Elsevier Editorial System(tm) for Tetrahedron
Manuscript Draft

Manuscript Number: TET-D-14-01329R2

Title: Positive allosteric binding behaviour of pyrene-appended triazole-modified thiacalix[4]arene-based fluorescent receptors

Article Type: Full Length Article

Corresponding Author: Prof. Takehiko Yamato, Ph.D.

Corresponding Author's Institution: Saga University

First Author: Hirotsugu Tomiyasu, MD

Order of Authors: Hirotsugu Tomiyasu, MD; Naoki Shigyo, BC; Xin–Long Ni, Ph.D.; Xi Zeng, Ph.D.; Carl Redshaw, Ph.D.; Takehiko Yamato, Ph.D.

Abstract: The novel heteroditopic receptors 5a∼c have been synthesized, which bear a thiacalix[4]arene in the 1,3-alternate conformation. Two urea moieties possessing various aryl groups with either electron-donating or -withdrawing groups at their p-positions function as anion-binding sites. At the opposite side of the cavity are two pyrene-appended triazole rings, which act as cation-binding sites. The binding property of receptor 5c was investigated by means of 1H NMR and UV-vis spectroscopy and by fluorescence titration experiments in the presence of various transition metal cations and anions in CH2Cl2-DMSO (10:1, v/v) solution. Interestingly, it was found that receptor 5c possessing two p-nitrophenyl ureido moieties, most efficiently complexes in the urea cavity or bistriazoles; the plausible allosteric effect of receptor 5c was also investigated.

Graphical Abstract

To create your abstract, type over the instructions in the template box below.
Fonts or abstract dimensions should not be changed or altered.

Positive allosteric binding behaviour of pyrene–appended triazole–modified thiacalix[4]arene –based fluorescent receptors

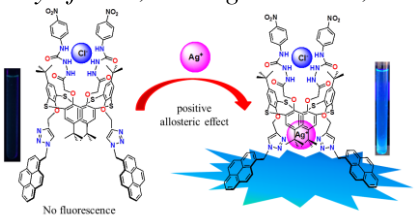
Leave this area blank for abstract info.

Hirotsugu Tomiyasu[a], Naoki Shigyo[a], Xin–Long Ni[b], Xi Zeng[b], Carl Redshaw[c], Takehiko Yamato[a,]*

[a] *Department of Applied Chemistry, Faculty of Science and Engineering, Saga University, Honjo-machi 1, Saga 840-8502, Japan*

[b] *Key Laboratory of Macrocyclic and Supramolecular Chemistry of Guizhou Province, Guizhou University,Guiyang 550025, People's Republic of China*

[c] *Department of Chemistry, The University of Hull, Cottingham Road, Hull, Yorkshire, HU6 7RX, UK*



Tetrahedron
journal homepage: www.elsevier.com

Positive allosteric binding behaviour of pyrene–appended triazole–modified thiacalix[4]arene–based fluorescent receptors

Hirotsugu Tomiyasu[a], Naoki Shigyo[a], Xin–Long Ni[b], Xi Zeng[b], Carl Redshaw[c], Takehiko Yamato[a,*]

[a] *Department of Applied Chemistry, Faculty of Science and Engineering, Saga University, Honjo-machi 1, Saga 840-8502, Japan*

[b] *Key Laboratory of Macrocyclic and Supramolecular Chemistry of Guizhou Province, Guizhou University,Guiyang 550025, People's Republic of China*

[c] *Department of Chemistry, The University of Hull, Cottingham Road, Hull, Yorkshire, HU6 7RX, UK*

ARTICLE INFO

Article history:
Received
Received in revised form
Accepted
Available online

Keywords:
Thiacalix[4]arene
1,3–*alternate* Conformation
Pyrenyl-appended triazole
Urea
Allosteric effect

ABSTRACT

The novel heteroditopic receptors **5**$_{a-c}$ have been synthesized, which bear a thiacalix[4]arene in the 1,3–*alternate* conformation. Two urea moieties possessing various aryl groups with either electron–donating or –withdrawing groups at their *p*–positions function as anion–binding sites. At the opposite side of the cavity are two pyrene–appended triazole rings, which act as cation–binding sites. The binding property of receptor **5**$_c$ was investigated by means of ^{1}H NMR and UV–vis spectroscopy and by fluorescence titration experiments in the presence of various transition metal cations and anions in CH_2Cl_2–DMSO (10:1, v/v) solution. Interestingly, it was found that receptor **5**$_c$ possessing two *p*–nitrophenyl ureido moieties, most efficiently complexes in the urea cavity or bistriazoles; the plausible allosteric effect of receptor **5**$_c$ was also investigated.

1. Introduction

The investigation of macrocycles such as calix[*n*]arenes[1] which are attractive building blocks for creating host systems capable of selectively recognizing cation, anion or neutral molecules has become an active area of research in supramolecular chemistry. Thiacalix[4]arenes[2,3] which are sulfur–bridged analogs of calix[4]arenes are excellent scaffolds and have been utilized in chemosensors, supramolecular self-assemblies and the catalytic activity of enzymes. A large number of enzymes have allosteric sites to control catalytic activity by stabilizing the active conformation. Many systems based on thiacalix[4]arenes are capable of host–guest interactions and involve conformational changes caused by the allosteric binding[4] of metal cations, and these relate to the maintenance of the essential material balance necessary for life. Anions also have been widely employed in biological, environmental and industrial processes.[5] The development of anion selective sensors[6] based on calix[*n*]arenes has received a considerable amount of attention in the area of supramolecular chemistry. Calix[*n*]arene urea derivatives are extremely prominent and are efficient for anion complexations via the N–H protons due to the formation of hydrogen bonds.[7,8] Click chemistry[9] is one of the most useful and widely employed reactions in synthetic chemistry. In particular, the Cu(I)–catalyzed azide–alkyne cycloaddition reaction is a highly versatile method which can be performed in high yield under very mild conditions. The 1,4–disubstituted–1,2,3–triazole products can act as relatively stable functional groups as covalent linkers or as ligands for metal cations, and have been utilized in the fields of drug discovery and materials science. Recently, many calix[*n*]arene derivatives bearing 1,4–disubstituted–1,2,3–triazoles as linking groups have been developed and investigated.[10]

Chung[11] and co–workers reported a fluorescent chemosensor bearing a calix[4]arene in a 1,3–*alternate* conformation, which contains two anthracene–appended triazole rings and the crown–ether moiety.[11a] This receptor exhibited a negative allosteric effect between the Pb^{2+} and K^+ ions in common organic solvents. Moreover, they also reported that a homobinuclear ditopic fluorescent chemosensor bearing a 1,3-*alternate* calix[4]arene, which contained two anthracene–appended triazole rings and two phenylenaminones at the opposite sides of the calix[4]arene cavity.[11d] This receptor exhibited a positive allosteric effect between two equivalents of Ag^+ ion in common organic solvents. However, investigations

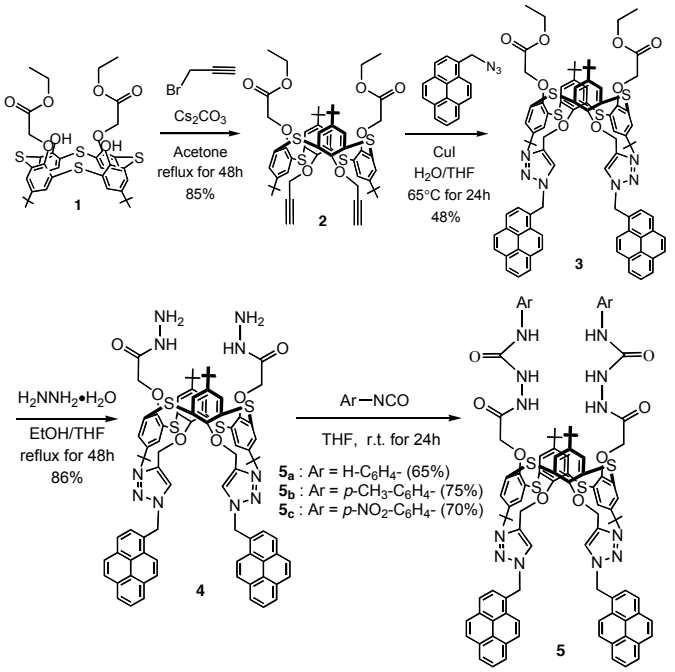
* Corresponding author. Fax: +81 952 28 8548; e-mail address: yamatot@cc.saga-u.ac.jp (T. Yamato).

concerning the appearance of allosteric effects in analogues based on thiacalix[4]arenes/metal cations/anions has not yet been reported. Herein, we have independently designed a heterodimeric system[12] based on a thiacalix[4]arene having two different side arms. Specifically, we have incorporated two ureas moieties which link various phenyl groups substituted with the electron–donating or –withdrawing groups at the *p*–positions and two pyrene–appended triazole rings at the opposite side of thiacalix[4]arene cavity. We built up the hypothesis that the heterodimeric system, which is controlled by the complexation of the opposite side arms with Cl^- and Ag^+ ions, exhibits an effective positive allosteric effect.

2. Results and discussion

2.1. Synthesis

O-Alkylation of *distal*-**1** was carried out with 10 equiv. of propargyl bromide in the presence of 10 equiv. of Cs_2CO_3 according to the reported procedure to afford the desired 1,3–*alternate*–**2** in 85 % yield.[12] A Cu(I)–catalyzed 1,3–dipolar cycloaddition reaction of 1,3–*alternate*–**2** with 4 equiv. of 1–azidomethylpyrene via Click chemistry was carried out according to the reported procedure, and afforded the 1,2,3–triazole thiacalix[4]arene 1,3–*alternate*–**3** in 48 % yield. The hydrazinolysis of 1,3–*alternate*–**3** was carried out with a large excess of hydrazine hydrate to afford the desired 1,3–*alternate*–**4** in 86 % yield. The condensation of 1,3–*alternate*–**4** with 4 equiv. of the appropriate isocyanate in THF furnished the receptors $\mathbf{5}_{\mathbf{a\sim c}}$ in good yield (Scheme 1). In general, the ^{1}H NMR spectra of receptors $\mathbf{5}_{\mathbf{a\sim c}}$ in $CDCl_3$–DMSO (10:1, v/v) exhibited the characteristics of a 1,3–*alternate* canformation, *viz* two singlets (18H each) for the *tert*-butyl protons, one singlet (4H) for OCH_2CO protons, one singlet (4H) for OCH_2–triazole protons, two singlets (4H each) for aromatic protons, two singlets (2H each) for four urea NH protons and one singlet (2H) for triazole–*H* protons. Moreover, a concentration dependence of the ^{1}H NMR chemical shifts of the ureido protons in receptor $\mathbf{5}_\mathbf{c}$ was not observed (Figure S13). This result suggests that receptor $\mathbf{5}_\mathbf{c}$ has a strong intramolecular hydrogen bond between the two ureas moieties.



Scheme 1 Synthesis of receptors 1,3-*alternate*-$\mathbf{5}_{\mathbf{a\sim c}}$.

Table 1 Association constants[a] of receptor $\mathbf{5}_{\mathbf{a\sim c}}$ with Cl^- ion[b]

Host	$\mathbf{5}_\mathbf{a}$	$\mathbf{5}_\mathbf{b}$	$\mathbf{5}_\mathbf{c}$
R	H	*p*-CH_3	*p*-NO_2
K_a [M^{-1}]	6250±438	3000±210	42500±2975

[a] Measured in CH_2Cl_2–DMSO (10:1, v/v) at 27 °C by fluorescence titration experiments (Figures S15–S21); host concentration was 1.0 μM. [b] Guests used: Bu_4NCl.

2.2. Binding studies

Upon addition of Cl^- ion (0–20 μM) to a solution of receptor $\mathbf{5}_\mathbf{c}$ (1.0 μM), Figure S19 shows that both the monomer and excimer emissions of the pyrene units gradually decrease. A Job's plot binding between receptor $\mathbf{5}_\mathbf{c}$ and Cl^- ion reveals a 1:1 stoichiometry (Figure S20), while the association constant (K_a value) for the complexation with Cl^- ion by receptor $\mathbf{5}_\mathbf{c}$ was determined to be 42500 ± 2975 M^{-1} as determined by the fluorescence titration experiment in CH_2Cl_2–DMSO (10:1, v/v) (Figure S21 and Table 1). Moreover, K_a values between the receptors $\mathbf{5}_{\mathbf{a\sim b}}$ and Cl^- ion were determined by analyzing fluorescence titration experiments, respectively (Figures S15–S18 and Table 1). These results suggest that the association constants depend on the electron–donating/withdrawing groups located at the *p*–position. In the presence of the electron–withdrawing group NO_2 (receptor $\mathbf{5}_\mathbf{c}$), the K_a value was greater than that for the unsubstituted receptor (receptor $\mathbf{5}_\mathbf{a}$). In contrast, in the case of receptor $\mathbf{5}_\mathbf{b}$, with the electron–donating Me group, there was a general decrease in the K_a value for the complexation with Cl^- ion in comparison to the case in the unsubstituted receptor $\mathbf{5}_\mathbf{a}$. Therefore, the introduction of electron–withdrawing groups at the *p*–position appears to increase the acidity of the urea protons, and hence enhance the anion–binding ability through hydrogen–bonding interactions. The K_a value of receptor $\mathbf{5}_\mathbf{c}$ with the electron–withdrawing NO_2 group at the *p*–position was the best out of all the K_a values between receptors $\mathbf{5}_{\mathbf{a\sim c}}$ and Cl^- ion. From

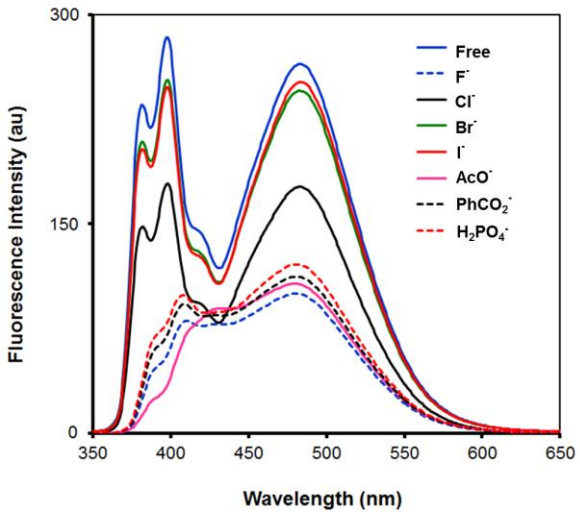


Fig. 1 Fluorescence spectral changes of receptor $\mathbf{5}_\mathbf{c}$ (1.0 μM) upon addition of various tested anions (1.0 μM) in CH_2Cl_2–DMSO (10:1, v/v). λ_{ex} = 343 nm.

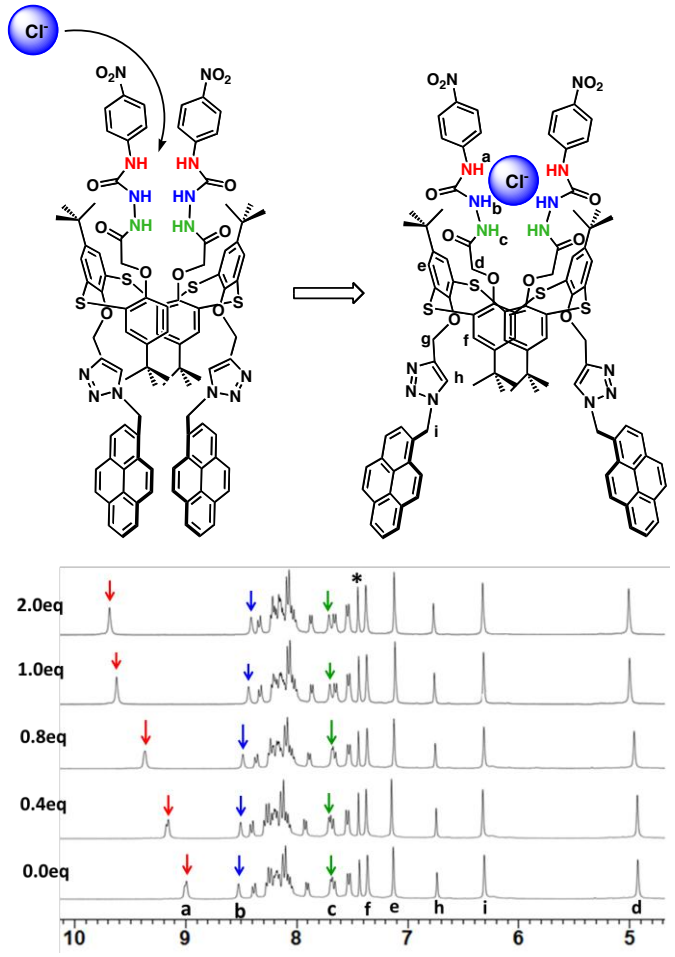


Fig. 2 Binding mode of receptor **5**$_c$ upon addition of Cl^- ion at 298 K as a tetrabutylammonium (TBA) salt and partial ^1H NMR spectra of **5**$_c$ (4.0 mM) in $CDCl_3$–DMSO–CH_3CN (10:1:1, v/v) upon addition of Ag^+ ion at 298 K.

