stoddart, The Royal Society of Chemistry, Cambridge, 1989.
83 C. Wieser, C. B. Dieleman and D. Matt, *Coord. Chem. Rev.*, 1997, **165**, 93.
84 P. Lhoták and S. Shinkai, *J. Phys. Org. Chem.*, 1997, **10**, 273.
85 R. Ungaro, A. Arduini, A. Casnati, A. Pochini and F. Ugozzoli, *Pure Appl. Chem.*, 1996, **68**, 1213.
86 F. Arnaud-Neu, S. Barboso, F. Berny, A. Casnati, N. Muzet, A. Pinalli, R. Ungaro, M.-J. Schwing-Weill and G. Wipff, *J. Chem. Soc., Perkin Trans. 2*, 1999, 1727.
87 F. Arnaud-Neu, Z. Asfari, B. Souley, J. Vicens, P. Thuery and M. Nierlich, *J. Chem. Soc., Perkin Trans. 2*, 2000, 495.
88 P. Schmitt, P. D. Beer, M. G. B. Drew and P. D. Sheen, *Angew. Chem., Int. Ed. Engl.*, 1997, **36**, 1840.
89 T. Jin, *Chem. Commun.*, 1999, 2491.
90 B. Bodenant, T. Weil, M. Businelli-Pourcel, F. Fages, B. Barbe, I. Pianet and M. Laguerre, *J. Org. Chem.*, 1999, **64**, 7034.
91 Y. Okada, M. Mizutani, F. Ishii and J. Nishimura, *Tetrahedron Lett.*, 1997, **38**, 9013.
92 Y. H. Shi and H. J. Schneider, *J. Chem. Soc., Perkin Trans. 2*, 1999, 1797.
93 P. D. Beer, M. G. B. Drew and K. Gradwell, *J. Chem. Soc., Perkin Trans. 2*, 2000, 511.
94 M. Staffilani, K. S. B. Hancock, J. W. Steed, K. T. Holman, J. L. Atwood, R. K. Juneja and R. S. Burkhalter, *J. Am. Chem. Soc.*, 1997, **119**, 6324.
95 K. Niikura and E. V. Anslyn, *J. Chem. Soc., Perkin Trans. 2*, 1999, 2769.
96 J. A. R. Navarro, M. B. L. Janik, E. Freisinger and B. Lippert, *Inorg. Chem.*, 1999, **38**, 426.
97 F. Sansone, S. Barboso, A. Casnati, M. Fabbi, A. Pochini, F. Ugozzoli and R. Ungaro, *Eur. J. Org. Chem.*, 1998, 897.
98 S. Shinkai and A. Ikeda, *Pure Appl. Chem.*, 1999, **71**, 275.
99 R. Pinalli, F. F. Nachtigall, F. Ugozzoli and E. Dalcanale, *Angew. Chem., Int. Ed.*, 1999, **38**, 2377.
100 Y. Kubo, *Synlett*, 1999, 161.
101 W. E. Allen, P. A. Gale, C. T. Brown, V. M. Lynch and J. L. Sessler, *J. Am. Chem. Soc.*, 1996, **118**, 12471.
102 H. S. Park, Q. Lin and A. D. Hamilton, *J. Am. Chem. Soc.*, 1999, **121**, 8.
103 H. J. van de Bovenkamp, M. M. G. Antonisse, J. F. J. Engbersen, D. N. Reinhoudt, G. L. J. Hesselink, P. V. Lambeck and T. J. A. Popma, *Sens. Actuators B*, 1995, **29**, 312.
104 D. M. Rudkevich, G. Hilmersson and J. Rebek Jr, *J. Am. Chem. Soc.*, 1998, **120**, 12216.
105 P. Timmerman, H. Boerrigter, W. Verboom and D. N. Reinhoudt, *Recl. Trav. Chim. Pays-Bas*, 1995, **114**, 103.
106 P. Timmerman, E. A. Brinks, W. Verboom and D. N. Reinhoudt, *J. Chem. Soc., Chem. Commun.*, 1995, 417.
107 A. M. A. van Wageningen, W. Verboom and D. N. Reinhoudt, *Pure Appl. Chem.*, 1996, **68**, 1273.
108 I. Higler, P. Timmerman, W. Verboom and D. N. Reinhoudt, *Eur. J. Org. Chem.*, 1998, 2689.
109 I. Higler, H. Boerrigter, W. Verboom, H. Kooijman, A. L. Spek and D. N. Reinhoudt, *Eur. J. Org. Chem.*, 1998, 1597.
110 P. Timmerman, R. H. Vreekamp, R. Hulst, W. Verboom, D. N. Reinhoudt, K. Rissanen, K. A. Udachin and J. Ripmeester, *Chem. Eur. J.*, 1997, **3**, 1823.
