Organic & Biomolecular Chemistry

PAPER

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Cite this: *Org. Biomol. Chem.*, 2016, **14**, 4233

Highly selective binding of methyl orange dye by cationic water-soluble pillar[5]arenes†

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Received 11th March 2016,
Accepted 1st April 2016

DOI: 10.1039/c6ob00539j

www.rsc.org/obc

A new water-soluble pillar[5]arene with an amide fragment and triethylammonium groups was synthesized by our original method of aminolysis of the ester groups. Using UV-spectroscopy, it is shown that cationic pillar[5]arenes are able to selectively form 1 : 1 complexes with some hydrophobic anions: the guests with bulky uncharged or negatively charged substituents hindering entry into the macrocycle cavity. Highly selective binding of the most lipophilic guest, methyl orange dye, in the form of organic anion salts by positively charged water-soluble pillar[5]arenes was detected. In the case of the azo dye the appropriate K_{ass} values were 10–100-fold higher than those calculated for the other sulfonic acid derivatives studied. The 2D NMR NOESY ^{1}H–^{1}H spectroscopy confirms the formation of the inclusion complex: negative charge sulfonate head is outside the cavity of pillar[5]arenes and the hydrophobic fragment of the guest is located in the cavity.

Introduction

Binding of the neutral and polar organic guest molecules in nonpolar solvents does not result in a significant increase of the energy due to the host–guest interactions.[1] Such a binding is typically performed by dipole–dipole interactions and hydrogen bonding, often with the participation of ion–dipole interactions.[2] Hydrophobic sites of a guest interact with the analogous sites of a host molecule. In water, the binding of an organic guest is greatly increased due to the hydrophobic effect.[1] The association of a host and a guest during the complex formation reduces the deformation of the solvent structure.[1]

Synthesis of water-soluble macrocycles[3] is of significant interest because most of the biologically important compounds that can act as guests are soluble in water.[4a–d] The first water-soluble pillar[*n*]arene, *i.e.*, carboxylatopillar[5]arene sodium salt, showed high water solubility and good selective binding ability toward basic amino acids, *e.g.*, L-lysine, L-arginine and L-histidine.[4e] The decacarboxylic acid has a rigid spatial structure stabilized by hydrogen bonds, and its salt makes it water-soluble and improves complexation properties. In 2011, the synthesis of the first water-soluble cationic pillar[5]arene was proposed.[4f] The cationic pillar[5]arenes bind anionic guests mainly by hydrophobic and electrostatic interactions as in inclusion complexes with *p*-toluenesulfonate[4g] and 1-octanesulfonate.[4f] Methyl orange is commonly used as a pH-indicator due to its clear and distinct colour change.[5] It is known that water-soluble macrocycles with negatively charged groups bind the protonated methyl orange[5b] whereas macrocycles with positively charged groups stabilize the non-protonated form of the azo dye.[5c,d] However, the binding of methyl orange with a large hydrophobic fragment requires pillar[5]arenes with higher hydrophobicity of the cavity. For this reason, besides well-known water-soluble pillar[5]arenes containing either carbonyl or ammonium groups, we first proposed to combine these structural fragments in the same molecule in order to increase the depth of the cavity and the selectivity of the binding. Moreover, we have expanded the family of cationic pillar[5]arenes (**1–3**) and sulfonic acid derivatives as guests (**G1–G8**) to estimate the influence of (a) the substituent at the *p*-position of the benzene ring in the guest molecule and (b) the length of the spacer and the alkyl substituent at the nitrogen atom in the host on the complexation properties and binding selectivity.

In our previous study, we have successfully synthesized two symmetric cationic water-soluble pillar[5]arenes **1** and **2** bearing trimethylammonium/methyldiethylammonium groups at both the rims and the formation of the 1 : 1 complexes with *p*-toluenesulfoacid **G1** was shown.[6] Now we have synthesized, in addition to macrocycles **1** and **2**, a new water-soluble pillar[5]arene **3** with an amide fragment and triethyl-

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†Electronic supplementary information (ESI) available: Some synthetic details, determination of association constants, and other materials. See DOI: 10.1039/c6ob00539j

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ammonium groups by our original method of aminolysis of the ester groups.[6] The structure of the compounds obtained was characterized by ^{1}H and ^{13}C NMR, IR spectroscopy and mass spectrometry (MALDI TOF) (ESI, Fig. S1, S2 and S4†). The spatial structure of the new functionalized pillar[5]arenes was established by 2D NMR NOESY ^{1}H–^{1}H spectroscopy (ESI, Fig. S3†).