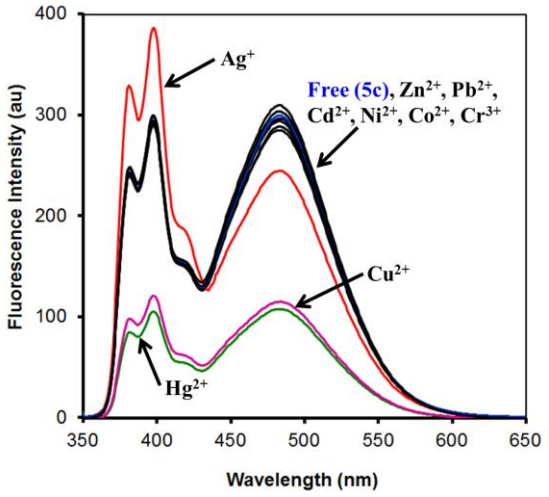


Fig. 3 Fluorescence spectral changes of receptor **5**$_c$ (1.0 μM) to upon addition of various tested metal cations (20 μM) in CH_2Cl_2–DMSO (10:1, v/v). λ_{ex} = 343 nm.

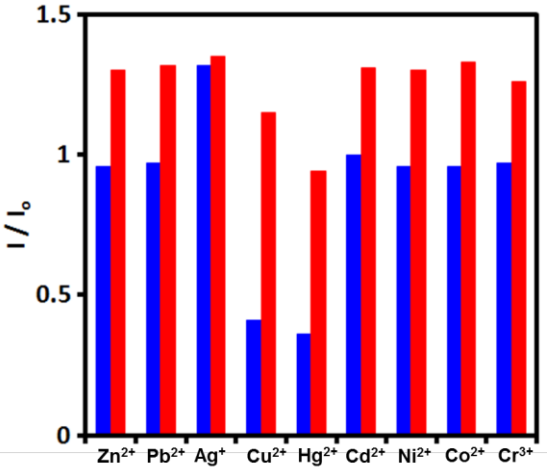


Fig. 4 Fluorescence response of receptor **5**$_c$ (1.0 μM) in CH_2Cl_2–DMSO (10:1, v/v) to various tested metal cations (20 μM) (blue bar) and to the mixture of tested metal ions (20 μM) with Ag^+ ion (20 μM) (red bar) at 298 K. I_o is the fluorescence intensity at 393 nm for free receptor **5**$_c$, and I is the fluorescence intensity after adding metal ions with an excitation at 343 nm.

the above, we can say that the receptor **5**$_c$, with the electron–withdrawing NO_2 group at the *p*–position, has the most effective recognition ability toward selected anions of the systems screened herein. Given this, complexation studies of receptor **5**$_c$ toward targeting various transition metal cations and anions were carried out using ^1H NMR and UV–vis spectroscopy and by fluorescence titration experiments.

The UV–vis absorption spectra of receptor **5**$_c$ (1.0 μM) were recorded in the presence of various anions (20 equiv.) in CH_2Cl_2–DMSO (10:1, v/v) as shown in Figure S14. The receptor **5**$_c$ (1.0 μM)exhibits an absorption band at 347 nm in the UV–vis absorption spectra in the absence of anions. Interestingly, significant changes moving to a longer wavelength in absorption spectra were observed in the presence of F^-, AcO^-, $PhCOO^-$ or $H_2PO_4^-$ with a color change from colourless to dark yellow by the naked eye, respectively. These results suggest that the quinoid structure was formed by the deprotonation of the urea NH groups in the *p*–nitrophenyl ureido moiety. Figure 1 reveals the fluorescence intensity changes of the monomer (393 nm) and excimer (486 nm) emissions for receptor **5**$_c$ in the presence of various anions. Receptor **5**$_c$ exhibited a decrease in intensity of both the monomer and excimer emissions with various anions. Upon addition of Cl^- ion to a solution of receptor **5**$_c$, the decrease of intensity of the monomer emission is presumably caused by a photo–induced electron transfer (PET) mechanism which operates from the oxygen of the urea moiety which complexes with the Cl^- ion via hydrogen bonding to the pyrene moieties. By contrast, upon addition of F^-, AcO^-, $PhCOO^-$ or $H_2PO_4^-$ ions to a solution of receptor **5**$_c$, the decreasing intensity of the monomer emission is caused by deprotonation of the urea NH groups which induces a PET mechanism from the anionic nitrogen to the pyrene moieties. On the other hand, upon addition of F^-, Cl^-, AcO^-, $PhCOO^-$ or $H_2PO_4^-$ ions to a solution of receptor **5**$_c$, the decreasing intensity of the excimer emission is caused by conformational unstacking of two pyrene ureas, which breaks down an intramolecular π–π interaction because of complex formation. As shown in Figure 2, the signals for the NH_a protons (red) progressively shifted downfield by 0.64 ppm (δ = 8.98 to 9.62 ppm) until one equiv. of Cl^- ion was added. On the other hand, the signals for the NH_b protons (blue) progressively shifted upfield by 0.09 ppm (δ = 8.50 to 8.41 ppm) until one equiv. of Cl^-

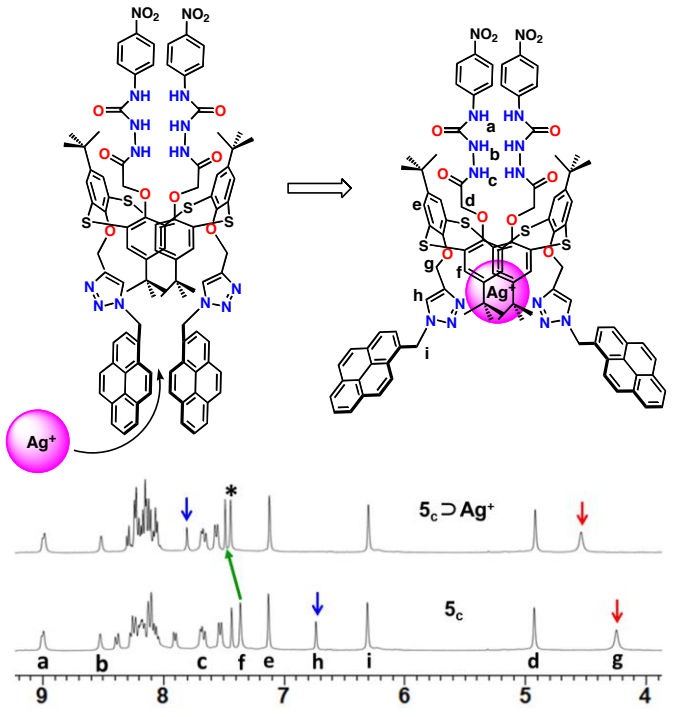


Fig. 5 Binding mode of receptors **5**$_c$ upon complexation with Ag^+ ion as trifluoromethanesulforic salt, and partial ^1H NMR spectra of receptors **5**$_c$ (4.0 mM) in $CDCl_3$–DMSO–CD_3CN (10:1:1, v/v) upon addition of Ag^+ ion (1.0 equiv.) at 298 K.

ion was added. These results strongly suggested Cl^- ion recognition by receptor **5**$_c$ via a hydrogen–bonding interaction between Cl^- ion and N–H protons as shown in Figure 2 and Figure S32. The fluorescence intensity changes of receptor **5**$_c$ were recorded in CH_2Cl_2–DMSO (10:1, v/v) in the presence of a 20–fold excess of various metal cations and their fluorescence spectra thus obtained were compared with that recorded in the absence of metal cations under similar experimental conditions. It was observed that both the monomer and excimer emissions of receptor **5**$_c$ were strongly quenched by Cu^{2+} and Hg^{2+} ions in Figure 3. The fluorescence titration behaviour was evaluated in the case of receptor **5**$_c$ with Cu^{2+} and Hg^{2+} ions (Figures S22–S25). From these observations, the association constants for complexation were calculated to be: **5**$_c$·Cu^{2+} = 330000±23100 M^{-1}, **5**$_c$·Hg^{2+} = 420000±29400 M^{-1}, respectively. In contrast, upon addition of Ag^+ ion into a solution of receptor **5**$_c$, the fluorescence monomer emission was enhanced, while the excimer emission decreased. As shown in Figue 4, competitive experiments were carried out in the presence of Ag^+ ion (20 μM) mixed with other metal cations (20 μM). These results suggested that the receptor **5**$_c$ exhibits selective fluorescent behaviour towards the Ag^+ ion. Upon addition of Ag^+ ion (0–20 μM) to a solution of receptor **5**$_c$ (1.0 μM), Figure S26 shows the excimer emission of the pyrene units (486 nm) dicreases and the monomer emission of the pyrene units (393 nm) increases. This is because the complexation of Ag^+ ion by receptor **5**$_c$ induces the conformational unstacking of two pyrene ureas resulting in quenching of an intramolecular π–π interaction. Meanwhile, a discernible isoemissive point was observed at 445 nm. A Job's plot binding between receptor **5**$_c$ and Ag^+ ion reveals a 1:1 stoichiometry (Figure S27), while the association constant (K_a) for the complexation with Ag^+ ion by receptor **5**$_c$ was determined to be 61975 ± 4336 M^{-1} as determined by the fluorescence titration experiment in CH_2Cl_2–DMSO (10:1, v/v) (Figure S28). The fluorescent titration profile for receptor **5**$_c$ with Ag^+ ion demonstrated that the detection limit of Ag^+ ion was 1.92 × 10^{-7} M (Figure S29). As a result, receptor **5**$_c$ can be regarded as being highly sensitive to the Ag^+ ion, especially given the large fluorescence dynamic range and the low detection limit of 1.92 × 10^{-7} M. The quantum yield of the free receptor **5**$_c$ is Φ = 0.11, for both the monomer and excimer emission (393 and 486 nm). The quantum yield of the receptor **5**$_c$•Ag^+ complex is Φ = 0.06 as a result of increased monomer emission. To elucidate the complexation behaviour of receptors **5**$_c$ with Ag^+ ion in detail, ^1H NMR spectroscopic titration experiments in $CDCl_3$–DMSO–CH_3CN (10:1:1, v/v) were carried out. Upon addition of 1.0 equiv. of Ag^+ ion to the solution of receptors **5**$_c$, a large downfield shift of 1.08 ppm (δ = 6.72 to 7.80 ppm) for the proton H_h on the triazole ring was observed, together with a downfield shift of 0.20 ppm (δ = 4.32 to 4.52 ppm) for the proton H_g on the OCH_2-triazole unit and a downfield shift of 0.17 ppm (δ = 7.33 to 7.50 ppm) for the proton H_f on the aromatic protons of thiacalix[4]arene cavity; the chemical shifts of the NH protons did not change. This result suggested that the Ag^+ ion can be selectively bound by the nitrogen atoms on the triazole rings and is included in the π–basic benzene cavity at the lower rim. The two distal benzene rings were flattened and the residual two benzene rings were standing upright for the binding of the Ag^+ ion as shown in Figure 5. On the basis of the above, we investigated the appearance of an allosteric effect by the complexation of the opposite side arms with Cl^- and Ag^+ ions by ^1H NMR spectroscopic and fluorescence titration experiments. The result of the fluorescence titration experiments of receptor **5**$_c$· Cl^- with Ag^+ ion are shown in Figure S33. When increasing concentrations of Ag^+ ion were added to a solution of receptor **5**$_c$· Cl^-, the fluorescence intensity of the monomer (393 nm) and excimer (486 nm) emissions of pyrene gradually increased because of an allosteric effect via an ion-pair electrostatic interaction and a conformational change of the flexible thiacalix[4]arene cavity. Further addition of more than 1.0 equiv. of Ag^+ ion led to a significant increase in the monomer emission of the pyrene units, while the accompanying excimer emission reached a plateau upon adding about 20 equiv of Ag^+ ion. The association constant of receptor **5**$_c$· Cl^- with Ag^+ ion was determined to be 325000±22750 M^{-1} by the fluorescence titration experiment in CH_2Cl_2–DMSO (10:1, v/v) (Figure S34). The results indicated that receptor **5**$_c$· Cl^- was complexed with the Ag^+ ion at two pyrene–appended triazole rings by a positive allosteric effect because the complexation with Cl^- ion in the urea cavity caused an ion-pair electrostatic interaction and a conformational change of the flexible thiacalix[4]arene cavity. The fluorescent titration profile for receptor **5**$_c$· Cl^- with Ag^+ ion demonstrated that the detection limit of Ag^+ ion was 1.02 × 10^{-8} M (Figure S35). As a result, in comparison to the case in the free receptor **5**$_c$ to the Ag^+ ion (1.92 × 10^{-7} M), receptor **5**$_c$· Cl^- can be regarded as being more highly sensitive to the Ag^+ ion. To investigate further the possible appearance of an effective allosteric effect between receptor **5**$_c$· Cl^- and the Ag^+ ion, ^1H NMR titration experiments in $CDCl_3$–DMSO–CD_3CN (10:1:1, v/v) were conducted. When only Cl^- ion was added, it was observed that the signal for the NH_a protons shifted downfield, while the signal for NH_b protons shifted upfield. However, the signals of the protons on the two pyrene–appended triazole ring moieties did not shift (Figures 6a and 6b). This result suggests a Cl^- ion recognition of receptor **5**$_c$ by a hydrogen–bonding interaction between the Cl^- ion and N–H protons.

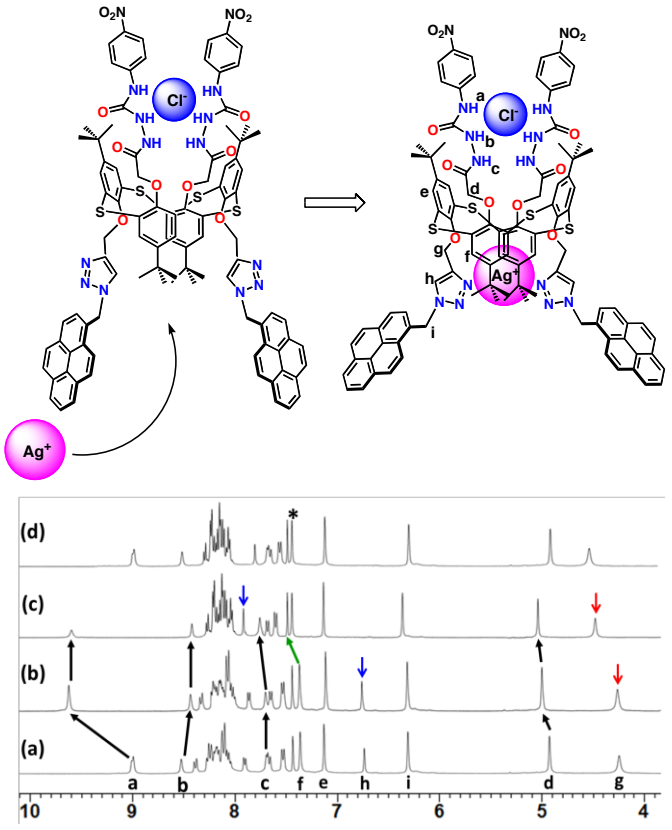


Fig. 6 Proposed positive allosteric behaviour of receptor $\mathbf{5}_c$ with Cl^- and Ag^+ ions. Partial ^1H NMR spectra of $\mathbf{5}_c$ /guest (H/G = 1:1); a) free $\mathbf{5}_c$; b) $\mathbf{5}_c \supset Bu_4NCl$; c) $AgSO_3CF_3 \subset [\mathbf{5}_c \supset Cl^-]$; d) $\mathbf{5}_c \supset AgSO_3CF_3$. Solvent: $CDCl_3$–DMSO–CD_3CN (10:1:1, v/v). 300 MHz at 298 K. *Denoted the solvent peak.

Furthermore, when Ag^+ ion was added to a solution of $[\mathbf{5}_c \supset Bu_4NCl]$ (Figure 6c), this addition induced a large downfield shift of 1.22 ppm (δ = 6.72 to 7.94 ppm) for the proton H_h on the triazole ring, a downfield shift of 0.18 ppm (δ = 4.32 to 4.50 ppm) for the proton H_g on the O*CH*$_2$–triazole unit and a downfield shift of 0.15 ppm (δ = 7.33 to 7.48 ppm) for the proton H_f of the aromatic protons of thiacalix[4]arene cavity. The chemical shifts for all NH protons did not change. These results suggested the formation of a heterogeneous dinuclear complex $Ag^+ \subset [\mathbf{5}_c \supset Cl^-]$ (Figure 6c), and we propose a positive allosteric effect for receptor $\mathbf{5}_c$ toward the Ag^+ ion in the presence of the Cl^- ion as shown in Figure 6.