111 K. Kobayashi, T. Shirasaka, K. Yamaguchi, S. Sakamoto, H. Horn and N. Furukawa, *Chem. Commun.*, 2000, 41.
112 L. R. MacGillivray and J. L. Atwood, *Chem. Commun.*, 1999, 181.
113 C. Félix, H. Parrot-Lopez, V. Kalchenko and A. W. Coleman, *Tetrahedron Lett.*, 1998, **39**, 9171.
114 G. Ferguson, J. F. Gallagher, A. J. Lough, A. Notti, S. Pappalardo and M. F. Parisi, *J. Org. Chem.*, 1999, **64**, 5876.
115 F. Diederich, *Cyclophanes*, ed. J. F. Stoddart, The Royal Society of Chemistry, Cambridge, 1991.
116 E. Martinborough, T. M. Denti, P. P. Castro, T. B. Wyman, C. B. Knobler and F. Diederich, *Helv. Chim. Acta*, 1995, **78**, 1037.
117 M. Asakawa, P. R. Ashton, S. Menzer, F. M. Raymo, J. F. Stoddart, A. J. P. White and D. J. Williams, *Chem. Eur. J.*, 1996, **2**, 877.
118 A. de Meijere and B. König, *Synlett*, 1997, 1221.
119 V. Bohmer, *Liebigs Ann. Chem.*, 1997, 2019.
120 M. Asakawa, P. R. Ashton, C. L. Brown, M. C. T. Fyfe, S. Menzer, D. Pasini, C. Scheuer, N. Spencer, J. F. Stoddart, A. J. P. White and D. J. Williams, *Chem. Eur. J.*, 1997, **3**, 1136.
121 K. Goto and R. Okazaki, *Liebigs Ann. Chem.*, 1997, 2393.
122 M. B. Nielsen and J. Becher, *Liebigs Ann. Chem.*, 1997, 2177.
123 A. Bahr, A. S. Droz, M. Puntener, U. Neidlein, S. Anderson, P. Seiler and F. Diederich, *Helv. Chim. Acta*, 1998, **81**, 1931.
124 T. Marti, B. R. Peterson, A. Furer, T. Mordasini-Denti, J. Zarske, B. Jaun, F. Diederich and V. Gramlich, *Helv. Chim. Acta*, 1998, **81**, 109.
125 M. P. Teulade-Fichou, J. P. Vigneron and J.-M. Lehn, *Supramol. Chem.*, 1995, **5**, 139.
126 P. Cudic, J. P. Vigneron, J.-M. Lehn, M. Cesario and T. Prange, *Eur. J. Org. Chem.*, 1999, 2479.
127 P. Cudic, M. Zinic, V. Tomisic, V. Simeon, J. P. Vigneron and J.-M. Lehn, *J. Chem. Soc., Chem. Commun.*, 1995, 1073.
128 D. Philp and J. F. Stoddart, *Angew. Chem., Int. Ed. Engl.*, 1996, **35**, 1155.
129 M. Asakawa, W. Dehaen, G. Labbe, S. Menzer, J. Nouwen, F. M. Raymo, J. F. Stoddart and D. J. Williams, *J. Org. Chem.*, 1996, **61**, 9591.
130 S. A. Staley and B. D. Smith, *Tetrahedron Lett.*, 1996, **37**, 283.
131 R. Castro, K. R. Nixon, J. D. Evanseck and A. E. Kaifer, *J. Org. Chem.*, 1996, **61**, 7298.
132 R. Castro, P. D. Davidov, K. A. Kumar, A. P. Marchand, J. D. Evanseck and A. E. Kaifer, *J. Phys. Org. Chem.*, 1997, **10**, 369.
133 M. Asakawa, C. L. Brown, D. Pasini, J. F. Stoddart and P. G. Wyatt, *J. Org. Chem.*, 1996, **61**, 7234.
134 J. A. Gavin, M. E. Garcia, A. J. Benesi and T. E. Mallouk, *J. Org. Chem.*, 1998, **63**, 7663.
135 T. Fessmann and J. D. Kilburn, *Angew. Chem., Int. Ed.*, 1999, **38**, 1993.
136 J. A. Gavin, N. L. Deng, M. Alcala and T. E. Mallouk, *Chem. Mater.*, 1998, **10**, 1937.
137 J. T. Bien, M. J. Eschner and B. D. Smith, *J. Org. Chem.*, 1995, **60**, 4525.
138 F. M. Menger and K. K. Catlin, *Angew. Chem., Int. Ed. Engl.*, 1995, **34**, 2147.
139 B. Altava, M. I. Burguete, S. V. Luis, J. F. Miravet, E. Garcia-Espana, V. Marcelino and C. Soriano, *Tetrahedron*, 1997, **53**, 4751.
140 B. R. Peterson, T. Mordasinidenti and F. Diederich, *Chem. Biol.*, 1995, **2**, 139.
141 B. Hinzen, P. Seiler and F. Diederich, *Helv. Chim. Acta*, 1996, **79**, 942.
142 C. Bazzicalupi, A. Bencini, A. Bianchi, V. Fusi, C. Giorgi, P. Paoletti, A. Stefani and B. Valtancoli, *Inorg. Chem.*, 1995, **34**, 552.
