Pergamon

Tetrahedron 58 (2002) 8993–8999

TETRAHEDRON

Synthesis and selective anion recognition of imidazolium cyclophanes

Yi Yuan,[a] Ge Gao,[a] Zong-Lin Jiang,[a] Jin-Song You,[a] Zhong-Yuan Zhou,[b] De-Qi Yuan[a] and Ru-Gang Xie[a,*]

[a]*Department of Chemistry, Sichuan University, Chengdu 610064, People's Republic of China*
[b]*Department of Applied Biology and Chemical Technology, The Hong Kong Polytechnic University, Hong Kong, People's Republic of China*

Received 18 June 2002; revised 23 August 2002; accepted 12 September 2002

Abstract—Cyclophanes based on imidazolium or benzimidazolium groups were synthesized as anion recognition motifs by quaternarization of the bridged imidazole or benzimidazole compounds with dibromides in acetonitrile under reflux with high dilution. X-Ray analysis showed that C–H···Br^- hydrogen bonds connected the hydrogen atoms of the cationic imidazolium rings, the *m*-xylene ring and the spacer of the macrocycle with bromide anions. ^{1}H NMR study in DMSO-d_6 showed that the H-2 of imidazolium rings and the proton of the benzene ring were shifted downfield upon addition of Br^-, suggesting the formation of the C–H···Br^-hydrogen bonds between the cyclophane and bromide anion in solution. UV spectroscopic titration in acetonitrile at 25°C showed 1:1 complexes between the cyclophanes and halide anions, and the binding constants (K_a) and Gibbs free energy changes ($-\Delta G°$) were calculated according to the modified Benesi–Hildebrand equation. Cyclophane **1·2PF$_6^-$** exhibits selective recognition for F^-, Cl^-, Br^- and I^- in acetonitrile. The binding constant of **1·2PF$_6^-$** with Cl^- is 4.06×10^4 M^{-1}, 2, 5 and 2000 times those of **1·2PF$_6^-$** with Br^-, F^- and I^-, respectively. Binding experiments indicate that the electrostatic interactions, hydrogen bonding and preorganization of the binding sites of the hosts play essential roles in the anion recognition by imidazolium cyclophanes.

1. Introduction

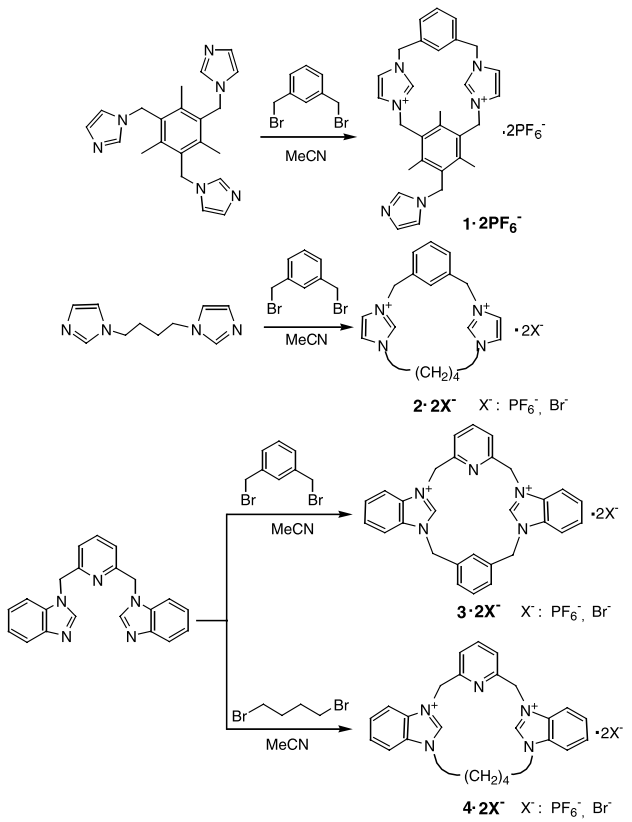
Host–guest systems for anionic species play important roles in the development of supramolecular chemistry.[1] The molecular recognition of anionic guests by artificial hosts is an area of ever increasing research activity. During the last two decades considerable efforts have been devoted to develop systems capable of recognizing, sensing, and transporting anionic species, but the design of effective hosts for anions are still particularly challenging because of the characteristics of the anions.[2]

Due to their macrocyclic properties and structural versatility, cyclophane compounds have received much attention in the field of host–guest coordination, molecular self-assembly and supramolecular catalysis in the last two decades.[3] Although much progress has been achieved, the construction of cyclophanes capable of selectively recognizing anions has not been fully exploited.[4] The design of such hosts requires the electronic and geometric characteristics of the anions to be taken into account.[5] For positively charged hosts with hydrogen bond donating groups, electrostatic interactions, especially hydrogen bonding may contribute to the attractive forces between anions and hosts. Based on this principle, various cyclophanes with ammonium or guanidinium groups as binding sites were designed and synthesized for anion recognition in recent years. Imidazole is an important group in biological systems,[6] and 1,3-disubstituted imidazole, namely imidazolium, is expected to be a good binding subunit for anions through cation–anion interactions and unconventional hydrogen bonds.[7] Pioneering work has been carried out by Howarth,[8a,b] Sato[8c] and their co-workers. They found that well-designed open-chain imidazolium salts bind strongly and selectively with anions in organic solvents. Different from other ammonium cyclophanes, imidazolium cyclophanes are stable both in acidic and basic media, which means that anion binding tests can be carried out in various media. Much work on the syntheses and structural analyses of imidazolium cyclophanes has been reported in recent years.[9] However, to the best of our knowledge, only one example using imidazolium cyclophanes as anion receptors has been reported by Alcalde and his colleagues in 1999.[10] They found that C–H···Cl^- hydrogen bonds play an important role in the anion binding of dicationic imidazoliophanes both in the solid state and in solution. Our research on imidazolium salts and cyclophanes[11] led us to investigate the anion recognition abilities of imidazolium cyclophanes. We report herein the facile synthesis and characterization of imidazolium and benzimidazolium cyclophanes **1**–**4** (Scheme 1), and their selective recognition of halide anions.