Results and discussion

Macrocycles **1–3** possess both a hydrophobic cavity and ten positively charged substituents that allow recognizing guests by electrostatic, hydrophobic and π–π stacking interactions between the host and a guest as the driving forces.[7] A series of organic sulfonic acid derivatives with various sizes and shapes were used, including aromatic guests without (**G1**, **G2**) and with alkyl linkers (**G4–G7**), linear aliphatic salt **G3** and methyl orange **G8** with two benzene units (Fig. 1).

To quantify molecular recognition of the sulfonic acid derivatives by pillar[5]arenes **1–3**, the stability constants and the stoichiometry of the host/guest complexes formed in water were estimated by UV-spectroscopy, which showed significant changes in the absorbance spectra of the macrocycles after the addition of the guest molecules. The hyperchromic effect was observed at 270–320 nm (ESI, Fig. S11†) in the case of the guest binding (Table 1). For methyl orange **G8**, changes in the absorbance were monitored at 350–600 nm, while the other hosts **1–3** did not absorb light waves (Fig. 2).

A new adsorption band with the maximum near 426 nm was found for the system **G8**/**3** with less than one equivalent of **G8** added. At its higher concentration, its band overlapped with the adsorption maximum of free guest **G8** (460 nm) in the visible spectral region. The new band probably corresponds to the complex formation in the system with methyl orange **G8**. The lg K_{ass} values of the complexes obtained varied from 1.22 to 3.97. The pillar[5]arenes **1–3** showed similar binding abilities toward **G1**, **G2**, **G4**, and **G7**.

In the case of the azo dye **G8** the appropriate K_{ass} values were 10–100-fold higher than those calculated for the other sulfonic acid derivatives studied. We can propose that the affinity of the guest toward a macrocycle cavity sharply increases with the lipophilicity of a guest. The log P value of

Table 1 lg K_{ass} values of host/guest complexes formed by sulfonate salts as guests **G1–G8** and pillar[5]arenes **1–3** as hosts at 298 K in D_2O

	1	2	3
G1	1.43 ± 0.12[a]	1.22 ± 0.08[a]	1.94 ± 0.01
G2	2.38 ± 0.10	2.52 ± 0.01	2.74 ± 0.02
G3	—[b]	—[b]	—[b]
G4	1.84 ± 0.15	2.25 ± 0.20	1.99 ± 0.01
G5	—[b]	—[b]	—[b]
G6	—[b]	—[b]	—[b]
G7	2.04 ± 0.02	2.70 ± 0.07	3.06 ± 0.04
G8	3.97 ± 0.03	3.84 ± 0.02	3.24 ± 0.01

[a] Values for lg K_{ass} were determined as described in ref. 5. [b] The guests **G3**, **G5** and **G6** form inclusion complexes with hosts **1–3** by very weak interactions (lg $K_{ass} \leq 0.5$).

