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Allosteric binding properties of a 1,3-*alternate* thiacalix[4]arene-based receptor having phenyl-thiolurea and 2-pyridylmethyl moieties on opposite faces

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The synthesis of three heteroditopic receptors (**5a–c**) based on a thiacalix[4]arene in the 1,3-*alternate* conformation, which have two thiourea moieties linking various phenyl groups substituted with electron- withdrawing groups at their *p*-positions, with two 2-pyridylmethyl groups at the opposite side of the thiacalix[4]arene cavity, have been synthesized. One example (**5a**) has been characterized by X-ray crystallography. The binding properties of these receptors were investigated by means of ^{1}H NMR spectroscopy and UV-vis absorption titration experiments in $CHCl_3$–DMSO–CD_3CN (10:1:1, v/v) using various anions. The structures and complexation energies were also studied by density functional theory (DFT) methods. The results suggested that receptor **5c**, which possesses two *p*-nitrophenyl thioureido moieties, can complex most efficiently in the thiourea cavity and exhibits high selectivity towards F^- and AcO^- ions. Interestingly, the formation of a heteroditopic dinuclear complex of receptor **5b**, with F^- and Ag^+ ions by a positive allosteric effect was observed.

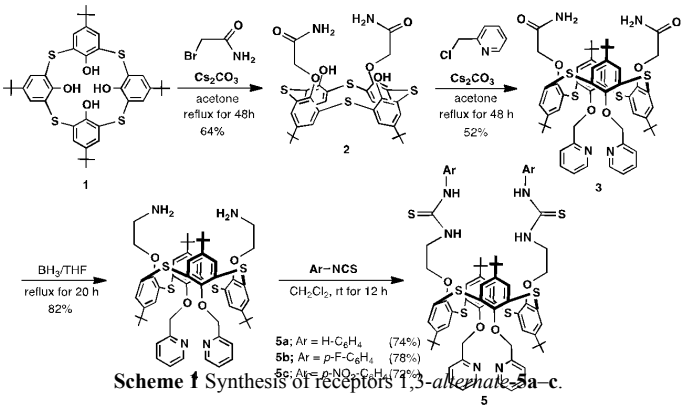
Introduction

Calix[*n*]arenes, which are macrocyclic compounds comprised of alternating numbers [*n* = 3–8] of phenolic groups typically linked via $-CH_2-$ groups, have proven to be versatile and useful building blocks for a variety of applications, especially in host-guest chemistry. This is due to the fact that they are easily synthesized and can be modified with a wide range of functional groups which can be fine-tuned for a variety of applications.[1] One of the most widely explored area of calix[*n*]arene chemistry has been in the development of sensitive and selective ionophoric receptors for cations, and also anions.[1] Included in the class of calix[*n*]arenes are the thiacalix[4]arene analogues, in which four alternating phenolic groups are linked via divalent sulfur atoms.[2] While not as extensively studied as the "classical" calix[4]arenes they nevertheless have shown similarities in host-guest chemistry as chemosensors for metal cations since they can also be relatively easily functionalized, not only at their narrow-rim phenolic oxygen atoms, but also the sulfur linkage can be synthetically modified.[3]

Several different types of artificial systems including calix[4]arenes have been shown to be suitable for allosteric effects in host-guest interactions with metal cations. Similar allosteric effects and regulation[4] in biological systems are of great importance in organic processes. Anions are also important for biological processes, involving DNA and as enzyme substrates. There is therefore much interest in developing anion selective sensors which,

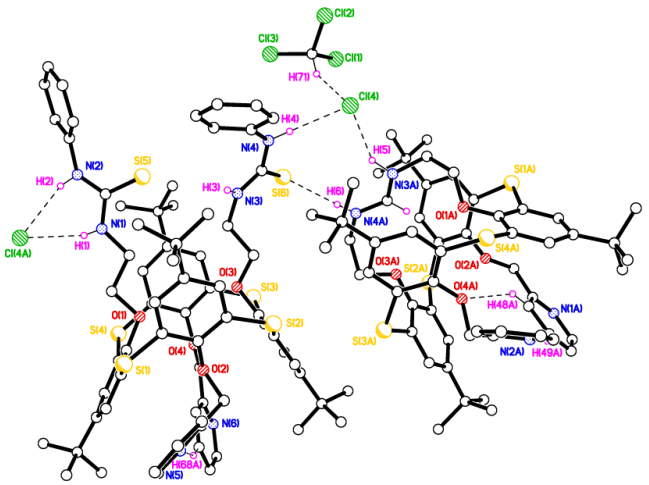
however, can be more challenging.[6] Besides halide anions which are spherical, anions can also be trigonal or Y–shaped such as *e.g.* acetate (AcO^-) or benzoate ions; or tetrahedral, such as e.g. dihydrogenphosphate ($H_2PO_4^-$) and perchlorate ions to name just a few. Many colorimetric anion chemosensors[7,8] have been reported with chromogenic signaling moieties such as anthraquinone, benzenediimide and *p*-nitro-phenylazo groups which have been incorporated in a variety of structural scaffolds which contain urea groups. These have proven to be efficient naked–eye colorimetric detectors for various anions since hydrogen-bonding interactions can occur between anions and the urea NH protons. However, there are relatively few reports of colorimetric anion chemosensors based on calix[4]arene[8(l),8(p),9] or thiacalix[4]arene scaffolds.[9,10]

Previously, we have reported the observation of allosteric effects resulting from the interaction of alkali metal cations and anions with thiacalix[4]arene derivatives.[11–13] Herein, we report further studies on such allosteric effects being observed with tetra-*p*-*tert*-butyl thiacalix[4]arene, the latter is in a 1,3-*alternate* conformation and is di-substituted on one rim with thiourea moieties linked to various *p*-substituted phenyl groups with electron-withdrawing groups (**5a**–**c**). At the opposite face of the thiacalix[4]arene cavity there are two 2-pyridylmethyl groups. We herein demonstrate that this heteroditopic system undergoes complexation with both anions and Ag^+ at the opposite rims of the receptor molecule and with effective, positive allosteric effects.



Scheme 1 Synthesis of receptors 1,3-*alternate*-**5a**–**c**.

The molecular structure of **5a**, which was recrystallized from a mixture of $CHCl_3$–CH_3CN (1:1, v/v) in the presence of one equiv. of tetrabutylammonium chloride by slow evaporation, was also verified by a single-crystal X-ray analysis (Fig. 1 and Figures S13–S17). The



asymmetric unit comprises two different calixarenes with moieties '$C_{70}H_{78}N_6O_4S_6$' (**5a**) and '$C_{57}H_{67}N_4O_4S_4^+$', a Cl^- counter ion and one molecule of $CHCl_3$ as the solvent of crystallization. The charge on the Cl^- anion is stabilised by charge-assisted hydrogen bonding from a fairly rare [–NH–CH–NH–]$^+$ functional group. This group has a delocalised positive charge on the second, modified, thiacalixarene molecule in the asymmetric unit (Fig. 2 & Figures S13–S14). From the N–C bond lengths, it is clear that individually they are neither single nor double bonds, but share the delocalised positive charge across both bonds. The asymmetry of the bond lengths is a result of H(5) interacting with the Cl^- anion, thus lengthening the N(3A)–H(5) bond and, as a result, shortening the adjacent N–C bond (Fig. 2). This cationic moiety is demonstrating an ability to capture chloride ions. There are currently 17 structures in the CSD which exhibit the same functional group (*e.g.* XANFIC, RURWUY, MAJSEV),[16] in which both C–N bonds are roughly 1.30 Å, with any asymmetry in the two bond lengths being attributed to different substituents either side of this functional group.