Keywords: molecular recognition; imidazole derivative; cyclophane; hydrogen bond; X-ray crystal structure.

* Corresponding author. Tel.: +86-28-85411684; fax: +86-28-85412285; e-mail: schemorg@mail.sc.cninfo.net

0040–4020/02/$ - see front matter
PII: S0040-4020(02)01153-5



Scheme 1.

2. Results and discussion

2.1. Design and synthesis of cyclophanes 1·2X⁻–4·2X⁻ (X⁻=PF₆⁻ or Br⁻)

Cyclophanes **1·2X⁻–4·2X⁻** (X^-=PF_6^- or Br^-) having different molecular structures and binding subunits were designed and synthesized. Cyclophane **1·2PF₆⁻** contains two imidazolium groups that could function as anion binding sites, and a side imidazolyl group on the macrocyclic skeleton might serve as a special cooperating recognition site. Cyclophane **2·2X⁻** has two imidazolium rings connected by flexible 1,4-butylene and rigid *m*-xylylene groups. For comparison, cyclophanes **3·2X⁻** and **4·2X⁻** with two less electron-deficient benzimidazolium subunits linked to 1,4-butylene or *m*-xylene group were also synthesized.

The bridged imidazole and benzimidazole intermediates were synthesized by the N-alkylation of imidazole and benzimidazole, respectively, with the corresponding tribromide and dibromides in the presence of a slight excess of NaH in dry DMF at 0°C.[11] The cyclization reactions by quaternarization of the bridged intermediates with dibromides were carried out in acetonitrile under reflux with high dilution technique (Scheme 1).[11,12] The slow and simultaneous addition of the two reactants made the cyclization facile and efficient. All compounds were obtained in good yields (>70%) except **4·2Br⁻**, indicating that 1,4-dibromobutane was too flexible to perform the cyclization in high yield under the experimental conditions. The hexafluorophosphate salts of these cyclophanes were obtained by treatment of aqueous solutions of the corresponding bromide salts with a saturated aqueous solution of NH_4PF_6 in high yields. The structures of cyclophanes **1·2PF₆⁻**, **2·2Br⁻**–**4·2Br⁻** were determined by ^{1}H NMR, MS, IR and elemental analysis.

2.2. Solid state crystal structure of 2·2Br⁻

The single crystal of cyclophane **2·2Br⁻** was obtained in methanol. Its structure was confirmed by X-ray analysis (Fig. 1). Hydrogen bonding interactions between the dicationic cyclophane **2** and the counterion Br^- were found (Table 1).

The distances between the bromides and the protons of the

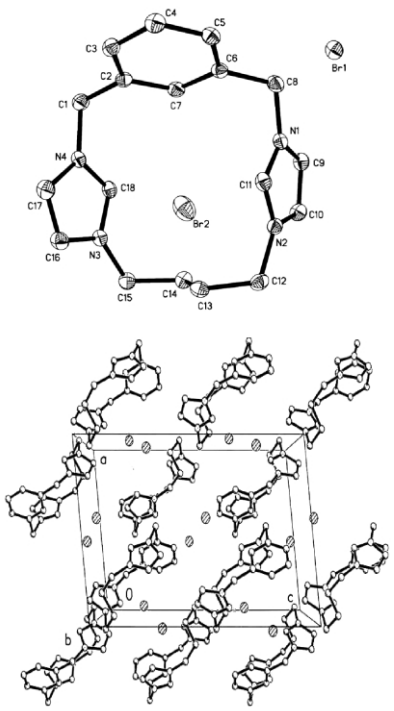


Figure 1. Crystal structure and cell packing of cyclophane **2·2Br⁻**. Hydrogen atoms are omitted for clarity. The conformation of the macrocyclic cation is characterized by the planarity of the C12···C15 chain and is defined by the dihedral angles formed by the planar parts of the cation: (C2···C7)/(N1, C9, C10, N2, C11)=73.05(5)°; (C2···C7)/(N3, C16, C17, N4, C18)=73.91(5)°; (C2···C7)/(C12···C15)=33.9(1)°; (N1, C9, C10, N2, C11)/(C12···C15)=85.81(8)°; (N3, C16, C17, N4, C18)/(C12···C15)=87.72(8)°.

Table 1. The C–H···Br^- interactions between dication imidazolium **2** and bromide anions (Fig. 1)

D–H···A	D–H(Å)	H···A(Å)	D···A(Å)	D–H···A(°)
C9–H9·Br1	0.90(2)	2.94(2)	3.797(2)	160(2)
C11–H11·Br2	0.87(2)	2.70(2)	3.543(2)	165(2)
C1–H1B·Br1^{i}	0.94(2)	2.96(2)	3.793(2)	149(1)
C7–H7·Br1^{ii}	0.92(2)	2.98(2)	3.860(2)	160(1)
C18–H18·Br1^{ii}	0.92(2)	2.66(2)	3.575(2)	171(2)
C8–H8B·Br2^{iii}	0.97	2.92	3.864(2)	165
C10–H10·Br2^{iv}	0.90(2)	2.91(2)	3.748(2)	156(2)
C15–H15B·Br2^{v}	0.97(2)	2.78(2)	3.744(2)	171(2)

D=donor, A=acceptor; symmetry transformations used to generate equivalent atoms are: ^{i} $-x-1$, $1/2+y$, $1/2-z$; ^{ii} $-x-1$, $-y$, $1-z$; ^{iii} $-x$, $y-1/2$, $1/2-z$; ^{iv} x, $1/2-y$, $1/2+z$; ^{v} $-x$, $1/2+y$, $1/2-z$.

