Complex interactions of pillar[5]arene with paraquats and bis(pyridinium) derivatives†

Chunju Li,*[a,b] Qianqian Xu,[a] Jian Li,[a] Feina Yao[a] and Xueshun Jia*[a,c]

Received 28th September 2009, Accepted 14th December 2009
First published as an Advance Article on the web 27th January 2010
DOI: 10.1039/b920146g

The complexation behavior of a series of paraquats (**G1**·2PF_6–**G5**·2PF_6) and bis(pyridinium) derivatives (**G6**·2PF_6–**G14**·2PF_6) with pillar[5]arene (**P5A**) host has been comprehensively investigated by ^{1}H NMR, ESI mass and UV-vis absorption spectroscopy. It is found that **P5A** forms 2 : 1 external complexes with *N*,*N*′-dialkyl-4,4′-bipyridiniums (**G1**–**G4**·2PF_6); while it forms 1 : 1 pseudorotaxane-type inclusion complexes with methylene [–$(CH_2)_n$–] linked bis(pyridinium) derivatives possessing appropriate chain lengths (n = 3–6, **G7**–**G10**·2PF_6). Host–guest association constants in dimethyl sulfoxide (DMSO) were determined, indicating **G7**–**G10**·2PF_6 axles form stable [2]pseudorotaxanes with **P5A** wheel in this very high polarity solvent and 1,4-bis(pyridinium)butane (**G8**·2PF_6) was the most suitable axle unit. Meanwhile, the nature of the substituents attached to 1,4-bis(pyridinium)butane dramatically affects the molecular recognition behavior. The introduction of pyridyls (**G13**·2PF_6) increases not only the K_a value ($4.5 \times 10^2 \rightarrow 7.4 \times 10^2$ M^{-1}), but also the charge transfer (CT) absorption (colorless→yellow). Furthermore, the solvent effects have also been investigated, showing they significantly influence the association strength during the course of host–guest complexation. Particularly, the K_a value of **P5A–G13**·2PF_6 in 1 : 1 (v:v) acetone-d_6/DMSO-d_6 is enhanced by a factor of 7.3 compared with pure DMSO-d_6 ($7.4 \times 10^2 \rightarrow 5.4 \times 10^3$ M^{-1}).

Introduction

Calixarenes are pronounced with regard to the third generation of supramolecular hosts, next to crown ethers and cyclodextrins, and are described as "macrocycles with (almost) unlimited possibilities".[1] Owing to the facile modification, perfect pre-organized structures and special binding characteristics, this class of molecules has now found application in a number of areas, including phase-transfer agents, ion-channel blockers, fluorescent probes, pharmaceutics, nanochemistry and crystal engineering.[2] To further improve their properties and functionalities, many efforts have been made to synthesize structurally similar scaffolds such as calixpyrroles,[3] calixpyridines,[4] calixfurans,[4b,5] resorcarenes[6] and heteroatom-bridged calixarenes.[7] It is well documented by Sessler *et al.*[3a,b,4] that calixpyrroles and calixpyridines show considerable promise in the area of anion recognition and sensing. Resorcarenes are cavity-shaped resorcinol derivatives, and are thought to be effective host cages to entrap small guests (ions and neutral molecules). The introduction of heteroatoms into the bridging positions of calixarenes, obtaining heteroatom-bridged calixarenes, could change the electronic and steric nature of typical calixarenes and therefore result in different binding properties. For example, Wang and co-workers[8] demonstrated that azacalix[*n*]pyridines (n = 5–10) were powerful host molecules able to bind with fullerenes C_{60} and C_{70}.

Recently, Ogoshi *et al.* reported the synthesis of a symmetrical calixarene analogue, pillar[5]arene (**P5A**).[9] **P5A** is a macrocyclic molecule made up of five hydroquinone units linked by methylene (–CH_2–) bridges at the 2 and 5 positions. Being different from the conventional calixarene's "basket" structure, **P5A** forms the symmetrical pillar architecture and its two cavity portals are identical. The structural features of **P5A** make it superior to calixarenes in the construction of pseudorotaxanes, polyrotaxanes and tubular assemblies. Therefore, comprehensive understanding of **P5A**'s binding behavior is very essential for developing pillararene-based nano-supramolecular assemblies. In this work, we choose a series of paraquats and bis(pyridinium) derivatives (Chart 1) as guest molecules, and carry out a systematic binding investigation using ^{1}H NMR spectra, ESI mass spectra and UV-vis spectra, which results in formation of some stable complexes with specific structures. Moreover, the solvent effects have also been investigated to see how they affect the association strength during the course of host–guest complexation. The present studies will serve to increase our understanding of this new class of host and therefore improve its applications in supramolecular chemistry.

Results and discussion

Complexation of paraquat derivatives by P5A

Paraquat (*N*,*N*′-dimethyl-4,4′-bipyridinium) and its derivatives have been widely utilized not only as herbicides,[10] but also as

[a]*Department of Chemistry, Shanghai University, Shanghai 200444, P. R. China. E-mail: cjli@shu.edu.cn, xsjia@mail.shu.edu.cn*
[b]*Beijing National Laboratory for Molecular Sciences, CAS Key Laboratory of Molecular Recognition and Function, Institute of Chemistry, Chinese Academy of Sciences, Beijing 100190, China*
[c]*Key Laboratory of Synthetic Chemistry of Natural Substances, Shanghai Institute of Organic Chemistry, Chinese Academy of Sciences, 345 Lingling Road, Shanghai 200032, China*

† Electronic supplementary information (ESI) available: Additional ^{1}H NMR spectra and ESI-MS spectra as mentioned in the text, and determination of association constants. See DOI: 10.1039/b920146g

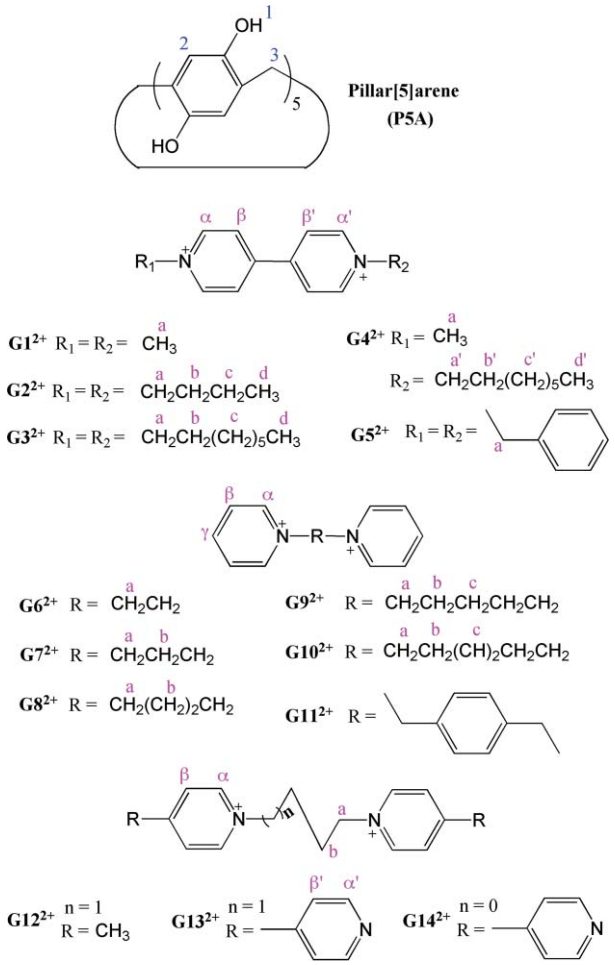

Chart 1 Structure and proton designations of the host and the guests.