143 C. Bazzicalupi, A. Bencini, A. Bianchi, V. Fusi, C. Giorgi, P. Paoletti, A. Stefani and B. Valtancoli, *J. Chem. Soc., Perkin Trans. 2*, 1995, 275.
144 C. Bazzicalupi, A. Bencini, A. Bianchi, V. Fusi, C. Giorgi, A. Granchi, P. Paoletti and B. Valtancoli, *J. Chem. Soc., Perkin Trans. 2*, 1997, 775.
145 K. G. Ragunathan and H. J. Schneider, *J. Chem. Soc., Perkin Trans. 2*, 1996, 2597.
146 G. J. Pernia, J. D. Kilburn, J. W. Essex, R. J. Mortishire-Smith and M. Rowley, *J. Am. Chem. Soc.*, 1996, **118**, 10220.
147 J. Dowden, P. D. Edwards, S. S. Flack and J. D. Kilburn, *Chem. Eur. J.*, 1999, **5**, 79.
148 M. Torneiro and W. C. Still, *J. Am. Chem. Soc.*, 1995, **117**, 5887.
149 S. S. Yoon and W. C. Still, *Tetrahedron*, 1995, **51**, 567.
150 M. T. Burger and W. C. Still, *J. Org. Chem.*, 1997, **62**, 4785.
151 M. Torneiro and W. C. Still, *Tetrahedron*, 1997, **53**, 8739.
152 D. J. Cram and J. M. Cram, *Container Molecules and Their Guests*, ed. J. F. Stoddart, The Royal Society of Chemistry, Cambridge, 1994.
153 A. Jasat and J. C. Sherman, *Chem. Rev.*, 1999, **99**, 931.
154 T. Sato, A. Suzuki, K. Sakai and T. Tsubomura, *Bull. Chem. Soc. Jpn.*, 1996, **69**, 379.
155 A. Bencini, A. Bianchi, V. Fusi, C. Giorgi, P. Paoletti and B. Valtancoli, *Tetrahedron Lett.*, 1997, **38**, 5327.
156 A. Bencini, A. Bianchi, S. Brazzini, V. Fusi, C. Giorgi, P. Paoletti and B. Valtancoli, *Inorg. Chim. Acta*, 1998, **273**, 326.
157 E. Graf, M. W. Hosseini, R. Ruppert, N. Kyritsakas, A. Decian, J. Fischer, C. Estournes and F. Taulelle, *Angew. Chem., Int. Ed. Engl.*, 1995, **34**, 1115.
158 T. N. Parac, D. L. Caulder and K. N. Raymond, *J. Am. Chem. Soc.*, 1998, **120**, 8003.

159 D. Whang, J. Heo, J. H. Park and K. Kim, *Angew. Chem.*, *Int. Ed.*, 1998, **37**, 78.
160 C. Seel, A. Galan and J. de Mendoza, *Top. Curr. Chem.*, 1995, **175**, 101.
161 P. D. Beer and P. Schmitt, *Curr. Opin. Chem. Biol.*, 1997, **1**, 475.
162 M. M. G. Antonisse and D. N. Reinhoudt, *Chem. Commun.*, 1998, 443.
163 K. Niikura, A. P. Bisson and E. V. Anslyn, *J. Chem. Soc.*, *Perkin Trans. 2*, 1999, 1111.
164 A. Cattani and F. P. Schmidtchen, *J. Prakt. Chem.*, 1999, **341**, 291.
165 O. Hayashida, A. Tanaka, S. Fujiyoshi, Y. Hisaeda and Y. Murakami, *Tetrahedron Lett.*, 1997, **38**, 1219.
166 A. Tanaka, S. Fujiyoshi, K. Motomura, O. Hayashida, Y. Hisaeda and Y. Murakami, *Tetrahedron*, 1998, **54**, 5187.
167 K. T. Holman, M. M. Halihan, S. S. Jurisson, J. L. Atwood, R. S. Burkhalter, A. R. Mitchell and J. W. Steed, *J. Am. Chem. Soc.*, 1996, **118**, 9567.
168 A. P. Davis and R. S. Wareham, *Angew. Chem.*, *Int. Ed.*, 1998, **37**, 2270.
169 K. M. Bhattarai, A. P. Davis, J. J. Perry, C. J. Walter, S. Menzer and D. J. Williams, *J. Org. Chem.*, 1997, **62**, 8463.
170 J. Jimenez-Barbero, E. Junquera, M. Martinpastor, S. Sharma, C. Vicent and S. Penadés, *J. Am. Chem. Soc.*, 1995, **117**, 11198.