imidazolium rings are 2.66–2.98 Å, which are significantly shorter than the sum of the van der Waals radius of a H-atom radius and the ionic radius of a bromide anion (3.15 Å), suggesting the formation of C–H···Br^- hydrogen bonds.[7] The strongest hydrogen bond is with the protons of the most electron-deficient carbons C11 (2.70 Å, θ=165°) and C18 (2.66 Å, θ=171°). Moreover, the bromide anion also forms a hydrogen bond with proton of the aromatic benzene ring. Interestingly, as the result of the influence of the imidazolium rings the protons of the methylene groups bind the bromide anions through C–H···Br^- interactions too. These results are unequivocal evidence for the attractive C–H···Br^- interaction between the dicationic imidazolium macrocycle and the bromide anions.[7,10]

2.3. ^{1}H NMR spectroscopic study of imidazolium cyclophane 1·2PF_6^- and its interaction with bromide anion

The ^{1}H NMR data of host **1·2PF$_6^-$** in DMSO-d_6 gives conformational information about the macrocycle (Fig. 2). The ^{1}H NMR spectrum of **1·2PF$_6^-$** having an imidazolylmethyl group as the side chain on the macrocycle shows split signals for the methylene protons on the macrocycle, indicating the conformational interconversion of the macrocycle in DMSO is slow on the NMR time-scale (Fig. 2a). This is different from the other cyclophanes **2·2Br$^-$**–**4·2Br$^-$** which show time-averaged signals for the methylene protons in the macrocycle in D_2O. The imidazolylmethyl and methyl groups on the benzene ring of the macrocyclic skeleton restrict the conformational freedom of the macrocyclic cavity, which might contribute to the selectivity of anion recognition. The H-2 signal of the side chain imidazolyl group was far downfield, indicating the strong deshielding effect of the two imidazolium rings on the imidazolyl side group.

The ^{1}H NMR study showed multipoint recognition of host **1·2PF$_6^-$** with bromide anion (Fig. 2, Table 2). In agreement with the reported results,[7,8,10] addition of an excess of tetrabutylammonium bromide to the DMSO-d_6 solution of

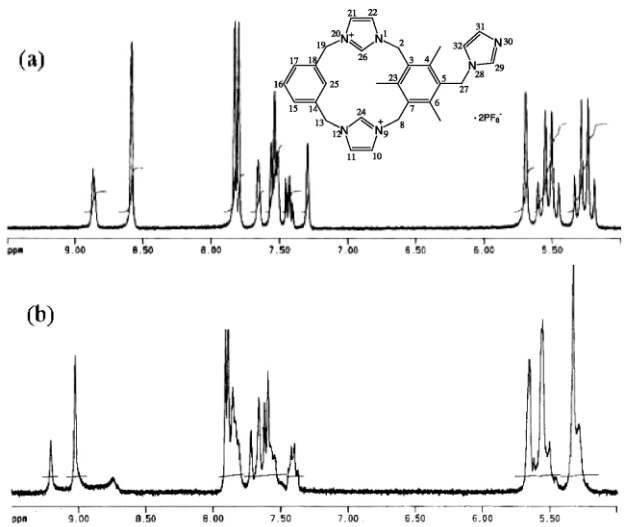


Figure 2. Selected regions of the ^{1}H NMR spectra of (a) cyclophane **1·2PF$_6^-$** (ca. 5 mM) and (b) cyclophane **1·2PF$_6^-$** with 15 equiv. of tetrabutylammonium bromide in DMSO-d_6 at 300 K.

Table 2. ^{1}H NMR chemical shift changes ($\Delta\delta=\delta_{complex}-\delta_{host}$, ppm) of selected protons of host **1·2PF$_6^-$** (ca. 5 mM) for the complexation of *n*-Bu_4NBr with **1·2PF$_6^-$** (ca. 75 mM) in DMSO-d_6 at 300 K

Proton	$\delta_{complex}$	δ_{host}	$\Delta\delta$
24,26-ImH-2	9.02	8.59	+0.43
25-ArH	7.72	7.30	+0.42
29-ImH-2	9.21	8.87	+0.34
10,11,21,22-ImH-4,5	7.90	7.82	+0.08
15,16,17-ArH	7.60	7.54	+0.06
27-CH_2	5.66	5.69	−0.03

1·2PF$_6^-$ resulted in a significant downfield shift of the imidazolium rings H-2 resonance (shifted from 8.59 to 9.02 ppm), which is consistent with the formation of C–H···X^- hydrogen-bonded complex. The signal of the benzene ring H-2 atom was shifted downfield too, showing the strong interaction of Br^- with the inner aromatic proton. Moreover, the H-2 of the side imidazole ring showed a downfield shift upon addition of Br^-, indicating that the imidazole group may stabilize the complex using ancillary non-covalent interactions. The other protons of the imidazolium, imidazole and benzene rings were shifted too, exhibiting the binding interactions between the cyclophane and bromide anion. A more detailed study of the hydrogen bonds between imidazole compounds and halide anions is under investigation.

2.4. Anion recognition of hosts 1·2PF_6^-–4·2PF_6^- in acetonitrile using UV spectroscopic titration

Among the various methods to characterize host–guest interactions, the UV–vis titration method is widely used for its high sensitivity to host–guest binding.[13] In this paper, the abilities of cyclophanes **1·2PF$_6^-$**–**4·2PF$_6^-$** to bind to anions were investigated using UV absorption methods.

In the UV spectroscopic titration experiments, addition of varying concentration of guest anions resulted in a gradual increase or decrease of the characteristic absorptions of the imidazolium host molecules. Typical UV spectral changes upon the addition of tetrabutylammonium bromide to host **3·2PF$_6^-$** are shown in Fig. 3.