probes to study DNA,[11] and as prooxidants in stress tests.[12] They have been extensively used in the fabrication of functional supramolecular systems with many kinds of hosts, including crown ethers,[13] cyclodextrins,[14] calixarenes[15] and cucurbiturils.[14a,16] Fig. 1 shows the ^{1}H NMR spectra of *N*,*N*′-dioctyl-4,4′-bipyridinium bishexafluorophosphate salt (**G3**·2PF$_6$) in acetone-d_6 recorded in the absence (Fig. 1c) and in the presence of approximately 1 equiv of host (Fig. 1b). The proton resonance bands attributed to both the viologen groups and methylene signals showed upfield shifts, accompanied with peak broadening. Therefore, we can deduce that the guest molecule is included in the cavity of **P5A**, which thus leads to an efficient shield toward guest protons.[17] The proton signal derived from the viologen α position (H$_\alpha$) exhibits a larger upfield shift than that from the β position (H$_\beta$), indicating that the **P5A** bead doesn't reach the central viologen nucleus of the guest. For methylenes, H$_a$ and H$_b$ exhibit the most remarkable complexation-induced broadening effects because their signals can't be observed in the ^{1}H NMR spectrum. In contrast, H$_c$ and H$_d$ protons of the guest don't show significant upfield shifts and broadening. These observations indicate that both the methylene moieties and pyridinium rings are partially included in the cavity of **P5A**. As we know, cation–π-electron interactions play a crucial role in the recognition of positively charged guests by the electron-rich π-systems of natural[18] and synthetic hosts.[19] Herein, the host **P5A** provides a three-dimensional, rigid, π-rich cavity. So the cation–π-electron interactions between host and pyridinium cations should be the important driving forces.[19]

We also attempted to perform ^{1}H NMR experiments for other guests (Chart 1) with **P5A** in acetone-d_6. Although these cationic guests have good solubility in acetone-d_6, in most cases, precipitation occurred immediately when mixing them with **P5A**, which itself signals an interaction between the host and guest. Therefore, we chose DMSO-d_6 as solvent for the ^{1}H NMR experiments. (Fig. S1) In DMSO-d_6, all of the host–guest mixtures are soluble. As can be seen from Fig. S1 (f & g), the changes of proton resonance bands of **G3**·2PF$_6$ observed upon **P5A** addition are not remarkable compared with using acetone-d_6 as solvent, indicating a weak binding interaction. But the broadening effects of H$_a$, H$_b$, H$_\alpha$ and H$_\beta$ protons of the guest **G3**·2PF$_6$ can also be observed. The NMR spectroscopic results suggest that **P5A** can bind paraquat derivative **G3**·2PF$_6$ in the highly polar DMSO solvent, but the association abilities are much weaker than in acetone. ^{1}H NMR experiments reveal that other alkyl-substituted viologens (**G1**·2PF$_6$, **G2**·2PF$_6$ and **G4**·2PF$_6$) behave similarly to **G3**·2PF$_6$, forming external complexation modes. (Fig. S1) In other words, in DMSO, inclusion complexation takes place with these four paraquats in such a way that the main binding site for the host is the joint of alkyl and aromatic viologen residues. The complexation of **P5A** with paraquat derivative **G5**·2PF$_6$ containing two benzyl groups has also been investigated. It is quite different from the complexation between the host and alkyl-substituted paraquats, because the addition of **P5A** doesn't result in the upfield displacement and broadening of the proton peaks in guest **G5**·2PF$_6$, indicating that the **P5A-G5**·2PF$_6$ complex does not form. This is reasonable because the benzyl unit is too bulky to entirely locate in the **P5A** cavity. Furthermore, the shape of the **G5**$^{2+}$ dication, with two pronounced methylene bending points, could be another reason for the uncomplexation between this guest and **P5A**.

Formation of pseudorotaxanes from P5A and bis(pyridinium) derivatives

As mentioned above, **P5A** forms a symmetrical architecture, with two identical cavity portals. However, because the viologen group is relatively bulky, **P5A** can't reside on the viologen nucleus of dicationic paraquat guests to form pseudorotaxane-type complexes. Thus, we prepared a series of symmetrical bis(pyridinium) bishexafluorophosphate salts in which two pyridinium units are connected by methylene [–(CH$_2$)$_n$–] linkers (n = 2–6, **G6**·2PF$_6$–**G10**·2PF$_6$). Fig. 2 & S2 shows the ^{1}H NMR spectra of these guests in DMSO-d_6 recorded in the absence and in the presence of an equivalent amount of **P5A** host.

As seen from Fig. 2 & S2, the addition of **P5A** dramatically affects the resonances of bis(pyridinium) guests, resulting in the upfield displacement and broadening of the α pyridinium aromatic protons and the methylene protons of the guest, except for the **P5A-G6**·2PF$_6$ system. In the latter case, it is reasonable because its carbon chain length is too short as compared with the **P5A** depth. In fact, **G6**·2PF$_6$ derivatives are well documented to construct pseudorotaxanes with 24-crown-8 ethers.[20,21] When the linker possesses 4 or 5 methylenes (**G8**·2PF$_6$ or **G9**·2PF$_6$), the complexation-induced upfield shift and broadening effect are more remarkable. As can be seen from Fig. 2e and S2i, in the

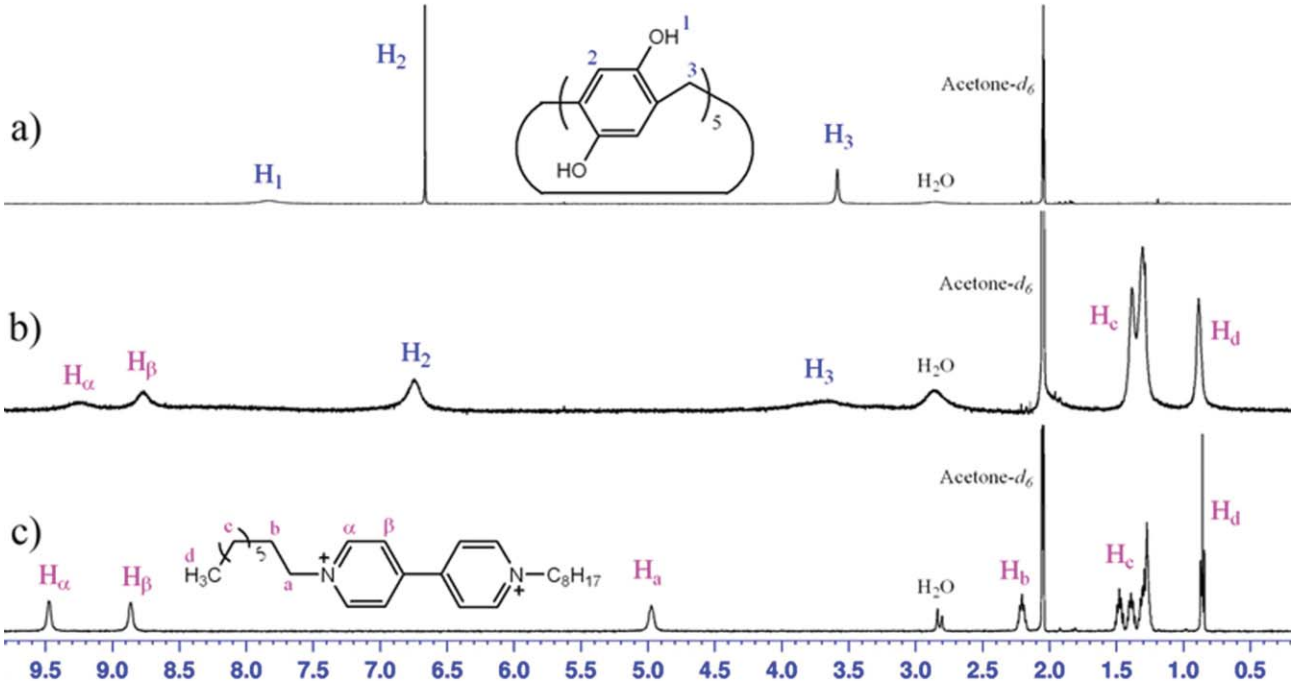

Fig. 1 ^{1}H NMR spectra (500 MHz) of (a) **P5A**, (b) **P5A** + **G3**·2PF$_6$, and (c) **G3**·2PF$_6$ in acetone-d_6 at 5.0 mM.