3. Conclusion

In summary, the novel heteroditopic receptors $\mathbf{5}_{a\sim c}$ bearing a thiacalix[4]arene in a 1,3–*alternate* conformation have been synthesized. These receptors possess two ureas moieties linking various aryl groups bearing electron–donating or –withdrawing substituents at their *p*–positions which act as anion–binding sites and two pyrene–appended triazole rings which act as cation–binding sites at the opposite side of thiacalix[4]arene cavity. Furthermore, we have shown that two ureas moieties can bind various anions having a wide range of geometries based on UV–vis absorption, fluorescence and ^1H NMR titration experiments. We have also shown that the triazole groups can bind Ag^+, Hg^{2+} and Cu^{2+} ions based on both fluorescence spectroscopy and ^1H NMR titration experiments. Upon addition of Hg^{2+} and Cu^{2+} ions to a solution of receptor $\mathbf{5}_c$ in CH_2Cl_2–DMSO (10:1, v/v), the fluorescence spectrum was strongly quenched because of a reverse PET from the pyrene moieties to the triazole groups. By contrast, upon addition of Ag^+ ion to a solution of receptor $\mathbf{5}_c$ in CH_2Cl_2–DMSO (10:1, v/v), the fluorescence monomer emission was enhanced, while the excimer emission declined because of the complexation of the Ag^+ ions with the triazole groups. Interestingly, the fluorescence of receptor $\mathbf{5}_c$ was quenched by Cl^- ion, but could be revived by the addition of Ag^+ ion to the receptor $\mathbf{5}_c \cdot Cl^-$ complex. The appearance of a positive allosteric effect in receptor $\mathbf{5}_c$ was investigated based on fluorescence and ^1H NMR titration experiments. Interestingly, the formation of heterogeneous dinuclear complex $Ag^+ \subset [\mathbf{5}_c \supset Cl^-]$ of receptor $\mathbf{5}_c$ with Cl^- and Ag^+ ions by a positive allosteric effect could be observed.

4. Experimental section

4.1 General

Unless otherwise stated, all reagents used were purchased from commercial sources and were used without further purification. Compounds **1**,[13] **2**[12e] and **3**[12e] were prepared following the reported procedures. All solvents used were dried and distilled by the usual procedures prior to use. All melting points (Yanagimoto MP-S1) are uncorrected. ^1H NMR and ^{13}C NMR spectra were recorded on a Nippon Denshi JEOL FT-300 NMR spectrometer and Varian-400MR-vnmrs400 with SiMe4 as an internal reference: J-values are given in Hz. IR spectra were measured for samples as KBr pellets on a Nippon Denshi JIR-AQ2OM spectrophotometer. Mass spectra were obtained with a Nippon Denshi JMS-HX110A Ultrahigh Performance mass spectrometer at 75 eV by using a direct-inlet system. UV-vis spectra were recorded using a Shimadzu UV-3150UV-vis-NIR spectrophotometer. Fluorescence spectroscopic studies of compounds in solution were performed in a semimicro fluorescence cell (Hellma®, 104F-QS, 10 × 4 mm, 1400 μL) with a Varian Cary Eclipse spectrophotometer. Fluorescence quantum yields were recorded in solution (Hamamatsu Photonics K. K. Quantaurus-QY A10094) using the integrated sphere absolute PL quantum yield measurement method. Elemental analyses were performed by a Yanaco MT-5.The elemental analysis, MS, and emission spectra were measured.

4.2. Materials

4.2.1. Synthesis of compound **4**. Compound **3** (300 mg, 0.202 mmol) was put into a round-bottom flask and ethanol (50 mL), THF (50 mL) and hydrazine hydrate (6 mL, large excess) were added and the system was refluxed for 24 h. After cooling, the solvents and excess hydrazine were removed under reduced pressure to give the crude product as a white solid. The residue was triturated sequentially with water and methanol and the product collected by filtration. The residue was adsorbed in silica gel and purified by column chromatography using ethyl acetate as eluent and washed with hexane to give receptor $\mathbf{4}_a$ (253 mg, 86 %) as a white solid. M.p. 157–161 °C. IR: υ_{max} (KBr)/cm^{-1}: 3422, 3322, 2869, 1677, 1623, 1590, 1432, 1381, 1362, 1266, 1239, 1087, 1045, 970, 817 and 708. ^1H NMR (400 MHz, $CDCl_3$): δ = 0.95 (18H, s, *t*Bu × 2), 0.99 (18H, s, *t*Bu × 2), 3.49 (4H, br, N*H*$_2$ × 2), 4.29 (4H, s, O*CH*$_2$–triazole × 2), 5.06 (4H, s, O*CH*$_2$CO × 2), 6.29 (4H, s, *CH*$_2$–pyrene × 2), 6.69 (2H, s, Triazole–*H* × 2), 7.07 (4H, s, Ar–*H* × 2), 7.26 (4H, s, Ar–*H* × 2), 7.36 (2H, s, N*H* × 2) and 7.86–8.33. (18H, m,

Pyrene–*H* × 18) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 30.7 (CH_3), 30.8 (CH_3), 33.9 ($C(CH_3)_3$), 51.8 (CH_2), 62.6 (OCH_2), 68.3 (OCH_2), 122.2 (ArC), 122.9 (ArC), 124.2 (ArC), 124.6 (ArC), 124.7 (ArC), 125.5 (ArC), 125.6 (ArC), 126.2 (ArC), 126.6 (ArC), 127.0 (ArC), 127.1 (ArC), 127.2 (ArC), 127.9 (ArC), 128.0 (ArC), 128.5 (ArC), 128.6 (ArC), 128.8 (ArC), 129.7 (ArC), 130.3 (ArC), 131.0 (ArC), 131.6 (ArC), 143.4 (ArC), 147.2 (ArC), 154.8 (ArC), 155.1 (ArC) and 167.7 (CO) ppm. FABMS: *m/z*: 1455.4 (M^+). $C_{84}H_{82}N_{10}O_6S_4$ (1455.8): calcd C 69.30, H 5.68, N 9.62. Found: C 69.45, H 5.58, N 9.45.

4.2.2. Synthesis of receptor $\mathbf{5_a}$. To compound **4** (100 mg, 0.0687 mmol) in THF (10 mL) was added phenyl isocyanate (45 mg, 0.275 mmol) and the mixture was stirred at room temperature for 24 h under argon. The resulting precipitate was collected by filtration, washed with methanol to give receptor $\mathbf{5_a}$ as a pale yellow solid. Recrystallization from chloroform–hexane (3:1) gave receptor $\mathbf{5_a}$ (154 mg, 83 %) as a pale yellow solid. M.p. 202–203 °C. IR: υ_{max} (KBr)/cm^{-1}: 3301, 2961, 2867, 1680, 1604, 1544, 1510, 1451, 1430, 1312, 1264, 1220, 1085, 1044, 842, 815, 708 and 506. ^{1}H NMR (400 MHz, $CDCl_3$–DMSO, 10:1): δ = 0.97 (18H, s, *t*Bu × 2), 1.04 (18H, s, *t*Bu × 2), 4.22 (4H, s, O*CH*$_2$–triazole × 2), 4.94 (4H, s, O*CH*$_2$CO × 2), 6.29 (4H, s, *CH*$_2$–pyrene × 2), 6.72 (2H, s, Triazole–*H* × 2), 6.90–7.47 (10H, m, Phenyl–*H* × 10), 7.12 (4H, s, Ar–*H* × 2), 7.30 (4H, s, Ar–*H* × 2), 7.54 (2H, s, N*H* × 2) and 7.81–8.39. (22H, m, Pyrene–*H* × 18 and N*H* × 4) ppm. ^{13}C NMR (100 MHz, $CDCl_3$–DMSO, 10:1): δ = 30.6 (CH_3), 30.8 (CH_3), 34.1 ($C(CH_3)_3$), 51.9 (CH_2), 62.8 (OCH_2), 69.1 (OCH_2), 118.6 (ArC), 118.7 (ArC), 122.1 (ArC), 122.3 (ArC), 122.4 (ArC), 123.2 (ArC), 124.3 (ArC), 125.6 (ArC), 125.8 (ArC), 126.1 (ArC), 126.3 (ArC), 127.1 (ArC), 127.3 (ArC), 127.7 (ArC), 128.0 (ArC), 128.6 (ArC), 128.8 (ArC), 128.9 (ArC), 130.4 (ArC), 130.7 (ArC), 131.0 (ArC), 131.9 (ArC), 138.9 (ArC), 139.6 (ArC), 143.2 (ArC), 146.9 (ArC), 148.1 (ArC), 144.4 (ArC), 153.4 (ArC), 154.9 (CO), 155.3 (ArC) and 167.4 (CO) ppm. FABMS: *m/z*: 1693.5 (M^+). $C_{98}H_{92}N_{12}O_8S_4$ (1694.11): calcd C 69.48, H 5.47, N 9.92. Found: C 69.56, H 5.35, N 9.79.

4.2.3. Synthesis of receptor $\mathbf{5_b}$. To compound **4** (100 mg, 0.0687 mmol) in THF (10 mL) was added *p*–tolyl isocyanate (37 mg, 0.275 mmol) and the mixture was stirred at room temperature for 24 h under argon. The resulting precipitate was collected by filtration, washed with hexane to give receptor $\mathbf{5_b}$ as a pale yellow solid. Recrystallization from chloroform–hexane (3:2) gave receptor $\mathbf{5_b}$ (88 mg, 75 %) as a pale yellow solid. M.p. 205–206 °C. IR: υ_{max} (KBr)/cm^{-1}: 3303, 2961, 2869, 1681, 1604, 1543, 1515, 1451, 1432, 1314, 1266, 1229, 1087, 1045, 847, 817, 708 and 507. ^{1}H NMR (400 MHz, $CDCl_3$–DMSO, 10:1): δ = 0.97 (18H, s, *t*Bu × 2), 1.02 (18H, s, *t*Bu × 2), 2.27 (6H, s, *CH*$_3$ × 2), 4.26 (4H, s, O*CH*$_2$–triazole × 2), 4.95 (4H, s, O*CH*$_2$CO × 2), 6.32 (4H, s, *CH*$_2$–pyrene × 2), 6.74 (2H, s, Triazole–*H* × 2), 6.98 (4H, d, *J* = 7.7 Hz, Phenyl–*H* × 4), 7.14 (4H, s, Ar–*H* × 2), 7.17 (4H, d, *J* = 7.7 Hz, Phenyl–*H* × 4), 7.31 (4H, s, Ar–*H* × 2), 7.54 (2H, s, N*H* × 2) and 7.86–8.36. (22H, m, Pyrene–*H* × 18 and N*H* × 4) ppm. ^{13}C NMR (100 MHz, $CDCl_3$–DMSO, 10:1): δ = 21.7 (CH_3), 31.6 (CH_3), 31.8 (CH_3), 34.9 ($C(CH_3)_3$), 52.3 (CH_2), 64.0 (OCH_2), 70.0 (OCH_2), 119.8 (ArC), 119.9 (ArC), 123.1 (ArC), 124.0 (ArC), 124.1 (ArC), 125.1 (ArC), 125.3 (ArC), 126.1 (ArC), 126.6 (ArC), 126.9 (ArC), 127.5 (ArC), 127.7 (ArC), 128.1 (ArC), 128.4 (ArC), 129.0 (ArC), 129.4 (ArC), 129.7 (ArC), 130.0 (ArC), 131.2 (ArC), 131.6 (ArC), 131.7 (ArC), 131.8 (ArC), 132.2 (ArC), 137.8 (ArC), 143.8 (ArC), 148.0 (ArC), 148.6 (ArC), 155.6 (ArC), 155.9 (ArC), 156.4 (ArC), 157.0 (CO) and 168.0 (CO) ppm. FABMS: *m/z*: 1721.5 (M^+). $C_{100}H_{96}N_{12}O_8S_4$ (1722.17): calcd C 69.74, H 5.64, N 9.76. Found: C 69.58, H 5.54, N 9.67.

4.2.4. Synthesis of receptor $\mathbf{5_c}$. To compound **4** (100 mg, 0.0687 mmol) in THF (10 mL) was added *p*-nitrophenyl isocyanate (45 mg, 0.275 mmol) and the mixture was stirred at room temperature for 24 h under argon. The resulting precipitate was collected by filtration, washed with methanol to give receptor $\mathbf{5_c}$ as a yellow solid. Recrystallization from chloroform–acetonitrile (3:1) gave receptor $\mathbf{5_c}$ (154 mg, 83 %) as white solid. M.p. 204–207 °C. IR: υ_{max} (KBr)/cm^{-1}: 3366, 3338, 2961, 1733, 1597, 1554, 1508, 1433, 1330, 1302, 1248, 1201, 1178, 1113, 1087, 848 and 752. ^{1}H NMR (400 MHz, $CDCl_3$–DMSO, 10:1): δ = 0.95 (18H, s, *t*Bu × 2), 1.04 (18H, s, *t*Bu × 2), 4.32 (4H, s, O*CH*$_2$–triazole × 2), 4.95 (4H, s, O*CH*$_2$CO × 2), 6.32 (4H, s, *CH*$_2$–pyrene × 2), 6.72 (2H, s, Triazole–*H* × 2), 7.12 (4H, s, Ar–*H* × 2), 7.33 (4H, s, Ar–*H* × 2), 7.49 (4H, d, *J* = 8.8 Hz, Phenyl–*H* × 4), 7.63 (4H, d, *J* = 8.8 Hz, Phenyl–*H* × 4), 7.66 (2H, s, N*H* × 2), 7.87–8.33. (18H, m, Pyrene–*H* × 18), 8.50 (2H, s, N*H* × 2) and 8.98 (2H, s, N*H* × 2) ppm. ^{13}C NMR (100 MHz, $CDCl_3$–DMSO, 10:1): δ = 30.6 (CH_3), 30.8 (CH_3), 34.0 ($C(CH_3)_3$), 51.9 (CH_2), 62.7 (OCH_2), 68.9 (OCH_2), 117.5 (ArC), 117.7 (ArC), 122.2 (ArC), 123.1 (ArC), 124.3 (ArC), 124.7 (ArC), 124.9 (ArC), 125.0 (ArC), 125.6 (ArC), 125.7 (ArC), 125.8 (ArC), 126.2 (ArC), 127.1 (ArC), 127.2 (ArC), 127.5 (ArC), 128.0 (ArC), 128.4 (ArC), 128.6 (ArC), 128.9 (ArC), 130.4 (ArC), 130.7 (ArC), 131.0 (ArC), 131.7 (ArC), 142.0 (ArC), 143.1 (ArC), 145.2 (ArC), 145.3 (ArC), 147.2 (ArC), 148.0 (ArC), 154.4 (ArC), 154.9 (CO) and 167.4 (CO) ppm. FABMS: *m/z*: 1783.6 (M^+). $C_{98}H_{90}N_{14}O_{12}S_4$ (1784.1): calcd C 65.97, H 5.08, N 10.99. Found: C 65.78, H 5.51, N 10.82.