Results and discussions

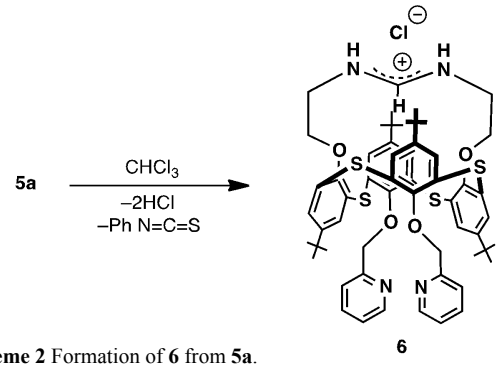
Synthesis

O-Alkylation of **1**[14] with 2 mol equiv. of 2-bromoacetamide in the presence of Na_2CO_3 using a reported procedure[15] afforded the 1,3-di-*O*-substitution product *distal*-**2** in 64 % yield as the major product. Other possible isomers were not observed. The reaction of **2** with 2-(chloromethyl)pyridine in acetone in the presence of Cs_2CO_3 formed 1,3-*alternate*-**3** in 52 % yield. Reduction of **3** with BH_3 under THF reflux conditions afforded 1,3-*alternate*-**4** in 82% yield. Condensation reactions of **4** with 2.2 equivalents of the appropriate thioisocyanate in CH_2Cl_2 furnished the corresponding thiourea receptors **5a**–**c** in good to excellent yields (Scheme 1). Each of the ^{1}H−NMR spectra of **5a**–**c** in $CDCl_3$–DMSO (10:1, v/v) exhibited the characteristics of 1,3-*alternate* canformations. The spectra showed two singlets (18H each) for the *tert*-butyl protons, one singlet (4H) for OCH_2CO protons, two triplets (4H each) for the –OCH_2CH_2– protons, two singlets (4H each) for aromatic protons and two singlets (2H each) for the four urea NH protons (Figures S1–S12).

Fig. 1 X–ray crystal structure of receptor **5a** (left hand side). The asymmetric unit shows an intermolecular S···H–N hydrogen bond between the two different thiacalixarenes and the N–H···Cl^- interactions between each thiacalixarene and the $Cl(4)^-$ anion; Cl(4A) is a symmetry equivalent. Minor disorder components and H atoms not involved in H-bonding are omitted for clarity.

Interestingly, it was found that one of the thiacalixarene molecules in the asymmetric unit of **5a**, which is in a 1,3-*alternate* conformation, shows weaker intramolecular C–H···N hydrogen bonding between the opposing pyridine rings (Fig. S15). The second thiacalixarene in the asymmetric unit also shows intramolecular hydrogen between the opposing pyridine groups in addition to the charge-assisted N–H···Cl^- hydrogen bonding (Figures S16–S17). There is an intermolecular S···H–N hydrogen bond between the two thiacalixarenes (Fig. 1 and Figures S16–S17). The receptor **5a** has a three-dimentional cavity which is large enough to accommodate a metal cation between the opposing 2-pyridyl side arms. The exact mechanism for the formation of compound **6** is not clear from the available data. However, it is clear that under the crystallization conditions employed, the two thiourea moieties react with a molecule of $CHCl_3$. The intramolecular condensation product is formed either via a step-wise or concerted elimination of two molecules of HCl and two thiourea moeites as two phenyl isothiocyanates.

Fig. 2 A zoomed-in view showing the bond lengths (Å) of the [–NH–CH–NH–]$^+$ moiety with it's delocalised positive charge.



Scheme 2 Formation of **6** from **5a**.

Binding studies

The binding properties of receptors **5a–c** in the presence of F^- as its tetrabutylammonium (TBA) salt, in $CDCl_3$–DMSO–CD_3CN (10:1:1, v/v) solution, were investigated by means of ^{1}H-NMR spectroscopic titration experiments. As shown in Fig. 3, for the complexation of F^- with **5b** for example, the signals for the NH_a protons (red) progressively shifted downfield by 5.99 ppm (δ = 8.06 to 14.05 ppm) until five equivalents of F^- were added. On the other hand, the signals for the NH_b protons (blue) progressively shifted downfield by 3.62 ppm (δ = 7.34 to 11.02 ppm) until five equiv. of F^- were added (Figure S19). These results are strongly suggestive of F^- recognition by the receptor **5b** *via* hydrogen–bonding interactions between F^- and the N–H protons. On the other hand, the methylene protons adjacent to the NH_b moiety (green) are shifted slightly upfield. A similar ^{1}H-NMR spectroscopic titration experiment with receptor **5a** in $CDCl_3$–DMSO-CD_3CN solution (Figure S18) showed that addition of F^- also resulted in clear downfield shifts of the ^{1}H NMR signals of the NH_a protons. Moreover, the addition of F^- (1.0 equiv.) to solutions of receptor **5c** in $CHCl_3$–DMSO–CD_3CN (10:1:1, v/v) during the titration experiments resulted in the disappearance of the signals for urea NH_a and NH_b protons. These results also indicate that strong interactions between these anions and the thiourea NH groups in the receptor **5c** occur and that the kinetics of these anion exchanges are on the NMR time scale (Fig. S20).

All of the results obtained from the ^{1}H-NMR spectroscopic titration experiments clearly suggest that anion recognition by the receptors is via hydrogen-bonding interactions between the anion and the NH protons. The binding or association constant (K_a) values for **5a** and **5b** and F^- from the ^{1}H NMR experiments were calculated using a 1:1 global fit analysis of the chemical shifts of the NH_a protons (K_a = (2.65 ± 0.19) × 10^6 M^{-1} for **5a** and K_a = (9.31± 0.65) × 10^6 M^{-1} for **5b**) (Figure S21).[17] The K_a value for **5b**, which has the electron-withdrawing F atoms on the phenyl ureido moieties, is greater than that for **5a**. These values indicate that the K_a values are influenced by the electron-withdrawing groups located at the *p*-position of the phenyl ureido moieties. The introduction of electron–withdrawing groups at the *p*-position of the phenyl ureido groups increases the acidity of the thiourea protons, and hence enhances the anion-binding ability through hydrogen-bonding interactions.

Fig. 3 Binding mode of receptor **5b** upon addition of F^-. and partial ^{1}H NMR (300 MHz) titration spectra of **5b** (4.0×10^{-3} M) in $CDCl_3$–DMSO–CD_3CN (10:1:1, v/v) upon addition of TBAF at 298 K.

Further complexation studies of **5a–c** with F^-, Cl^-, AcO^- and $H_2PO_4^-$ ions were carried out using UV–vis spectroscopic titration experiments in CH_2Cl_2. Receptor **5c** (2.5 μM) exhibits a broad absorption band at 305 nm in its UV–vis absorption spectrum (Fig. 4).

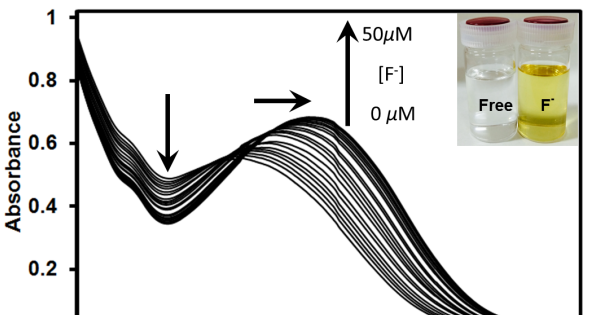


Fig. 4 UV–vis absorption spectra of receptor **5c** (2.5 μM) upon the addition of Bu_4NF (0–50 μM) in CH_2Cl_2–DMSO (10:1, v/v).

Table 1 Association constants (K_a [M^{-1}]) [a] of receptors **5a–c** with anions.[b]

	K_a [M^{-1}] (± K_{error}[c])			
Host	F^- (spherical)	Cl^- (spherical)	AcO^- (spherical)	$H_2PO_4^-$ (spherical)
5a	2.3×10^6 ($\pm1.6\times10^5$)	2.0×10^4 ($\pm1.4\times10^3$)	1.9×10^6 ($\pm1.3\times10^5$)	4.6×10^4 ($\pm3.3\times10^3$)
5b	9.3×10^6 ($\pm1.6\times10^5$)	4.4×10^4 ($\pm3.0\times10^3$)	4.6×10^6 ($\pm3.3\times10^5$)	9.4×10^4 ($\pm6.6\times10^3$)
5c	3.1×10^7 ($\pm2.2\times10^6$)	2.5×10^5 ($\pm1.7\times10^3$)	2.3×10^7 ($\pm1.6\times10^6$)	4.5×10^5 ($\pm1.7\times10^3$)

[a] Measured in CH_2Cl_2 at 298 K by UV–vis titration method; host concentration was 2.5 μM. [b] Guests used: TBA salts. [c] The ± error here is not a measure of precision of replicates but represents the %error resulting from the global-fit calculations since only single titration experiments in each case were conducted.