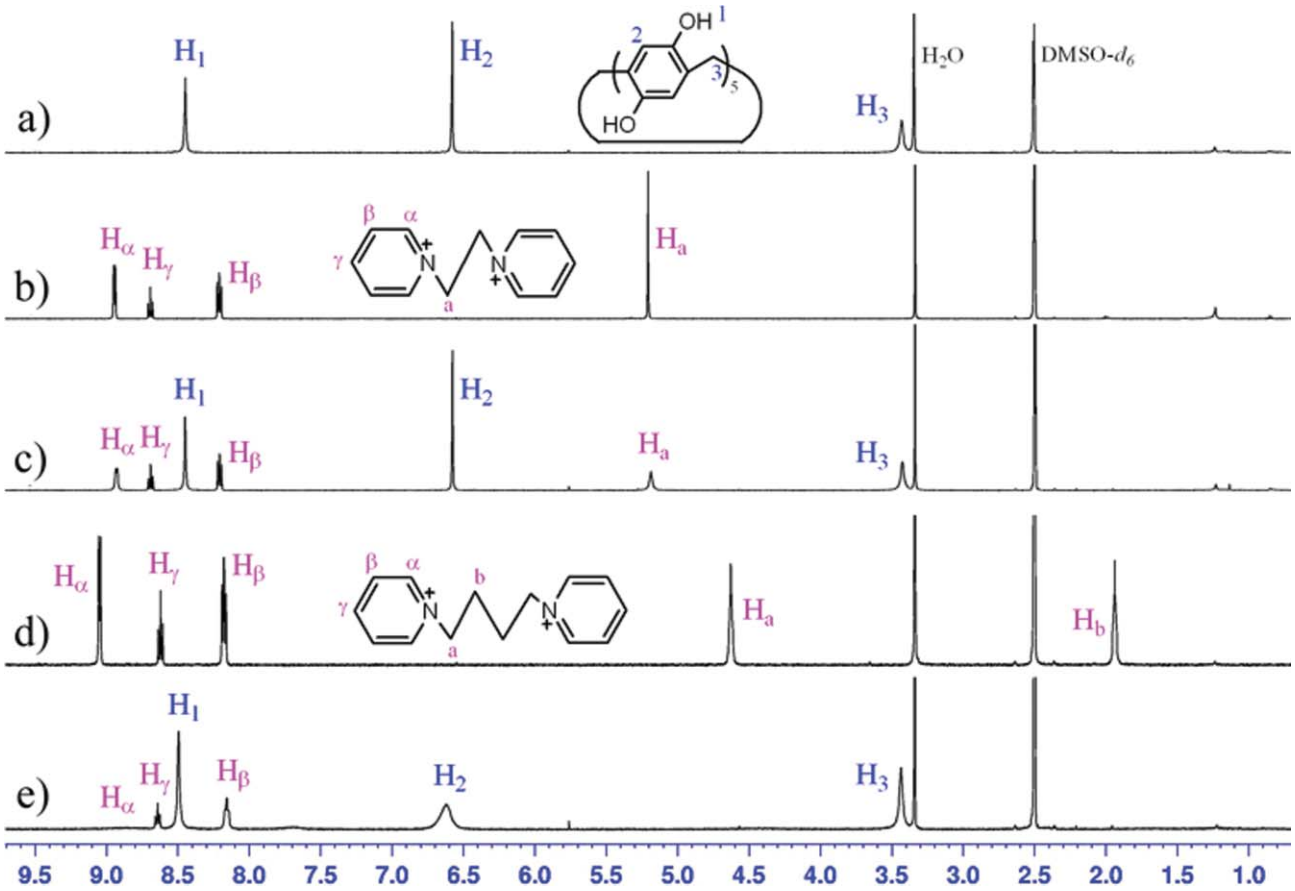

Fig. 2 ^{1}H NMR spectra (500 MHz) of (a) **P5A**, (b) **G6**·2PF$_6$, (c) **P5A** + **G6**·2PF$_6$, (d) **G8**·2PF$_6$ and (e) **P5A** + **G8**·2PF$_6$ in DMSO-d_6 at 4.5–5.0 mM.

presence of about 1 equiv of **P5A**, proton signals derived from methylene (H_a, H_b & H_c) of the linked chain show very significant broadening effects and we can't identify them in the NMR spectra. At the same time, the signal corresponding to the α-protons of the pyridine group exhibits a pronounced upfield shift and broadening effect, while no obvious changes were observed for the β- and γ-protons. In the control experiments, under identical conditions no NMR changes of **G8**·2PF_6 and **G9**·2PF_6 occurred upon addition of hydroquinone, *i.e.*, the monomeric unit of **P5A** host. Hence, the **P5A**-induced upfield shifts and broadening effects on the pyridine α-protons and methylene protons reveal that the host engulfs the central part, forming stable internal inclusion complexes with **G8**·2PF_6 and **G9**·2PF_6. Similar **P5A** complexation-induced effects are observed for guests **G7**·2PF_6 and **G10**·2PF_6, having three- and six-carbon chains. But the broadening effects are relatively weak by comparison with **G8**·2PF_6 and **G9**·2PF_6 systems.

Due to the similar complexation effects observed with **G7**·2PF_6–**G10**·2PF_6, all guests must have a similar mode of binding with **P5A**. That is to say, the host is fully threaded by these four bis(pyridinium) guests and the main binding site for the host is the methylene linker. Meanwhile, a small part of the pyridinium ring (N^+ & α-position) is also included in the host cavity. These inclusion complexes can be considered to have pseudorotaxane structures. Furthermore, we can deduce from the NMR changes that the two pyridinium units bridged by 4 and 5 methylenes (**G8**·2PF_6 and **G9**·2PF_6) are more suitable for **P5A**; longer or shorter chain lengths weaken the association abilities. The present formation of **P5A**-based pseudorotaxanes will broaden calixarene analogues' applications in supramolecular chemistry. Usually, calixarenes and their analogues are difficult to convert to pseudorotaxane-type complexes due to their "basket" structures.[22] Credi and Arduini *et al.*[22b] demonstrated the pseudorotaxane complexes between *N*-phenylureido-substituted calix[6]arene wheel and viologen axles. In this system, the calix[6]arene's cavity was extended and rigidified by *N*-phenylureido groups on the upper rim, so a viologen guest can be threaded into it. Beer and coworkers[22e] reported the anion-templated pseudorotaxanes and catenanes in which the wheel component is provided by a calix[4]arene macrobicyclic unit.

We also prepared compound **G11**·2PF_6, in which two pyridinium units are attached to a central phenylene unit *via* methylene linkers. In the presence of **P5A**, no signal change was observed for the proton signals of this guest. Similar to **G5**·2PF_6, **G11**·2PF_6 can't be bound because of the bulky volume of phenylene group and the steric hindrance of methylene bending points.

To examine the influence of substituted groups on the binding interaction of bis(pyridinium) guests by **P5A**, we prepared **G12**·2PF_6 and **G13**·2PF_6. When methyl groups are substituted to the *para* position of axle **G8**·2PF_6, affording **G12**·2PF_6, similar signal changes were observed from NMR spectra. (Fig. 3b) In contrast, for **G13**·2PF_6, having larger pyridyl groups, the **P5A**-induced changes in the ^{1}H NMR spectrum clearly depart from those observed with **G8**·2PF_6 and **G12**·2PF_6. Fig. 3d shows the corresponding spectra. Notice that a new species occurs, in addition to the corresponding signals for the uncomplexed cation and the pillararene host, indicating slow exchange on the NMR timescale. The resonances of the new species are consistent with the formation of an interpenetrated complex, the peaks for the methylene protons exhibit substantial upfield shifts compared to the free axle ($\Delta\delta = -2.11$ and -2.02 ppm for H_a and H_b, respectively) as a consequence of inclusion-induced