4.3. Determination of the Association Constants

The association constants were determined by using ^{1}H NMR titration experiments in a constant concentration of host receptor (4.0×10^{-3} M) by varying the guest concentration (0–8.0×10^{-3} M). The ^{1}H NMR chemical shift of the urea protons (NH) signal was used as a probe. The association constant (K_a) for the complexes of receptor $\mathbf{5_{a\sim c}}$ were calculated by nonlinear curve-fitting analysis of the observed chemical shifts of the NH protons according to the literature procedure.[14]

4.4. ^{1}H NMR Titration Experiments

A solution of Bu_4NX (X = F, Cl, Br, I, AcO, PhCOO, H_2PO_4) in CD_3CN (4.0×10^{-3} M) was added to a $CDCl_3$–DMSO (10:1, v/v) solution of receptor $\mathbf{5_{a\sim c}}$ in the absence or presence of $AgSO_3CF_3$ in an NMR tube. ^{1}H NMR spectra were recorded after addition of the reactants and the

temperature of the NMR probe was kept constant at 27 °C. The ^{1}H NMR data of the most-representative complexes are given below:

receptor $\mathbf{5_a}\supset Ag^+$: ^{1}H NMR (300 MHz, $CDCl_3$–DMSO–CD_3CN, 10:1:1, v/v): δ = 4.52 (4H, br, CH_2–triazole × 2), 4.94 (4H, s, OCH_2CO × 2), 6.29 (4H, s, CH_2–pyrene × 2), 7.13 (4H, s, Ar–H × 2), 7.34 (4H, s, Ar–H × 2), 7.54 (2H, br, NH_c × 2), 7.68 (2H, s, Triazole–H × 2) and 7.79–8.38. (18H, m, Pyrene-H × 18) ppm.

receptor $\mathbf{5_b}\supset Ag^+$: ^{1}H NMR (300 MHz, $CDCl_3$–DMSO–CD_3CN, 10:1:1, v/v): δ = 4.56 (4H, br, CH_2–triazole × 2), 5.00 (4H, s, OCH_2CO × 2), 6.32 (4H, s, CH_2–pyrene × 2), 7.07 (4H, d, J = 8.8 Hz, Phenyl–H × 4), 7.12 (4H, s, Ar–H × 2), 7.30 (4H, d, J = 8.8 Hz, Phenyl–H × 4), 7.48 (4H, s, Ar–H × 2), 7.90 (2H, br, NH_c × 2), 7.95 (2H, s, Triazole–H × 2) and 8.00–8.41. (18H, m, Pyrene-H × 18) ppm.

receptor $\mathbf{5_c}\supset Ag^+$: ^{1}H NMR (300 MHz, $CDCl_3$–DMSO–CD_3CN, 10:1:1, v/v): δ = 4.52 (4H, br, CH_2–triazole × 2), 4.95 (4H, s, OCH_2CO × 2), 6.32 (4H, s, CH_2–pyrene × 2), 7.12 (4H, s, Ar–H × 2), 7.50 (4H, s, Ar–H × 2), 7.63 (4H, d, J = 8.8 Hz, Phenyl–H × 4), 7.69 (4H, d, J = 8.8 Hz, Phenyl–H × 4), 7.70 (2H, br, NH_c × 2), 7.80 (2H, s, Triazole–H × 2), 8.02–8.30. (18H, m, pyrene-H × 18), 8.45 (2H, br, NH_b × 2) and 8.98 (2H, br, NH_a × 2) ppm.

receptor $\mathbf{5_c}\supset Cl^-$: ^{1}H NMR (300 MHz, $CDCl_3$–DMSO–CD_3CN, 10:1:1, v/v): δ = 4.32 (4H, br, CH_2–triazole × 2), 5.00 (4H, s, OCH_2CO × 2), 6.32 (4H, s, CH_2–pyrene × 2), 6.72 (2H, s, triazole–H × 2), 7.12 (4H, s, Ar–H × 2), 7.33 (4H, s, Ar–H × 2), 7.49 (4H, d, J = 8.8 Hz, Phenyl–H × 4), 7.63 (4H, d, J = 8.8 Hz, Phenyl–H × 4), 7.70 (2H, br, NH_c × 2), 7.87–8.33. (18H, m, Pyrene-H × 18), 8.41 (2H, br, NH_b × 2) and 9.62 (2H, br, NH_a × 2) ppm.

$Ag^+ \subset$ [receptor $\mathbf{5_c}\supset Cl^-$]: ^{1}H NMR (300 MHz, $CDCl_3$–DMSO–CD_3CN, 10:1:1, v/v): δ = 4.50 (4H, br, CH_2–triazole × 2), 5.00 (4H, s, OCH_2CO × 2), 6.32 (4H, s, CH_2–pyrene × 2), 7.12 (4H, s, Ar–H × 2), 7.48 (4H, s, Ar–H × 2), 7.63 (4H, d, J = 8.8 Hz, Phenyl–H × 4), 7.69 (4H, d, J = 8.8 Hz, Phenyl–H × 4), 7.86 (2H, br, NH_c × 2), 7.94 (2H, s, Triazole–H × 2), 8.02–8.30. (18H, m, Pyrene-H × 18), 8.44 (2H, br, NH_b × 2) and 9.60 (2H, br, NH_a × 2) ppm.

Acknowledgments

This work was performed under the Cooperative Research Program of "Network Joint Research Center for Materials and Devices (Institute for Materials Chemistry and Engineering, Kyushu University)". We would like to thank the OTEC at Saga University and the International Cooperation Projects of Guizhou Province (No. 20137005) for financial support. The EPSRC is thanked for a travel grant (to CR).

Supplementary data

Electronic Supplementary Information (ESI) available: Details of the ^{1}H/^{13}C NMR spectra, ^{1}H NMR and UV-vis titration experimental data, the Bensei–Hilderbrand plot and Job's plot, See DOI: 10.1039/b000000x/

References and notes

1. (a) Gutsche, C. D. *Calixarenes, An Introduction,* Royal Society of Chemistry: Cambridge, UK, **2008**; (b) Ikeda, A.; Shinkai, S. *Chem. Rev.* **1997**, *97*, 1713–1734; (c) Coquière, D.; Le Gac, S.; Darbost, U.; Sénèque, O.; Jabin, I.; Reinaud, O. *Org. Biomol. Chem.* **2009**, *7*, 2485–2500; (d) Cottet, K.; Marcos, P. M.; Cragg, P. J. *Beilstein J. Org. Chem.* **2012**, *8*, 201–226; (e) Mutihac, L.; Lee, J. H.; Kim, J. S.; Vicens, J. *Chem. Soc. Rev.* **2011**, *40*, 2777–2796; (f) Baldini, L.; Casnati, A.; Sansone, F.; Ungaro, R. *Chem. Soc. Rev.* **2007**, *36*, 254–266; (g) Kim, J. S.; Quang, D. T. *Chem. Rev.* **2007**, *107*, 3780–3799; (h) Joseph, R.; Rao, C. P. *Chem. Rev.* **2011**, *111*, 4658–4702; (i) Capici, C.; Cohen, Y.; D'Urso, A.; Gattuso, G.; Notti, A.; Pappalardo, A.; Pappalardo, S.; Parisi, M. F.; Purrello, R.; Slovak, S.; Villari, V. *Angew. Chem., Int. Ed.* **2011**, *50*, 12162–12167; (j) Talotta, C.; Gaeta1, C.; Qi, Z.; Schalley, C. A.; Neri, P. *Angew. Chem., Int. Ed.* **2013**, *52*, 7437–7441; (k) Wang, M.–X. *Acc. Chem. Res.* **2012**, *45*, 182–195.
2. (a) Kumagi, H.; Hasegawa, M.; Miyanari, S.; Sugawa, Y.; Sato, Y.; Hori, T.; Ueda, S.; Kamiyama, H.; Miyano, S. *Tetrahedron Lett.* **1997**, *38*, 3971–3972.
3. (a) Lhoták, P.; *Eur. J. Org. Chem.* **2004**, 1675–1692; (b) Morohashi, N.; Narumi, F.; Iki, N.; Hattori T.; Miyano, S. *Chem. Rev.* **2006**, *106*, 5291–5316.
4. (*a*) Nabeshima, T.; Saiki, T.; Kumitomo, S. *Org. Lett.* **2002**, *4*, 3207–3209; (b) Nabeshima, T.; Yoshihira, Y.; Saiki, T.; Akine, S.; Horn, E. *J. Am. Chem. Soc.* **2003**, *125*, 28–29; (c) Scarso, A.; Zaupa, G.; Houillon, F. B.; Prins, L. J.; Scrimin, P. *J. Org. Chem.* **2007**, *72*, 376–385; (d) Mohr, K.; Schmitz, J.; Schrage, R.; Trnkle, C.; Holzgrabe, U. *Angew. Chem., Int. Ed.* **2013**, *52*, 508–516; (e) Nussinov, R.; Tsai, C.–J. *Cell* **2013**, *153*, 293–305; (f) López–Vidal, E. M.; Fernández–Mato, A.; García, M. D.; Pérez–Lorenzo, M.; Peinador, C.; Quintetela, J. M. *J. Org. Chem.* **2014**, *79*, 1265–1270.
5. (a) Sessler, J. L.; Gale, P. A.; Cho, W. S. *Anion Receptor Chemistry*; Royal Society of Chemistry: Cambridge, U.K., **2006**; (b) Beer, P. D.; Gale, P. A. *Angew. Chem., Int. Ed.* **2001**, *40*, 486–516.
6. (a) Lee, J.–Y.; Cho, E.–J.; Mukamel, S.; Nam, K.–C. *J. Org. Chem.* **2004**, *69*, 943–950; (b) Kwon, J.–Y.; Jang, Y.–J.; Kim, S.–K.; Lee, K.–H., Kim J.–S.; Yoon, J. *J. Org. Chem.* **2004**, *69*, 5155–5157; (c) Esteban–Go´mez, D.; Fabbrizzi, L.; Licchelli, M. *J. Org. Chem.* **2005**, *70*, 5717–5720; (d) Thiagarajan, V.; Ramamurthy, P.; Thirumalai, D.; Ramakrishnan, V. T. *Org. Lett.* **2005**, *7*, 657–660; (e) Lu, H.; Xu, W.; Zhang, D.; Chen, C.; Zhu, D. *Org. Lett.* **2005**, *7*, 4629–4632; (f) Pfeffer, F. M.; Gunnlaugsson, T.; Jensen, P.; Kruger, P. E. *Org. Lett.* **2005**, *7*, 5357–5360; (g) Fang, L.; Chan, W.–H.; He, Y.–B.; Kwong, D. W.–J.; Lee, A. W.–M. *J. Org. Chem.* **2005,** *70*, 7640–7646; (h) Gunnlaugsson,T.; Kruger, P. E.; Jensen, P.; Tierney, J.; Paduka Ali, H. D.; Hussey, G. M. *J. Org. Chem.* **2005**, *70*, 10875–10878; (i) Dahan, A.; Ashkenazi, T.; Kuznetsov, V.; Makievski, S.; Drug, E.; Fadeev, L.; Bramson, M.; Schokoroy, S.; Rozenshine–Kemelmakher, E.; Gozin, M. *J. Org. Chem.* **2007**, *72*, 2289–2296; (j) Saha, S.; Ghosh, A.; Mahato, P.; Mishra, S.; Mishra, S. K.; Suresh, E.; Das, S.; Das, A. *Org. Lett.* **2010**, *12*, 3406–3409; (k) Lin, K.–K.; Wu, S.–C.; Hsu, K.–M.; Hung, C.–H.; Liaw, W.–F.; Wang, Y.–M. *Org. Lett.* **2013**, *15*, 4242–4245.
7. (a) Kundrat, O.; Dvorakova, H.; Eigner, V.; Lhoták, P. *J. Org. Chem.* **2010**, *75*, 407–411; (b) Kundrat, O.; Kroupa, J.; Böhm, S.; Budka, J.; Eigner, V.; Lhoták, P. *J. Org. Chem.* **2010**, *75*, 8372–8375; (c) Kundrát, O.; Eigner, V.; Cuřínová, P.; Kroupa, J.; Lhoták, P. *Tetrahedron*, **2011**, *67*, 8367–8372; (d) Kundrat, O.; Eigner, V.; Dvorakova, H.; Lhoták, P. *Org. Lett.* **2011**, *13*, 4032–4035; (e) Slavik, P.; Dudic, M.; Flidrova, K.; Sykora, J.; Cisarova, I.; Pojarova, M.; Lhoták, P. *Org. Lett.* **2012**, *14*, 3628–3631; (f) Kundrat, O.; Dvorakova, H.; Böhm, S.; Eigner, V.; Lhoták, P. *J. Org. Chem.* **2012**, *77*, 2272–2278.
8. (a) Kumar, M.; Dhir, A.; Bhalla, V. *Org. Lett.* **2009**, *11*, 2567–2570; (b) Kumar, M.; Kumar. R.; Bhalla, V. *Tetrahedron,* **2009**, *65*, 4340–4344; (c) Kumar, M.; Kumar, R.; Bhalla, V.; *Tetrahedron Lett.* **2010**, *51*, 5559–5562; (d) Kumar, M.; Kumar, R.; Bhalla, V. *Org. Lett.* **2011**, *13*, 366–369; (e) Kumar, M.; Kumar, R.; Bhalla, V. *Org. Bio. Chem.* **2011**, *9*, 8237–8245; (f) Kumar, M.; Kumar, R.; Bhalla, V. *Tetrahedron Lett.* **2013**, *54*, 1524–1527.
9. (a) Li, Y.; Cai, C. *Chem. Asian. J.* **2011**, *6*, 2592–2605; (b) Li, X. *Chem. Asian. J.* **2011**, *6*, 2606–2616; (c) Kim, S.–H.; Park, S.–H.; Choi, J.–H.; Chang, S. *Chem. Asian. J.* **2011**, *6*, 2618–2634; (d) Wu, Y.; Dong, Y.; Li, J.; Huang, X.; Cheng, Y.; Zhu, C.; *Chem. Asian. J.* **2011**, *6*, 2725–2729; (e) Xu, J.; Filion, T. M., Prifti, F.; Song, J. *Chem. Asian. J.* **2011**, *6*, 2730–2737; (f) Wu, W.; Fu, Y.; Wang, C.; Ye, C.; Qin, J.; Li, Z. *Chem.*

Asian. *J*. **2011**, *6*, 2787–2795; (g) Wang, W.; Hong, S.; Tran, A.; Jiang, H.; Triano, R.; Liu, Y.; Chen, X.; Wu, P. *Chem*. *Asian*. *J*. **2011**, *6*, 2796–2802; (h) Michaels, H. A.; Zhu, L. *Chem*. *Asian*. *J*. **2011**, *6*, 2825–2834; (i) Wan, X.; Zhang, G.; Ge, Z.; Narain, R.; Liu, S. *Chem*. *Asian*. *J*. **2011**, *6*, 2835–2845.

10. (a) Dondoni, A.; Marra, A. *Tetrahedron*, **2007**, *63*, 6339–6345; (b) Galante, E.; Geraci, C.; Sciuto, S.; Campo, V. L.; Carvalho, I.; Sesti–Costa, R.; Guedes, P. M. M.; Silva, J. S.; Hill, L.; Nepogodiev, S. A.; Field, R. A. *Tetrahedron*, **2011**, *67*, 5902–5912; (c) Pathak, R. K.; Tabbasum, K.; Hinge, V. K.; Rao, C. P. *Chem*. *Eur*. *J*. **2011**, *17*, 13999–14003; (d) Picot, S. C.; Mullancy, B. R.; Beer, P. D. *Chem*. *Eur*. *J*. **2012**, *18*, 6230–6237; (e) Cagnoni, A. J.; Varela, O.; Uhrig, M. L.; Kovensky, J.; *Eur*. *J*. *Org*. *Chem*., **2013**, 972–983; (f) Zhang, F.; Luo, L.; Sun, Y.; Miao, F.; Bi, J.; Tan, S.; Tian, D.; Li, H. *Tetrahedron*, **2013**, *69*, 9886–9889; (g) Cho, J.; Lee, S.; Hwang, S.; Kim, S.–H.; Kim, J.–S.; and Kim, S. *Eur*. *J*. *Org*. *Chem*. **2013**, 4614–4623; (h) Menard, N.; Hériot, Y.; Mest, Y. L.; Reinaud, O.; Poul, N. L.; Colasson, B. *Chem*. *Eur*. *J*. **2013**, *19*, 10611–10618; (i) Nierengarten, I.; Nothisen, M.; Sigwalt, D.; Biellmann, T.; Holler, M.; Remy J.–S.; Nierengarten, J.–F. *Chem*. *Eur*. *J*. **2013**, *19*, 17552–17558.
11. (a) Chang, K.–C.; Su, I.–H.; Senthilvelan, A.; Chung, W.–S. *Org*. *Lett*. **2007**, *17*, 3363–3366; (b) Chen, Y.–J.; Chung, W.–S. *Eur*. *J*. *Org*. *Chem*. **2009**, 4770–4776; (c) Chang, K.–C.; Su, I.–H.; Wang, Y.–Y; Chung, W.–S. *Eur*. *J*. *Org*. *Chem*. **2010**, 4700–4704; (d) Ho, I.–T.; Haung, K.–C.; Chung, W.–S. *Chem*. *Asian*. *J*. **2011**, *6*, 2738–2746; (e) Hung, H.–C.; Chang, Y.–Y.; Luo, L.; Hung, C.–H.; Diau, E. W.–G.; Chung, W.–S. *Photochem*. *Photobiol*. *Sci*. **2014**, *13*, 370–379.
12. (a) Perez–Casas, C.; Yamato, T. *J*. *Incl*. *Phenom*. *Macrocyclic Chem*. **2005**, *53*, 1–8; (b) Yamato, T.; Perez-Casas, C.; Yamamoto, H.; Elsegood, M. R. J.; Dale, S. H.; Redshaw, C. *J*. *Incl*. *Phenom*. *Macrocyclic Chem*. **2006**, *54*, 261–269; (c) Perez–Casas, C.; Rahman, S.; Begum, N.; Xi, Z.; Yamato, T. *J*. *Incl*. *Phenom*. *Macrocyclic Chem*. **2008**, *60*, 173–185; (d) Ni, X.–L.; Zeng, X.; Redshaw, C.; Yamato, T. *J*. *Org*. *Chem*. **2011**, *76*, 3358–3370; (e) Ni, X.–L.; Zeng, X.; Redshaw, C.; Yamato, T. *Tetrahedron* **2011**, *67*, 3248–3253; (f) Ni, X.–L.; Tahara, J.; Rahman, S.; Zeng, X.; Hughes, D. L.; Redshaw, C.; Yamato, T. *Chem*. *Asian*. *J*. **2012**, *7*, 519–527; (g) Ni, X.–L.; Cong, H.; Yoshizawa, A.; Rahman, S.; Tomiyasu, H.; Rayhan, U.; Zeng X.; Yamato, T. *J*. *Mol*. *Struct*. **2013**, *1046*, 110–115; (h) Tomiyasu, H.; Jin, C.–C.; Ni, X.–L.; Zeng, X.; Redshaw, C.; Yamato, T. *Org*. *Biomol*. *Chem*. **2014**, *12*, 4917–4923.
13. Iki, N.; Morohashi, N.; Narumi, F.; Fujimoto, T.; Suzuki T.; S. Miyano, *Tetrahedron Lett*., **1999**, *40*, 7337–7341.
14. Benesi, H. A.; Hildebrand, J. H. *J*. *Am*. *Chem*. *Soc*. **1949**, *71*, 2703–2707.