Upon addition of aliqots of F^- (0–50 μM) to the CH_2Cl_2–DMSO solution of **5c** (Fig. 4 and Fig. S24), a gradual decrease in the absorption of the band at 305 nm with a simultaneous increase in the absorption at 360 nm and a clear isosbestic point at 335 nm can be seen. From a Job's plot,[17c] a 1:1 stoichiometry for the binding between the receptor **5c** and F^- (Figure S25) was established, and the K_a was determined to be 3.1×10^7 M^{-1} from the UV–vis titrations.[17b] The colour of the solution changed and was easily visible, from colourless to yellow upon addition of 5 equiv. F^-, indicating that a quinoidal structure was formed by the deprotonation of urea NH groups in the *p*–nitrophenyl ureido moiety.

The K_a values obtained from similar UV-vis titration experiments of **5a–c** with F^- are summarized in Table 1. The order of the F^- complexation abilities is **5c** > **5b** > **5a**, with the NO_2-bearing receptor **5c** showing the best recognition ability toward F^-. Also, **5b** has a larger K_a than **5a**. The presence of electron–withdrawing groups at the *p*-position of the phenyl thioureido groups clearly increases the acidity of the thiourea protons, and hence enhances the anion-binding ability through hydrogen-fluoride bonding interactions. Similarly, further UV–vis spectroscopic titration complexation studies of **5a–c** with Cl^- and AcO^- and $H_2PO_4^-$ were conducted and the K_a values are summarized in Table 1. The order of the anion complexation abilities of receptors **5a–c** is found to be: F^- > AcO^- > $H_2PO_4^-$ > Cl^-. Receptor **5c** therefore was capable of complexing with all of the anions tested and demonstrated the best recognition ability toward all of the anions tested, irrespective of their shapes, but was especially sensitive to F^-.

A computational study was undertaken to further investigate the binding properties of receptors **5a–c** with the anions tested. The individual structures were fully geometry-optimized in the gas-phase using Gaussian 09[18] at the B3LYP level of DFT and the LANL2DZ basis set. Significant changes were observed for the distances between the two thiourea NH moieties in each of the receptors in their anion complexes. The conformational changes for example as shown for the 1:1 complex of **5b** with F^- can be seen in Fig. 5 (more precise details for the computation studies for receptors **5a–5c** with the different anions are shown in Table S1, and Figures S28 and S30).

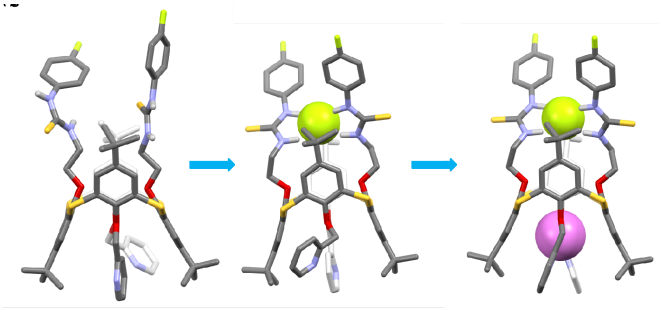


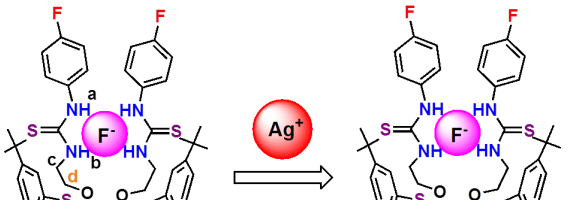
Fig. 5 Geometry-optimized (ball-and-stick) structures (in the gas phase) of: (a): Free ligand **5b**; (b): **5b**⊃F^- and (c): Ag^+⊂[**5b**⊃F^-]. Colour code: F^- = green, nitrogen = blue, sulfur = yellow, oxygen = red, carbon = grey, hydrogen = white and Ag^+ = violet.

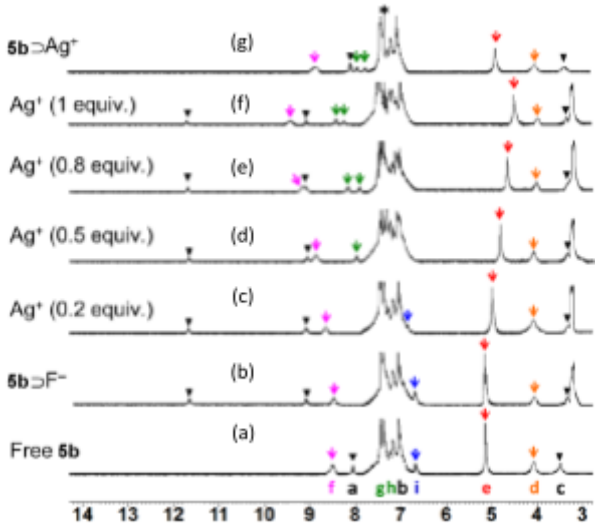
Fig. 5 shows the computed structures of (a) **5b** and (b) the 1:1 complex of **5b** with F^-. The hydrogen-bonding distances between the F^- ion and each of the thiourea NH protons ($NH_a\cdots NH_{a'}$ and $NH_b\cdots NH_{b'}$) on the two *p*-fluorophenyl ureido moieties (Fig. 6) decrease from 8.783 to 2.530 (Å) and from 8.379 to 3.251 (Å), respectively. This also strongly supports the experimental evidence obtained for the formation of the 1:1 (**5b**⊃F^-) complex. The calculated interaction energies (ΔIE kJ mol^{-1}) for receptor **5b** with all anion complexes are shown in Table 2. The trend for the interaction energies for **5b** are in the order: F^- > AcO^- > $H_2PO_4^-$ > Cl^-, which is in agreement with the trend observed for the observed complexation data obtained from the UV-vis absorption titration experiments.

Table 2. Calculated interaction energies for receptors **5a–c** with anions.

		Interaction energies ΔIE (kJ mol^{-1})			
Host	Ar	F^-	Cl^-	AcO^-	$H_2PO_4^-$
5a	C_6H_5–	–481.33	–296.45	–294.52	–286.66
5b	*p*-F–C_6H_4–	–501.95	–317.00	–314.05	–289.58
5c	*p*-NO_2–C_6H_4–	–551.35	–362.33	–361.34	–339.47

^{1}H-NMR titration experiments of **5b** with $AgSO_3CF_3$ were conducted in $CDCl_3$–DMSO (Fig. 6). Addition of a molar equiv. of $AgSO_3CF_3$ causes an upfield shift ($\Delta\delta$ = 0.25 ppm) from δ = 5.13 to 4.88 ppm for the methylene −OCH_2Py protons of **5b**. The pyridine protons ($H_{f\text{-}i}$) all show downfield shifts, indicating that the Ag^+ is bound to the phenolic oxygens and the nitrogen atoms of the pyridine appendage (1:1 Ag^+⊂**5b** complex in Fig. 6g). The chemical shift change ($\Delta\delta$) of the H_f-pyridyl protons adjacent to the nitrogen is shifted downfield by a larger amount ($\Delta\delta$= –0.39 ppm, from δ = 8.50 to 8.89 ppm) than those of the other pyridyl protons. Spectral changes of the 1:1 Ag^+⊂**5b** complex in the presence of an excess of $AgSO_3CF_3$ were not detectable, which supports the exclusive formation of the 1:1 Ag^+⊂**5b** complex. From these observations, it is clear that for the complexation of **5b** with Ag^+, the pyridine nitrogens turn inward to bind with the Ag^+ within the cavity of the receptor, as is also shown in Fig. 5c. On the other hand, the methylene protons in −OCH_2Py shifted in the opposite direction due to the ring current effect of the benzene moieties. The Job's plot for the titration of **5b** with Ag^+ exhibited a 1:1 stoichiometry. From the ^{1}H-NMR spectroscopic titration experiments in CH_2Cl_2–DMSO (10:1, v/v), the K_a value for the complexation with Ag^+ ion was determined to be $K_a = 7.58 \pm 0.53 \times 10^2$ M^{-1}.