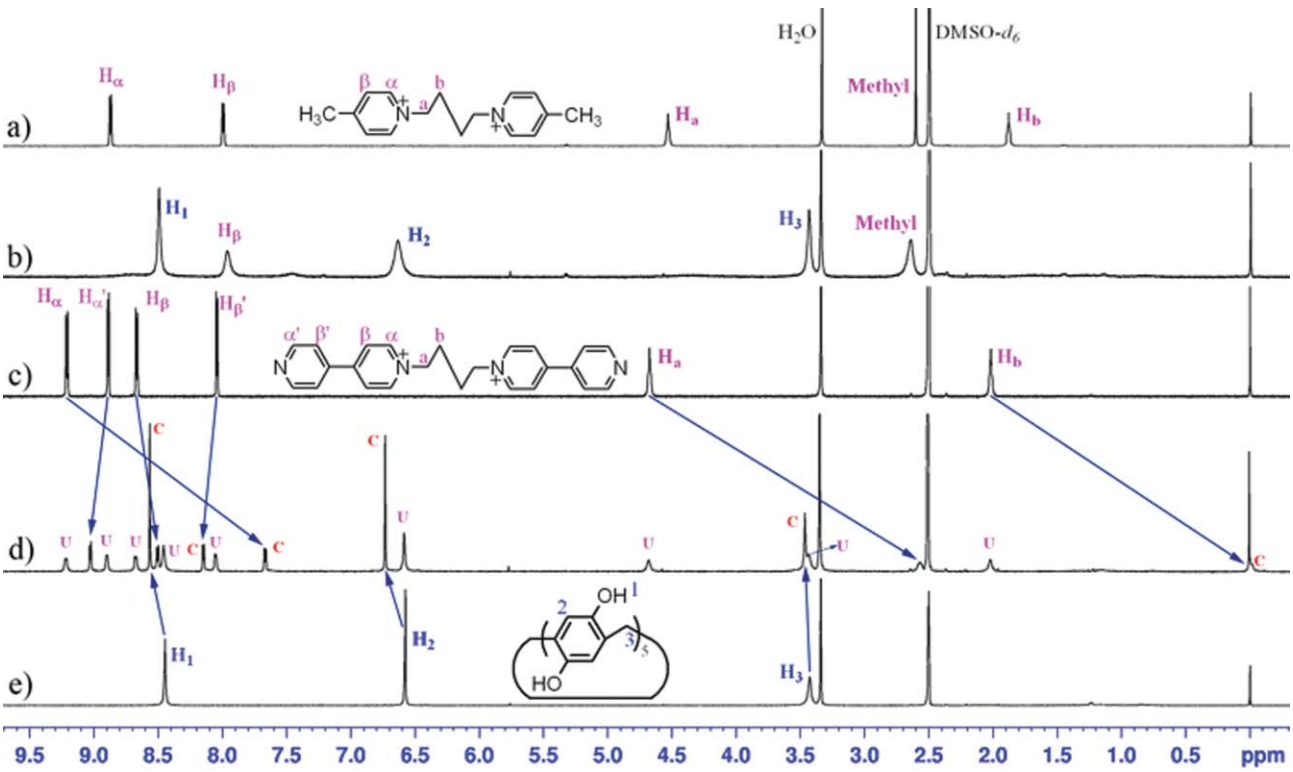

Fig. 3 ^{1}H NMR spectra (500 MHz) of (a) **G12**·2PF_6, (b) **P5A** + **G12**·2PF_6, (c) **G13**·2PF_6, (d) **P5A** + **G13**·2PF_6 and (e) **P5A** in DMSO-d_6 at 4.6–4.9 mM.

shielding effects.[17] The signals for the α'- and β'-protons (for proton identification, see Chart 1 or Fig. 3c) shift downfield no more than 0.15 ppm, while those for the α- and β-protons exhibit upfield shifts of 1.55 and 0.17 ppm, respectively. The NMR spectroscopic results show that internal complexation [at the central bis(pyridinium)-1,4-butane unit] occurs between **G13**·2PF$_6$ and **P5A**. Similar NMR signal changes were observed for **P5A–G14**·2PF$_6$ complex. But the proportion of complexed species of **P5A–G14**·2PF$_6$ was much smaller than that of **P5A–G13**·2PF$_6$, showing the weaker association strength between **P5A** and **G14**·2PF$_6$.

Complexation stoichiometry

It's essential to point out that the binding stoichiometries of paraquats and bis(pyridinium) derivatives with **P5A** are possibly different, due to their different complexation modes. Electrospray ionization mass spectrometry (ESI-MS) is a very convenient technique for determining the stoichiometry of the charged host–guest complexes. As shown in Fig. 4, the ESI mass spectrum of 1 : 1 mixture of **G1**·2PF$_6$ and **P5A** in methanol solution showed peaks for both 1 : 1{[**G1–P5A**]$^{2+}$ (*m*/*z* 398.6), [**G1**·PF$_6$–**P5A**]$^+$ (*m*/*z* 941.1)} and 2 : 1{[**G1–P5A**$_2$]$^{2+}$ (*m*/*z* 703.5), [**G1**·PF$_6$–**P5A**$_2$]$^+$ (*m*/*z* 1551.0)} host–guest complexes. Similar results were found when using other paraquat derivatives (**G2**·2PF$_6$–**G4**·2PF$_6$) as the guest molecules. (See Electronic Supplementary Information).

When we further tested the complexation stoichiometry between the host and the bis(pyridinium) derivatives **G6–G10**·2PF$_6$, it was interesting that the complexation stoichiometry was totally different from the cases of the paraquat derivatives. In the ESI mass spectrum of an equimolar mixture of **G8**·2PF$_6$ and **P5A** (Fig. 4), only two intense peaks for a 1 : 1 complex were observed, one for [**G8–P5A**]$^{2+}$ (*m*/*z* 412.5), and one for [**G8**·PF$_6$–**P5A**]$^+$ (*m*/*z* 969.1). Similarly, the host also forms a 1 : 1 complex with other bis(pyridinium) derivatives, **G6**·2PF$_6$, **G7**·2PF$_6$, **G9**·2PF$_6$ and **G10**·2PF$_6$ (see Electronic Supplementary Information).

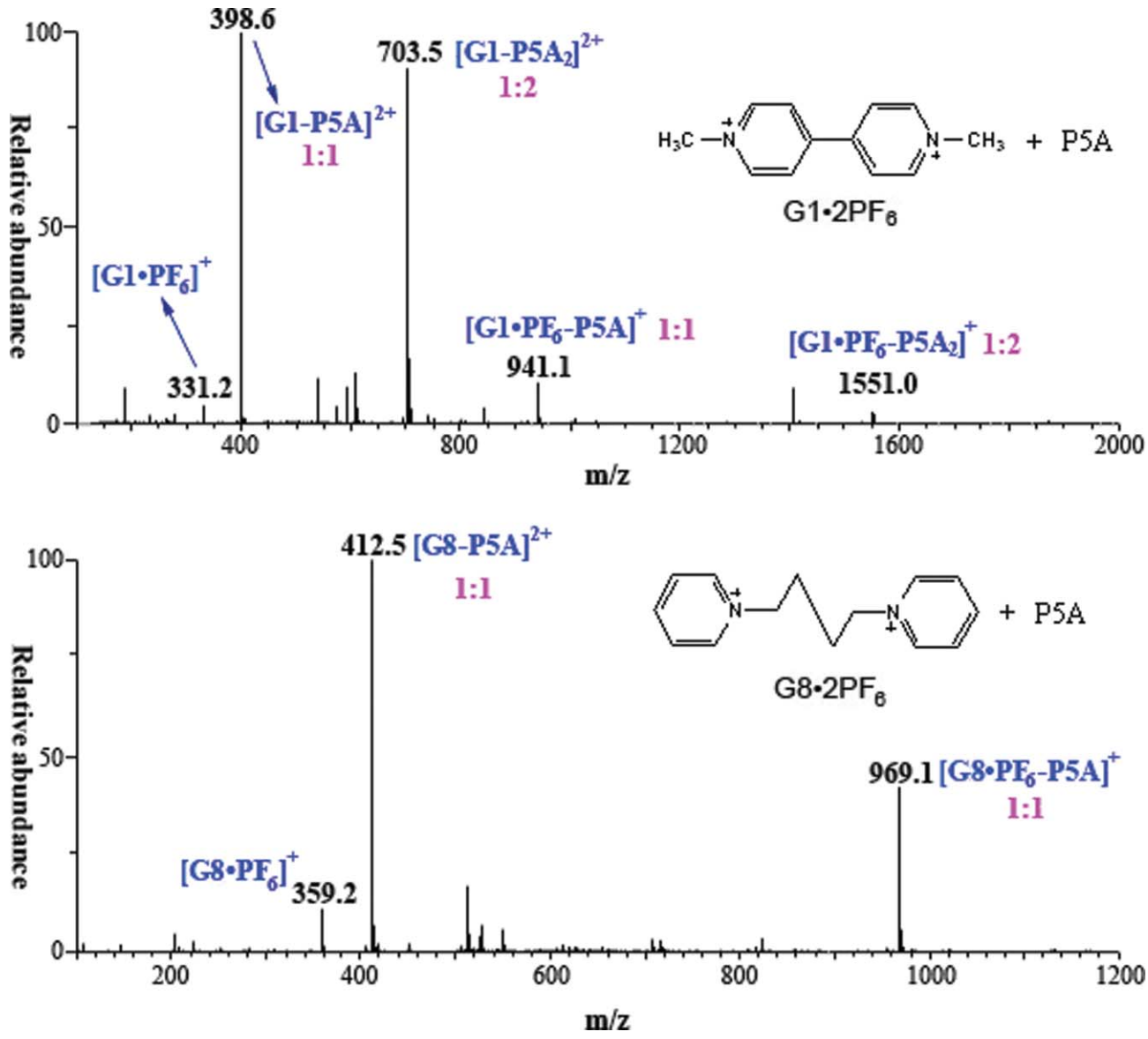

Fig. 4 ESI mass spectra of **G1**·2PF$_6$ and **G8**·2PF$_6$ in the presence of 1.2 eq **P5A** in methanol solution.