171 O. Hayashida, K. Nishiyama, Y. Matsuda and Y. Aoyama, *Tetrahedron Lett.*, 1999, **40**, 3407.
172 R. J. Pieters, J. Cuntze, M. Bonnet and F. Diederich, *J. Chem. Soc.*, *Perkin Trans. 2*, 1997, 1891.
173 M. J. Cloninger and H. W. Whitlock, *J. Org. Chem.*, 1998, **63**, 6153.
174 R. Neugebauer and W. Knoche, *J. Chem. Soc.*, *Perkin Trans. 2*, 1998, 529.
175 J. Schlogl and B. Kräutler, *Synlett*, 1999, 969.
176 J. Cuntze, L. Owens, V. Alcazar, P. Seiler and F. Diederich, *Helv. Chim. Acta*, 1995, **78**, 367.
177 R. Bishop, *Chem. Soc. Rev.*, 1996, **25**, 311.
178 T. W. Bell, P. J. Cragg, A. Firestone, A. D. I. Kwok, J. Liu, R. Ludwig and A. Sodoma, *J. Org. Chem.*, 1998, **63**, 2232.
179 C. S. Li, J. C. Medina, G. E. M. Maguire, E. Abel, J. L. Atwood and G. W. Gokel, *J. Am. Chem. Soc.*, 1997, **119**, 1609.
180 M. Inouye, Y. Hyodo and H. Nakazumi, *J. Org. Chem.*, 1999, **64**, 2704.
181 G. T. W. Gieling, H. W. Scheeren, R. Israel and R. J. M. Nolte, *Chem. Commun.*, 1996, 241.
182 J. L. M. van Nunen, B. F. B. Folmer and R. J. M. Nolte, *J. Am. Chem. Soc.*, 1997, **119**, 283.
183 J. N. H. Reek, H. Engelkamp, A. E. Rowan, J. Elemans and R. J. M. Nolte, *Chem. Eur. J.*, 1998, **4**, 716.
184 J. V. Hernandez, M. Almaraz, C. Raposo, M. Martin, A. Lithgow, M. Crego, C. Caballero and J. R. Moran, *Tetrahedron Lett.*, 1998, **39**, 7401.
185 D. Lowik, S. J. E. Mulders, Y. Cheng, Y. F. Shao and R. M. J. Liskamp, *Tetrahedron Lett.*, 1996, **37**, 8253.
186 A. P. Davis and R. S. Wareham, *Angew. Chem.*, *Int. Ed.*, 1999, **38**, 2979.
187 M. Segura, V. Alcazar, P. Prados and J. de Mendoza, *Tetrahedron*, 1997, **53**, 13119.
188 T. Schrader, *Angew. Chem.*, *Int. Ed. Engl.*, 1996, **35**, 2649.
189 T. Schrader, *Chem. Eur. J.*, 1997, **3**, 1537.
190 T. Schrader, *J. Org. Chem.*, 1998, **63**, 264.
191 T. Schrader, *J. Am. Chem. Soc.*, 1998, **120**, 11816.
192 M. Herm and T. Schrader, *Chem. Eur. J.*, 2000, **6**, 47.
193 T. W. Bell, A. B. Khasanov, M. G. B. Drew, A. Filikov and T. L. James, *Angew. Chem.*, *Int. Ed.*, 1999, **38**, 2543.
194 H. Xie, S. Yi and S. Wu, *J. Chem. Soc.*, *Perkin Trans. 2*, 1999, 2751.
195 P. Buhlmann, S. Nishizawa, K. P. Xiao and Y. Umezawa, *Tetrahedron*, 1997, **53**, 1647.
196 S. Tomas, R. Prohens, M. Vega, M. C. Rotger, P. M. Deya, P. Ballester and A. Costa, *J. Org. Chem.*, 1996, **61**, 9394.
197 S. Tomas, R. Prohens, G. Deslongchamps, P. Ballester and A. Costa, *Angew. Chem.*, *Int. Ed.*, 1999, **38**, 2208.
198 S. Goswami and K. Ghosh, *Tetrahedron Lett.*, 1997, **38**, 4503.
199 Y. Kato, M. M. Conn and J. Rebek Jr, *Proc. Natl. Acad. Sci. U.S.A.*, 1995, **92**, 1208.
200 P. Tecilla, V. Jubian and A. D. Hamilton, *Tetrahedron*, 1995, **51**, 435.
201 F. G. Klärner, J. Benkhoff, R. Boese, U. Burkert, M. Kamieth and U. Naatz, *Angew. Chem.*, *Int. Ed. Engl.*, 1996, **35**, 1130.
202 F. G. Klärner, U. Burkert, M. Kamieth, R. Boese and J. Benet-Buchholz, *Chem. Eur. J.*, 1999, **5**, 1700.
203 P. Lustenberger, R. Welti and F. Diederich, *Helv. Chim. Acta*, 1998, **81**, 2190.
204 P. Lustenberger, E. Martinborough, T. M. Denti and F. Diederich, *J. Chem. Soc.*, *Perkin Trans. 2*, 1998, 747.
205 U. Lüning and C. Kühl, *Tetrahedron Lett.*, 1998, **39**, 5735.
206 J. Sartorius and H. J. Schneider, *Chem. Eur. J.*, 1996, **2**, 1446.
207 H. Adams, K. D. M. Harris, G. A. Hembury, C. A. Hunter, D. Livingstone and J. F. McCabe, *Chem. Commun.*, 1996, 2531.