F 00
N ve
a b)

5b⊃Bu_4NF (1:1)**;** (c) $AgSO_3CF_3$ (0.20 equiv.)⊂[**5b**⊃F^-]; (d) $AgSO_3CF_3$ (0.50 equiv.)⊂[**5b**⊃F^-]; (e) $AgSO_3CF_3$ (0.80 equiv.)⊂[**5b**⊃F^-]; (f) $AgSO_3CF_3$ (1.0 equiv.)⊂[**5b**⊃F^-]; (g) $AgSO_3CF_3$⊂**5b** (1:1). *Denotes the solvent peak.

The different sites of complexation for the anions and Ag^+ suggested the potential for an effective positive or negative allosteric effect between receptor **5b**⊃F^- and Ag^+. Thus, a ^{1}H-NMR spectroscopic titration experiment was conducted to determine this possibility. Figs. 6c–f show that when Ag^+ ion was added to the solution of **5b**⊃F^-, the addition induces a downfield shift of the pyridine protons and upfield shifts of the −OCH_2Py methylene protons, while the chemical shifts for the amido urea protons did not change. The addition of 1.0 equiv. of $AgSO_3CF_3$ to **5b**⊃F^- causes a larger upfield shift for the −OCH_2Py methylene protons ($\Delta\delta$ = 0.79 ppm, δ = 5.13 to 4.56 ppm) than that previously seen when a molar equivalent of Ag^+ was added to **5b** ($\Delta\delta$ = 0.25 ppm) itself. Moreover, a larger downfield shift was observed for the pyridyl H_f proton ($\Delta\delta$ = 0.89 ppm, δ = 8.50 to 9.39 ppm) than that previously seen with **5b**. These observations show that a stronger binding ability occurs for the preformed **5b**⊃F^- complex with Ag^+ than for **5b** alone. This is supported by the fact that the K_a value for the complexation of **5b**⊃F^- with Ag^+ was determined to be (4.49 ± 0.31) × 10^3 M^{-1}, which is 6 times higher than that of the complexation of **5b** with Ag^+. These results suggest the formation of a heteroditopic dinuclear complex such as Ag^+⊂[**5b**⊃F^-] as shown in Figs. 5c and 6, and that a positive allosteric effect of receptor **5b** towards Ag^+ in the presence of F^- occurs. Presumably this occurs as a result of the anion-electrostatic interactions with the N-H atoms of the thioureido pair resulting in a conformational change of the flexible thiacalix[4]arene allowing for the Ag^+ complexation within the cavity.

The binding properties of receptor **5b** with Ag^+ and fluoride anion were subjected to an additional computational study. The individual structures were fully geometry-optimized, in the gas-phase, using Gaussian 09[18] at the B3LYP level of DFT and the LANL2DZ basis set. The calculated interaction energies (ΔIE kJ mol^{-1}) are shown in Table 3.

Table 3. The DFT interaction energies Δ/E (kJ mol^{-1}) and selected distances (in Å) for receptor **5b** and its complexes with F^-, in the absence of and in the presence of Ag^+.

		Average distances (Å)

	ΔIE (kJ mol^{-1})	Pyridine (N-N')	Thiourea (NH-N'H')	Thiourea (NH-N'H')-F^-	Pyridine (N-N')-Ag^{++}
5b	–	6.437	6.806	–	–
5b⊃F^-	-501.95	–	3.050	1.742	6.512
Ag^+⊂**5b**	-436.59	3.677	4.076	–	2.386
Ag^+⊂[**5b**⊃F^-]	-1090.36	3.708	3.710	1.734	2.417

The interaction energies for Ag^+⊂**5b**, **5b**⊃F^-, and Ag^+⊂[**5b**⊃F^-] are –501.95, –436.59, and 1090.36 kJ mol^{-1}, respectively, and are in agreement with the trend for the observed experimental complexation data obtained. The geometry-optimized structures (in the gas phase) **5b**⊃ F^- and Ag^+⊂[**5b**⊃F^-] are shown in Fig. 5.

Conclusion

In summary, a new family of heteroditopic receptors **5a–c** based on a thiacalix[4]arene which is in the 1,3-*alternate* conformation has been synthesized and their anion complexation ability studied. These receptors have two thiourea moieties bearing various phenyl groups substituted with electron-withdrawing groups at their *p*-positions, as well as 2-pyridyl moieties at the opposite rims of the thiacalix[4]arene cavity. Using ^{1}H-NMR spectroscopic and UV–vis titration experiments, receptor **5c** which has electron–withdrawing NO_2 groups at the *p*-positions of the phenylthioureido moieties was shown to have the most effective recognition ability towards the selected anions. The binding of Ag^+ at the 2-pyridyl moieties and the binding of the anions at the two thiourea NH groups of the two *p*-nitrophenylureido moieties, respectively, was investigated. The results indicated the likely complexation mode, and it was found that receptor **5c** was able to bind all of the anions tested, irrespective of their shapes. Receptor **5c** exhibited the high selectivity towards F^- amongst all of the anions tested and indicated that this receptor might be a promising candidate as a colorimetric chemosensor. The appearance of a positive allosteric effects with receptor **5b** was also found using ^{1}H-NMR spectroscopic titration experiments. Interestingly, the formation of a heteroditopic dinuclear complex of receptor **5b** with F^- and Ag^+ ions by a positive allosteric effect could be observed.

Experimental Section

General

All melting points were determined with Yanagimoto MP-S1. ^{1}H-NMR spectra were determined at 300 MHz with a Nippon Denshi JEOL FT-300 NMR spectrometer with $SiMe_4$ as an internal reference; *J*-values are given in Hz. UV spectra were measured by a Shimadzu 240 spectrophotometer. Mass spectra were obtained on a Nippon Denshi JMS-01SG-2 mass spectrometer at an ionization energy of 70 eV using a direct inlet system through GLC. Elemental analyses were performed by Yanaco MT-5.

Materials

Unless otherwise stated, all reagents used were purchased from commercial sources and used without further purification. 5,11,17,23-Tetra-*tert*-butyl-2,8,14,20-tetrathiacalix[4]arene-25,26,27,28-tetraol **1**[14] and *distal*-5,11,17,23-tetra-*tert*-butyl-25,27-bis(carbamoylmethoxy)-26,28-dihydroxy-2,8,14,20-tetrathiacalix[4]arene **2**[15] were prepared following the reported procedures.

Synthesis of *distal*-5,11,17,23-tetra-*tert*-butyl-25,27-bis-(carbamoylmethoxy)-26,28-dihydroxy-2,8,14,20-tetrathia-calix[4]arene 2

A mixture of **1** (1.0 g, 1.4 mmol) and Na_2CO_3 (0.22 g, 1.5 mmol) in dry acetone (20 mL) was heated at reflux for 1 h under argon. Then 2-bromoacetamide (418 mg, 3.04 mmol) was added and the mixture was heated at reflux for an additional 48 h under argon. After cooling the reaction mixture to room temperature, the solvent was evaporated under reduced pressure. The residue was made alkaline with 30% NaOH (20 mL) and extracted with CH_2Cl_2 (30 mL × 3). The combined extracts were washed with water (30 mL × 3) and brine (30 mL × 3). After washing, the organic layer was dried over magnesium sulfate and condensed under reduced pressure to give a crude product. Crystallization from $CHCl_3$–MeOH (3:1, v/v) gave compound **2** (738 mg, 64 %) as colourless prisms. M.p. 148–151 °C. IR (KBr)/cm^{-1} 3467 (NH), 3334 (OH), 3187 (NH) and 1694 (CO). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 1.05 (s, 18H, *t*Bu), 1.24 (s, 18H, *t*Bu), 4.75 (s, 4H, OCH_2CO), 6.19 (br, 2H, N*H*), 7.05 (br, 2H, N*H*), 7.43 (s, 4H, Ar*H*), 7.67 (s, 4H, Ar*H*) and 8.40 (s, 2H, O*H*) ppm. ^{13}C NMR (400 MHz, $CDCl_3$): δ = 30.9, 34.2, 68.8, 120.0, 120.7, 122.8, 123.3, 144.2, 164.8, 166.1 and 170.0 ppm. FABMS: *m/z*: 835.29 (M^+). Anal. calcd for $C_{44}H_{54}N_2O_6S_4$ (835.17): C 63.28, H 6.52, N 3.35; found: C 63.02, H 6.49, N 3.33.