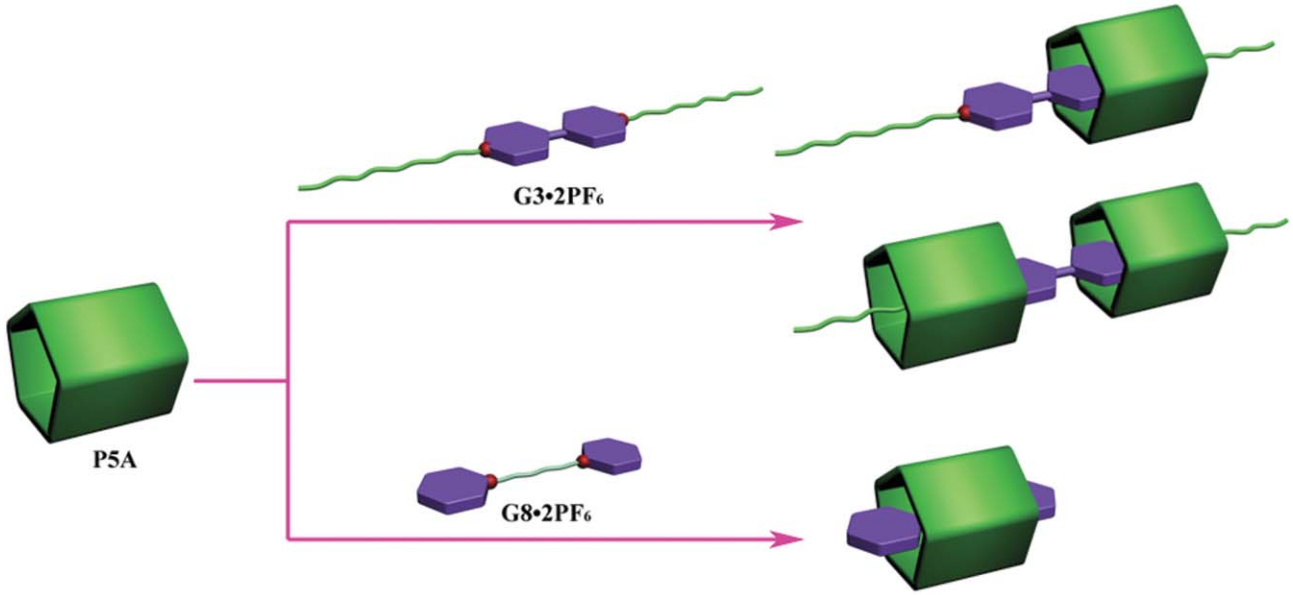

Fig. 5 Two different modes of binding interaction between the investigated guests and the **P5A** host.

Consequently, the ESI mass experiments indicate that **P5A** forms 2 : 1 host–guest complexes with paraquats, but 1 : 1 complexes with bis(pyridinium) derivatives.

Additionally, we performed a Job plot experiment. Job plots also showed the different complexation stoichiometries by calculating the host–guest charge transfer band (see Electronic Supplementary Information). Combined with the ^{1}H NMR experiments, we can unambiguously conclude the quite different binding modes of these two types of guests, as shown in Fig. 5.

Charge transfer

As can be seen from Fig. 6, upon addition of paraquat derivatives (**G1**·2PF$_6$–**G5**·2PF$_6$) to the DMSO solution of **P5A**, different spectroscopic behaviors were observed. While the mixture of **P5A** and **G5**·2PF$_6$ does not show a charge transfer (CT) band, the complexes **P5A** with **G1**–**G4**·2PF$_6$ give the obvious CT bands. Interestingly, the CT bands that appeared at about 450 nm lead these complexes to become light red. Upon mixing hydroquinone (the monomeric unit of **P5A**) with paraquat derivatives, no color change and CT band were observed. One may reasonably deduce that the longer CT band comes from the stronger π-stacking interactions between the electron-rich hydroquinone and the electron-poor viologen aromatic rings of paraquats. Moreover, the paraquat possessing four-carbon chains (**G4**·2PF$_6$) gives the strongest CT peak upon complexation with **P5A**. The CT absorption also implies that the pyridinium ring of paraquat is at least partially included in the **P5A** cavity, which is consistent with the binding mode determined by ^{1}H NMR spectra.

On the other hand, the equimolar mixture of **P5A** and bis(pyridinium) cations **G6**–**G11**·2PF$_6$ does not show a significant CT band. (Fig. 6) This is reasonable because pyridinium groups are relative weak electron acceptors compared with viologens. The introduction of electron-donating methyl groups (**G12**·2PF$_6$) to **G8**·2PF$_6$ doesn't change the CT band obviously, while the introduction of pyridyl groups (**G13**·2PF$_6$) significantly improves

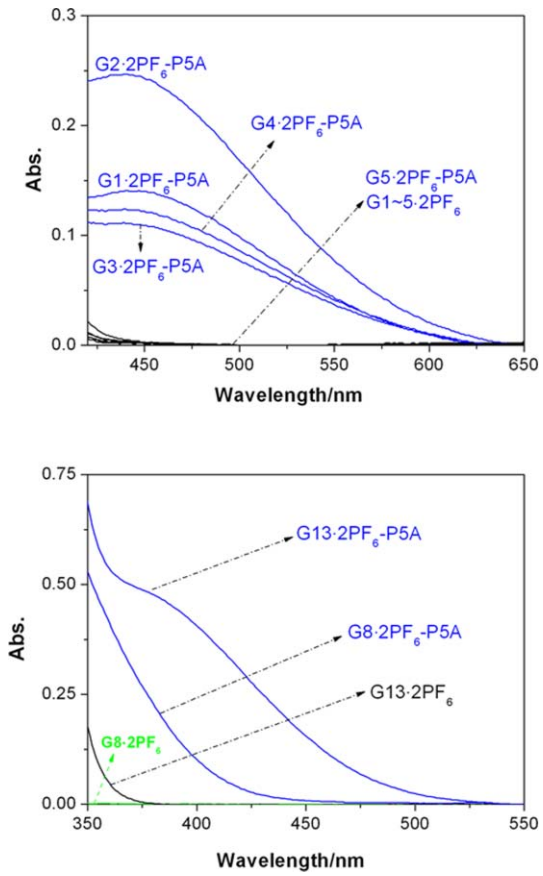

Fig. 6 Upper: UV-vis spectra of **G1**–**G5**·2PF$_6$ (1.9–2.0 mM) in the presence of about 2 eq **P5A** (4.0 mM); Lower: UV-vis spectra of **G8**·2PF$_6$ and **G13**·2PF$_6$ (1.9–2.1 mM) in the presence of about 1 eq **P5A** (2.0 mM) in DMSO at 298 K.

the CT absorption, leading the complex to become yellow. Pyridyl is a stronger electron-withdrawing group, and the resulting

Table 1 Association constants[23,24] (K_a/M^{-1}) for 1 : 1 inclusion complexation of **G6**–**G14**·2PF_6 with **P5A** in DMSO at 298 K

Guest	K_a
G6·2PF_6	—[a]
G7·2PF_6	$(8.8 \pm 0.7) \times 10$[b]
G8·2PF_6	$(4.5 \pm 0.4) \times 10^2$[b]
G9·2PF_6	$(3.7 \pm 0.3) \times 10^2$[b]
G10·2PF_6	$(1.2 \pm 0.1) \times 10^2$[b]
G11·2PF_6	—[a]
G12·2PF_6	$(4.0 \pm 0.3) \times 10^2$[b]
G13·2PF_6	$(7.4 \pm 0.3) \times 10^2$[c]
G14·2PF_6	$(1.2 \pm 0.2) \times 10^2$[c]

[a] The K_a value was too small to be calculated. [b] The K_a value was determined by probing the charge-transfer bands of the complex by UV-vis spectroscopy employing a titration method. [c] Chemical exchange was slow on the NMR time scale and peaks were observed for both complexed and uncomplexed species. K_a was determined by integration from a 1 : 1 mixture ([**G13**·2PF_6] = 4.7 mM, [**G14**·2PF_6] = 4.6 mM, [**P5A**] = 4.8 mM).

increased π-stacking interaction results in the stronger CT effect. This complexation-induced CT absorption is similar to that observed in the dibenzo-24-crown-8–1,2-bis(pyridinium)ethane inclusion complex, as previously reported by us.[21] Therefore, the chromophoric sensor behavior of complexation between **P5A** and bis(pyridinium) cations can be controlled by changing the substituting groups of the axles.