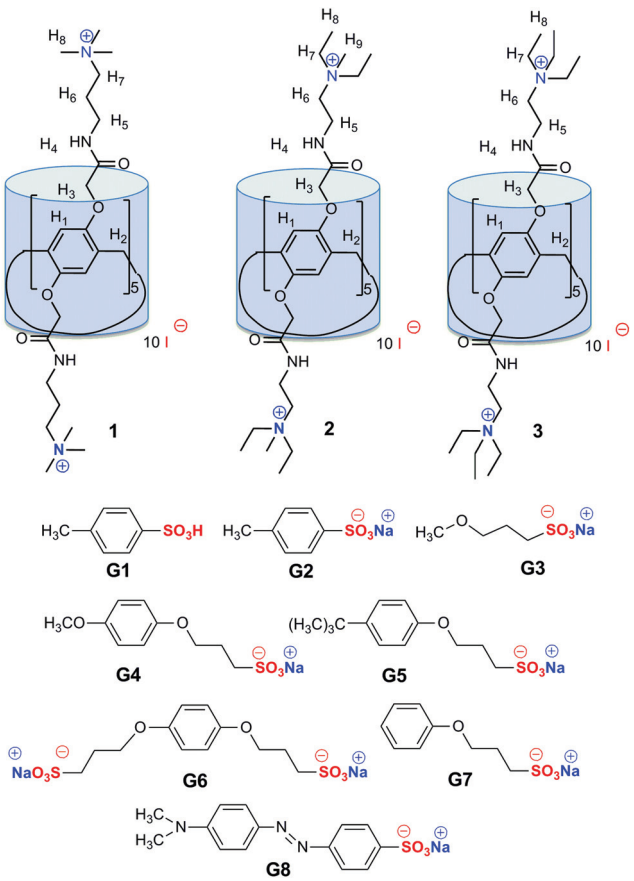

Fig. 1 Structures of the ammonium pillar[5]arenes **1–3** and sulfonate salts as guests **G1–G8**.

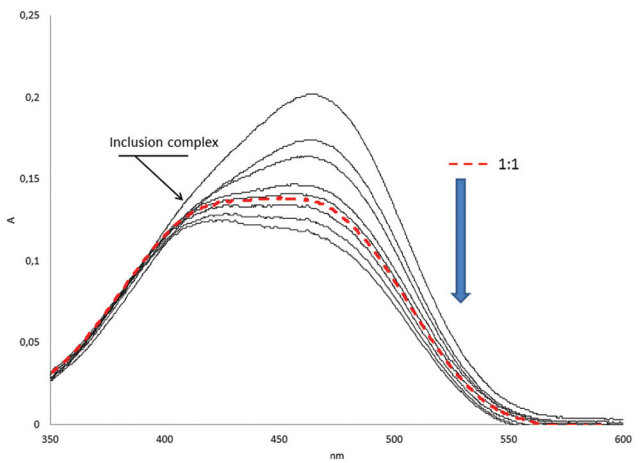

Fig. 2 Spectrophotometric titration of the system pillar[5]arene **3** and **G8** in water. The molar ratio of the host and the guest was changed from 0.3 : 1 to 2 : 1 (0.3 : 1, 0.5 : 1, 0.8 : 1, 0.9 : 1, 1 : 1, 1.1 : 1, 1.3 : 1, 1.5 : 1, 2 : 1).

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methyl orange (2.0593) is more than two-fold higher than that of the other guests that formed an inclusion complex. Selectivity of complexation towards the guests studied decreases in the row of pillar[5]arenes **1–3**.

The pillar[5]arene **1** with a propyl linker forms more stable inclusion complexes with methyl orange **G8** than pillar[5]arenes **2** and **3** with an ethyl linker despite longer ethyl fragments at the ammonium group. Hence, pillar[5]arenes with a cavity depth larger due to alkyl linkers are able to highly selectively and efficiently bind methyl orange as compared with the other guests studied.

The guest **G3** forms the inclusion complex with **3** in accordance with ^{1}H NMR spectroscopy (ESI, Fig. S7†). The complex shows very weak interactions, so the association constant could not be quantified. No complexation of **1–3** with **G5** and **G6** was found. Despite the maximal lipophilicity ($\log P$ = 2.6096), **G5** has a bulky *tert*-butyl substituent which hinders the substrate entering the macrocycle cavity. This suggests the complex formation by inclusion of an uncharged fragment of the guest into the macrocycle cavity and electrostatic association of the charged sulfonate moiety of a guest with the ammonium group of pillar[5]arene. A second negatively charged alkylsulfonate substituent at the *p*-position of **G6** hinders its inclusion into the π-electron rich cavity. These phenomena offered evidence for the formation of an inclusion complex between the hosts **1–3** and the guests **G1–G8** mainly driven by hydrophobic interactions and to a lesser extent by electrostatic interactions.