Synthesis of compound 3

To a solution of **2** (1.0 g, 1.2 mmol) and Cs_2CO_3 (3.9 g, 12 mmol) in dry acetone (20 mL) was added 2-(chloromethyl)pyridine (2.0 g, 12 mmol) and the reaction mixture was heated at refluxed for 48 h under argon. After cooling the reaction mixture to room temperature, the solvent was evaporated under reduced pressure. The residue was made alkaline with 30% NaOH (20 mL) and extracted with $CHCl_3$ (30 mL × 3). The combined extracts were washed with water (30 mL × 3) and brine (30 mL × 3). After washing, the organic layer was dried over magnesium sulfate and condensed under reduced pressure to give a crude product. The residue was purified by column chromatography using $CHCl_3$ as eluent to provide a pale-yellow powder. Crystallization from $CHCl_3$–hexane (3:1, v/v) gave compound **3** (634 mg, 52 %) as pale-yellow prisms. M.p. 195–197 °C. ^{1}H NMR (300 MHz, $CDCl_3$): δ = 0.83 (18H, s, *t*Bu), 1.28 (18H, s, *t*Bu), 4.48 (4H, s, OCH_2), 5.10 (2H, br, N*H*), 5.20 (4H, s, OCH_2), 5.51 (2H, br, N*H*), 6.57 (2H, d, *J* = 8.5 Hz, Pyridine–H_3), 7.09 (4H, s, Ar*H*), 7.00–7.42. (2H, m, Pyridine–$H_{4,5}$), 7.40 (4H, s, Ar*H*) and 8.51 (2H, d, *J* = 7.7 Hz, Pyridine–H_6) ppm. ^{13}C NMR (400 MHz, $CDCl_3$): δ = 31.5, 31.9, 34.2, 34.3, 66.1, 70.7, 121.8, 122.0, 126.4, 126.8, 127.5, 127.8, 128.1, 135.9, 146.9, 147.0, 147.4 153.7, 155.3, 156.1 and 169.8 ppm. FABMS: *m/z*: 1017.40 (M^+). Anal. calcd for $C_{56}H_{64}N_4O_6S_4$ (1017.39): C 66.11, H 6.34, N 5.51; found: C 66.23, H 6.29, N 5.55.

Synthesis of compound 4

A solution of BH_3/THF (50 mL, large excess) was added to **3** (600 mg, 0.590 mmol) and the reaction mixture was heated at reflux for 20 h under argon. After cooling the reaction mixture to room temperature, it was quenched by the slow addition of aqueous 1.0 M HCl (30 mL). The mixture was again heated at reflux for 1 h under argon. After cooling the reaction mixture to room temperature, the solvent was evaporated under reduced pressure. The residue was made alkaline with 30% NaOH (20 mL) and extracted with $CHCl_3$ (30 mL × 3). The combined extracts were washed with water (30 mL × 3) and brine (30 mL × 3). After washing, the organic layer was dried over magnesium sulfate and condensed under reduced pressure to give a crude product. The residue was purified by column chromatography using $CHCl_3$–MeOH (10:1) as eluent to provide a colourless powder. Crystallization from $CHCl_3$–hexane (7:3, v/v) gave compound **4** (479 mg, 82 %) as colourless prisms. M.p. 180–182 °C. ^{1}H-NMR (300 MHz, $CDCl_3$): δ = 0.82 (18H, s, *t*Bu), 1.31(18H, s, *t*Bu), 2.20 (4H, br, NH_2), 2.52 (4H, t, *J* = 9.0 Hz, $OCH_2CH_2NH_2$), 4.02 (t, *J* = 9.0Hz, 4H, $OCH_2CH_2NH_2$), 5.12 (s, 4H, Pyridine–CH_2), 6.50 (2H, d, *J* = 8.5 Hz, Pyridine–H_3), 7.05 (s, 4H, Ar–*H*), 7.13 (2H, br, Pyridine–H_4), 7.42 (s, 4H, Ar–*H*), 7.49–7.60. (2H, m, Pyridine–H_5) and 8.49 (2H, d, *J* = 7.7 Hz, Pyridine–H_6) ppm. ^{13}C NMR (400 MHz, $CDCl_3$): δ = 30.0, 33.8, 33.9, 68.9, 70.6, 120.0, 128.1, 128.5, 128.8, 129.4, 129.9, 136.0, 149.8, 150.5, 150.8, 154.0, 156.4 and 158.0 ppm. FABMS: *m/z*: 989.40 (M^+). Anal. calcd for $C_{56}H_{68}N_4O_4S_4$ (989.43): C 67.89, H 6.93, N 5.66; found: C 67.45, H 6.50, N 5.45.

Synthesis of compound 5a

To compound **4** (100 mg, 0.101 mmol) in dry CH_2Cl_2 (15 mL) was added phenyl isothiocyanate (82 mg, 0.61 mmol) and the mixture was stirred at room temperature for 12 h under argon. The solvent was then evaporated under reduced pressure. The residue was purified by column chromatography using $CHCl_3$–MeOH–aqueous 28% NH_3 solution (95:4:1, v/v) as eluent to provide a colourless powder. Crystallization from $CHCl_3$–Hexane (3:1, v/v) gave **5a** (94 mg, 74 %) as colourless prisms. M.p. 223–224 °C. ^{1}H NMR (300 MHz, $CDCl_3$–DMSO, 10:1, v/v): δ = 0.87 (18H, s, *t*Bu), 1.29 (18H, s, *t*Bu), 3.52 (4H, br, OCH_2CH_2NH), 4.10 (4H, br, OCH_2CH_2NH), 5.12 (4H, s, Pyridine–CH_2), 6.70 (2H, d, *J* = 7.8 Hz, Pyridine–H_3), 7.03 (4H, s, Ar–*H*), 7.10–7.70. (m, 16H, Phenyl–*H*, CH_2NH and Pyridine–$H_{4,5}$), 7.46 (4H, s, Ar–*H*), 7.72 (2H, s, Phenyl–N*H*) and 8.60 (2H, s, Pyridine–H_6) ppm. ^{13}C NMR (400 MHz, $CDCl_3$–DMSO, 10:1): δ = 30.7, 34.0, 45.9, 64.8, 68.8, 122.3, 124.0, 126.2, 129.2, 130.1, 131.2, 132.4, 134.5, 136.0, 146.0, 146.3, 155.3, 156.0, 169.4 and 182.0 ppm. FABMS: *m/z*: 1259.46 (M^+). Anal. calcd for $C_{70}H_{78}N_6O_4S_6$ (1259.80): C 66.74, H 6.24 N 6.67; found: C 66.69, H 6.32, N 6.76.

Synthesis of compound 5b

To compound **4** (100 mg, 0.101 mmol) in dry CH_2Cl_2 (15 mL) was added 4-fluorophenyl isothiocyanate (93 mg, 0.61 mmol) and the mixture was stirred at room temperature for 12 h under argon. The solvent was then evaporated under reduced pressure. The residue was purified by column chromatography using $CHCl_3$–MeOH–28% aqueous NH_3 solution (95:4:1) as eluent to provide a colourless powder. Recrystallization from $CHCl_3$–Hexane (3:1, v/v) gave receptor **5b** (102 mg, 78 %) as colourless prisms. M.p. 209–210 °C. ^{1}H NMR (300 MHz, $CDCl_3$–DMSO, 10:1, v/v): δ = 0.82 (18H, s, *t*Bu), 1.12 (18H, s, *t*Bu), 3.49 (4H, br, OCH_2CH_2NH), 4.10 (4H, br, OCH_2CH_2NH), 5.13 (4H, s, Pyridine–CH_2), 6.68 (2H, d, *J* = 7.8 Hz, Pyridine–H_3), 7.04 (4H, s, Ar–*H*), 6.88–7.80. (m, 14H, *p*–F–C_6H_4, CH_2NH and Pyridine–$H_{4,5}$), 7.40 (4H, s, Ar–*H*), 8.06 (2H, br, *p*–F–C_6H_4–N*H*) and 8.50 (2H, s, Pyridine–H_6) ppm. ^{13}C NMR (400 MHz, $CDCl_3$–DMSO, 10:1): δ = 31.0, 34.0, 44.8, 66.0, 69.9, 121.8, 122.6, 124.0, 124.3, 126.1, 126.5, 128.3, 131.9, 132.4, 133.0, 133.8, 135.2, 135.9, 146.8, 148.2, 155.1, 155.6, 156.2, 156.4, 160.0, 160.7 and 181.8 ppm. FABMS: *m/z*: 1295.5188 (M^+). $C_{70}H_{76}F_2N_6O_4S_6$

(1295.5386): calcd C 64.88, H 6.49, N 5.91; found: C 64.76, H 6.33, N 5.76.