Molecular binding ability

As mentioned above (Fig. 3d), chemical exchange is slow on the NMR time scale and peaks are observed for both complexed and uncomplexed species in **P5A–G13**·2PF_6 and **P5A–G14**·2PF_6 host–guest complexes. So association constants[23,24] for these two complexes could be determined by integration from a 1 : 1 mixture using the ^{1}H NMR single point method.[25] For other bis(pyridinium) cations (**G6**–**G12**·2PF_6), however, it is not possible to determine values of K_a for **P5A**-guest complexes by direct NMR measurements, because they display fast exchange kinetics relative to the NMR chemical shift time scale. The association constants between **P5A** and **G6**–**G12**·2PF_6 were determined by UV-vis spectral titrations[26] (probing the CT bands) and the indirect method based on ^{1}H NMR spectroscopy[27] (See Electronic Supplementary Information). For paraquat derivatives, the average association constants[26,28] with the host are very small (K_{av} < 50 M^{-1}) in DMSO, and can't be calculated accurately. The K_a values of bis(pyridinium) derivatives (**G6**–**G14**·2PF_6) by **P5A** are listed in Table 1.

As can be seen from Table 1, large differences in the association constants are observed for complexation of bis(pyridinium) derivatives **G6**–**G11**·2PF_6 with **P5A**, suggesting that the linker pattern has a dramatic effect upon the molecular recognition behavior. The K_a value decreases in the following order:

$$\mathbf{G8}^{2+} > \mathbf{G9}^{2+} > \mathbf{G10}^{2+} > \mathbf{G7}^{2+} \gg \mathbf{G6}^{2+}, \mathbf{G11}^{2+}$$

When the two pyridinium cations are connected by ethylene and 1,4-xylylene to afford **G6**·2PF_6 and **G11**·2PF_6, the association constants are too small to be calculated. In contrast, **G8**·2PF_6, possessing four methylenes in its linker, gives the largest K_a value (4.5×10^2 M^{-1}), indicating that a bis(pyridinium) axle with four-carbon linker is the most suitable for a **P5A** wheel. The K_a values for **G7**·2PF_6, **G9**·2PF_6 and **G10**·2PF_6 with the host are reduced by factors of 5.1, 1.2, and 3.8, respectively, compared with that of **G8**·2PF_6. We also examined the electronic effect of the substituent groups on the complexation of **G8**·2PF_6 with **P5A**. Axle **G12**·2PF_6 possesses electron-donating methyl groups, while axle **G13**·2PF_6 presents electron-withdrawing pyridyl groups in their structures. The association constants follow the expected trend based on the electronic nature of the substituents. The substitution of methyl for hydrogen in **G8**·2PF_6, affording **G12**$^{2+}$·2PF_6, does not dramatically alter the original association ability ($K_a = 4.0 \times 10^2$ M^{-1}), but the introduction of pyridinium rings increases the K_a value 1.6 times for **G13**·2PF_6 ($K_a = 7.4 \times 10^2$ M^{-1}), implying increased π-stacking interactions with **P5A** host (Table 2). The association constants for the interaction of **P5A** with 1,4-bis(pyridinium)butane derivatives (**G8**·2PF_6, **G12**·2PF_6 and **G13**·2PF_6) in a very high-polarity DMSO solvent are comparable with the reported values of the formation of some pseudorotaxanes in relatively low-polarity CH_3CN.[20,21,29] Furthermore, since the pyridyl groups are located at the two ends of pseudorotaxane **P5A–G13**·2PF_6, it is convenient to construct **P5A**-based rotaxanes and catenanes through metal coordination and nucleophilic substitution.[13a,30]

Table 2 Association constants (K_a/M^{-1}) for 1 : 1 inclusion complexation of **P5A** and **G13**·2PF_6 in different solvents at 298 K

Solvent	K_a[a]
DMSO-d_6	$(7.4 \pm 0.3) \times 10^2$
DMSO-d_6 : CD_3OD[b]	$(2.3 \pm 0.2) \times 10^3$
DMSO-d_6 : CD_3CN[b]	$(4.9 \pm 0.1) \times 10^3$
DMSO-d_6 : $(CD_3)_2CO$[b]	$(5.4 \pm 0.2) \times 10^3$

[a] Chemical exchange was slow on the NMR time scale and peaks were observed for both complexed and uncomplexed species. K_a was determined by integration from a 1 : 1 mixture (4.5–4.8 mM). [b] 1 : 1 (v:v).

Solvent effects

It is well documented that solvents could significantly affect the K_a values upon complexation of host with guest. Warner and Liu *et al.*[31] have demonstrated that the addition of a small amount of organic solvents, such as alcohols, could alter the association abilities of cyclodextrin hosts toward model substrates in aqueous solution. Our previous work[32] reported the solvent effects of complexation of β-CD, calix[4]arenesulfonate and cucurbit[7]uril with dyes, and cucurbit[7]uril with alkaloids. The results indicated that the solvent effects dramatically influence not only the host–guest association affinity, but also the complexation selectivity. Recently, Clarkson[29b] and Huang[13f] *et al.* investigated the solvent effects on pseudorotaxane or taco-complex formation between macrocyclic crown ether and dicationic guests. Hence, it is interesting to study the effects of solvent in the host–guest association behaviors for the new synthetic receptor **P5A**.

To examine the influence of solvents on the association abilities of **P5A**, we performed the ^{1}H NMR experiments in 1 : 1 (v:v) CD_3OD/DMSO-d_6, CD_3CN/DMSO-d_6 and $(CD_3)_2CO$/DMSO-d_6 solution. The results for a representative **G13**·2PF_6 system are listed in Table 2. It can be seen that the solvent effects are very pronounced on the formation of **P5A–G13**·2PF_6 inclusion complex since the association constant significantly increased when the pure DMSO-d_6 was replaced by 1 : 1 solution mixed by CD_3OD,

CD_3CN or $(CD_3)_2CO$. During the course of complexation of **P5A** with these positively charged guests, cation–π-electron interactions should be the important driving forces,[19] which are dramatically affected by the solvent polarity. The solvent polarity increases in the order of $(CD_3)_2CO$ < CD_3CN < CD_3OD < DMSO-d_6. Therefore, it is reasonable that the **P5A–G13**·2PF_6 K_a values in 1 : 1 (v:v) CD_3OD/DMSO-d_6 (2.3×10^3 M^{-1}), CD_3CN/DMSO-d_6 (4.9×10^3 M^{-1}) and $(CD_3)_2CO$/DMSO-d_6 (5.4×10^3 M^{-1}) are enhanced by factors of 3.1, 6.6 and 7.3 compared with pure DMSO-d_6. Accordingly, the association strength of guests with **P5A** can be effectively modulated by changing solvents.

Conclusion

In summary, we have presented the binding behavior of paraquats and bis(pyridinium) derivatives by **P5A**. Different binding modes and complexation stoichiometry for the two types of guests were given. The host forms 2 : 1 external complexes with alkyl-substituted paraquats, and it forms 1 : 1 pseudorotaxane-type inclusion complexes with methylene connected bis(pyridinium) derivatives. The complexes constructed from **P5A** and paraquats resulted in a visible color change from colorless to light red, but their association constants are very small in high polarity DMSO solvent. In contrast, moderate K_a values were found for the formation of [2]pseudorotaxanes between bis(pyridinium) dicationic axles and the **P5A** wheel in DMSO. The nature of the substituents attached to the pyridinium rings in bis(pyridinium) guests affects the molecular recognition behavior. For the electron-withdrawing pyridyl groups, both the association ability and CT absorption are dramatically enhanced. For the electron-donating methyl groups, the K_a and CT absorption changes are not obvious. We have also explored the effect on the association constant of the solvent, indicating that solvent polarity exerted an extraordinary influence over the association ability. The decrease of solvent polarity can effectively enhance the association affinity of **P5A** host with guests. The present studies will clarify the inclusion characteristics of the new supramolecular host, pillar[5]arene, and therefore provide reference for further investigating the pillararene-based molecular recognition and assembly.