^{1}H NMR data confirmed the host–guest complexation in solution.[7c,8] As shown in Fig. 3, upon addition of one equiv. of the host **3**, the signals of the guest **G8** protons (A–E) exhibit an obvious upfield shift and a broadening effect against free guest signals. Strong upfield shifts ($\Delta\delta$) of the aromatic and methyl signals indicate that guest **G8** is located in the host cavity. These shifts appeared due to rather fast proton exchange observed for complexation in the ^{1}H NMR timescale. It should be noted that $\Delta\delta$ (A) > $\Delta\delta$ (B) > $\Delta\delta$ (E) > $\Delta\delta$ (C) > $\Delta\delta$ (D). Thus, methyl groups of **G8** should be deeper incorporated into the macrocycle cavity of **3** ($\Delta\delta$ = 0.71 ppm for A). Besides, the AB quadruplet of the proton signals $\mathbf{H_3}$ (diastereotopic protons) of the host merges into an unresolved multiplet in the inclusion complex. Also, significant chemical shifts ($\Delta\delta$) from 0.11 to 0.25 ppm were observed for the inclusion complexes of the host **3** with **G2**, **G3** and **G7** (ESI, Fig. S6–S8†).

The 2D NMR NOESY ^{1}H–^{1}H of the complexes confirms host–guest complexation (Fig. 4). The aromatic protons of **G8** (B, C, D) have cross-peaks with $\mathbf{H_3}$ and $\mathbf{H_8}$ of the host **3**. The methyl protons of the dimethylamino fragment (A) show cross-peaks with protons of the aromatic units ($\mathbf{H_1}$) and the methoxycarbonyl fragment ($\mathbf{H_3}$). Thus, we can conclude that the inclusion complex in which the guest threads the cavity of the pillar[5]arene **3** is formed. Its negative sulfonate head is close to the positive triethylammonium groups of **3**, the fragment $N(CH_3)_2$-Ar– in methyl orange **G8** is located in the cavity and the fragment –Ar-SO_3Na is outside the cavity. From the UV spectroscopy results (Job's plot), the formation of the 1 : 1 inclusion complex between the host and the guest (see ESI, Fig. S23–S25†) can be proposed. The formation of the complex might be mainly driven by hydrophobic and electrostatic interactions, because the hydrophobic cavity of the host **3** meets hydrophobic alkyl and aryl chains of **G8** and the cationic triethylammonium groups of the host **3** bind the anionic sulfonate group of **G8** by electrostatic interactions.

The diffusion experiments with ^{1}H NMR (DOSY) for the system **3**/**G8** offer information on the formation of the host–guest inclusion complex:[9] the diffusion coefficient of a small guest molecule is large and decreases with complex formation. The DOSY spectrum (ESI, Fig. S5 and Table S1†) indicates a decrease of the mobility of the guest **G8** after complexation (with diffusion coefficients of 3.43×10^{-10} m^2 s^{-1} and 2.21×10^{-10} m^2 s^{-1} for free and complexed **G8**, respectively). Also, in the DOSY spectrum the contour peaks lie on a horizontal line (ESI, Fig. S5†). All of these results confirm the formation of the inclusion complex between the host **3** and the guest **G8**.

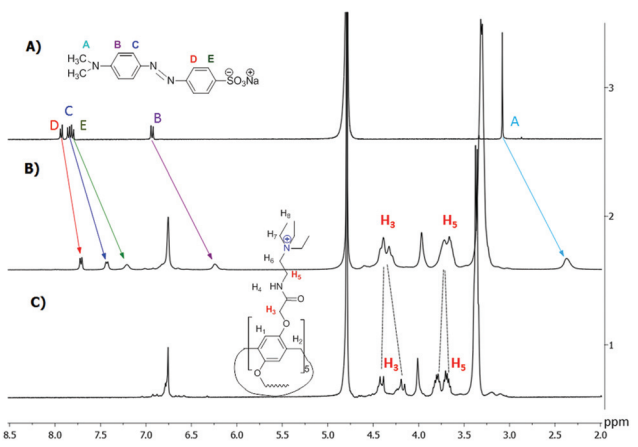

Fig. 3 ^{1}H NMR spectra (D_2O, 293 K, 400 MHz): (a) **G8** (0.0112 mol l^{-1}); (b) **G8** (0.0112 mol l^{-1}) + **3** (0.0112 mol l^{-1}); (c) **3** (0.0112 mol l^{-1}).