Synthesis of compound 5c

To compound **4** (100 mg, 0.101 mmol) in dry CH_2Cl_2 (15 mL) was added 4-nitrophenyl isothiocyanate (109 mg, 0.606 mmol) and the mixture was stirred for at room temperature for 12 h under argon. After the reaction, the solvent was evaporated under reduced pressure. The residue was purified by column chromatography using $CHCl_3$–MeOH– aqueous 28% NH_3 solution (95:4:1, v/v) as eluent to provide a colourless powder. Crystallization from $CHCl_3$–CH_3CN (3:2, v/v) gave receptor **5c** (98 mg, 72 %) as pale–yellow prisms. M.p. 206–207 °C. ^{1}H-NMR (300 MHz, $CDCl_3$–DMSO, 10:1): δ = 0.82 (18H, s, *t*Bu), 1.31 (18H, s, *t*Bu), 3.50 (4H, br, OCH_2CH_2NH), 4.10 (4H, br, OCH_2CH_2NH), 5.19 (4H, s, Pyridine–CH_2), 6.69 (2H, d, J = 7.8 Hz, Pyridine–H_3), 7.10 (4H, s, Ar–*H*), 7.20–7.68. (4H, m, Pyridine–$H_{4,5}$), 7.53 (4H, s, Ar–*H*), 7.80 (4H, d, J = 9.0 Hz, *p*–NO_2–C_6H_4), 8.15 (4H, d, J = 9.0 Hz, *p*–NO_2–C_6H_4), 8.50 (2H, s, Pyridine–H_6), 8.70 (2H, br, CH_2NH), and 9.72 (2H, br, *p*–NO_2–C_6H_4–N*H*) ppm. ^{13}C NMR (400 MHz, $CDCl_3$–DMSO, 10:1): δ = 30.2, 34.0, 44.1, 66.0, 71.3, 120.1, 122.0, 125.8, 127.0, 128.2, 129.6, 131.2, 132.4, 134.0, 134.9, 136.0, 138.0, 148.1, 151.0, 156.1, 157.7, 158.4, 164.0 and 183.9 ppm. FABMS: *m/z*: 1349.4189 (M^+). $C_{70}H_{76}N_8O_8S_6$ (1349.5154): calcd C 62.29, H 5.68, N 8.30.

Determination of the Association Constants

The association constants were determined using ^{1}H-NMR spectroscopic titration experiments at a constant concentration of host receptor (4.0×10^{-3} M) and varying the guest concentration (0–8.0×10^{-3} M). The ^{1}H-NMR chemical shifts of the urea protons (NH) signal was used as a probe. The association constants (K_a) for the complexes of receptors **5a–c** were calculated by nonlinear curve-fitting analysis of the observed chemical shifts of the NH protons according to the literature procedure.[17]

^{1}H NMR Titration Experiments

A solution of Bu_4NF in CD_3CN (4.0×10^{-3} M) was added to $CDCl_3$ solutions of receptors **5a–c** in the absence of, or presence of $AgSO_3CF_3$. ^{1}H-NMR spectra were recorded after addition of the reactants and the temperature of the NMR probe was kept constant at 27 °C.

Crystallographic Analysis of Receptor 5a

Crystal *data for* **5a**: $C_{70}H_{78}N_6O_4S_6{\cdot}C_{57}H_{67}N_4O_4S_4^+{\cdot}Cl^-{\cdot}CHCl_3$, M_r =2415.05. Orthorhombic, *Pbca*; a =26.9078 (10), b =27.1717 (11), c = 34.4369 (13) Å; V = 25177.9 (17) Å^3; Z = 8; D_x = 1.274 Mg m^{-3}; F(000) =10208; T = 150 K; μ = 0.40 mm^{-1}; λ = 0.7749 Å, crystal size 0.15 × 0.15 × 0.03 mm^3. Crystals were yellow blocks. Diffraction data were measured at ALS Station 11.3.1 using synchrotron radiation on a Bruker D8 with PHOTON 100 detector diffractometer equipped with a silicon 111 monchromator using thin-slice ω-scans.[19] 218318 measured reflections, 23240 independent reflections (R_{int} = 0.055) to θ_{max} = 27.9°; 17514 reflections with $I > 2\sigma(I)$. The structure was determined by iterative, dual-space methods using the *SHELXT* program and refined by the full-matrix least-squares method, on F^2, in *SHELXL-2013/14*.[20–21] The non-hydrogen atoms were refined with anisotropic thermal parameters. Hydrogen atoms on C were included in idealized positions and their U_{iso} values were set to ride on the U_{eq} values of the parent atoms. H atoms on N were freely refined. At the conclusion of the refinement, wR_2 = 0.156 (all data) and R_1 = 0.051 (observed data), 1520 parameters, $\Delta\rangle_{max}$ = 0.61 eÅ^{-3}; $\Delta\rangle_{min}$ = –0.88 eÅ^{-3}; 134 restraints. The choroform molecule was modelled as disordered over two, closely-spaced sites with major site occupancy of 68.1(6) %. The crystallographic data (excluding structure factors) for the structure in this paper have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication number CCDC 2075593 for **5a**.

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Notes and references

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1 (*a*) C. D. Gutsche, *Calixarenes, An Introduction,* Royal Society of Chemistry*:* Cambridge, UK, 2008; (*b*) Neri, P., J. L. Sessler, M.-X. Wang, Eds., *Calixarenes and Beyond*; Springer International Publishing AG, Switzerland, 2016. (*c*) Z. Asfari, V. Böhmer, J. Harrowfield, J. Vicens, (Eds.) *Calixarenes 2001*; Kluwer Acad. Publ.: Dordrecht, 2001.
2 (*a*) N. Iki pp 335-362, *In Calixarenes and Beyond*; Neri, P., J. L. Sessler, M.-X. Wang, Eds., Springer International Publishing AG, Switzerland, 2016; (*b*) H. Kumagi, M. Hasegawa, S. Miyanari, Y. Sugawa, Y. Sato, T. Hori, S. Ueda, H. Kamiyama and S. Miyano, *Tetrahedron Lett.,* 1997, **38**, 3971–3972.
3 (*a*) P. Lhoták, *Eur. J. Org. Chem.*, 2004, 1675–1692; (*b*) N. Morohashi, F. Narumi, N. Iki, T. Hattori and S. Miyano, *Chem. Rev.,* 2006, **106**, 5291–5316.

4 (*a*) P. D. Beer and P. A. Gale, *Angew. Chem. Int. Ed.,* **2001**, 40, 486–516; (*b*) T. Nabeshima, T. Saiki and S. Kumitomo, *Org. Lett*., 2002, **4**, 3207–3209; (*c*) T. Nabeshima, Y. Yoshihira, T. Saiki, S. Akine and E. Horn, *J. Am. Chem. Soc.,* 2003, **125**, 28–29; (*d*) A. Y. Zhukov, T. A. Fink, I. I. Stoikov and I. S. Antipin, *Russ. Chem. Bull., Int. Ed.,* 2009, **58**, 1007–1014; (*e*) K. Mohr, J. Schmitz, R. Schrage, C. Trnkle and U. Holzgrabe, *Angew. Chem. Int. Ed*., 2013, **52**, 508–516; (*f*) R. Nussinov and C.–J. Tsai, *Cell,* 2013, **153**, 293–305.