208 H. Adams, F. J. Carver, C. A. Hunter, J. C. Morales and E. M. Seward, *Angew. Chem.*, *Int. Ed. Engl.*, 1996, **35**, 1542.
209 F. J. Carver, C. A. Hunter and E. M. Seward, *Chem. Commun.*, 1998, 775.
210 F. J. Carver, C. A. Hunter and E. M. Seward, *Chem. Commun.*, 1998, 1237.
211 A. R. Fersht and L. Serrano, *Curr. Opin. Struct. Biol.*, 1993, **3**, 75.
212 A. P. Bisson, C. A. Hunter, J. C. Morales and K. Young, *Chem. Eur. J.*, 1998, **4**, 845.
213 C. A. Hunter and M. J. Packer, *Chem. Eur. J.*, 1999, **5**, 1891.
214 E. K. Fan, C. Vicent and A. D. Hamilton, *New J. Chem.*, 1997, **21**, 81.
215 K. Kavallieratos, C. M. Bertao and R. H. Crabtree, *J. Org. Chem.*, 1999, **64**, 1675.
216 K. Kavallieratos and R. H. Crabtree, *Chem. Commun.*, 1999, 2109.
217 A. Robertson, D. Philp and N. Spencer, *Tetrahedron*, 1999, **55**, 11365.
218 R. J. Pieters, I. Huc and J. Rebek Jr, *Tetrahedron*, 1995, **51**, 485.
219 A. Robertson, A. J. Sinclair and D. Philp, *Chem. Soc. Rev.*, 2000, **29**, 141.
220 H. Tye, C. Eldred and M. Wills, *Synlett*, 1995, 770.
221 H. Tye, C. Eldred and M. Wills, *J. Chem. Soc.*, *Perkin Trans. 1*, 1998, 457.
222 S. Goswami, K. Ghosh and S. Dasgupta, *Tetrahedron*, 1996, **52**, 12223.
223 A. Metzger, V. M. Lynch and E. V. Anslyn, *Angew. Chem.*, *Int. Ed. Engl.*, 1997, **36**, 862.
224 M. Almaraz, C. Raposo, M. Martin, M. C. Caballero and J. R. Moran, *J. Am. Chem. Soc.*, 1998, **120**, 3516.
225 T. Schuster and M. W. Göbel, *Synlett*, 1999, 966.
226 M. P. Hughes and B. D. Smith, *J. Org. Chem.*, 1997, **62**, 4492.
227 D. L. Beckles, J. Maioriello, V. J. Santora, T. W. Bell, E. Chapoteau, B. P. Czech and A. Kumar, *Tetrahedron*, 1995, **51**, 363.
228 D. G. Lonergan and G. Deslongchamps, *Tetrahedron*, 1998, **54**, 14041.
229 C. A. Hunter and J. K. M. Sanders, *J. Am. Chem. Soc.*, 1990, **112**, 5525.
230 J. S. Albert, M. S. Goodman and A. D. Hamilton, *J. Am. Chem. Soc.*, 1995, **117**, 1143.
231 J. S. Albert, M. W. Peczuh and A. D. Hamilton, *Bioorg. Med. Chem.*, 1997, **5**, 1455.
232 M. W. Peczuh, A. D. Hamilton, J. Sanchez-Quesada, J. de Mendoza, T. Haack and E. Giralt, *J. Am. Chem. Soc.*, 1997, **119**, 9327.
233 J. Sanchez-Quesada, C. Seel, P. Prados, J. de Mendoza, I. Dalcol and E. Giralt, *J. Am. Chem. Soc.*, 1996, **118**, 277.