The association constant of the supramolecular system formed were calculated according to the modified Benesi–Hildebrand equation, Eq. (1),[14] where $[H]_0$ and $[G]_0$ refer to the total concentration of the cyclophane and anion, respectively, $\Delta\varepsilon$ is the change in molar extinction coefficient between the free and complexed cyclophane, and ΔA denotes the absorption changes of the cyclophane on addition of guest anion.

$$\frac{[H]_0[G]_0}{\Delta A} = \frac{1}{\Delta\varepsilon K_a} + \frac{[G]_0}{\Delta\varepsilon} \quad (1)$$

The binding constants (K_a) and free-energy changes ($-\Delta G^\circ$) of these hosts with guest anions obtained from usual curve fitting analyses of observed absorbance changes are summarized in Table 3. Typical plots are shown for the complexation of host **3·2PF$_6^-$** with Br^- in Fig. 4. For the anions examined, Benesi–Hildebrand-type analyses give

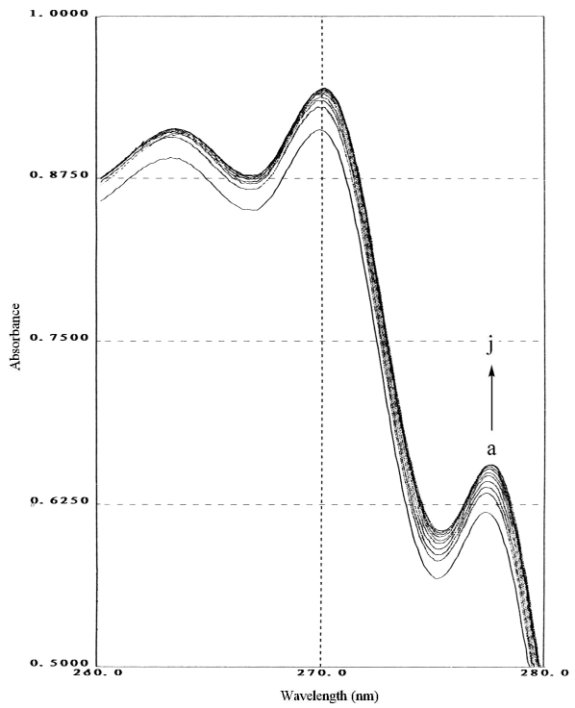


Figure 3. Selected regions of the UV titration spectra of **3·2PF$_6^-$** (5.99×10^{-5} mol dm^{-3}) with *n*-Bu_4NBr in acetonitrile at 298.2 K: [Br^-] a: 0, b: 0.83, c: 1.65, d: 3.30, e: 4.94, f: 6.58, g: 8.21, h: 9.84, i: 11.46 and j: 13.08×10^{-4} mol dm^{-3}.

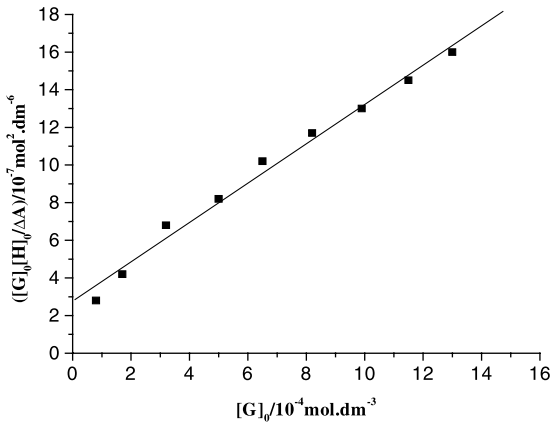


Figure 4. Typical plot of $[H]_0[G]_0/\Delta A$ versus $[G]_0$ for the host–guest complexation of **3·2PF$_6^-$** with *n*-Bu_4NBr in acetonitrile at 298.2 K.

good linear relationships (γ>0.99), consistent with the proposed 1:1 binding stoichiometry in each case.

Acetonitrile was used to investigate the binding abilities of hosts **1·2PF$_6^-$**–**4·2PF$_6^-$** to halide anions. As can be seen from Table 3, the imidazolium cyclophane **1·2PF$_6^-$** shows selective binding to halide anions in acetonitrile. The free energies of the complexes between **1·2PF$_6^-$** and halide anions followed the order $Cl^->Br^->F^->I^-$. Host **1·2PF$_6^-$** binds Cl^- most strongly, giving a binding constant K_a of 4.06×10^{-4} M^{-1}, 2, 5 and 2000 times of those of host **1·2PF$_6^-$** to Br^-, F^- and I^-, respectively. Examination of CPK molecular models suggests that the dimension of the cavity of imidazolium **1·2PF$_6^-$** is more suitable for chloride anion than other halide anions. It has been known that imidazolium compounds can bind halide anions using electrostatic interactions and C–H···X^- hydrogen bonds.[7,8,10] In view of the relative hydrogen-bonding ability, basicity and surface charge density of halide anions, the interaction between simple imidazolium cations and halide anions should be in the order of $F^->Cl^->Br^->I^-$. This experimental result of the binding order of cyclophane **1·2PF$_6^-$** to halide anions suggests that the selectivity of the anion recognition is also dependent upon the structure, shape and rigidity of the host cavity. In these cases fluoride and iodide anions are either too small or too big to form a stable complex with the macrocyclic cavity. Host **2·2PF$_6^-$** strongly binds to Cl^- and Br^- too, but the selectivity of **2·2PF$_6^-$** is much smaller than that of **1·2PF$_6^-$**. This difference indicates that the combination of imidazolylmethyl group to the macrocyclic cavity as a cooperating binding site resulted in good preorganization of the macrocycle compound **1·2PF$_6^-$**, contributing to the selective molecular recognition for halide anions. When less electron-deficient benzimidazolium cyclophanes (**3·2PF$_6^-$** and **4·2PF$_6^-$**) were used, the binding constants for Br^- were about one-third of those of **1·2PF$_6^-$** and **2·2PF$_6^-$**. This demonstrates that the cation–anion interaction and hydrogen bonding originating from the positively charged imidazoliums and benzimidazoliums play important roles in the binding process.