Graphical Abstract

To create your abstract, type over the instructions in the template box below.
Fonts or abstract dimensions should not be changed or altered.

Positive allosteric binding behaviour of pyrene–appended triazole–modified thiacalix[4]arene –based fluorescent receptors

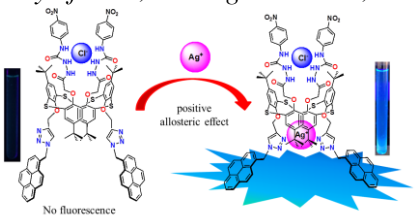
Leave this area blank for abstract info.

Hirotsugu Tomiyasu[a], Naoki Shigyo[a], Xin–Long Ni[b], Xi Zeng[b], Carl Redshaw[c], Takehiko Yamato[a,]*

[a] *Department of Applied Chemistry, Faculty of Science and Engineering, Saga University, Honjo-machi 1, Saga 840-8502, Japan*

[b] *Key Laboratory of Macrocyclic and Supramolecular Chemistry of Guizhou Province, Guizhou University,Guiyang 550025, People's Republic of China*

[c] *Department of Chemistry, The University of Hull, Cottingham Road, Hull, Yorkshire, HU6 7RX, UK*



Tetrahedron
journal homepage: www.elsevier.com

Positive allosteric binding behaviour of pyrene–appended triazole–modified thiacalix[4]arene–based fluorescent receptors

Hirotsugu Tomiyasu[a], Naoki Shigyo[a], Xin–Long Ni[b], Xi Zeng[b], Carl Redshaw[c], Takehiko Yamato[a,*]

[a] *Department of Applied Chemistry, Faculty of Science and Engineering, Saga University, Honjo-machi 1, Saga 840-8502, Japan*

[b] *Key Laboratory of Macrocyclic and Supramolecular Chemistry of Guizhou Province, Guizhou University,Guiyang 550025, People's Republic of China*

[c] *Department of Chemistry, The University of Hull, Cottingham Road, Hull, Yorkshire, HU6 7RX, UK*

ARTICLE INFO

Article history:
Received
Received in revised form
Accepted
Available online

Keywords:
Thiacalix[4]arene
1,3–*alternate* Conformation
Pyrenyl-appended triazole
Urea
Allosteric effect

ABSTRACT

The novel heteroditopic receptors **5**$_{a-c}$ have been synthesized, which bear a thiacalix[4]arene in the 1,3–*alternate* conformation. Two urea moieties possessing various aryl groups with either electron–donating or –withdrawing groups at their *p*–positions function as anion–binding sites. At the opposite side of the cavity are two pyrene–appended triazole rings, which act as cation–binding sites. The binding property of receptor **5**$_c$ was investigated by means of ^{1}H NMR and UV–vis spectroscopy and by fluorescence titration experiments in the presence of various transition metal cations and anions in CH_2Cl_2–DMSO (10:1, v/v) solution. Interestingly, it was found that receptor **5**$_c$ possessing two *p*–nitrophenyl ureido moieties, most efficiently complexes in the urea cavity or bistriazoles; the plausible allosteric effect of receptor **5**$_c$ was also investigated.

1. Introduction

The investigation of macrocycles such as calix[*n*]arenes[1] which are attractive building blocks for creating host systems capable of selectively recognizing cation, anion or neutral molecules has become an active area of research in supramolecular chemistry. Thiacalix[4]arenes[2,3] which are sulfur–bridged analogs of calix[4]arenes are excellent scaffolds and have been utilized in chemosensors, supramolecular self-assemblies and the catalytic activity of enzymes. A large number of enzymes have allosteric sites to control catalytic activity by stabilizing the active conformation. Many systems based on thiacalix[4]arenes are capable of host–guest interactions and involve conformational changes caused by the allosteric binding[4] of metal cations, and these relate to the maintenance of the essential material balance necessary for life. Anions also have been widely employed in biological, environmental and industrial processes.[5] The development of anion selective sensors[6] based on calix[*n*]arenes has received a considerable amount of attention in the area of supramolecular chemistry. Calix[*n*]arene urea derivatives are extremely prominent and are efficient for anion complexations via the N–H protons due to the formation of hydrogen bonds.[7,8] Click chemistry[9] is one of the most useful and widely employed reactions in synthetic chemistry. In particular, the Cu(I)–catalyzed azide–alkyne cycloaddition reaction is a highly versatile method which can be performed in high yield under very mild conditions. The 1,4–disubstituted–1,2,3–triazole products can act as relatively stable functional groups as covalent linkers or as ligands for metal cations, and have been utilized in the fields of drug discovery and materials science. Recently, many calix[*n*]arene derivatives bearing 1,4–disubstituted–1,2,3–triazoles as linking groups have been developed and investigated.[10]

Chung[11] and co–workers reported a fluorescent chemosensor bearing a calix[4]arene in a 1,3–*alternate* conformation, which contains two anthracene–appended triazole rings and the crown–ether moiety.[11a] This receptor exhibited a negative allosteric effect between the Pb^{2+} and K^+ ions in common organic solvents. Moreover, they also reported that a homobinuclear ditopic fluorescent chemosensor bearing a 1,3-*alternate* calix[4]arene, which contained two anthracene–appended triazole rings and two phenylenaminones at the opposite sides of the calix[4]arene cavity.[11d] This receptor exhibited a positive allosteric effect between two equivalents of Ag^+ ion in common organic solvents. However, investigations

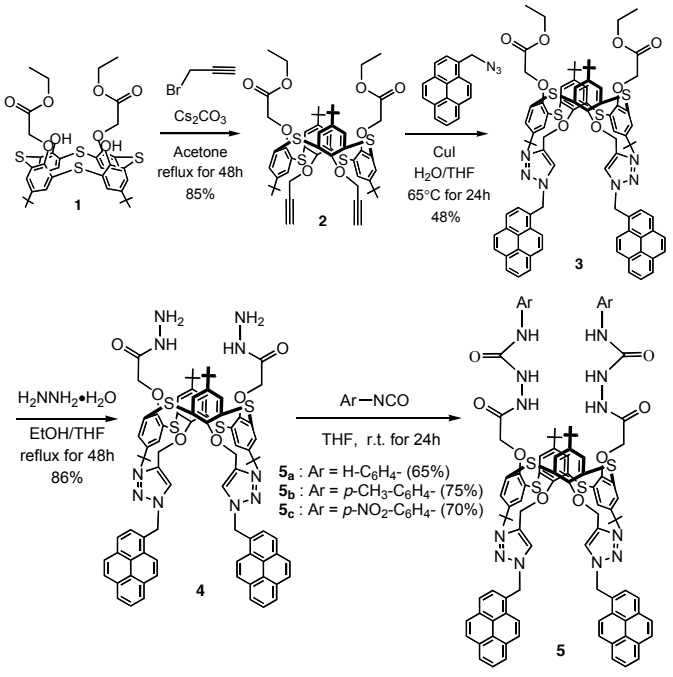
* Corresponding author. Fax: +81 952 28 8548; e-mail address: yamatot@cc.saga-u.ac.jp (T. Yamato).

concerning the appearance of allosteric effects in analogues based on thiacalix[4]arenes/metal cations/anions has not yet been reported. Herein, we have independently designed a heterodimeric system[12] based on a thiacalix[4]arene having two different side arms. Specifically, we have incorporated two ureas moieties which link various phenyl groups substituted with the electron–donating or –withdrawing groups at the *p*–positions and two pyrene–appended triazole rings at the opposite side of thiacalix[4]arene cavity. We built up the hypothesis that the heterodimeric system, which is controlled by the complexation of the opposite side arms with Cl^- and Ag^+ ions, exhibits an effective positive allosteric effect.

2. Results and discussion

2.1. Synthesis

O-Alkylation of *distal*-**1** was carried out with 10 equiv. of propargyl bromide in the presence of 10 equiv. of Cs_2CO_3 according to the reported procedure to afford the desired 1,3–*alternate*–**2** in 85 % yield.[12] A Cu(I)–catalyzed 1,3–dipolar cycloaddition reaction of 1,3–*alternate*–**2** with 4 equiv. of 1–azidomethylpyrene via Click chemistry was carried out according to the reported procedure, and afforded the 1,2,3–triazole thiacalix[4]arene 1,3–*alternate*–**3** in 48 % yield. The hydrazinolysis of 1,3–*alternate*–**3** was carried out with a large excess of hydrazine hydrate to afford the desired 1,3–*alternate*–**4** in 86 % yield. The condensation of 1,3–*alternate*–**4** with 4 equiv. of the appropriate isocyanate in THF furnished the receptors $\mathbf{5}_{\mathbf{a\sim c}}$ in good yield (Scheme 1). In general, the ^{1}H NMR spectra of receptors $\mathbf{5}_{\mathbf{a\sim c}}$ in $CDCl_3$–DMSO (10:1, v/v) exhibited the characteristics of a 1,3–*alternate* canformation, *viz* two singlets (18H each) for the *tert*-butyl protons, one singlet (4H) for OCH_2CO protons, one singlet (4H) for OCH_2–triazole protons, two singlets (4H each) for aromatic protons, two singlets (2H each) for four urea NH protons and one singlet (2H) for triazole–*H* protons. Moreover, a concentration dependence of the ^{1}H NMR chemical shifts of the ureido protons in receptor $\mathbf{5}_\mathbf{c}$ was not observed (Figure S13). This result suggests that receptor $\mathbf{5}_\mathbf{c}$ has a strong intramolecular hydrogen bond between the two ureas moieties.



Scheme 1 Synthesis of receptors 1,3-*alternate*-$\mathbf{5}_{\mathbf{a\sim c}}$.

Table 1 Association constants[a] of receptor $\mathbf{5}_{\mathbf{a\sim c}}$ with Cl^- ion[b]

Host	$\mathbf{5}_\mathbf{a}$	$\mathbf{5}_\mathbf{b}$	$\mathbf{5}_\mathbf{c}$
R	H	*p*-CH_3	*p*-NO_2
K_a [M^{-1}]	6250±438	3000±210	42500±2975

[a] Measured in CH_2Cl_2–DMSO (10:1, v/v) at 27 °C by fluorescence titration experiments (Figures S15–S21); host concentration was 1.0 μM. [b] Guests used: Bu_4NCl.

2.2. Binding studies

Upon addition of Cl^- ion (0–20 μM) to a solution of receptor $\mathbf{5}_\mathbf{c}$ (1.0 μM), Figure S19 shows that both the monomer and excimer emissions of the pyrene units gradually decrease. A Job's plot binding between receptor $\mathbf{5}_\mathbf{c}$ and Cl^- ion reveals a 1:1 stoichiometry (Figure S20), while the association constant (K_a value) for the complexation with Cl^- ion by receptor $\mathbf{5}_\mathbf{c}$ was determined to be 42500 ± 2975 M^{-1} as determined by the fluorescence titration experiment in CH_2Cl_2–DMSO (10:1, v/v) (Figure S21 and Table 1). Moreover, K_a values between the receptors $\mathbf{5}_{\mathbf{a\sim b}}$ and Cl^- ion were determined by analyzing fluorescence titration experiments, respectively (Figures S15–S18 and Table 1). These results suggest that the association constants depend on the electron–donating/withdrawing groups located at the *p*–position. In the presence of the electron–withdrawing group NO_2 (receptor $\mathbf{5}_\mathbf{c}$), the K_a value was greater than that for the unsubstituted receptor (receptor $\mathbf{5}_\mathbf{a}$). In contrast, in the case of receptor $\mathbf{5}_\mathbf{b}$, with the electron–donating Me group, there was a general decrease in the K_a value for the complexation with Cl^- ion in comparison to the case in the unsubstituted receptor $\mathbf{5}_\mathbf{a}$. Therefore, the introduction of electron–withdrawing groups at the *p*–position appears to increase the acidity of the urea protons, and hence enhance the anion–binding ability through hydrogen–bonding interactions. The K_a value of receptor $\mathbf{5}_\mathbf{c}$ with the electron–withdrawing NO_2 group at the *p*–position was the best out of all the K_a values between receptors $\mathbf{5}_{\mathbf{a\sim c}}$ and Cl^- ion. From

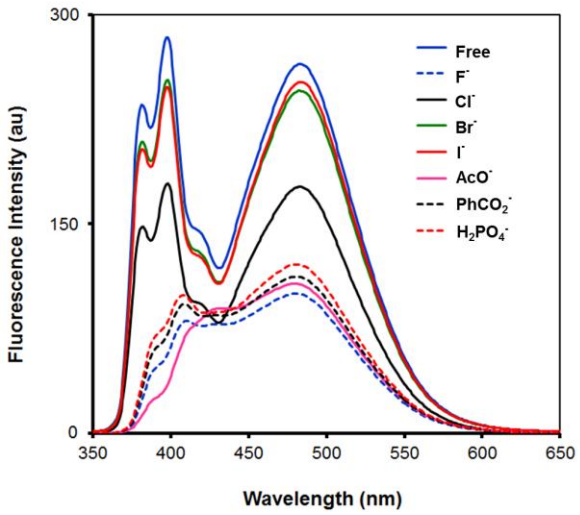


Fig. 1 Fluorescence spectral changes of receptor $\mathbf{5}_\mathbf{c}$ (1.0 μM) upon addition of various tested anions (1.0 μM) in CH_2Cl_2–DMSO (10:1, v/v). λ_{ex} = 343 nm.

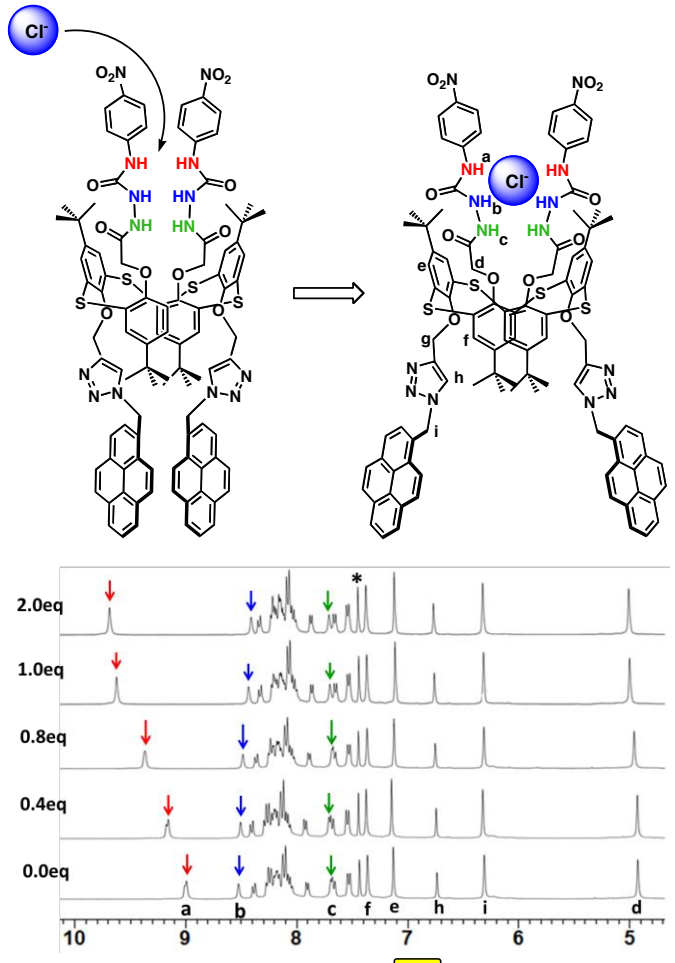


Fig. 2 Binding mode of receptor **5**$_c$ upon addition of Cl^- ion at 298 K as a tetrabutylammonium (TBA) salt and partial ^{1}H NMR spectra of **5**$_c$ (4.0 mM) in $CDCl_3$–DMSO–CH_3CN (10:1:1, v/v) upon addition of Ag^+ ion at 298 K.

the above, we can say that the receptor **5**$_c$, with the electron–withdrawing NO_2 group at the *p*–position, has the most effective recognition ability toward selected anions of the systems screened herein. Given this, complexation studies of receptor **5**$_c$ toward targeting various transition metal cations and anions were carried out using ^{1}H NMR and UV–vis spectroscopy and by fluorescence titration experiments.