234 H. Adams, F. J. Carver, C. A. Hunter and N. J. Osborne, *Chem. Commun.*, 1996, 2529.
235 C. Allott, H. Adams, P. L. Bernad, C. A. Hunter, C. Rotger and J. A. Thomas, *Chem. Commun.*, 1998, 2449.
236 P. Boullanger, *Top. Curr. Chem.*, 1997, **187**, 275.
237 C. G. Claessens and J. F. Stoddart, *J. Phys. Org. Chem.*, 1997, **10**, 254.
238 J. Rebek Jr, *Chem. Soc. Rev.*, 1996, **25**, 255.
239 M. Fujita and K. Ogura, *Bull. Chem. Soc. Jpn.*, 1996, **69**, 1471.
240 M. Fujita and K. Ogura, *Coord. Chem. Rev.*, 1996, **148**, 249.
241 M. Fujita, *Chem. Soc. Rev.*, 1998, **27**, 417.
242 M. S. Goodman, A. D. Hamilton and J. Weiss, *J. Am. Chem. Soc.*, 1995, **117**, 8447.
243 A. W. Schwabacher, A. D. Stefanescu and A. U. Rehman, *J. Org. Chem.*, 1999, **64**, 1784.
244 S. Rigault, C. Piguet, G. Bernardinelli and G. Hopfgartner, *Angew. Chem.*, *Int. Ed.*, 1998, **37**, 169.
245 O. Temme, T. Dickner, S. Laschat, R. Frohlich, S. Kotila and K. Bergander, *Eur. J. Org. Chem.*, 1998, 651.
246 H. Chen, S. Ogo and R. H. Fish, *J. Am. Chem. Soc.*, 1996, **118**, 4993.
247 L. G. Mackay, H. L. Anderson and J. K. M. Sanders, *J. Chem. Soc.*, *Perkin Trans. 1*, 1995, 2269.
248 S. Mann, G. Huttner, L. Zsolnai and K. Heinze, *Angew. Chem.*, *Int. Ed. Engl.*, 1996, **35**, 2808.
249 R. V. Slone and J. T. Hupp, *Inorg. Chem.*, 1997, **36**, 5422.
250 M. Scherer, D. L. Caulder, D. W. Johnson and K. N. Raymond, *Angew. Chem.*, *Int. Ed.*, 1999, **38**, 1588.
251 R. M. Grotzfeld, N. Branda and J. Rebek Jr, *Science*, 1996, **271**, 487.
252 J. Rebek Jr, *Chem. Commun.*, 2000, 637.
253 J. de Mendoza, *Chem. Eur. J.*, 1998, **4**, 1373.

254 Y. Tokunaga, D. M. Rudkevich, J. Santamaria, G. Hilmersson and J. Rebek Jr, *Chem. Eur. J.*, 1998, **4**, 1449.
255 J. J. Gonzalez, P. Prados and J. de Mendoza, *Angew. Chem.*, *Int. Ed.*, 1999, **38**, 525.
256 J. J. Gonzalez, R. Ferdani, E. Albertini, J. M. Blasco, A. Arduini, A. Pochini, P. Prados and J. de Mendoza, *Chem. Eur. J.*, 2000, **6**, 73.
257 R. K. Castellano and J. Rebek Jr, *J. Am. Chem. Soc.*, 1998, **120**, 3657.
258 S. K. Korner, F. C. Tucci, D. M. Rudkevich, T. Heinz and J. Rebek Jr, *Chem. Eur. J.*, 2000, **6**, 187.
259 K. N. Houk, S. Menzer, S. P. Newton, F. M. Raymo, J. F. Stoddart and D. J. Williams, *J. Am. Chem. Soc.*, 1999, **121**, 1479.
260 V. R. Pedireddi, W. Jones, A. P. Chorlton and R. Docherty, *Tetrahedron Lett.*, 1998, **39**, 5409.
261 E. Kimura, T. Ikeda, M. Shionoya and M. Shiro, *Angew. Chem.*, *Int. Ed. Engl.*, 1995, **34**, 663.
262 T. D. James, H. Kawabata, R. Ludwig, K. Murata and S. Shinkai, *Tetrahedron*, 1995, **51**, 555.
263 T. D. James, K. R. A. S. Sandanayake and S. Shinkai, *Supramol. Chem.*, 1995, **6**, 141.
264 T. D. James, K. R. A. S. Sandanayake and S. Shinkai, *Angew. Chem.*, *Int. Ed. Engl.*, 1996, **35**, 1911.
265 T. D. James, P. Linnane and S. Shinkai, *Chem. Commun.*, 1996, 281.
266 K. R. A. S. Sandanayake, T. D. James and S. Shinkai, *Pure Appl. Chem.*, 1996, **68**, 1207.
267 A. P. de Silva, T. Gunnlaugsson and T. E. Rice, *Analyst* (*London*), 1996, **121**, 1759.
268 A. P. de Silva, H. Q. N. Gunaratne, T. Gunnlaugsson and P. L. M. Lynch, *New J. Chem.*, 1996, **20**, 871.
269 A. P. de Silva, H. Q. N. Gunaratne, T. Gunnlaugsson, C. P. McCoy, P. R. S. Maxwell, J. T. Rademacher and T. E. Rice, *Pure Appl. Chem.*, 1996, **68**, 1443.
270 A. P. de Silva, H. Q. N. Gunaratne and C. P. McCoy, *J. Am. Chem. Soc.*, 1997, **119**, 7891.
271 A. P. de Silva, H. Q. N. Gunaratne, T. Gunnlaugsson, A. J. M. Huxley, C. P. McCoy, J. T. Rademacher and T. E. Rice, *Chem. Rev.*, 1997, **97**, 1515.