Table 3. Binding constants (K_a) and free energy of complexation ($-\Delta G°$) for the 1:1 complexes between cyclophanes **1·2PF$_6^-$**–**4·2PF$_6^-$** and halide anions in acetonitrile at 298.2 K

Host	Guest[a]	K_a (dm^3 mol^{-1})[b]	$-\Delta G°$ (kJ mol^{-1})
1·2PF$_6^-$	F^-	7760	22.2
	Cl^-	40,600	26.3
	Br^-	18,400	24.3
	I^-	20	7.4
2·2PF$_6^-$	F^-	2210	19.1
	Cl^-	15,700	23.9
	Br^-	17,900	24.3
	I^-	470	15.2
3·2PF$_6^-$	Br^-	5850	21.5
4·2PF$_6^-$	Br^-	6100	21.6

[a] The guest anions were used as the salts of Bu_4NF, Et_3NBnCl, Bu_4NBr and Bu_4NI, respectively.
[b] Binding constants were represented as the average of 2–3 experiments, errors were ±15%.

In addition, we also investigated the binding abilities of the bromide salts of these cyclophanes to anions in water. Because both the anions and hosts are strongly hydrated in water, the interactions between these hosts and anions are much weaker than those of the hexafluorophosphate salts of the same cyclophanes in acetonitrile.

3. Conclusion

In conclusion, a facile and efficient synthesis led to cyclophanes based on imidazolium and benzimidazolium units as molecular recognition motifs for anions. X-Ray structure analysis and ^1H NMR study show that the dicationic imidazolium cyclophanes form C–H···Br^- hydrogen bonds with bromide anions. Cyclophane **1·2PF$_6^-$** exhibits good selective anion recognition for halide anions in acetonitrile. The binding constant of **1·2PF$_6^-$** with Cl^- is up to 4.06×10^4 M^{-1}, 2, 5 and 2000 times of those of **1·2PF$_6^-$** with Br^-, F^- and I^-, respectively. **2·2PF$_6^-$** also shows

strong binding to Cl^- and Br^- in acetonitrile. Binding experiments indicate that the electrostatic interactions, hydrogen bonding and preorganization of binding sites of hosts play essential roles in the anion recognition.

4. Experimental

4.1. Physical measurements

Melting points were taken on a micro-melting point apparatus and are uncorrected. ^1H NMR spectra were recorded on a Bruker DPX-300 instrument and chemical shifts in ppm are reported with TMS as the internal standard. Mass spectra were measured on a Finnigan MAT-4510 or VG Autospec 3000 instrument. Elemental analyses were performed on a Carlo Erba 1106 instrument. IR spectra were obtained with a Nicolet FT-IR 170SX. UV–vis spectra were obtained with either a TU-1901 or a Perkin–Elmer Lambda 4B spectrophotometer. X-Ray diffraction analysis was performed with a Bruker CCD Area Detector Diffractometor apparatus.

4.2. Reagents and general techniques

Anhydrous DMF was purified according to the standard method. 1,3,5-Trimethyl-2,4,6-tris(*N*-imidazolylmethyl) benzene,[11f] 1,3-bis(bromomethyl)benzene[15] and 1,4-di-imidazolylbutane[11a] were prepared according to literature procedures. Acetonitrile was HPLC reagent grade. Deionized water was distilled before use. All other chemicals and reagents were obtained commercially and used without further purification.

4.2.1. Procedure for the preparation of 2,6-bis(*N*-benzimidazolylmethyl)pyridine. To a solution of benzimidazole (1.18 g, 10 mmol) in 20 mL dry DMF under nitrogen, NaH (0.26 g, 11 mmol) was added at 0°C. After stirring at the same temperature for 30 min, 2,6-bis(bromomethyl)pyridine (1.32 g, 5 mmol) in 20 mL DMF was added dropwise over 3 h. The mixture was stirred at the room temperature for 20 h, the solvent was removed in vacuo and the residue was purified by column chromatography on silica gel (CH_2Cl_2/EtOAc, 1:1, v/v) to give 2,6-bis(*N*-benzimidazolylmethyl)pyridine as a white powder in 81% yield (1.37 g), mp 162–164°C. Found: C, 74.1; H, 5.0; N, 20.8. Calcd for $C_{21}H_{17}N_5$: C, 74.3; H, 5.1; N, 20.6%. IR (KBr, ν_{max}, cm^{-1}): 3075s, 1613, 1585, 1495vs, 1458s, 1425, 1363s, 1270s, 1169s, 737vs, 639w. ^1H NMR (DMSO-d_6): 5.52 (s, 4H, CH_2), 7.02–7.24 (m, 6H, Py3,5-H, Benzimidazole ring H-5,6), 7.31–7.43 (m, 4H, BIH-4,7), 7.71 (m, 1H, PyH-4), 8.30 (s, 2H, BIH-2). MS (*m*/*z*, RA%): 339 (M^+, 28).

4.2.2. General procedure for the preparation of imidazolium cyclophanes 1·2PF$_6^-$ and 2·2X$^-$–4·2X$^-$ (X$^-$=Br$^-$ or PF$_6^-$). To 150 mL acetonitrile, the dibromide compound (1.0 mmol) in 200 mL acetonitrile and the 200 mL acetonitrile solution of the bridged imidazole or benzimidazole (1.0 mmol) was added slowly at the same rate over 15 h under reflux. The resulting mixture was stirred and refluxed for another 10–20 h until the bromide had disappeared (monitored by TLC). Then the solution was concentrated, cooled and filtered to give the crude bromide salt. On treatment of the aqueous solution of the bromide salt with a saturated aqueous solution of NH_4PF_6 a precipitate formed. This precipitate was collected, washed with water and dried to give the hexafluorophosphate salt of the cyclophane.