The UV–vis absorption spectra of receptor **5**$_c$ (1.0 μM) were recorded in the presence of various anions (20 equiv.) in CH_2Cl_2–DMSO (10:1, v/v) as shown in Figure S14. The receptor **5**$_c$ (1.0 μM)exhibits an absorption band at 347 nm in the UV–vis absorption spectra in the absence of anions. Interestingly, significant changes moving to a longer wavelength in absorption spectra were observed in the presence of F^-, AcO^-, $PhCOO^-$ or $H_2PO_4^-$ with a color change from colourless to dark yellow by the naked eye, respectively. These results suggest that the quinoid structure was formed by the deprotonation of the urea NH groups in the *p*–nitrophenyl ureido moiety. Figure 1 reveals the fluorescence intensity changes of the monomer (393 nm) and excimer (486 nm) emissions for receptor **5**$_c$ in the presence of various anions. Receptor **5**$_c$ exhibited a decrease in intensity of both the monomer and excimer emissions with various anions. Upon addition of Cl^- ion to a solution of receptor **5**$_c$, the decrease of intensity of the monomer emission is presumably caused by a photo–induced electron transfer (PET) mechanism which

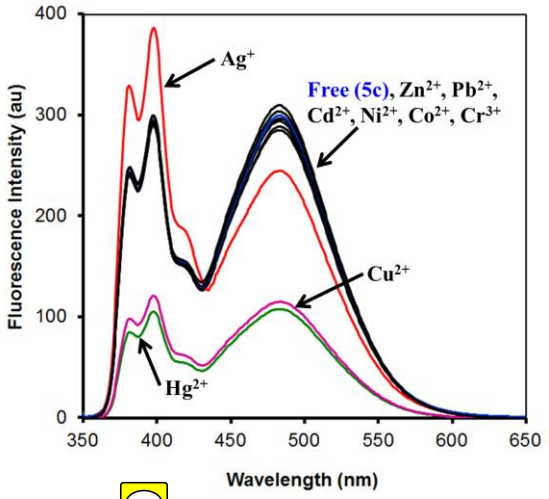


Fig. 3 Fluorescence spectral changes of receptor **5**$_c$ (1.0 μM) to upon addition of various tested metal cations (20 μM) in CH_2Cl_2–DMSO (10:1, v/v). λ_{ex} = 343 nm.

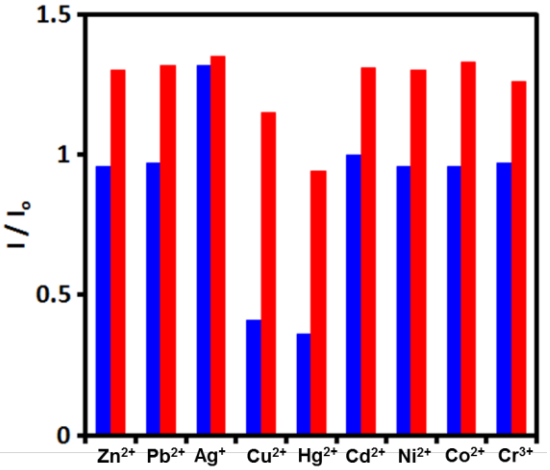


Fig. 4 Fluorescence response of receptor **5**$_c$ (1.0 μM) in CH_2Cl_2–DMSO (10:1, v/v) to various tested metal cations (20 μM) (blue bar) and to the mixture of tested metal ions (20 μM) with Ag^+ ion (20 μM) (red bar) at 298 K. I_o is the fluorescence intensity at 393 nm for free receptor **5**$_c$, and I is the fluorescence intensity after adding metal ions with an excitation at 343 nm.

operates from the oxygen of the urea moiety which complexes with the Cl^- ion via hydrogen bonding to the pyrene moieties. By contrast, upon addition of F^-, AcO^-, $PhCOO^-$ or $H_2PO_4^-$ ions to a solution of receptor **5**$_c$, the decreasing intensity of the monomer emission is caused by deprotonation of the urea NH groups which induces a PET mechanism from the anionic nitrogen to the pyrene moieties. On the other hand, upon addition of F^-, Cl^-, AcO^-, $PhCOO^-$ or $H_2PO_4^-$ ions to a solution of receptor **5**$_c$, the decreasing intensity of the excimer emission is caused by conformational unstacking of two pyrene ureas, which breaks down an intramolecular π–π interaction because of complex formation. As shown in Figure 2, the signals for the NH_a protons (red) progressively shifted downfield by 0.64 ppm (δ = 8.98 to 9.62 ppm) until one equiv. of Cl^- ion was added. On the other hand, the signals for the NH_b protons (blue) progressively shifted upfield by 0.09 ppm (δ = 8.50 to 8.41 ppm) until one equiv. of Cl^-

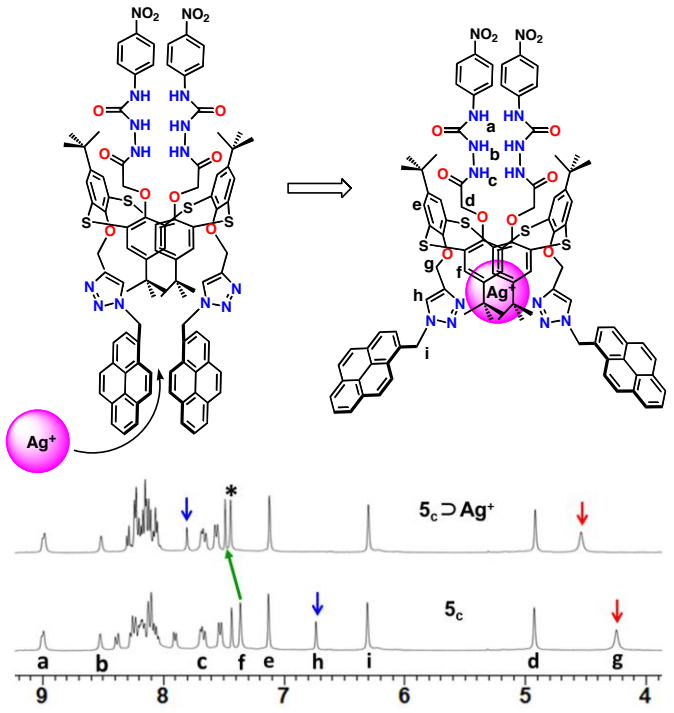


Fig. 5 Binding mode of receptors **5**$_c$ upon complexation with Ag^+ ion as trifluoromethanesulforic salt, and partial ^1H NMR spectra of receptors **5**$_c$ (4.0 mM) in $CDCl_3$–DMSO–CD_3CN (10:1:1, v/v) upon addition of Ag^+ ion (1.0 equiv.) at 298 K.

ion was added. These results strongly suggested Cl^- ion recognition by receptor **5**$_c$ via a hydrogen–bonding interaction between Cl^- ion and N–H protons as shown in Figure 2 and Figure S32. The fluorescence intensity changes of receptor **5**$_c$ were recorded in CH_2Cl_2–DMSO (10:1, v/v) in the presence of a 20–fold excess of various metal cations and their fluorescence spectra thus obtained were compared with that recorded in the absence of metal cations under similar experimental conditions. It was observed that both the monomer and excimer emissions of receptor **5**$_c$ were strongly quenched by Cu^{2+} and Hg^{2+} ions in Figure 3. The fluorescence titration behaviour was evaluated in the case of receptor **5**$_c$ with Cu^{2+} and Hg^{2+} ions (Figures S22–S25). From these observations, the association constants for complexation were calculated to be: **5**$_c$·Cu^{2+} = 330000±23100 M^{-1}, **5**$_c$·Hg^{2+} = 420000±29400 M^{-1}, respectively. In contrast, upon addition of Ag^+ ion into a solution of receptor **5**$_c$, the fluorescence monomer emission was enhanced, while the excimer emission decreased. As shown in Figue 4, competitive experiments were carried out in the presence of Ag^+ ion (20 μM) mixed with other metal cations (20 μM). These results suggested that the receptor **5**$_c$ exhibits selective fluorescent behaviour towards the Ag^+ ion. Upon addition of Ag^+ ion (0–20 μM) to a solution of receptor **5**$_c$ (1.0 μM), Figure S26 shows the excimer emission of the pyrene units (486 nm) dicreases and the monomer emission of the pyrene units (393 nm) increases. This is because the complexation of Ag^+ ion by receptor **5**$_c$ induces the conformational unstacking of two pyrene ureas resulting in quenching of an intramolecular π–π interaction. Meanwhile, a discernible isoemissive point was observed at 445 nm. A Job's plot binding between receptor **5**$_c$ and Ag^+ ion reveals a 1:1 stoichiometry (Figure S27), while the association constant (K_a) for the complexation with Ag^+ ion by receptor **5**$_c$ was determined to be 61975 ± 4336 M^{-1} as determined by the fluorescence titration experiment in CH_2Cl_2–DMSO (10:1, v/v) (Figure S28). The fluorescent titration profile for receptor **5**$_c$ with Ag^+ ion demonstrated that the detection limit of Ag^+ ion was 1.92 × 10^{-7} M (Figure S29). As a result, receptor **5**$_c$ can be regarded as being highly sensitive to the Ag^+ ion, especially given the large fluorescence dynamic range and the low detection limit of 1.92 × 10^{-7} M. The quantum yield of the free receptor **5**$_c$ is Φ = 0.11, for both the monomer and excimer emission (393 and 486 nm). The quantum yield of the receptor **5**$_c$•Ag^+ complex is Φ = 0.06 as a result of increased monomer emission. To elucidate the complexation behaviour of receptors **5**$_c$ with Ag^+ ion in detail, ^1H NMR spectroscopic titration experiments in $CDCl_3$–DMSO–CH_3CN (10:1:1, v/v) were carried out. Upon addition of 1.0 equiv. of Ag^+ ion to the solution of receptors **5**$_c$, a large downfield shift of 1.08 ppm (δ = 6.72 to 7.80 ppm) for the proton H_h on the triazole ring was observed, together with a downfield shift of 0.20 ppm (δ = 4.32 to 4.52 ppm) for the proton H_g on the OCH_2-triazole unit and a downfield shift of 0.17 ppm (δ = 7.33 to 7.50 ppm) for the proton H_f on the aromatic protons of thiacalix[4]arene cavity; the chemical shifts of the NH protons did not change. This result suggested that the Ag^+ ion can be selectively bound by the nitrogen atoms on the triazole rings and is included in the π–basic benzene cavity at the lower rim. The two distal benzene rings were flattened and the residual two benzene rings were standing upright for the binding of the Ag^+ ion as shown in Figure 5. On the basis of the above, we investigated the appearance of an allosteric effect by the complexation of the opposite side arms with Cl^- and Ag^+ ions by ^1H NMR spectroscopic and fluorescence titration experiments. The result of the fluorescence titration experiments of receptor **5**$_c$· Cl^- with Ag^+ ion are shown in Figure S33. When increasing concentrations of Ag^+ ion were added to a solution of receptor **5**$_c$· Cl^-, the fluorescence intensity of the monomer (393 nm) and excimer (486 nm) emissions of pyrene gradually increased because of an allosteric effect via an ion-pair electrostatic interaction and a conformational change of the flexible thiacalix[4]arene cavity. Further addition of more than 1.0 equiv. of Ag^+ ion led to a significant increase in the monomer emission of the pyrene units, while the accompanying excimer emission reached a plateau upon adding about 20 equiv of Ag^+ ion. The association constant of receptor **5**$_c$· Cl^- with Ag^+ ion was determined to be 325000±22750 M^{-1} by the fluorescence titration experiment in CH_2Cl_2–DMSO (10:1, v/v) (Figure S34). The results indicated that receptor **5**$_c$· Cl^- was complexed with the Ag^+ ion at two pyrene–appended triazole rings by a positive allosteric effect because the complexation with Cl^- ion in the urea cavity caused an ion-pair electrostatic interaction and a conformational change of the flexible thiacalix[4]arene cavity. The fluorescent titration profile for receptor **5**$_c$· Cl^- with Ag^+ ion demonstrated that the detection limit of Ag^+ ion was 1.02 × 10^{-8} M (Figure S35). As a result, in comparison to the case in the free receptor **5**$_c$ to the Ag^+ ion (1.92 × 10^{-7} M), receptor **5**$_c$· Cl^- can be regarded as being more highly sensitive to the Ag^+ ion. To investigate further the possible appearance of an effective allosteric effect between receptor **5**$_c$· Cl^- and the Ag^+ ion, ^1H NMR titration experiments in $CDCl_3$–DMSO–CD_3CN (10:1:1, v/v) were conducted. When only Cl^- ion was added, it was observed that the signal for the NH_a protons shifted downfield, while the signal for NH_b protons shifted upfield. However, the signals of the protons on the two pyrene–appended triazole ring moieties did not shift (Figures 6a and 6b). This result suggests a Cl^- ion recognition of receptor **5**$_c$ by a hydrogen–bonding interaction between the Cl^- ion and N–H protons.

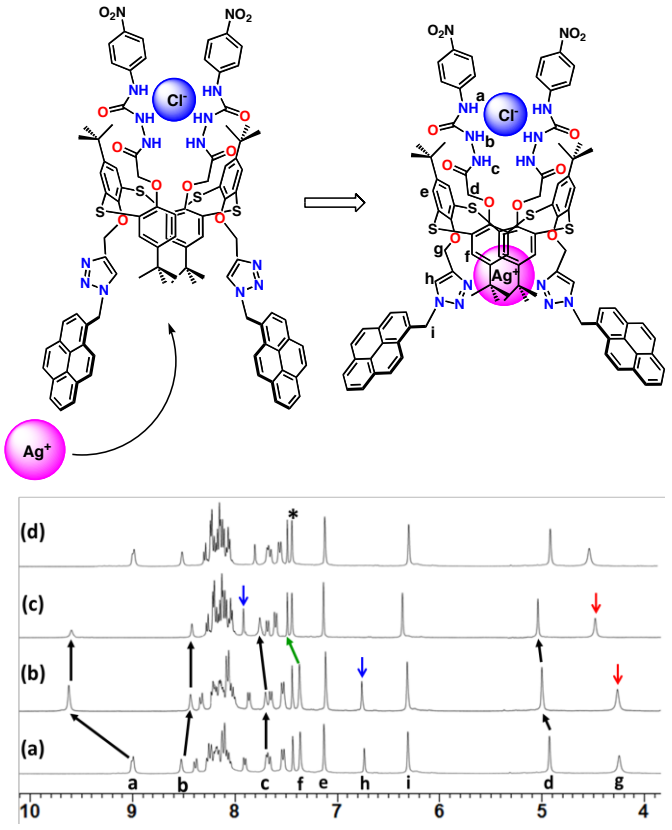


Fig. 6 Proposed positive allosteric behaviour of receptor $\mathbf{5}_c$ with Cl^- and Ag^+ ions. Partial ^1H NMR spectra of $\mathbf{5}_c$ /guest (H/G = 1:1); a) free $\mathbf{5}_c$; b) $\mathbf{5}_c \supset Bu_4NCl$; c) $AgSO_3CF_3 \subset [\mathbf{5}_c \supset Cl^-]$; d) $\mathbf{5}_c \supset AgSO_3CF_3$. Solvent: $CDCl_3$–DMSO–CD_3CN (10:1:1, v/v). 300 MHz at 298 K. *Denoted the solvent peak.

Furthermore, when Ag^+ ion was added to a solution of $[\mathbf{5}_c \supset Bu_4NCl]$ (Figure 6c), this addition induced a large downfield shift of 1.22 ppm (δ = 6.72 to 7.94 ppm) for the proton H_h on the triazole ring, a downfield shift of 0.18 ppm (δ = 4.32 to 4.50 ppm) for the proton H_g on the OCH_2–triazole unit and a downfield shift of 0.15 ppm (δ = 7.33 to 7.48 ppm) for the proton H_f of the aromatic protons of thiacalix[4]arene cavity. The chemical shifts for all NH protons did not change. These results suggested the formation of a heterogeneous dinuclear complex $Ag^+ \subset [\mathbf{5}_c \supset Cl^-]$ (Figure 6c), and we propose a positive allosteric effect for receptor $\mathbf{5}_c$ toward the Ag^+ ion in the presence of the Cl^- ion as shown in Figure 6.