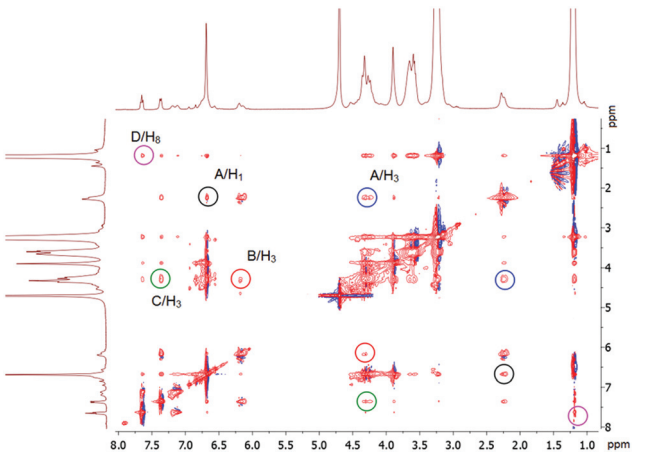

Fig. 4 2D NMR ^{1}H–^{1}H NOESY (500 MHz) analysis of complex **3** with **G8** in D_2O. The concentrations of the host and the guest are 0.0112 M.

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Materials and methods

Instrumentation

^{1}H NMR spectra were recorded on a Bruker Avance-400 (400 MHz) spectrometer and ^{13}C and 2D NOESY NMR spectra were recorded on an impulse spectrometer Bruker Avance II (with 125 MHz and 500 MHz respectively). Chemical shifts were determined against the signals of residual protons of a deuterated solvent (D_2O, $CDCl_3$). The concentration of sample solutions was 3–5%. Attenuated total internal reflectance IR spectra were recorded with a Spectrum 400 (Perkin Elmer) Fourier spectrometer. Elemental analysis was performed with a Perkin Elmer 2400 Series II instrument. Mass spectra (ESI) were recorded on an AmaZonX mass spectrometer (Bruker Daltonik GmbH, Germany). The drying gas was nitrogen at 300° C. The capillary voltage was 4.5 kV. The samples were dissolved in acetonitrile (concentration ~10^{-6} g ml^{-1}). Melting points were determined using a Boetius Block apparatus. Additional control of the purity of compounds and monitoring of the reaction were carried out by thin-layer chromatography using Silica G, 200 μm plates, UV 254. ^{1}H Diffusion Ordered Spectroscopy (DOSY): the spectra were recorded on a Bruker Avance 400 spectrometer, at 9.4 tesla, at the resonating frequency of 400.17 MHz for ^{1}H, using a BBO Bruker 5 mm gradient probe. The temperature was regulated at 298 K and no spinning was applied to the NMR tube. DOSY experiments were performed using the STE bipolar gradient pulse pair (stebpgp1s) pulse sequence. 16 scans of 16 data points were collected. The maximum gradient strength produced in the z direction was 5.35 G mm^{-1}. The duration of the magnetic field pulse gradients (δ) was optimized for each diffusion time (Δ) in order to obtain a 2% residual signal with the maximum gradient strength. The values of δ and Δ were 1.800 μs and 100 ms, respectively. The pulse gradients were incremented from 2 to 95% of the maximum gradient strength in a linear ramp.[10–14]

Most chemicals were purchased from Aldrich and used as received without additional purification. Organic solvents were purified in accordance with standard procedures.

Synthesis of the compounds 3 and G3–G7

For the preparation of a new pillar[5]arene **3**, initially, a four step literature procedure of 4,8,14,18,23,26,28,31,32,35-decakis-[*N*-(2′,2′-diethylaminoethyl)-carbamoylmethoxy]-pillar[5]arene was performed, starting from commercially available 1,4-dimethoxybenzene.[11,12]