4,6,23-Trimethyl-5-*N*-imidazolylmethyl-12,20-diaza-1,9-diazanium pentacyclo[18. $2^{1,20}.1^{1,20}.1^{3,7}.1^{9,12}.1^{14,18}$]-hexacosane-1(26), 3, 5, 7(23), 9(24), 10, 14, 16, 18(25), 21-decene bis(hexafluorophosphate) salt (**1·2PF$_6^-$**): the crude bromide salt was purified by column chromatography on silica gel using MeOH/NH_3·H_2O/saturated aqueous NH_4HCO_3 (10:4:1, v/v/v) as eluant. The eluant was concentrated to dryness and water was added, the insoluble precipitate was filtered off. Then a saturated aqueous NH_4PF_6 solution was added to the filtrate leading to a white precipitate. The precipitate was washed several times with water and dried in vacuo. The hexafluorophosphate salt was obtained as a white solid in 71% yield (0.54 g), mp 268–270°C. Found: C, 46.3; H, 4.5; N, 10.9. Calcd for $C_{29}H_{32}N_6P_2F_{12}$: C, 46.1; H, 4.3; N, 11.1%. IR (KBr, ν_{max}, cm^{-1}): 3092, 2964, 1554s, 1456, 1316, 1285, 1145vs, 1076w, 895, 822, 749vs, 634s. ^1H NMR (DMSO-d_6): 1.53 (s, 3H, CH_3), 2.49 (s, 6H, CH_3), 5.26 (dd, J=14.4, 14.8 Hz, 4H, CH_2), 5.52 (dd, J=15.5, 14.4 Hz, 4H, $CH_{2'}$), 5.69 (s, 2H, CH_2), 7.30 (s, 1H, ArH), 7.43–7.46 (m, 1H, Imidazole ring H-4(5)), 7.52–7.56 (m, 3H, ArH), 7.65 (s, 1H, ImH-5(4)), 7.80 (d, J=1.5 Hz, 2H, imidazolium ring H-4(5)), 7.83 (d, J=1.5 Hz, 2H, Im^+H-5(4)), 8.59 (s, 2H, Im^+H-2), 8.87 (s, 1H, ImH-2). FAB-MS: 755$[M+1]^+$, 609 $[M-PF_6]^+$, 463 $[M-2PF_6-1]^+$.

12,17-Diaza-1,9-diazanium tetracyclo [$15.2^{1,17}.1^{1,17}.1^{3,7}.1^{9,12}$] docosane-1(20), 3(21), 4, 6, 9(22), 10, 18-heptaene dibromide salt (**2·2Br$^-$**) was obtained as colorless prisms after recrystallizing from methanol in 87% yield (0.37 g), mp 288–290°C. MS (*m*/*z*, RA%): 292 ($M^+-2Br-2$, 52).[11a]

16,24,32-Triaza-1,9-diazanium heptacyclo[$22.6^{1,24}.1^{1,24}.1^{3,7}.1^{9,16}.1^{18,22}.0^{10,15}.0^{25,30}$]-tetratriacontane-1(31), 3(32), 4, 6, 9(33), 10(15), 11, 13, 18, 20, 22(34), 25(30), 26, 28-tetradecene dibromide salt (**3·2Br$^-$**) was obtained as white crystals after recrystallizing from methanol and water in 82% yield (0.51 g), mp>300°C. Found: C, 55.6; H, 4.3; N, 11.1. Calcd for $C_{29}H_{24}N_5Br_2$·$1.5H_2O$: C, 55.5; H, 4.3; N, 11.2%. ^1H NMR (D_2O): 5.61 (s, 4H, $PyCH_2$), 5.70 (s, 4H, CH_2), 6.82–6.85 (m, 5H, PyH-3,5, ArH), 7.02–7.06 (m, 5H, benzimidazolium ring H-5, 6, ArH), 7.55–7.72 (m, 5H, BIH-4,7, PyH-3), 8.04 (m, 2H, BIH-2). FAB-MS: 521 $[M-Br-1]^+$.

16,21,29-Triaza-1,9-diazanium hexacyclo[$19.6^{1,21}.1^{1,21}.1^{3,7}.1^{9,16}.0^{10,15}.0^{22,27}$]triacontane-1(28), 3(29), 4, 6, 9(30), 10(15), 11, 13, 22(27), 23, 25-undenene dibromide salt (**4·2Br$^-$**) was obtained as a white powder after recrystallizing from methanol and water in 27% yield (0.15 g), mp 315–317°C. Found: C, 52.2; H, 4.7; N, 12.1. Calcd for $C_{25}H_{25}N_5Br_2$·H_2O: C, 52.5; H, 4.8; N, 12.3%. ^1H NMR (D_2O): 2.02 (s, 4H, $CH_2CH_2CH_2CH_2$), 4.41 (s, 4H, CH_2CH_2N), 5.62 (s, 4H, $PyCH_2$), 7.08 (d, J=7.6 Hz, 2H, PyH-3,5), 7.18–7.24 (m, 4H, BIH-5,6), 7.31–7.36 (m, 1H,

PyH-4), 7.54–7.61 (m, 4H, BIH-4,7), 7.92 (m, 2H, BIH-2). FAB-MS: 473 $[M-Br-1]^+$, 393 $[M-2Br-2]^+$.

4.3. Crystal data for cyclophane 2·2Br$^-$

A colorless single crystal with dimensions of 0.38×0.10×0.08 mm^3 obtained from a methanol solution was used for data collection. $C_{18}H_{22}N_4$·2Br, M=454.22, monoclinic, space group $P2_1/c$, a=9.7364(9), b=12.3721(12), c=15.6576(15) Å, β=96.865(2)°, V=1872.6(3) Å^3, T=294(2) K, Z=4, μ=4.336 mm^{-1}, unique reflections (12251) were obtained, and 4289 observed reflections (R_{int}=0.0376) were used for refinement to give R_1=0.0562 and Rw=0.1023. Crystallographic data (excluding structure factors) for the structure **2·2Br$^-$** have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication number CCDC 165417. Copies of the data can be obtained, free of charge, on application to CCDC, 12 Union Road, Cambridge, CB21EZ, UK [fax: +44(0)-1223-336033 or e-mail: deposit@ccdc.cam.ac.uk].