3. Conclusion

In summary, the novel heteroditopic receptors $\mathbf{5}_{a\sim c}$ bearing a thiacalix[4]arene in a 1,3–*alternate* conformation have been synthesized. These receptors possess two ureas moieties linking various aryl groups bearing electron–donating or –withdrawing substituents at their *p*–positions which act as anion–binding sites and two pyrene–appended triazole rings which act as cation–binding sites at the opposite side of thiacalix[4]arene cavity. Furthermore, we have shown that two ureas moieties can bind various anions having a wide range of geometries based on UV–vis absorption, fluorescence and ^1H NMR titration experiments. We have also shown that the triazole groups can bind Ag^+, Hg^{2+} and Cu^{2+} ions based on both fluorescence spectroscopy and ^1H NMR titration experiments. Upon addition of Hg^{2+} and Cu^{2+} ions to a solution of receptor $\mathbf{5}_c$ in CH_2Cl_2–DMSO (10:1, v/v), the fluorescence spectrum was strongly quenched because of a reverse PET from the pyrene moieties to the triazole groups. By contrast, upon addition of Ag^+ ion to a solution of receptor $\mathbf{5}_c$ in CH_2Cl_2–DMSO (10:1, v/v), the fluorescence monomer emission was enhanced, while the excimer emission declined because of the complexation of the Ag^+ ions with the triazole groups. Interestingly, the fluorescence of receptor $\mathbf{5}_c$ was quenched by Cl^- ion, but could be revived by the addition of Ag^+ ion to the receptor $\mathbf{5}_c \cdot Cl^-$ complex. The appearance of a positive allosteric effect in receptor $\mathbf{5}_c$ was investigated based on fluorescence and ^1H NMR titration experiments. Interestingly, the formation of heterogeneous dinuclear complex $Ag^+ \subset [\mathbf{5}_c \supset Cl^-]$ of receptor $\mathbf{5}_c$ with Cl^- and Ag^+ ions by a positive allosteric effect could be observed.

4. Experimental section

4.1 General

Unless otherwise stated, all reagents used were purchased from commercial sources and were used without further purification. Compounds **1**,[13] **2**[12e] and **3**[12e] were prepared following the reported procedures. All solvents used were dried and distilled by the usual procedures prior to use. All melting points (Yanagimoto MP-S1) are uncorrected. ^1H NMR and ^{13}C NMR spectra were recorded on a Nippon Denshi JEOL FT-300 NMR spectrometer and Varian-400MR-vnmrs400 with SiMe4 as an internal reference: J-values are given in Hz. IR spectra were measured for samples as KBr pellets on a Nippon Denshi JIR-AQ2OM spectrophotometer. Mass spectra were obtained with a Nippon Denshi JMS-HX110A Ultrahigh Performance mass spectrometer at 75 eV by using a direct-inlet system. UV-vis spectra were recorded using a Shimadzu UV-3150UV-vis-NIR spectrophotometer. Fluorescence spectroscopic studies of compounds in solution were performed in a semimicro fluorescence cell (Hellma®, 104F-QS, 10 × 4 mm, 1400 μL) with a Varian Cary Eclipse spectrophotometer. Fluorescence quantum yields were recorded in solution (Hamamatsu Photonics K. K. Quantaurus-QY A10094) using the integrated sphere absolute PL quantum yield measurement method. Elemental analyses were performed by a Yanaco MT-5.The elemental analysis, MS, and emission spectra were measured.

4.2. Materials

4.2.1. Synthesis of compound **4**. Compound **3** (300 mg, 0.202 mmol) was put into a round-bottom flask and ethanol (50 mL), THF (50 mL) and hydrazine hydrate (6 mL, large excess) were added and the system was refluxed for 24 h. After cooling, the solvents and excess hydrazine were removed under reduced pressure to give the crude product as a white solid. The residue was triturated sequentially with water and methanol and the product collected by filtration. The residue was adsorbed in silica gel and purified by column chromatography using ethyl acetate as eluent and washed with hexane to give receptor $\mathbf{4}_a$ (253 mg, 86 %) as a white solid. M.p. 157–161 °C. IR: υ_{max} (KBr)/cm^{-1}: 3422, 3322, 2869, 1677, 1623, 1590, 1432, 1381, 1362, 1266, 1239, 1087, 1045, 970, 817 and 708. ^1H NMR (400 MHz, $CDCl_3$): δ = 0.95 (18H, s, *t*Bu × 2), 0.99 (18H, s, *t*Bu × 2), 3.49 (4H, br, NH_2 × 2), 4.29 (4H, s, OCH_2–triazole × 2), 5.06 (4H, s, OCH_2CO × 2), 6.29 (4H, s, CH_2–pyrene × 2), 6.69 (2H, s, Triazole–*H* × 2), 7.07 (4H, s, Ar–*H* × 2), 7.26 (4H, s, Ar–*H* × 2), 7.36 (2H, s, N*H* × 2) and 7.86–8.33. (18H, m,

Pyrene–*H* × 18) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 30.7 (CH_3), 30.8 (CH_3), 33.9 ($C(CH_3)_3$), 51.8 (CH_2), 62.6 (OCH_2), 68.3 (OCH_2), 122.2 (ArC), 122.9 (ArC), 124.2 (ArC), 124.6 (ArC), 124.7 (ArC), 125.5 (ArC), 125.6 (ArC), 126.2 (ArC), 126.6 (ArC), 127.0 (ArC), 127.1 (ArC), 127.2 (ArC), 127.9 (ArC), 128.0 (ArC), 128.5 (ArC), 128.6 (ArC), 128.8 (ArC), 129.7 (ArC), 130.3 (ArC), 131.0 (ArC), 131.6 (ArC), 143.4 (ArC), 147.2 (ArC), 154.8 (ArC), 155.1 (ArC) and 167.7 (CO) ppm. FABMS: *m/z*: 1455.4 (M^+). $C_{84}H_{82}N_{10}O_6S_4$ (1455.8): calcd C 69.30, H 5.68, N 9.62. Found: C 69.45, H 5.58, N 9.45.

4.2.2. Synthesis of receptor $\mathbf{5_a}$. To compound **4** (100 mg, 0.0687 mmol) in THF (10 mL) was added phenyl isocyanate (45 mg, 0.275 mmol) and the mixture was stirred at room temperature for 24 h under argon. The resulting precipitate was collected by filtration, washed with methanol to give receptor $\mathbf{5_a}$ as a pale yellow solid. Recrystallization from chloroform–hexane (3:1) gave receptor $\mathbf{5_a}$ (154 mg, 83 %) as a pale yellow solid. M.p. 202–203 °C. IR: υ_{max} (KBr)/cm^{-1}: 3301, 2961, 2867, 1680, 1604, 1544, 1510, 1451, 1430, 1312, 1264, 1220, 1085, 1044, 842, 815, 708 and 506. ^{1}H NMR (400 MHz, $CDCl_3$–DMSO, 10:1): δ = 0.97 (18H, s, *t*Bu × 2), 1.04 (18H, s, *t*Bu × 2), 4.22 (4H, s, OCH_2–triazole × 2), 4.94 (4H, s, OCH_2CO × 2), 6.29 (4H, s, CH_2–pyrene × 2), 6.72 (2H, s, Triazole–*H* × 2), 6.90–7.47 (10H, m, Phenyl–*H* × 10), 7.12 (4H, s, Ar–*H* × 2), 7.30 (4H, s, Ar–*H* × 2), 7.54 (2H, s, N*H* × 2) and 7.81–8.39. (22H, m, Pyrene–*H* × 18 and N*H* × 4) ppm. ^{13}C NMR (100 MHz, $CDCl_3$–DMSO, 10:1): δ = 30.6 (CH_3), 30.8 (CH_3), 34.1 ($C(CH_3)_3$), 51.9 (CH_2), 62.8 (OCH_2), 69.1 (OCH_2), 118.6 (ArC), 118.7 (ArC), 122.1 (ArC), 122.3 (ArC), 122.4 (ArC), 123.2 (ArC), 124.3 (ArC), 125.6 (ArC), 125.8 (ArC), 126.1 (ArC), 126.3 (ArC), 127.1 (ArC), 127.3 (ArC), 127.7 (ArC), 128.0 (ArC), 128.6 (ArC), 128.8 (ArC), 128.9 (ArC), 130.4 (ArC), 130.7 (ArC), 131.0 (ArC), 131.9 (ArC), 138.9 (ArC), 139.6 (ArC), 143.2 (ArC), 146.9 (ArC), 148.1 (ArC), 144.4 (ArC), 153.4 (ArC), 154.9 (CO), 155.3 (ArC) and 167.4 (CO) ppm. FABMS: *m/z*: 1693.5 (M^+). $C_{98}H_{92}N_{12}O_8S_4$ (1694.11): calcd C 69.48, H 5.47, N 9.92. Found: C 69.56, H 5.35, N 9.79.

4.2.3. Synthesis of receptor $\mathbf{5_b}$. To compound **4** (100 mg, 0.0687 mmol) in THF (10 mL) was added *p*–tolyl isocyanate (37 mg, 0.275 mmol) and the mixture was stirred at room temperature for 24 h under argon. The resulting precipitate was collected by filtration, washed with hexane to give receptor $\mathbf{5_b}$ as a pale yellow solid. Recrystallization from chloroform–hexane (3:2) gave receptor $\mathbf{5_b}$ (88 mg, 75 %) as a pale yellow solid. M.p. 205–206 °C. IR: υ_{max} (KBr)/cm^{-1}: 3303, 2961, 2869, 1681, 1604, 1543, 1515, 1451, 1432, 1314, 1266, 1229, 1087, 1045, 847, 817, 708 and 507. ^{1}H NMR (400 MHz, $CDCl_3$–DMSO, 10:1): δ = 0.97 (18H, s, *t*Bu × 2), 1.02 (18H, s, *t*Bu × 2), 2.27 (6H, s, CH_3 × 2), 4.26 (4H, s, OCH_2–triazole × 2), 4.95 (4H, s, OCH_2CO × 2), 6.32 (4H, s, CH_2–pyrene × 2), 6.74 (2H, s, Triazole–*H* × 2), 6.98 (4H, d, *J* = 7.7 Hz, Phenyl–*H* × 4), 7.14 (4H, s, Ar–*H* × 2), 7.17 (4H, d, *J* = 7.7 Hz, Phenyl–*H* × 4), 7.31 (4H, s, Ar–*H* × 2), 7.54 (2H, s, N*H* × 2) and 7.86–8.36. (22H, m, Pyrene–*H* × 18 and N*H* × 4) ppm. ^{13}C NMR (100 MHz, $CDCl_3$–DMSO, 10:1): δ = 21.7 (CH_3), 31.6 (CH_3), 31.8 (CH_3), 34.9 ($C(CH_3)_3$), 52.3 (CH_2), 64.0 (OCH_2), 70.0 (OCH_2), 119.8 (ArC), 119.9 (ArC), 123.1 (ArC), 124.0 (ArC), 124.1 (ArC), 125.1 (ArC), 125.3 (ArC), 126.1 (ArC), 126.6 (ArC), 126.9 (ArC), 127.5 (ArC), 127.7 (ArC), 128.1 (ArC), 128.4 (ArC), 129.0 (ArC), 129.4 (ArC), 129.7 (ArC), 130.0 (ArC), 131.2 (ArC), 131.6 (ArC), 131.7 (ArC), 131.8 (ArC), 132.2 (ArC), 137.8 (ArC), 143.8 (ArC), 148.0 (ArC), 148.6 (ArC), 155.6 (ArC), 155.9 (ArC), 156.4 (ArC), 157.0 (CO) and 168.0 (CO) ppm. FABMS: *m/z*: 1721.5 (M^+). $C_{100}H_{96}N_{12}O_8S_4$ (1722.17): calcd C 69.74, H 5.64, N 9.76. Found: C 69.58, H 5.54, N 9.67.

4.2.4. Synthesis of receptor $\mathbf{5_c}$. To compound **4** (100 mg, 0.0687 mmol) in THF (10 mL) was added *p*-nitrophenyl isocyanate (45 mg, 0.275 mmol) and the mixture was stirred at room temperature for 24 h under argon. The resulting precipitate was collected by filtration, washed with methanol to give receptor $\mathbf{5_c}$ as a yellow solid. Recrystallization from chloroform–acetonitrile (3:1) gave receptor $\mathbf{5_c}$ (154 mg, 83 %) as white solid. M.p. 204–207 °C. IR: υ_{max} (KBr)/cm^{-1}: 3366, 3338, 2961, 1733, 1597, 1554, 1508, 1433, 1330, 1302, 1248, 1201, 1178, 1113, 1087, 848 and 752. ^{1}H NMR (400 MHz, $CDCl_3$–DMSO, 10:1): δ = 0.95 (18H, s, *t*Bu × 2), 1.04 (18H, s, *t*Bu × 2), 4.32 (4H, s, OCH_2–triazole × 2), 4.95 (4H, s, OCH_2CO × 2), 6.32 (4H, s, CH_2–pyrene × 2), 6.72 (2H, s, Triazole–*H* × 2), 7.12 (4H, s, Ar–*H* × 2), 7.33 (4H, s, Ar–*H* × 2), 7.49 (4H, d, *J* = 8.8 Hz, Phenyl–*H* × 4), 7.63 (4H, d, *J* = 8.8 Hz, Phenyl–*H* × 4), 7.66 (2H, s, N*H* × 2), 7.87–8.33. (18H, m, Pyrene–*H* × 18), 8.50 (2H, s, N*H* × 2) and 8.98 (2H, s, N*H* × 2) ppm. ^{13}C NMR (100 MHz, $CDCl_3$–DMSO, 10:1): δ = 30.6 (CH_3), 30.8 (CH_3), 34.0 ($C(CH_3)_3$), 51.9 (CH_2), 62.7 (OCH_2), 68.9 (OCH_2), 117.5 (ArC), 117.7 (ArC), 122.2 (ArC), 123.1 (ArC), 124.3 (ArC), 124.7 (ArC), 124.9 (ArC), 125.0 (ArC), 125.6 (ArC), 125.7 (ArC), 125.8 (ArC), 126.2 (ArC), 127.1 (ArC), 127.2 (ArC), 127.5 (ArC), 128.0 (ArC), 128.4 (ArC), 128.6 (ArC), 128.9 (ArC), 130.4 (ArC), 130.7 (ArC), 131.0 (ArC), 131.7 (ArC), 142.0 (ArC), 143.1 (ArC), 145.2 (ArC), 145.3 (ArC), 147.2 (ArC), 148.0 (ArC), 154.4 (ArC), 154.9 (CO) and 167.4 (CO) ppm. FABMS: *m/z*: 1783.6 (M^+). $C_{98}H_{90}N_{14}O_{12}S_4$ (1784.1): calcd C 65.97, H 5.08, N 10.99. Found: C 65.78, H 5.51, N 10.82.

4.3. Determination of the Association Constants

The association constants were determined by using ^{1}H NMR titration experiments in a constant concentration of host receptor (4.0×10^{-3} M) by varying the guest concentration (0–8.0×10^{-3} M). The ^{1}H NMR chemical shift of the urea protons (NH) signal was used as a probe. The association constant (K_a) for the complexes of receptor $\mathbf{5_{a\sim c}}$ were calculated by nonlinear curve-fitting analysis of the observed chemical shifts of the NH protons according to the literature procedure.[14]

4.4. ^{1}H NMR Titration Experiments

A solution of Bu_4NX (X = F, Cl, Br, I, AcO, PhCOO, H_2PO_4) in CD_3CN (4.0×10^{-3} M) was added to a $CDCl_3$–DMSO (10:1, v/v) solution of receptor $\mathbf{5_{a\sim c}}$ in the absence or presence of $AgSO_3CF_3$ in an NMR tube. ^{1}H NMR spectra were recorded after addition of the reactants and the

temperature of the NMR probe was kept constant at 27 °C. The ^{1}H NMR data of the most-representative complexes are given below:

receptor $\mathbf{5}_a\supset Ag^+$: ^{1}H NMR (300 MHz, $CDCl_3$–DMSO–CD_3CN, 10:1:1, v/v): δ = 4.52 (4H, br, CH_2–triazole × 2), 4.94 (4H, s, OCH_2CO × 2), 6.29 (4H, s, CH_2–pyrene × 2), 7.13 (4H, s, Ar–H × 2), 7.34 (4H, s, Ar–H × 2), 7.54 (2H, br, NH_c × 2), 7.68 (2H, s, Triazole–H × 2) and 7.79–8.38. (18H, m, Pyrene-H × 18) ppm.

receptor $\mathbf{5}_b\supset Ag^+$: ^{1}H NMR (300 MHz, $CDCl_3$–DMSO–CD_3CN, 10:1:1, v/v): δ = 4.56 (4H, br, CH_2–triazole × 2), 5.00 (4H, s, OCH_2CO × 2), 6.32 (4H, s, CH_2–pyrene × 2), 7.07 (4H, d, J = 8.8 Hz, Phenyl–H × 4), 7.12 (4H, s, Ar–H × 2), 7.30 (4H, d, J = 8.8 Hz, Phenyl–H × 4), 7.48 (4H, s, Ar–H × 2), 7.90 (2H, br, NH_c × 2), 7.95 (2H, s, Triazole–H × 2) and 8.00–8.41. (18H, m, Pyrene-H × 18) ppm.

receptor $\mathbf{5}_c\supset Ag^+$: ^{1}H NMR (300 MHz, $CDCl_3$–DMSO–CD_3CN, 10:1:1, v/v): δ = 4.52 (4H, br, CH_2–triazole × 2), 4.95 (4H, s, OCH_2CO × 2), 6.32 (4H, s, CH_2–pyrene × 2), 7.12 (4H, s, Ar–H × 2), 7.50 (4H, s, Ar–H × 2), 7.63 (4H, d, J = 8.8 Hz, Phenyl–H × 4), 7.69 (4H, d, J = 8.8 Hz, Phenyl–H × 4), 7.70 (2H, br, NH_c × 2), 7.80 (2H, s, Triazole–H × 2), 8.02–8.30. (18H, m, pyrene-H × 18), 8.45 (2H, br, NH_b × 2) and 8.98 (2H, br, NH_a × 2) ppm.

receptor $\mathbf{5}_c\supset Cl^-$: ^{1}H NMR (300 MHz, $CDCl_3$–DMSO–CD_3CN, 10:1:1, v/v): δ = 4.32 (4H, br, CH_2–triazole × 2), 5.00 (4H, s, OCH_2CO × 2), 6.32 (4H, s, CH_2–pyrene × 2), 6.72 (2H, s, triazole–H × 2), 7.12 (4H, s, Ar–H × 2), 7.33 (4H, s, Ar–H × 2), 7.49 (4H, d, J = 8.8 Hz, Phenyl–H × 4), 7.63 (4H, d, J = 8.8 Hz, Phenyl–H × 4), 7.70 (2H, br, NH_c × 2), 7.87–8.33. (18H, m, Pyrene-H × 18), 8.41 (2H, br, NH_b × 2) and 9.62 (2H, br, NH_a × 2) ppm.