5 (*a*) J.–Y Kwon, Y.–J Jang, S.–K Kim, K.–H Lee, J.–S Kim and J. Yoon, *J. Org. Chem.,* 2004, ***69***, 5155–5157; (*b*) D. Amilan Jose, D. K. Kumar, B. Ganguly and A. Das, *Org. Lett.*, 2004, **6**, 3445–3448; (*c*) J.–Y. Lee, E.–J Cho, S. Mukamel and K.–C. Nam, *J. Org. Chem.*, 2004, **69**, 943–950; (*d*) D. Esteban-Go´mez, L. Fabbrizzi and M. Licchelli, *J. Org. Chem.,* 2005, ***70***, 5717–5720; (*e*) V. Thiagarajan, P. Ramamurthy, D. Thirumalai and V. T. Ramakrishnan, *Org. Lett.*, 2005, **7**, 657–660; (*f*) H. Lu, W. Xu, D. Zhang, C. Chen and D. Zhu, *Org. Lett.*, 2005, **7**, 4629–4632; (*g*) F. M. Pfeffer, T. Gunnlaugsson, P. Jensen and P. E. Kruger, *Org. Lett.*, 2005, **7**, 5357–5360; (*h*) L. Fang, W.–H. Chan, Y.–B. He, D. W.–J. Kwong and A. W.–M. Lee, *J. Org. Chem.,* 2005, **70**, 7640–7646; (*i*) T. Gunnlaugsson, P. E. Kruger, P. Jensen, J. Tierney, H. D. Paduka Ali and G. M. Hussey, *J. Org. Chem.*, 2005, **70**, 10875–10878; (*j*) A. Dahan, T. Ashkenazi, V. Kuznetsov, S. Makievski, E. Drug, L. Fadeev, M. Bramson, S. Schokoroy, E. Rozenshine–Kemelmakher and M. Gozin, *J. Org. Chem.,* 2007, **72**, 2289–2296; (*k*) S. Saha, A. Ghosh , P. Mahato , S. Mishra , S. K. Mishra, E. Suresh , S. Das and A. Das, *Org. Lett.*, 2010, **12**, 3406–3409.

6 (a) J. L. Sessler, P. A. Gale and W. S. Cho, Anion Receptor Chemistry; Royal Society of Chemistry: Cambridge, U.K., 2006; (b) P. D. Beer, P.A. Gale, *Angew. Chem., Int. Ed*., 2001, **40**, 486–516.

7 (a) J. F. Zhang, Y. Zhou, J. Yoon and J. S. Kim, *Chem. Soc. Rev*., 2011, **40**, 3416–3429; (b) C. Lodeiro, J. L. Capelo, J. C. Mejuto, E. Oliveira, H. M. Santos, B. Pedras and C. Nuñez, *Chem. Soc. Rev*., 2010, **39**, 2948–2976; (c) L. E. Santos-Figueroa, M. E. Moragues, E. Climent, A. Agostini, R. Martínez-Máñez and F. Sancenón, *Chem. Soc. Rev*., 2013, **42**, 3489–3613.

8 (*a*) R. M. F. Batista, E. Oliveira, S. P. G. Costa, C. Lodeiro and M. M. M. Raposo, *Org. Lett.* 2007, **9**, 3201–3204; (*b*) F. Zapata, A. Caballero, A. Espinosa, A. Tárraga, and P. Molina, *Org. Lett.*, 2008, **10**, 41–44; (*c*) R. D. Rasberry, M. D. Smith and K. D. Shimizu, *Org. Lett.* 2008, **10**, 2889–2892; (*d*) C. Pérez-Casas and A. K. Yatsimirsky, *J. Org. Chem.*, 2008, **73**, 2275–2284; (*e*) J. P. Clare, A. Statnikov, V. Lynch, A. L. Sargent and J. W. Sibert, *J. Org. Chem.*, 2009, **74**, 6637–6646; (*f*) Q.–S Lu, L. Dong, J. Zhang, J. Li, L. Jiang, Y. Huang, S. Qin, C.–W. Hu and X.–Q. Yu, *Org. Lett.*, 2009, **11**, 669–672; (*g*) S. Goswami, D. Sen and N. K. Das, *Org. Lett.*, 2010, **12**, 856–859; (*h*) A. Aldrey, C. Núñez, V. García, R. Bastida, C. Lodeiro, A. Macías, *Tetrahedron*, 2010, **66**, 9223–9230; (*i*) P. Dydio, T. Zieliński and J. Jurczak, *Org. Lett.*, 2010, **12**, 1076–1078; (*j*) V. K. Bhardwaj, S. Sharma, N. Singh, M. S. Hundal and G. Hundal, *Supramol. Chem.*, 2011, **23**, 790–800; (*k*) G.–W. Lee, N.–K. Kim and K.–S. Jeong, *Org. Lett.*, 2011, **13**, 3024–3027; (*l*) H. M. Chawla, S. N. Sahu, R. Shrivastava, S. Kumar, *Tetrahedron Lett*., 2012, **53**, 2244–2247; (*m*) S. Goswami, A. Manna, S. Paul, K. Aich, A. K. Das and S. Chakraborty, *Tetrahedron Lett.*, 2013, **54**, 1785–1789; (*n*) K. Pandurangan, J. A. Kitchen and T. Gunnlaugsson, *Tetrahedron Lett.*, 2013, **54**, 2770–2775; (*o*) S. Areti, J. K. Khedkar, R. Chilukula and C. P. Rao, *Tetrahedron Lett*., 2013, **54**, 5629–5634; (*p*) C. Jin, M. Zhang, C. Deng, Y. Guan, J. Gong, D. Zhu, Y. Pan, J. Jiang and L. Wang, *Tetrahedron Lett.*, 2013, **54**, 796–801.

9 (*a*) K. Lang, P. Cuřínová, M. Dudič, P. Proščová, I. Stibor, V. Šťastný and P. Lhoták, *Tetrahedron Lett.*, 2005, **46**, 4469–4472; (*b*) P. Lhoták, J. Svoboda and I. Stibor, *Tetrahedron Lett.*, 2006, **62**, 1253–1257; (*c*) J. Kroupa, I. Stibor, M. Pojarová, M. Tkadlecová and P. Lhoták, *Tetrahedron*, 2008, **64**, 10075–10079; (*d*) O. Kundrat, H. Dvorakova, I. Cisarova, M. Pojarova and P. Lhoták, *Org. Lett.*, 2009, **11**, 4188–4191; (*e*) O. Kundrat, I. Cisarova, S. Böhm, M. Pojarova and P. Lhoták, *J. Org. Chem.*, 2009, **74**, 4592–4596; (*f*) O. Kundrat, H. Dvorakova, V. Eigner and P. Lhoták, *J. Org. Chem.*, 2010, **75**, 407–411; (*g*) O. Kundrat, J. Kroupa, S. Böhm, J. Budka, V. Eigner and P. Lhoták, *J. Org. Chem.*, 2010, **75**, 8372–8375; (*h*) O. Kundrát, V. Eigner, P. Cuřínová, J. Kroupa and P. Lhoták, *Tetrahedron*, 2011, **67**, 8367–8372; (*i*) O. Kundrat, V. Eigner, H. Dvorakova, and P. Lhoták, *Org. Lett.*, 2011, **13**, 4032–4035; (*j*) P. Slavik, M. Dudic, K. Flidrova, J. Sykora, I. Cisarova, M. Pojarova and P. Lhoták, *Org. Lett.*, 2012, **14**, 3628–3631; (*k*) O. Kundrat, H. Dvorakova, S. Böhm, V. Eigner and P. Lhoták, *J. Org. Chem.*, 2012, **77**, 2272–2278.