272 A. P. de Silva, T. Gunnlaugsson and C. P. McCoy, *J. Chem. Educ.*, 1997, **74**, 53.
273 J. Yoon and A. W. Czarnik, *J. Am. Chem. Soc.*, 1992, **114**, 5874.
274 J. P. Lorand and J. O. Edwards, *J. Org. Chem.*, 1959, **24**, 769.
275 H. Suenaga, M. Mikami, K. R. A. S. Sandanayake and S. Shinkai, *Tetrahedron Lett.*, 1995, **36**, 4825.
276 H. Suenaga, H. Yamamoto and S. Shinkai, *Pure Appl. Chem.*, 1996, **68**, 2179.
277 T. D. James, K. R. A. S. Sandanayake and S. Shinkai, *Angew. Chem.*, *Int. Ed. Engl.*, 1994, **33**, 2207.
278 T. D. James, K. R. A. S. Sandanayake, R. Iguchi and S. Shinkai, *J. Am. Chem. Soc.*, 1995, **117**, 8982.
279 M. Bielecki, H. Eggert and J. C. Norrild, *J. Chem. Soc.*, *Perkin Trans. 2*, 1999, 449.
280 J. C. Norrild and H. Eggert, *J. Am. Chem. Soc.*, 1995, **117**, 1479.
281 C. R. Cooper and T. D. James, *Chem. Lett.*, 1998, 883.
282 T. D. James, K. R. A. S. Sandanayake and S. Shinkai, *Nature* (*London*), 1995, **374**, 345.
283 T. D. James, H. Shinmori and S. Shinkai, *Chem. Commun.*, 1997, 71.
284 P. Linnane, T. D. James and S. Shinkai, *J. Chem. Soc.*, *Chem. Commun.*, 1995, 1997.
285 K. Lu, Y. J. Wu, H. X. Wang and Z. X. Zhou, *Polyhedron*, 1999, **18**, 1153.
286 F. Ohseto, H. Yamamoto, H. Matsumoto and S. Shinkai, *Tetrahedron Lett.*, 1995, **36**, 6911.
287 H. Matsumoto, A. Ori, F. Inokuchi and S. Shinkai, *Chem. Lett.*, 1996, 301.
288 T. D. James and S. Shinkai, *J. Chem. Soc.*, *Chem. Commun.*, 1995, 1483.
289 K. R. A. S. Sandanayake, T. D. James and S. Shinkai, *Chem. Lett.*, 1995, 503.
290 T. D. James, H. Shinmori, M. Takeuchi and S. Shinkai, *Chem. Commun.*, 1996, 705.
291 C. R. Cooper and T. D. James, *Chem. Commun.*, 1997, 1419.
292 C. R. Cooper and T. D. James, *J. Chem. Soc.*, *Perkin Trans. 1*, 2000, 963.
293 M. Takeuchi, M. Yamamoto and S. Shinkai, *Chem. Commun.*, 1997, 1731.
294 M. Yamamoto, M. Takeuchi and S. Shinkai, *Tetrahedron*, 1998, **54**, 3125.
295 H. Kijima, M. Takeuchi, A. Robertson, S. Shinkai, C. Cooper and T. D. James, *Chem. Commun.*, 1999, 2011.
296 K. R. A. S. Sandanayake, S. Imazu, T. D. James, M. Mikami and S. Shinkai, *Chem. Lett.*, 1995, 139.
297 M. Takeuchi, T. Mizuno, H. Shinmori, M. Nakashima and S. Shinkai, *Tetrahedron*, 1996, **52**, 1195.
298 M. Takeuchi, S. Yoda, T. Imada and S. Shinkai, *Tetrahedron*, 1997, **53**, 8335.
299 H. Eggert, J. Frederiksen, C. Morin and J. C. Norrild, *J. Org. Chem.*, 1999, **64**, 3846.
300 H. R. Snyder and C. Weaver, *J. Am. Chem. Soc.*, 1948, **70**, 232.
301 H. S. Snyder and S. L. Meisel, *J. Am. Chem. Soc.*, 1948, **70**, 774.
302 A. P. Russell, WO 91/04488, 1991.
303 H. Shinmori, M. Takeuchi and S. Shinkai, *J. Chem. Soc.*, *Perkin Trans. 2*, 1996, 1.
304 M. Takeuchi, M. Taguchi, H. Shinmori and S. Shinkai, *Bull. Chem. Soc. Jpn.*, 1996, **69**, 2613.
305 C. J. Davis, P. T. Lewis, M. E. McCarroll, M. W. Read, R. Cueto and R. M. Strongin, *Org. Lett.*, 1999, **1**, 331.
306 K. R. A. S. Sandanayake and S. Shinkai, *J. Chem. Soc.*, *Chem. Commun.*, 1994, 1083.
307 C. J. Ward, P. Patel, P. R. Ashton and T. D. James, *Chem. Commun.*, 2000, 229.
308 L. A. Cabell, M. K. Monahan and E. V. Anslyn, *Tetrahedron Lett.*, 1999, **40**, 7753.
309 J. J. Lavigne and E. V. Anslyn, *Angew. Chem.*, *Int. Ed.*, 1999, **38**, 3666.
310 J. H. Hartley and T. D. James, *Tetrahedron Lett.*, 1999, **40**, 2597.