$Ag^+\subset$ [receptor $\mathbf{5}_c\supset Cl^-$]: ^{1}H NMR (300 MHz, $CDCl_3$–DMSO–CD_3CN, 10:1:1, v/v): δ = 4.50 (4H, br, CH_2–triazole × 2), 5.00 (4H, s, OCH_2CO × 2), 6.32 (4H, s, CH_2–pyrene × 2), 7.12 (4H, s, Ar–H × 2), 7.48 (4H, s, Ar–H × 2), 7.63 (4H, d, J = 8.8 Hz, Phenyl–H × 4), 7.69 (4H, d, J = 8.8 Hz, Phenyl–H × 4), 7.86 (2H, br, NH_c × 2), 7.94 (2H, s, Triazole–H × 2), 8.02–8.30. (18H, m, Pyrene-H × 18), 8.44 (2H, br, NH_b × 2) and 9.60 (2H, br, NH_a × 2) ppm.

Acknowledgments

This work was performed under the Cooperative Research Program of "Network Joint Research Center for Materials and Devices (Institute for Materials Chemistry and Engineering, Kyushu University)". We would like to thank the OTEC at Saga University and the International Cooperation Projects of Guizhou Province (No. 20137005) for financial support. The EPSRC is thanked for a travel grant (to CR).

Supplementary data

Electronic Supplementary Information (ESI) available: Details of the ^{1}H/^{13}C NMR spectra, ^{1}H NMR and UV-vis titration experimental data, the Bensei–Hilderbrand plot and Job's plot, See DOI: 10.1039/b000000x/

References and notes

1. (a) Gutsche, C. D. *Calixarenes, An Introduction*, Royal Society of Chemistry: Cambridge, UK, **2008**; (b) Ikeda, A.; Shinkai, S. *Chem. Rev.* **1997**, *97*, 1713–1734; (c) Coquière, D.; Le Gac, S.; Darbost, U.; Sénèque, O.; Jabin, I.; Reinaud, O. *Org. Biomol. Chem.* **2009**, *7*, 2485–2500; (d) Cottet, K.; Marcos, P. M.; Cragg, P. J. *Beilstein J. Org. Chem.* **2012**, *8*, 201–226; (e) Mutihac, L.; Lee, J. H.; Kim, J. S.; Vicens, J. *Chem. Soc. Rev.* **2011**, *40*, 2777–2796; (f) Baldini, L.; Casnati, A.; Sansone, F.; Ungaro, R. *Chem. Soc. Rev.* **2007**, *36*, 254–266; (g) Kim, J. S.; Quang, D. T. *Chem. Rev.* **2007**, *107*, 3780–3799; (h) Joseph, R.; Rao, C. P. *Chem. Rev.* **2011**, *111*, 4658–4702; (i) Capici, C.; Cohen, Y.; D'Urso, A.; Gattuso, G.; Notti, A.; Pappalardo, A.; Pappalardo, S.; Parisi, M. F.; Purrello, R.; Slovak, S.; Villari, V. *Angew. Chem., Int. Ed.* **2011**, *50*, 12162–12167; (j) Talotta, C.; Gaeta1, C.; Qi, Z.; Schalley, C. A.; Neri, P. *Angew. Chem., Int. Ed.* **2013**, *52*, 7437–7441; (k) Wang, M.–X. *Acc. Chem. Res.* **2012**, *45*, 182–195.
2. (a) Kumagi, H.; Hasegawa, M.; Miyanari, S.; Sugawa, Y.; Sato, Y.; Hori, T.; Ueda, S.; Kamiyama, H.; Miyano, S. *Tetrahedron Lett.* **1997**, *38*, 3971–3972.
3. (a) Lhoták, P.; *Eur. J. Org. Chem.* **2004**, 1675–1692; (b) Morohashi, N.; Narumi, F.; Iki, N.; Hattori T.; Miyano, S. *Chem. Rev.* **2006**, *106*, 5291–5316.
4. (*a*) Nabeshima, T.; Saiki, T.; Kumitomo, S. *Org. Lett.* **2002**, *4*, 3207–3209; (b) Nabeshima, T.; Yoshihira, Y.; Saiki, T.; Akine, S.; Horn, E. *J. Am. Chem. Soc.* **2003**, *125*, 28–29; (c) Scarso, A.; Zaupa, G.; Houillon, F. B.; Prins, L. J.; Scrimin, P. *J. Org. Chem.* **2007**, *72*, 376–385; (d) Mohr, K.; Schmitz, J.; Schrage, R.; Trnkle, C.; Holzgrabe, U. *Angew. Chem., Int. Ed.* **2013**, *52*, 508–516; (e) Nussinov, R.; Tsai, C.–J. *Cell* **2013**, *153*, 293–305; (f) López–Vidal, E. M.; Fernández–Mato, A.; García, M. D.; Pérez–Lorenzo, M.; Peinador, C.; Quintetela, J. M. *J. Org. Chem.* **2014**, *79*, 1265–1270.
5. (a) Sessler, J. L.; Gale, P. A.; Cho, W. S. *Anion Receptor Chemistry*; Royal Society of Chemistry: Cambridge, U.K., **2006**; (b) Beer, P. D.; Gale, P. A. *Angew. Chem., Int. Ed.* **2001**, *40*, 486–516.
6. (a) Lee, J.–Y.; Cho, E.–J.; Mukamel, S.; Nam, K.–C. *J. Org. Chem.* **2004**, *69*, 943–950; (b) Kwon, J.–Y.; Jang, Y.–J.; Kim, S.–K.; Lee, K.–H., Kim J.–S.; Yoon, J. *J. Org. Chem.* **2004**, *69*, 5155–5157; (c) Esteban–Go´mez, D.; Fabbrizzi, L.; Licchelli, M. *J. Org. Chem.* **2005**, *70*, 5717–5720; (d) Thiagarajan, V.; Ramamurthy, P.; Thirumalai, D.; Ramakrishnan, V. T. *Org. Lett.* **2005**, *7*, 657–660; (e) Lu, H.; Xu, W.; Zhang, D.; Chen, C.; Zhu, D. *Org. Lett.* **2005**, *7*, 4629–4632; (f) Pfeffer, F. M.; Gunnlaugsson, T.; Jensen, P.; Kruger, P. E. *Org. Lett.* **2005**, *7*, 5357–5360; (g) Fang, L.; Chan, W.–H.; He, Y.–B.; Kwong, D. W.–J.; Lee, A. W.–M. *J. Org. Chem.* **2005,** *70*, 7640–7646; (h) Gunnlaugsson,T.; Kruger, P. E.; Jensen, P.; Tierney, J.; Paduka Ali, H. D.; Hussey, G. M. *J. Org. Chem.* **2005**, *70*, 10875–10878; (i) Dahan, A.; Ashkenazi, T.; Kuznetsov, V.; Makievski, S.; Drug, E.; Fadeev, L.; Bramson, M.; Schokoroy, S.; Rozenshine–Kemelmakher, E.; Gozin, M. *J. Org. Chem.* **2007**, *72*, 2289–2296; (j) Saha, S.; Ghosh, A.; Mahato, P.; Mishra, S.; Mishra, S. K.; Suresh, E.; Das, S.; Das, A. *Org. Lett.* **2010**, *12*, 3406–3409; (k) Lin, K.–K.; Wu, S.–C.; Hsu, K.–M.; Hung, C.–H.; Liaw, W.–F.; Wang, Y.–M. *Org. Lett.* **2013**, *15*, 4242–4245.
7. (a) Kundrat, O.; Dvorakova, H.; Eigner, V.; Lhoták, P. *J. Org. Chem.* **2010**, *75*, 407–411; (b) Kundrat, O.; Kroupa, J.; B□ hm, S.; Budka, J.; Eigner, V.; Lhoták, P. *J. Org. Chem.* **2010**, *75*, 8372–8375; (c) Kundrát, O.; Eigner, V.; Cuřínová, P.; Kroupa, J.; Lhoták, P. *Tetrahedron*, **2011**, *67*, 8367–8372; (d) Kundrat, O.; Eigner, V.; Dvorakova, H.; Lhoták, P. *Org. Lett.* **2011**, *13*, 4032–4035; (e) Slavik, P.; Dudic, M.; Flidrova, K.; Sykora, J.; Cisarova, I.; Pojarova, M.; Lhoták, P. *Org. Lett.* **2012**, *14*, 3628–3631; (f) Kundrat, O.; Dvorakova, H.; Böhm, S.; Eigner, V.; Lhoták, P. *J. Org. Chem.* **2012**, *77*, 2272–2278.
8. (a) Kumar, M.; Dhir, A.; Bhalla, V. *Org. Lett.* **2009**, *11*, 2567–2570; (b) Kumar, M.; Kumar. R.; Bhalla, V. *Tetrahedron*, **2009**, *65*, 4340–4344; (c) Kumar, M.; Kumar, R.; Bhalla, V.; *Tetrahedron Lett.* **2010**, *51*, 5559–5562; (d) Kumar, M.; Kumar, R.; Bhalla, V. *Org. Lett.* **2011**, *13*, 366–369; (e) Kumar, M.; Kumar, R.; Bhalla, V. *Org. Bio. Chem.* **2011**, *9*, 8237–8245; (f) Kumar, M.; Kumar, R.; Bhalla, V. *Tetrahedron Lett.* **2013**, *54*, 1524–1527.
9. (a) Li, Y.; Cai, C. *Chem. Asian. J.* **2011**, *6*, 2592–2605; (b) Li, X. *Chem. Asian. J.* **2011**, *6*, 2606–2616; (c) Kim, S.–H.; Park, S.–H.; Choi, J.–H.; Chang, S. *Chem. Asian. J.* **2011**, *6*, 2618–2634; (d) Wu, Y.; Dong, Y.; Li, J.; Huang, X.; Cheng, Y.; Zhu, C.; *Chem. Asian. J.* **2011**, *6*, 2725–2729; (e) Xu, J.; Filion, T. M., Prifti, F.; Song, J. *Chem. Asian. J.* **2011**, *6*, 2730–2737; (f) Wu, W.; Fu, Y.; Wang, C.; Ye, C.; Qin, J.; Li, Z. *Chem.*

Asian. *J*. **2011**, *6*, 2787–2795; (g) Wang, W.; Hong, S.; Tran, A.; Jiang, H.; Triano, R.; Liu, Y.; Chen, X.; Wu, P. *Chem*. *Asian*. *J*. **2011**, *6*, 2796–2802; (h) Michaels, H. A.; Zhu, L. *Chem*. *Asian*. *J*. **2011**, *6*, 2825–2834; (i) Wan, X.; Zhang, G.; Ge, Z.; Narain, R.; Liu, S. *Chem*. *Asian*. *J*. **2011**, *6*, 2835–2845.

10. (a) Dondoni, A.; Marra, A. *Tetrahedron*, **2007**, *63*, 6339–6345; (b) Galante, E.; Geraci, C.; Sciuto, S.; Campo, V. L.; Carvalho, I.; Sesti–Costa, R.; Guedes, P. M. M.; Silva, J. S.; Hill, L.; Nepogodiev, S. A.; Field, R. A. *Tetrahedron*, **2011**, *67*, 5902–5912; (c) Pathak, R. K.; Tabbasum, K.; Hinge, V. K.; Rao, C. P. *Chem*. *Eur*. *J*. **2011**, *17*, 13999–14003; (d) Picot, S. C.; Mullancy, B. R.; Beer, P. D. *Chem*. *Eur*. *J*. **2012**, *18*, 6230–6237; (e) Cagnoni, A. J.; Varela, O.; Uhrig, M. L.; Kovensky, J.; *Eur*. *J*. *Org*. *Chem*., **2013**, 972–983; (f) Zhang, F.; Luo, L.; Sun, Y.; Miao, F.; Bi, J.; Tan, S.; Tian, D.; Li, H. *Tetrahedron*, **2013**, *69*, 9886–9889; (g) Cho, J.; Lee, S.; Hwang, S.; Kim, S.–H.; Kim, J.–S.; and Kim, S. *Eur*. *J*. *Org*. *Chem*. **2013**, 4614–4623; (h) Menard, N.; Hériot, Y.; Mest, Y. L.; Reinaud, O.; Poul, N. L.; Colasson, B. *Chem*. *Eur*. *J*. **2013**, *19*, 10611–10618; (i) Nierengarten, I.; Nothisen, M.; Sigwalt, D.; Biellmann, T.; Holler, M.; Remy J.–S.; Nierengarten, J.–F. *Chem*. *Eur*. *J*. **2013**, *19*, 17552–17558.
11. (a) Chang, K.–C.; Su, I.–H.; Senthilvelan, A.; Chung, W.–S. *Org*. *Lett*. **2007**, *17*, 3363–3366; (b) Chen, Y.–J.; Chung, W.–S. *Eur*. *J*. *Org*. *Chem*. **2009**, 4770–4776; (c) Chang, K.–C.; Su, I.–H.; Wang, Y.–Y; Chung, W.–S. *Eur*. *J*. *Org*. *Chem*. **2010**, 4700–4704; (d) Ho, I.–T.; Haung, K.–C.; Chung, W.–S. *Chem*. *Asian*. *J*. **2011**, *6*, 2738–2746; (e) Hung, H.–C.; Chang, Y.–Y.; Luo, L.; Hung, C.–H.; Diau, E. W.–G.; Chung, W.–S. *Photochem*. *Photobiol*. *Sci*. **2014**, *13*, 370–379.
12. (a) Perez–Casas, C.; Yamato, T. *J*. *Incl*. *Phenom*. *Macrocyclic Chem*. **2005**, *53*, 1–8; (b) Yamato, T.; Perez-Casas, C.; Yamamoto, H.; Elsegood, M. R. J.; Dale, S. H.; Redshaw, C. *J*. *Incl*. *Phenom*. *Macrocyclic Chem*. **2006**, *54*, 261–269; (c) Perez–Casas, C.; Rahman, S.; Begum, N.; Xi, Z.; Yamato, T. *J*. *Incl*. *Phenom*. *Macrocyclic Chem*. **2008**, *60*, 173–185; (d) Ni, X.–L.; Zeng, X.; Redshaw, C.; Yamato, T. *J*. *Org*. *Chem*. **2011**, *76*, 3358–3370; (e) Ni, X.–L.; Zeng, X.; Redshaw, C.; Yamato, T. *Tetrahedron* **2011**, *67*, 3248–3253; (f) Ni, X.–L.; Tahara, J.; Rahman, S.; Zeng, X.; Hughes, D. L.; Redshaw, C.; Yamato, T. *Chem*. *Asian*. *J*. **2012**, *7*, 519–527; (g) Ni, X.–L.; Cong, H.; Yoshizawa, A.; Rahman, S.; Tomiyasu, H.; Rayhan, U.; Zeng X.; Yamato, T. *J*. *Mol*. *Struct*. **2013**, *1046*, 110–115; (h) Tomiyasu, H.; Jin, C.–C.; Ni, X.–L.; Zeng, X.; Redshaw, C.; Yamato, T. *Org*. *Biomol*. *Chem*. **2014**, *12*, 4917–4923.
13. Iki, N.; Morohashi, N.; Narumi, F.; Fujimoto, T.; Suzuki T.; S. Miyano, *Tetrahedron Lett*., **1999**, *40*, 7337–7341.
14. Benesi, H. A.; Hildebrand, J. H. *J*. *Am*. *Chem*. *Soc*. **1949**, *71*, 2703–2707.

Supplementary Material

Click here to download Supplementary Material: 7. SI.pdf

Supplementary Material

Click here to download Supplementary Material: 7. SI (Marked) .pdf