Experimental section

General

Ultraviolet-visible spectra were measured employing a Shimadzu UV-2401PC using a conventional 1 cm path (1 × 0.25 cm) quartz cell in a thermostated compartment, which was kept at 25 °C through a Shimadzu TB-85 Thermo Bath unit. ^{1}H NMR spectra were recorded on a Bruker AV500 instrument. ESI Mass spectra were performed on a Thermofinnigan LCQ Advantage LC-MS.

Materials

Starting materials were commercially available unless noted otherwise. The host **P5A**[9] was prepared according to the literature procedures. With the exception of methyl viologen, which is commercially available, all other paraquat and bis(pyridinium) citromide salts (**G2**·2Br–**G14**·2Br) were prepared by literature methods.[16b,33,34] The hexafluorophosphate salts were precipitated from water by the addition of saturated aqueous NH_4PF_6 and recrystallized before use.

Acknowledgements

The authors thank the National Natural Science Foundation of China (Nos: 20902057 and 20872087), the Key Laboratory of Synthetic Chemistry of Natural Substances, Chinese Academy of Sciences, Leading Academic Discipline Project of Shanghai Municipal Education Commission (No: J50101) and the Innovation Fund of Shanghai University for financial support.

References

1 V. Böhmer, *Angew. Chem., Int. Ed. Engl.*, 1995, **34**, 713–745.
2 For reviews, see: (*a*) A. Ikeda and S. Shinkai, *Chem. Rev.*, 1997, **97**, 1713–1734; (*b*) S. J. Dalgarno, P. K. Thallapally, L. J. Barbour and J. L. Atwood, *Chem. Soc. Rev.*, 2007, **36**, 236–245; (*c*) D. M. Homden and C. Redshaw, *Chem. Rev.*, 2008, **108**, 5086–5130; (*d*) P. K. Lo and M. S. Wong, *Sensors*, 2008, **8**, 5313–5335; (*e*) V. I. Kalchenko, *Pure Appl. Chem.*, 2008, **80**, 1449–1458; (*f*) D.-S. Guo, K. Wang and Y. Liu, *J. Inclusion Phenom. Macrocyclic Chem.*, 2008, **62**, 1–21.
3 For reviews, see: (*a*) C.-H. Lee, H. Miyaji, D.-W. Yoon and J. L. Sessler, *Chem. Commun.*, 2008, 24–34; (*b*) J. L. Sessler, S. Camiolo and P. A. Gale, *Coord. Chem. Rev.*, 2003, **240**, 17–55; (*c*) P. Anzenbacher, R. Nishiyabu and M. A. Palacios, *Coord. Chem. Rev.*, 2006, **250**, 2929–2938.
4 (*a*) V. Kral, P. A. Gale, P. Anzenbacher, Jr., K. Jursikova, V. Lynch and J. L. Sessler, *Chem. Commun.*, 1998, 9–10; (*b*) J. L. Sessler, W.-S. Cho, V. Lynch and V. Král, *Chem.–Eur. J.*, 2002, **8**, 1134–1143.
5 K. Goto, *Chemistry of calixfurans. Topics in Heterocyclic Chemistry.*, 2008, **17**(Heterocyclic Supramolecules I), 97–121.
6 For reviews, see: (*a*) B. Botta, M. Cassani, I. D'Acquarica, D. Misiti, D. Subissati and G. Delle Monache, *Curr. Org. Chem.*, 2005, **9**, 337–355; (*b*) B. Botta, M. Cassani, I. D'Acquarica, D. Subissati, G. Zappia and G. Delle Monache, *Curr. Org. Chem.*, 2005, **9**, 1167–1202.
7 For reviews, see: (*a*) M.-X. Wang, *Chem. Commun.*, 2008, 4541–4551; (*b*) W. Maes and W. Dehaen, *Chem. Soc. Rev.*, 2008, **37**, 2393–2402; (*c*) T. Kajiwara, N. Iki and M. Yamashita, *Coord. Chem. Rev.*, 2007, **251**, 1734–1746; (*d*) N. Morohashi, F. Narumi, N. Iki, T. Hattori and S. Miyano, *Chem. Rev.*, 2006, **106**, 5291–5316.
8 (*a*) M.-X. Wang, X.-H. Zhang and Q.-Y. Zheng, *Angew. Chem., Int. Ed.*, 2004, **43**, 838–842; (*b*) E.-X. Zheng, D.-X. Wang, Q.-Y. Zheng and M.-X. Wang, *Org. Lett.*, 2008, **10**, 2565–2568.
9 (*a*) T. Ogoshi, S. Kanai, S. Fujinami, T. Yamagishi and Y. Nakamoto, *J. Am. Chem. Soc.*, 2008, **130**, 5022–5023; (*b*) T. Ogoshi, K. Umeda, T. Yamagishi and Y. Nakamoto, *Chem. Commun.*, 2009, 4874–4876; (*c*) D. Cao, Y. Kou, J. Liang, Z. Chen, L. Wang and H. Meier, *Angew. Chem. Int. Ed.*, 2009, **48**, 9721–9723.
10 (*a*) R. K. Russell, *J. Agric. Food Chem.*, 1978, **26**, 1460–1463; (*b*) M. A. Bacigalupo and G. Meroni, *J. Agric. Food Chem.*, 2007, **55**, 3823–3828.
11 A. M. Brun and A. Harriman, *J. Am. Chem. Soc.*, 1991, **113**, 8153–8159.
12 (*a*) E. Migliaccio, M. Giorgio, S. Mele, G. Pelicci, P. Reboldi, P. P. Pandolfi, L. Lanfrancone and P. G. Pelicci, *Nature*, 1999, **402**, 309–313; (*b*) J. Muffat, D. W. Walker and S. Benzer, *Proc. Natl. Acad. Sci. U. S. A.*, 2008, **105**, 7088–7093.
13 (*a*) J. D. Badjic, V. Balzani, A. Credi, S. Silvi and J. F. Stoddart, *Science*, 2004, **303**, 1845–1849; (*b*) J. D. Badjic, S. J. Cantrill and J. F. Stoddart, *J. Am. Chem. Soc.*, 2004, **126**, 2288–2289; (*c*) F. Huang, D. S. Nagvekar, C. Slebodnick and H. W. Gibson, *J. Am. Chem. Soc.*, 2005, **127**, 484–485; (*d*) F. Huang, H. W. Gibson, W. S. Bryant, D. S. Nagvekar and F. R. Fronczek, *J. Am. Chem. Soc.*, 2003, **125**, 9367–9371; (*e*) J. Zhang, F. Huang, N. Li, H. Wang, H. W. Gibson, P. Gantzel and A. L. Rheingold, *J. Org. Chem.*, 2007, **72**, 8935–8938; (*f*) K. Zhu, S. Li, F. Wang and F. Huang, *J. Org. Chem.*, 2009, **74**, 1322–1328; (*g*) X.-X. Peng, H.-Y. Lu, T. Han and C.-F. Chen, *Org. Lett.*, 2007, **9**, 895–898; (*h*) J.-M. Zhao, Q.-S. Zong, T. Han, J.-F. Xiang and C.-F. Chen, *J. Org. Chem.*, 2008, **73**, 6800–6806.
14 (*a*) Y. Liu, X.-Y. Li, H.-Y. Zhang, C.-J. Li and F. Ding, *J. Org. Chem.*, 2007, **72**, 3640–3645; (*b*) A. Harada, *Acc. Chem. Res.*, 2001, **34**, 456–464; (*c*) Y. Kawaguchi and A. Harada, *Org. Lett.*, 2000, **2**, 1353–1356.

15 (*a*) D.-S. Guo, L.-H. Wang and Y. Liu, *J. Org. Chem.*, 2007, **72**, 7775–7778; (*b*) D.-S. Guo, X. Su and Y. Liu, *Cryst. Growth Des.*, 2008, **8**, 3514–3517; (*c*) A. R. Bernardo, T. Lu, E. Córdova, L. Zhang, G. W. Gokel and A. E. Kaifer, *J. Chem. Soc., Chem. Commun.*, 1994, 529–530; (*d*) R. Castro, L. A. Godínez, C. M. Criss and A. E. Kaifer, *J. Org. Chem.*, 1997, **62**, 4928–4935.