10 (*a*) V. Bhalla, M. Kumar, H. Katagiri, T. Hattori and S. Miyano, *Tetrahedron Lett*., 2005, **46**, 121–124; (*b*) V. Bhalla, J. N. Babu, M. Kumar, T. Hattori and S. Miyano, *Tetrahedron Lett.,* 2007, **48**, 1581–1585; (*c*) V. Bhalla, R. Kumar, M. Kumar and A. Dhir, *Tetrahedron*, 2007, **63**, 11153–11159; (*d*) A. Dhir, V. Bhalla and M. Kumar, *Org. Lett*., 2008, **10**, 4891–4894; (*e*) R. Kumar, V. Bhalla and M. Kumar, *Tetrahedron*, 2008, **64**, 8095–8101; (*f*) R. K. Mahajan, R. Kaur, V. Bhalla, M. Kumar, T. Hattori and S. Miyano, *Sens. Actuators B*, 2008, **130**, 290–294; (*g*) J. N. Babu, V. Bhalla, M. Kumar, R. K. Mahajan and R. K. Puri, *Tetrahedron Lett.*, 2008, **49**, 2772–2775; (*h*) M. Kumar, A. Dhir and V. Bhalla, *Org. Lett*., 2009, **11**, 2567–2570; (*i*) M. Kumar, R. Kumar and V. Bhalla, *Tetrahedron,* 2009, **65**, 4340–4344 (*j*) M. Kumar, A. Dhir and V. Bhalla; *Org. Lett.,* 2009, **11**, 2567–2570; (*k*) M. Kumar, R. Kumar and V. Bhalla, *Tetrahedron Lett*., 2010, **51**, 5559–5562; (*l*) M. Kumar, R. Kumar and V. Bhalla, *Org. Lett.*, 2011, **13**, 366–369; (*m*) M. Kumar, R. Kumar and V. Bhalla, *Org. Bio. Chem.*, 2011, **9**, 8237–8245; (*n*) M. Kumar, R. Kumar and V. Bhalla, *Org. Lett.*, 2011, **13**, 366–369; (*o*) M. Kumar, R. Kumar and V. Bhalla, *Tetrahedron Lett.*, 2013, **54**, 1524–1527.

11 (*a*) C. Perez-Casas and T. Yamato, *J. Incl. Phenom. Macrocyclic Chem.,* 2005, **53**, 1–8; (*b*) T. Yamato, C. Perez-Casas, H. Yamamoto, M. R. J. Elsegood, S. H. Dale and C. Redshaw, *J. Incl. Phenom. Macrocyclic Chem.,* 2006, **54**, 261–269; (c) C. Perez-Casas, S. Rahman, N. Begum, Z. Xi and T. Yamato, *J. Incl. Phenom. Macrocyclic Chem.*, 2008, **60**, 173–185; (*d*) X.–L. Ni, X. Zeng, C. Redshaw and T. Yamato, *J. Org. Chem.*, 2011, **76**, 3358–3370; (e) X.-L. Ni, X. Zeng, C. Redshaw and T. Yamato, *Tetrahedron*, 2011, **67**, 3248–3253; (*h*) X.–L. Ni, J. Tahara, S. Rahman, X. Zeng, D. L. Hughes, C. Redshaw and T. Yamato, *Chem. Asian. J.*, 2012, **7**, 519–527; (*i*) X.–L. Ni, H. Cong, A. Yoshizawa, S. Rahman, H. Tomiyasu, U. Rayhan, X. Zeng and T. Yamato, *J. Mol. Struct.*, 2013, **1046**, 110–115.

12 (a) J.-L. Zhao, H. Tomiyasu, X.–L. Ni, X. Zeng, M. R. J. Elsegood, C. Redshaw, S. Rahman, P. E. Georghiou and T. Yamato, *New J. Chem.,* 2014, **38**, 6041– 6049; (*b*) J.-L. Zhao, H. Tomiyasu, X.–L. Ni, X. Zeng, M. R. J. Elsegood, C. Redshaw, S. Rahman, P. E. Georghiou, S. J. Teat and T. Yamato,

Org. Biomol. Chem., 2015, **13**, 3476–3483; (*c*) J.–L. Zhao, H. Tomiyasu, C. Wu, H. Cong, X. Zeng, S. Rahman, P. E. Georghiou, D. L. Hughes, C. Redshaw and T. Yamato, *Tetrahedron*, 2015, **71**, 8521–8527; (*d*) J.–L. Zhao, C. Wu, H. Tomiyasu, X. Zeng, M. R. J. Elsegood, C. Redshaw and T. Yamato, *Chemistry Asian J.,* 2016, **11**, 1606–1612; (*e*) J.–L. Zhao, C. Wu, X. Zeng, S. Rahman, P. E. Georghiou, M. R. J. Elsegood, T. G. Warwick, C. Redshaw, S. J. Teat and T. Yamato, *ChemistrySelect*, 2016, **1**, 1541–1547; (*f*) J.–L. Zhao, X.-K. Jiang, C. Wu, C.-Z. Wang, X. Zeng, C. Redshaw and T. Yamato, *ChemPhyChem*, 2016, **17**, 3217–3222.

13 (*a*) H. Tomiyasu, J.–L. Zhao, X.–L. Ni, X. Zeng, M. R. J. Elsegood, B. Jones, C. Redshaw, S. J. Teat and T. Yamato, *RSC Adv.*, 2015, **5**, 14747–14755; (*b*) M.–Q. Ran, J.–Y. Yuan, Y.–H. Zhao, L. Mu, X. Zeng, C. Redshaw, L. Jiang and T. Yamato, *Supramolecular Chemistry*, 2016, **28**, 418–426; (*c*) S. Rahman, H. Tomiyasu, H. Kawazoe, J.–L. Zhao, H. Cong, X.–L. Ni, X. Zeng, M. R. J. Elsegood, T. G. Warwick, S. J. Teat, C. Redshaw, P. E. Georghiou and T. Yamato, *New J. Chem.,* 2016, **40**, 9245–9251.

14 S. Rahman, T. Shimizu, Z. Xi and T. Yamato, *J. Chem. Research*, **2009**, 1–4.

15 (*a*) N. Iki, F. Marumi, T. Fujimoto, N. Morohashi and S. Miyano, *J. Chem. Soc. Perkin Trans. 2*, **1998**, 2745; (*b*) N. Iki, N. Morohashi, F. Narumi, T. Fujimoto, T. Suzuki and S. Miyano, *Tetrahedron. Lett.*, 1999, **40**, 7337–7341.

16 For the the Cambridge Structural Database: C. R. Groom, I. J. Bruno, M. P. Lightfoot and S. C. Ward, *Acta Crystallogr*., *Sect. B: Struct. Sci. Cryst. Eng. & Mat*., 2016, **72**, 171–179.

17 (*a*) P. Thordarson, *Chem. Soc. Rev*., 2011, **40**, 1305–1323; (*b*) http://supramolecular.org; (*c*) P. Job, *Ann. Chim.*, 1928, **9**, 113–203.

18 M. J. Frisch, G. W. Trucks, H. B. Schlegel, G. E. Scuseria, M. A. Robb, J. R. Cheeseman, G. Scalmani, V. Barone, B. Mennucci, G. A. Petersson, H. Nakatsuji, M. Caricato, X. Li, H. P. Hratchian, A. F. Izmaylov, J. Bloino, G. Zheng, J. L. Sonnenberg, M. Hada, M. Ehara, K. Toyota, R. Fukuda, J. Hasegawa, M. Ishida, T. Nakajima, Y. Honda, O. Kitao, H. Nakai, T. Vreven, J. A. Montgomery, Jr., J. E. Peralta, F. Ogliaro, M. Bearpark, J. J. Heyd, E. Brothers, K. N. Kudin, V. N. Staroverov, T. Keith, R. Kobayashi, J. Normand, K. Raghavachari, A. Rendell, J. C. Burant, S. S. Iyengar, J. Tomasi, M. Cossi, N. Rega, J. M. Millam, M. Klene, J. E. Knox, J. B. Cross, V. Bakken, C. Adamo, J. Jaramillo, R. Gomperts, R. E. Stratmann, O. Yazyev, A. J. Austin, R. Cammi, C. Pomelli, J. W. Ochterski, R. L. Martin, K. Morokuma, V. G. Zakrzewski, G. A. Voth, P. Salvador, J. J. Dannenberg, S. Dapprich, A. D. Daniels, O. Farkas, J. B. Foresman, J. V. Ortiz, J. Cioslowski and D. J. Fox, Gaussian 09, Revision D.01, Gaussian, Inc., Wallingford CT, 2013.

19 SAINT and APEX 2 (2008) software for CCD diffractometers. Bruker AXS Inc., Madison, USA.

20 G. M. Sheldrick, *Acta Crystallogr., Sect. A: Found. Crystallogr.*, 2015, **71**, 3–8.

21 G. M. Sheldrick, *Acta Crystallogr*., *Sect. C: Struct. Chem.*, 2015, **71**, 3–8.