311 T. Imada, H. Kijima, M. Takeuchi and S. Shinkai, *Tetrahedron Lett.*, 1995, **36**, 2093.
312 T. Imada, H. Kijima, M. Takeuchi and S. Shinkai, *Tetrahedron*, 1996, **52**, 2817.
313 M. Takeuchi, H. Kijima, I. Hamachi and S. Shinkai, *Bull. Chem. Soc. Jpn.*, 1997, **70**, 699.
314 L. D. Sarson, K. Ueda, R. Takeuchi and S. Shinkai, *Chem. Commun.*, 1996, 619.
315 M. Takeuchi, T. Imada and S. Shinkai, *J. Am. Chem. Soc.*, 1996, **118**, 10658.
316 M. Takeuchi, T. Imada and S. Shinkai, *Bull. Chem. Soc. Jpn.*, 1998, **71**, 1117.
317 S. Arimori, M. Takeuchi and S. Shinkai, *Chem. Lett.*, 1996, 77.
318 H. Suenaga, S. Arimori and S. Shinkai, *J. Chem. Soc.*, *Perkin Trans. 2*, 1996, 607.
319 S. Arimori, H. Murakami, M. Takeuchi and S. Shinkai, *J. Chem. Soc.*, *Chem. Commun.*, 1995, 961.
320 H. Kijima, M. Takeuchi and S. Shinkai, *Chem. Lett.*, 1998, 781.
321 M. Takeuchi, Y. Chin, T. Imada and S. Shinkai, *Chem. Commun.*, 1996, 1867.
322 M. Takeuchi, S. Yoda, Y. Chin and S. Shinkai, *Tetrahedron Lett.*, 1999, **40**, 3745.
323 K. Nakashima and S. Shinkai, *Chem. Lett.*, 1995, 443.
324 T. Mizuno, M. Takeuchi, I. Hamachi, K. Nakashima and S. Shinkai, *Chem. Commun.*, 1997, 1793.
325 T. Mizuno, M. Takeuchi, I. Hamachi, K. Nakashima and S. Shinkai, *J. Chem. Soc.*, *Perkin Trans. 2*, 1998, 2281.
326 G. Nuding, K. Nakashima, R. Iguchi, T. Ishii and S. Shinkai, *Tetrahedron Lett.*, 1998, **39**, 9473.
327 M. Yamamoto, M. Takeuchi and S. Shinkai, *Tetrahedron Lett.*, 1998, **39**, 1189.
328 M. Yamamoto, M. Takeuchi, S. Shinkai, F. Tani and Y. Naruta, *J. Chem. Soc.*, *Perkin Trans. 2*, 2000, 9.
329 T. Mizuno, M. Takeuchi and S. Shinkai, *Tetrahedron*, 1999, **55**, 9455.
330 V. W. W. Yam and A. S. F. Kai, *Chem. Commun.*, 1998, 109.
331 T. Mizuno, T. Fukumatsu, M. Takeuchi and S. Shinkai, *J. Chem. Soc.*, *Perkin Trans. 1*, 2000, 407.
332 M. J. Deetz and B. D. Smith, *Tetrahedron Lett.*, 1998, **39**, 6841.
333 P. R. Westmark, S. J. Gardiner and B. D. Smith, *J. Am. Chem. Soc.*, 1996, **118**, 11093.
334 M. F. Paugam, J. A. Riggs and B. D. Smith, *Chem. Commun.*, 1996, 2539.
335 S. J. Gardiner, B. D. Smith, P. J. Duggan, M. J. Karpa and G. J. Griffin, *Tetrahedron*, 1999, **55**, 2857.
336 J. A. Riggs, K. A. Hossler, B. D. Smith, M. J. Karpa, G. Griffin and P. J. Duggan, *Tetrahedron Lett.*, 1996, **37**, 6303.
337 M. Takeuchi, K. Koumoto, M. Goto and S. Shinkai, *Tetrahedron*, 1996, **52**, 12931.
338 J. T. Bien, M. Y. Shang and B. D. Smith, *J. Org. Chem.*, 1995, **60**, 2147.
339 M. F. Paugam, J. T. Bien, B. D. Smith, L. A. J. Chrisstoffels, F. de Jong and D. N. Reinhoudt, *J. Am. Chem. Soc.*, 1996, **118**, 9820.

340 S. Jacobson and R. Pizer, *J. Am. Chem. Soc.*, 1993, **115**, 11216.
341 K. Worm, F. P. Schmidtchen, A. Schier, A. Schafer and M. Hesse, *Angew. Chem.*, *Int. Ed. Engl.*, 1994, **33**, 327.
342 C. Dusemund, K. R. A. S. Sandanayake and S. Shinkai, *J. Chem. Soc.*, *Chem. Commun.*, 1995, 333.
343 H. Yamamoto, A. Ori, K. Ueda, C. Dusemund and S. Shinkai, *Chem. Commun.*, 1996, 407.
344 A. Ori and S. Shinkai, *J. Chem. Soc.*, *Chem. Commun.*, 1995, 1771.
345 C. R. Cooper, N. Spencer and T. D. James, *Chem. Commun.*, 1998, 1365.
346 H. Shiratori, T. Ohno, K. Nozaki, I. Yamazaki, Y. Nishimura and A. Osuka, *Chem. Commun.*, 1998, 1539.
347 H. Shiratori, T. Ohno, K. Nozaki and A. Osuka, *Chem. Commun.*, 1999, 2181.