16 (*a*) M. Kwangyul, J. Grindstaff, D. Sobransingh and A. E. Kaifer, *Angew. Chem., Int. Ed.*, 2004, **43**, 5496–5499; (*b*) M. Kwangyul and A. E. Kaifer, *Org. Lett.*, 2004, **6**, 185–188; (*c*) Y. H. Ko, E. Kim, I. Hwang and K. Kim, *Chem. Commun.*, 2007, 1305–1315; (*d*) H.-J. Kim, W. S. Jeon, Y. H. Ko and K. Kim, *Proc. Natl. Acad. Sci. U. S. A.*, 2002, **99**, 5007–5011; (*e*) P. Mukhopadhyay, A. Wu and L. Isaacs, *J. Org. Chem.*, 2004, **69**, 6157–6164.

17 (*a*) G. Arena, S. Gentile, F. G. Gulino, D. Sciotto and C. Sgarlata, *Tetrahedron Lett.*, 2004, **45**, 7091–7094; (*b*) N. Kon, N. Iki and S. Miyano, *Org. Biomol. Chem.*, 2003, **1**, 751–755; (*c*) Y. Liu, D.-S. Guo, H.-Y. Zhang, Y.-H. Ma and E.-C. Yang, *J. Phys. Chem. B*, 2006, **110**, 3428–3434.

18 J. L. Sussman, M. Harel, F. Frolow, C. Oefner, A. Goldman, L. Toker and I. Silman, *Science*, 1991, **253**, 872–879.

19 (*a*) P. C. Kearney, L. S. Mizoue, R. A. Kumpf, J. F. Forman, A. McCurdy and D. A. Dougherty, *J. Am. Chem. Soc.*, 1993, **115**, 9907–9919; (*b*) K. Araki, H. Shimizu and S. Shinkai, *Chem. Lett.*, 1993, 205–208; (*c*) R. Ungaro, A. Casnati, F. Ugozzoli, A. Pochini, J.-F. Dozol, C. Hill and H. Rouquette, *Angew. Chem., Int. Ed. Engl.*, 1994, **33**, 1506–1509; (*d*) J. C. Ma and D. A. Dougherty, *Chem. Rev.*, 1997, **97**, 1303–1324; (*e*) F. Arnaud-Neu, S. Fuangswasdi, A. Notti, S. Pappalardo and M. F. Parisi, *Angew. Chem., Int. Ed.*, 1998, **37**, 112–114; (*f*) J. T. Lenthalla and J. W. Steed, *Coord. Chem. Rev.*, 2007, **251**, 1747–1760.

20 (*a*) S. J. Loeb and J. A. Wisner, *Angew. Chem., Int. Ed.*, 1998, **37**, 2838–2840; (*b*) S. J. Loeb, J. Tiburcio and S. J. Vella, *Org. Lett.*, 2005, **7**, 4923–4926.

21 (*a*) Y. Liu, C.-J. Li, H.-Y. Zhang, L.-H. Wang and X.-Y. Li, *Eur. J. Org. Chem.*, 2007, 4510–4516; (*b*) Y. Liu, C.-J. Li, H.-Y. Zhang, L.-H. Wang, Q. Luo and G. Wang, *J. Chem. Phys.*, 2007, **126**, 064705.

22 (*a*) A. Arduini, R. Bussolati, A. Credi, G. Faimani, S. Garaud, A. Pochini, A. Secchi, M. Semeraro, S. Silvi and M. Venturi, *Chem.–Eur. J.*, 2009, **15**, 3230–3242; (*b*) A. Credi, S. Dumas, S. Silvi, M. Venturi, A. Arduini, A. Pochini and A. Secchi, *J. Org. Chem.*, 2004, **69**, 5881–5887; (*c*) A. Arduini, F. Ciesa, M. Fragassi, A. Pochini and A. Secchi, *Angew. Chem., Int. Ed.*, 2005, **44**, 278–281; (*d*) L. Wang, M. Vysotsky, A. Pop, M. Bolte and V. Böhmer, *Science*, 2004, **304**, 1312–1314; (*e*) M. D. Lankshear, N. H. Evans, S. R. Bayly and P. D. Beer, *Chem.–Eur. J.*, 2007, **13**, 3861–3870; (*f*) D. E. Phipps and P. D. Beer, *Tetrahedron Lett.*, 2009, **50**, 3454–3457.

23 K_a reported here should be taken as approximate because it does not take into account the extent of ion pairdissociation on the observed binding interaction with **P5A**. For a detailed discussion, see ref. 24.

24 (*a*) F. Huang, J. W. Jones, C. Slebodnick and H. W. Gibson, *J. Am. Chem. Soc.*, 2003, **125**, 14458–14464; (*b*) J. W. Jones and H. W. Gibson, *J. Am. Chem. Soc.*, 2003, **125**, 7001–7004.

25 J. C. Adrian, Jr. and C. S. Wilcox, *J. Am. Chem. Soc.*, 1991, **113**, 678–680.

26 H. A. Benesi and J. H. Hildebrand, *J. Am. Chem. Soc.*, 1949, **71**, 2703–2707.

27 (*a*) W. L. Mock and N. Y. Shih, *J. Org. Chem.*, 1986, **51**, 4440–4446; (*b*) S. Liu, C. Ruspic, P. Mukhopadhyay, S. Chakrabarti, P. Y. Zavalij and L. Isaacs, *J. Am. Chem. Soc.*, 2005, **127**, 15959–15967.

28 (*a*) K. A. Connors, *Binding Constants*, J. Wiley and Sons, New York, 1987, pp 78–86; (*b*) K. Zhu, J. He, S. Li, M. Liu, F. Wang, M. Zhang, Z. Abliz, H. Yang, N. Li and F. Huang, *J. Org. Chem.*, 2009, **74**, 3905–3912; (*c*) F. Huang, L. N. Zakharov, A. L. Rheingold, M. Ashraf-Khorassani and H. W. Gibson, *J. Org. Chem.*, 2005, **70**, 809–813.

29 (*a*) A. B. Braunschweig, C. M. Ronconi, J.-Y. Han, F. Arico, S. J. Cantrill, J. F. Stoddart, S. I. Khan, A. J. P. White and D. J. Williams, *Eur. J. Org,. Chem.*, 2006, 1857–1866; (*b*) L. Li and G. J. Clarkson, *Org. Lett.*, 2007, **9**, 497–500; (*c*) D. Castillo, P. Astudillo, J. Mares, F. J. González, A. Vela and J. Tiburcio, *Org. Biomol. Chem.*, 2007, **5**, 2252–2256.

30 For similar systems for crown ether-, cucurbituril- and cyclodextrin-based rotaxanes, please see: (*a*) S. J. Loeb, *Chem. Commun.*, 2005, 1511–1518; (*b*) S. J. Loeb and D. A. Tramontozzi, *Org. Biomol. Chem.*, 2005, **3**, 1393–1401; (*c*) V. Sindelar, K. Moon and A. E. Kaifer, *Org. Lett.*, 2004, **6**, 2665–2668; (*d*) J. Wu, F. Fang, W.-Y. Lu, J.-L. Hou, C. Li, Z.-Q. Wu, X.-K. Jiang, Z.-T. Li and Y.-H. Yu, *J. Org. Chem.*, 2007, **72**, 2897–2905; (*e*) Y. Liu, Y.-L. Zhao, H.-Y. Zhang and H.-B. Song, *Angew. Chem. Int. Ed.*, 2003, **42**, 3260–3263.

31 (*a*) J. M. Schuette, T. T. Ndou, A. M. de la Pela, S. Mukundan and I. M. Warner, Jr., *J. Am. Chem. Soc.*, 1993, **115**, 292–298; (*b*) E. L. Roberts, J. Dey and I. M. Warner, *J. Phys. Chem. A*, 1997, **101**, 5296–5301; (*c*) Y. Liu, Y. Song, Y. Chen, Z.-X. Yang and F. Ding, *J. Phys. Chem. B*, 2005, **109**, 10717–10726.

32 (*a*) C. Li, J. Li and X. Jia, *Org. Biomol. Chem.*, 2009, **7**, 2699–2703; (*b*) Y. Liu, C.-J. Li, D.-S. Guo, Z.-H. Pan and Z. Li, *Supramol. Chem.*, 2007, **19**, 517–523.

33 M. I. Attalla, N. S. McAlpine and L. A. Summers, *Z. Naturforsch. B*, 1984, **39**, 74–78.

34 J. Joseph, N. V. Eldho and D. Ramaiah, *Chem.–Eur. J.*, 2003, **9**, 5926–5935.