4,8,14,18,23,26,28,31,32,35-Decakis-[(*N*-(2′,2′-diethylaminoethyl)-carbamoylmethoxy]-pillar[5]arene (A). Product yield: 71%. ^{1}H NMR (CD_3SOCD_3) δ_H, ppm (J/Hz): 0.91 (t, 60H, $^3J_{HH}$ = 7.1, –N($CH_2\underline{CH_3}$)$_2$), 2.41–2.52 (m, 60H, –$CH_2\underline{CH_2}$–N($\underline{CH_2}CH_3$)$_2$), 3.24 (m, 20H, –$\underline{CH_2}CH_2$–N(CH_2CH_3)$_2$), 3.79 (s, 10H, –$\underline{CH_2}$–), 4.32 (s, 20H, O–$\underline{CH_2}$C(O)–), 6.85 (s, 10H, ArH), 7.86 (t, 10H, $^3J_{HH}$ = 5.2, –C(O)NH). ^{13}C NMR (CD_3SOCD_3) δ_C ppm: 167.64, 148.95, 127.97, 114.71, 67.71, 51.37, 46.47, 36.59, 28.80, 11.75. ^{1}H–^{1}H NOESY (NOE) (the major cross-peaks): H^8/H^4; H^7/H^4; H^5/H^4; H^2/H^4; H^3/H^4; H^1/H^4; H^1/H^8; H^1/H^7; H^1/H^5; H^1/H^5; H^1/H^2; H^1/H^3; H^3/H^8; H^3/H^7; H^3/H^5; H^3/H^1; H^2/H^8; H^2/H^7; H^2/H^5; H^2/H^3; H^5/H^6; H^8/H^7. IR ν cm^{-1}: 3311.05 (N–H), 1661.33 (C═O). MALDI-TOF MS: calculated [M$^+$] m/z = 2172.4, found [M + H]$^+$ m/z = 2173.4, [M + Na]$^+$ m/z = 2195.4. Found: C, 63.57; H, 8.81; N, 12.89. $C_{115}H_{190}N_{20}O_{20}$. Calculated for $C_{115}H_{190}N_{20}O_{20}$: C, 63.02; H, 8.55; N, 12.49.

General procedure of the synthesis of compound 3

An equimolar amount of ethyl iodide was added to the solution of compound **A** (0.30 g, 0.14 mmol) in 10 ml acetonitrile. The reaction mixture was refluxed for 72 h and the solvent was removed under reduced pressure. The powder obtained was dried under reduced pressure (P_2O_5).

4,8,14,18,23,26,28,31,32,35-Decakis-[(*N*-(2′,2′,2′-triethylammoniumethyl)-carbamoylmethoxy]-pillar[5]arene deca iodide (3). Product yield: 0.52 g (84%). Mp: 153 °C. ^{1}H NMR (D_2O) δ_H, ppm (J/Hz): 1.31 (t, 90H, $^3J_{HH}$ = 7.0, –N($CH_2\underline{CH_3}$)$_3$), 3.36 (m, 80H, –$CH_2\underline{CH_2}$–N($\underline{CH_2}CH_3$)$_3$), 3.63–3.85 (m, 20H, –$\underline{CH_2}CH_2$–N(CH_2CH_3)$_3$), 3.98 (s, 10H, –$\underline{CH_2}$–), 4.08 (d, 10H, AB-system, $^2J_{HH}$ = 15.0, O–$\underline{CH_2}$C(O)NH–), 4.37 (d, 10H, AB-system, $^2J_{HH}$ = 15.0, O–$\underline{CH_2}$C(O)NH–), 6.73 (s, 10H, ArH). ^{13}C NMR (CD_3SOCD_3) δ_C ppm: 168.95, 148.30, 127.45, 114.61, 66.94, 52.94, 52.94, 52.38, 32.28, 28.56, 7.21. IR ν cm^{-1}: 3331.5 (–N$^+$–(CH_2CH_3)$_3$), 2975.3 (–CH_2–CH_3, –CH_2–), 1665.9 (C═O). ESI: calcd for [M − 4 I$^-$]$^{4+}$ m/z = 806.2, [M − 5 I$^-$]$^{5+}$ m/z = 619.6, [M − 6 I$^-$]$^{6+}$ m/z = 496.8, found m/z = 806.1, 619.5, 495.2. Found: C, 57.4; H, 8.23; N, 9.65. $C_{135}H_{240}N_{20}O_{20}$. Calculated for $C_{135}H_{240}Cl_{10}N_{20}O_{20}$: C, 57.54; H, 8.58; N, 9.94.