4.4. UV spectral measurements

The abilities of cyclophanes **1·2PF$_6^-$**–**4·2PF$_6^-$** to coordinate to anions were investigated using UV spectroscopic titration.[13] In the experiments, the cells were kept at constant temperature (298.2±0.1 K) with thermostated cell compartment. The same concentrations of guest solutions were added to the sample cell and reference cell, respectively, and the differential absorption spectra were obtained directly using the instrument. The effect of the slight volume changes caused by the addition of guest solutions on the absorption values was corrected before the regression analyses.

Acknowledgements

We wish to thank the National Natural Science Foundation of China and the Research Foundation of Sichuan Province for financial support.

References

1. Steed, J. W.; Atwood, J. L. *Supramolecular Chemistry: A Concise Introduction*. Wiley: Chichester, 2000. (b) Lehn, J.-M. *Supramolecular Chemistry: Concepts and Perspective*. VCH: Weinheim, 1995. (c) Vögtle, F. *Supramolekulare Chemie*. Teubner: Stuttgart, 1991.
2. Beer, P. D.; Gale, P. A. *Angew. Chem., Int. Ed.* **2001**, *40*, 486. (b) Beer, P. D. *Acc. Chem. Res.* **1998**, *31*, 71. (c) Schmidtchen, F. P.; Berger, M. *Chem. Rev.* **1997**, *97*, 1609. (d) In *Supramolecular Chemistry of Anions*. Bianchi, A., Bowman-James, K., García-España, E., Eds.; Wiley–VCH: New York, 1997. (e) Gale, P. A. *Coord. Chem. Rev.* **2000**, *199*, 181. (f) Antonisse, M. M. G.; Reinhoudt, D. N. *Chem. Commun.* **1998**, 443. (g) Gale, P. A.; Sessler, J. L.; Král, V. *Chem. Commun.* **1998**, 1.
3. Seel, C.; de Mendoza, J. *Comprehensive Supramolecular Chemistry*, Lehn, J.-M., Atwood, J. L., Davies, J. E. D., MacNicol, D. D., Vögtle, F., Eds.; Elsevier: Oxford, 1996; Vol. 2. (b) Vögtle, F. *Cyclophane Chemistry*. Wiley: Chichester, 1993. (c) Seel, C.; Vögtle, F. *Angew. Chem., Int. Ed. Engl.* **1992**, *31*, 528. (d) Diederich, F. In *Cyclophanes, Monographs in Supramolecular Chemistry*. Stoddart, J. F., Ed.; Royal Society of Chemistry: Cambridge, 1991.
4. Examples of cyclophanes as hosts for anion recognition: (a) Szumna, A.; Jurczak, J. *Eur. J. Org. Chem.* **2001**, 4031. (b) Sasaki, S.; Mizuno, M.; Naemura, K.; Tobe, Y. J. *J. Org. Chem.* **2000**, *65*, 275. (c) Reuter, C.; Wienard, W.; Hübner, G. N.; Seel, C.; Vögtle, F. *Angew. Chem., Int. Ed. Engl.* **1999**, *38*, 383. (d) Tanaka, A.; Fujiyoshi, S.; Motomura, K.; Hayashida, O.; Hiseada, Y.; Murakami, Y. *Tetrahedron* **1998**, *54*, 5187. (e) Beer, P. D.; Szemes, F.; Balzani, V.; Salà, C. M.; Drew, N. G. B.; Dent, S. W.; Maestri, M. *J. Am. Chem. Soc.* **1997**, *119*, 11864. (f) Bisson, A. P.; Lynch, V. M.; Monahan, M.-K. C.; Anslyn, E. V. *J. Am. Chem. Soc.* **1997**, *119*, 2340. (g) Hinzeu, B.; Seiler, P.; Diederich, F. *Helv. Chim. Acta* **1996**, *79*, 942.
5. Schneider, H.-J.; Yatsimirsky, A. *Principles and Methods in Supramolecular Chemistry*. Wiley: Chichester, 1999. (b) In *Principles of Molecular Recognition*. Buckingham, A. D., Legon, A. C., Roberts, S. M., Eds.; Blackie: London, 1993.
6. Dugas, H. *Bioorganic Chemistry*. 3rd ed. Springer: New York, 1996. (b) Hamilton, A. D. *Bioorganic Chemistry Frontiers*, Dugas, H., Ed.; Springer: New York, 1992; Vol. 2.
7. Wisner, J. A.; Beer, P. D.; Berry, N. G.; Tomapatanaget, B. *Proc. Natl Acad. Sci. USA* **2002**, *99*, 4983. (b) Howarth, J. *Recent Res. Dev. Org. Chem.* **2000**, *4*, 155. (c) Aakeroy, C. B.; Evans, T. A.; Seddon, K. R.; Palinko, I. *New J. Chem.* **1999**, 145. (d) Elaiwi, A.; Hitchcock, P. B.; Seddon, K. R.; Srinivasan, N.; Tan, Y.-M.; Welton, T.; Zora, J. A. *J. Chem. Soc., Dalton Trans.* **1995**, 3467. (e) Avent, A. G.; Chaloner, P. A.; Day, M. P.; Seddon, K. R.; Welton, T. *J. Chem. Soc., Dalton Trans.* **1994**, 3405.
8. Howarth, J.; Al-Hashimy, N. A. *Tetrahedron Lett.* **2001**, *42*, 5777. (b) Thomas, J.-L.; Howarth, J.; Hanlon, K.; McGuirk, D. *Tetrahedron Lett.* **2000**, *41*, 413. (c) Sato, K.; Arai, S.; Yamagishi, T. *Tetrahedron Lett.* **1999**, *40*, 5219; and references cited therein.
9. Simons, R. S.; Garrison, J. C.; Kofron, W. G.; Tessier, C. A.; Youngs, W. J. *Tetrahedron Lett.* **2002**, *43*, 3423. (b) Alcalde, E.; Mesquida, N.; Perez-Garcia, L.; Ramos, S.; Alemany, M.; Rodriguez, M. L. *Chem. Eur. J.* **2002**, *8*, 474. (c) Bitter, I.; Torok, Z.; Csokai, V.; Grun, A.; Balazs, B.; Toth, G.; Keseru, G. M.; Kovari, Z.; Czugler, M. *Eur. J. Org. Chem.* **2001**, 2861. (d) Baker, M. V.; Skelton, B. W.; White, A. H.; Williams, C. C. *J. Chem. Soc., Dalton Trans.* **2001**, 111. (e) Garrison, J. C.; Simons, R. S.; Kofron, W. G.; Tessier, C. A.; Youngs, W. *J. Chem. Commun.* **2001**, 1780. (f) Garrison, J. C.; Simons, R. S.; Talley, J. M.; Wesdemiotis, C.; Tessier, C. A.; Youngs, W. *J. Organomet.* **2001**, *20*, 1276. (g) Alcalde, E.; Ayala, C.; Dinares, I.; Mesquida, N.; Sanchez-Ferrando, F. *J. Org. Chem.* **2001**, *66*, 2281. (h) Baker, M. V.; Bosnich, M. J.; Williams, C. C.; Skelton, B. W.; White, A. H. *Aust. J. Chem.* **1999**, *52*, 823.
10. Alcalde, E.; Alvarez-Rúa, C.; García-Granda, S.; García-Rodriguez, E.; Mesquida, N.; Pérez-García, L. *J. Chem. Soc., Chem. Commun.* **1999**, 295; and references cited therein.
11. Luo, M.-M.; Guo, S.-G.; Zhou, C.-H.; Xie, R.-G. *Heterocycles* **1995**, *41*, 1421. (b) Zhou, C.-H.; Xie, R.-G.; Zhao, H.-M. *Org. Prep. Proc.* **1996**, *28*, 345. (c) Liu, Z.-C.; Zhou, C.-H.; Xie, R.-G. *Chin. Chem. Lett.* **1997**, *8*, 387. (d) Luo, M.-M.; Xie,