Pillar[5]arenes **1** and **2** were synthesized according our original method.[6]

4,8,14,18,23,26,28,31,32,35-Decakis-[(*N*-(3′,3′,3′-trimethylammoniumpropyl)-carbamoylmethoxy]-pillar[5]arene decaiodide (1). Product yield: 0.48 g (96%). Mp: 124 °C. ^{1}H NMR (CD_3SOCD_3) δ_H, ppm (J/Hz): 1.93 (m, 20H, ═N$CH_2\underline{CH_2}CH_2$NH–), 3.13 (s, 90H, $(CH_3)_3N^+$–), 3.25 (m, 20H, ═N$CH_2CH_2\underline{CH_2}$NH–), 3.39 (m, 20H, ═N$\underline{CH_2}CH_2CH_2$NH–), 3.9 (s, 10H, –$\underline{CH_2}$–), 4.41 (dd, 20H, O–$\underline{CH_2}$C(O)–), 6.83 (s, 10H, ArH), 7.74 (t, 10H, $^3J_{HH}$ = 5.6, –C(O)NH). ^{13}C NMR (CD_3SOCD_3) δ_C ppm: 170.89, 149.48, 129.88, 116.22, 68.30, 64.09, 53.09, 35.88, 29.12, 22.68. ^{1}H–^{1}H NOESY (NOE) (the major cross-peaks): H^1/H^3; H^2/H^1; H^4/H^8; H^5/H^6; H^7/H^8; H^3/H^2. IR ν cm^{-1}: 3285.31, 3386.07 (N–H), 1662.39 (C═O). MALDI-TOF MS: calculated [M − I$^-$]$^+$ m/z = 3324.6, found [M − I$^-$]$^+$ m/z = 3325.2. Found: C, 40.01; H, 5.84; N, 8.13. $C_{115}H_{200}N_{20}O_{20}$. Calculated for $C_{115}H_{200}N_{20}O_{20}$: C, 39.05; H, 5.43; N, 8.10.

4,8,14,18,23,26,28,31,32,35-Decakis-[(*N*-(2′-methyl-2′,2′-diethylammoniumethyl)-carbamoylmethoxy]-pillar[5]arene decaiodide (2). Product yield: 0.45 g (88%). Mp: 153 °C. ^{1}H NMR (CD_3SOCD_3) δ_H, ppm (J/Hz): 1.32 (t, 60H, $^3J_{HH}$ = 6.1, –N($CH_2\underline{CH_3}$)$_2$), 3.02 (s, 30H, –N–CH_3), 3.41 (m, 40H, –$CH_2\underline{CH_2}$–N($\underline{CH_2}CH_3$)$_2$), 3.77 (m, 20H, –$\underline{CH_2}CH_2$–N(CH_2CH_3)$_2$), 4.01 (s, 10H, –$\underline{CH_2}$–), 4.20 (d, 10H, AB-system, $^2J_{HH}$ = 15.1, O–$\underline{CH_2}$C(O)NH–), 4.40 (d, 10H, AB-system, $^2J_{HH}$ = 15.1, O–$\underline{CH_2}$C(O)NH–), 6.76 (s, 10H, ArH). ^{13}C NMR (CD_3SOCD_3) δ_C, ppm: 171.06, 149.17, 128.90, 115.35, 67.88, 64.09, 57.74, 57.17, 47.48, 32.68, 30.36, 7.50. ^{1}H–^{1}H NOESY (NOE) (the major cross-peaks):

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H^1/H^8; H^7/H^1; H^3/H^8; H^6/H^7; H^8/H^9. IR ν cm^{-1}: 3331.48 (N–H), 1665.92 (C=O). MALDI-TOF MS: calculated $[M]^+$ m/z = 3591.73, found $[M - I^-]^+$ m/z = 3463.7. Found: C, 41.79; H, 6.17; N, 7.80. $C_{125}H_{220}N_{20}O_{20}$. Calculated for $C_{125}H_{220}N_{20}O_{20}$: C, 40.53; H, 5.93; N, 7.45.

Compounds **G3–G7** were obtained from commercially available alcohols and phenols by literature methods.[13, 14]

Sodium 3-methoxypropane-1-sulfonate G3. Product yield: 0.47 g (87%). Mp: >300 °C. ^{1}H NMR (D_2O) δ_H, ppm: 3.43 (t, 4H, –O–CH_2–), 2.80 (tt, 4H, –CH_2–), 1.85 (t, 4H, –CH_2–SO_3^-).

Sodium 3-(4-methoxyphenoxy)propane-1-sulfonate G4. Product yield: 0.87 g (76%). Mp: >300 °C. ^{1}H NMR (D_2O) δ_H, ppm: 6.88 (s, 2H, ArH), 4.03 (t, 4H, –O–CH_2–), 2.08 (tt, 4H, –CH_2–), 2.97 (t, 4H, –CH_2–SO_3^-), 3.07 (s, 3H, –OCH_3).

Sodium 3-(4-(*tert*-butyl)phenoxy)propane-1-sulfonate G5. Product yield: 0.87 g (76%). Mp: >300 °C. ^{1}H NMR (D_2O) δ_H, ppm: 6.90 (s, 2H, ArH), 7.38 (s, 2H, ArH), 4.07 (t, 4H, –O–CH_2–), 2.13 (tt, 4H, –CH_2–), 2.99 (t, 4H, –CH_2–SO_3^-) 1.18 (s, 6H, –CH_3).

Sodium 3,3′-(1,4-phenylenebis(oxy))bis(propane-1-sulfonate) G6. Product yield: 0.41 g (34%). Mp: >300 °C. ^{1}H NMR (D_2O) δ_H, ppm: 6.89 (s, 4H, ArH), 4.03 (t, 4H, –O–CH_2–), 2.08 (tt, 4H, –CH_2–), 2.98 (t, 4H, –CH_2–SO_3–).

Sodium 3-phenylpropane-1-sulfonate G7. Product yield: 1.07 g (96%). Mp: >300 °C. ^{1}H NMR (D_2O) δ_H, ppm: 6.95 (s, 2H, ArH), 7.28 (s, 2H, ArH), 4.09 (t, 4H, –O–CH_2–), 2.11 (tt, 4H, –CH_2–), 2.99 (t, 4H, –CH_2–SO_3–).

Determination of the stability constant and stoichiometry of the complex by UV titration

The UV measurements were performed with a "Shimadzu UV-3600" instrument. A 1×10^{-3} M solution of **G1**, **G2**, **G4** or **G7** (0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9 and 1 ml) in water was added to 0.5 ml of the solution of receptors **1–3** (3×10^{-4} M) in water and diluted to a final volume of 3 ml with water. In the case of **G8**: a 3×10^{-5} M solution of hosts **1–3** (0.3, 0.5, 0.6, 0.8, 0.9, 1, 1.1, 1.3, 1.5 and 2 ml) in water was added to 0.03 ml of the solution of **G8** (1×10^{-3} M) in water and diluted to a final volume of 3 ml with water. The UV spectra of the solutions were then recorded. The stability constant and stoichiometry of complexes were calculated as described in ESI.† Three independent experiments were carried out for each series. A Student's *t*-test was applied for statistical data processing.

Job's plots

Series of solutions of pillar[5]arene derivatives **1–3** and sulfonic acid derivatives were prepared in water. The volume of the host and guest solutions varied from 0.6 : 2.4 to 2.4 : 0.6, respectively, with the total concentration of the host (H) and the guest (G) being constant and equal to 1×10^{-5} M. The solutions were used without further stirring. The absorbance A_i of the complexation systems was measured at the maximum absorbance wavelength of the complex. The absorbance values were used to plot a diagram from whose maximum the structures of the complexes were deduced. Three independent experiments were carried out for each system.

Conclusions

The recognition properties of pillar[5]arenes containing both carbonyl and ammonium groups at both the rims were confirmed regarding a series of charged organic sulfonate guests of various shapes and sizes. Cationic water-soluble pillar[5]arenes **1–3** are able to selectively form 1 : 1 complexes with hydrophobic anions (**G1**, **G2**, **G4**, and **G7**). The guests with bulky uncharged or negatively charged substituents (**G5** and **G6**) hindering entry into the macrocycle cavity. Highly selective binding of the most lipophilic guest, *i.e.* methyl orange **G8**, in the form of organic anion salts by positively charged water-soluble pillar[5]arenes was detected.

Acknowledgements

The work was supported by the Russian Science Foundation (no. 14-13-00058).

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