R.-G.; Yuan, D.-Q.; Lu, W.; Xia, P.-F.; Zhao, H.-M. *Chin. J. Chem.* **1999**, *17*, 384. (e) Liu, Z.-C.; Zhou, C.-H.; Su, X.-Y.; Xie, R.-G. *Synth. Commun.* **1999**, *29*, 2979. (f) Yuan, Y.; Yan, J.-M.; Chan, A. S. C.; Jiang, Z.-L.; Gao, G.; Xie, R.-G. *Synth. Commun.* **2000**, *30*, 4555. (g) You, J.-S.; Yu, X.-Q.; Zhang, G.-L.; Xiang, Q.-X.; Lan, J.-B.; Xie, R.-G. *Chem. Commun.* **2001**, 1816.

12. Cabildo, P.; Sanz, D.; Claramunt, R. M.; Bourne, S. A.; Alkorta, I.; Elguero, J. *Tetrahedron* **1999**, *55*, 2327. (b) Alcalde, E.; Ramos, S.; Pérez-García, L. *Org. Lett.* **1999**, *1*, 1035. (c) Alcalde, E.; Alemany, M.; Gisbert, M. *Tetrahedron* **1996**, *52*, 15171. (d) Alcalde, E.; Gisbert, M. *Synlett* **1996**, 285. (e) Alcalde, E.; Alemany, M.; Pérez-García, L.; Rodriguez, M. L. *J. Chem. Soc., Chem. Commun.* **1995**, 1239.
13. Examples of the UV–visible titrimetric method being used in molecular recognition: (a) Chen, G.; John, T.; Alcala, M.; Mallouk, T. E. *J. Org. Chem.* **2001**, *66*, 3027. (b) Kimura, E.; Kitamura, H.; Ohtani, K.; Koike, T. *J. Am. Chem. Soc.* **2000**, *122*, 4668. (c) Black, C. B.; Andrioletti, B.; Try, A. C.; Ruiperez, C.; Sessler, J. L. *J. Am. Chem. Soc.* **1999**, *121*, 10438. (d) Watanabe, S.; Onogawa, O.; Komatsu, Y.; Yoshida, K. *J. Am. Chem. Soc.* **1998**, *120*, 229. (e) Liu, Y.; Li, B.; Han, B.-H.; Li, Y.-M.; Chen, R.-T. *J. Chem. Soc., Perkin Trans. 2* **1997**, 1275. (f) Asakawa, M.; Brown, C. L.; Pasini, D.; Stoddart, J. F.; Wyatt, P. G. *J. Org. Chem.* **1996**, *61*, 7234. (g) Kuroda, Y.; Kato, Y.; Higashioji, T.; Hasegawa, J.-y.; Kawanami, S.; Takahashi, M.; Shiraishi, N.; Tanabe, K.; Ogoshi, H. *J. Am. Chem. Soc.* **1995**, *117*, 10950. (h) Mizutani, T.; Ema, T.; Tomita, T.; Kuroda, Y. m.; Ogoshi, H. *J. Am. Chem. Soc.* **1994**, *116*, 4240.
14. Polster, J.; Lachmann, H. *Spectrometric Titrations*. VCH: Weinheim, 1989. (b) Connors, K. A. *Binding Constants. The Measurement of Molecular Complex*. Wiley: New York, 1987. (c) Benesi, H. A.; Hildebrand, J. H. *J. Am. Chem. Soc.* **1949**, *71*, 2703.
15. Offermann, W.; Vögtle, F. *Synthesis* **1977**, 272.