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ARTICLE

Calix[4]arenes Containing Ureido Functionality on the Lower Rim as Highly Efficient Receptors for Anion Recognition

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The introduction of nosyl moieties onto the lower rim of the calix[4]arene skeleton led to compounds immobilised in the *cone* conformations. Subsequent reduction of the nitro group and reaction with aryl isocyanates enabled the construction of new calixarene-based ligands for anion recognition. As proven by NMR and UV/vis titration experiments, diaryl urea moieties with electron-withdrawing substituents on both sides represent very efficient tools for the complexation of selected anions (AcO^-, BzO^-, $H_2PO_4^-$) even in highly competitive solvents such as DMSO-d_6.

Introduction

Calix[n]arenes[1] are macrocyclic compounds, well-known for their complexation abilities and are easily obtainable by base-catalysed condensation of *p*-substituted phenols with formaldehyde. These compounds have been attracting attention for decades as one can easily select the appropriate size of the cavity depending on the application. Moreover, in the case of calix[4]arene, the 3D shape of the macrocycle can be deliberately tuned to obtain one of the four basic conformations (atropoisomers), known as *cone*, *partial cone*, *1,2-alternate* and *1,3-alternate*. All of these features make calix[4]arene a logical choice for the role of molecular scaffolds in the design of molecular receptors.

The role of anions in various biological systems and their function in living organisms is well recognized. Due to their ubiquity, the study of anion complexation and/or recognition has become an integral part of modern supramolecular chemistry as can be demonstrated by the vast number of papers, review articles[2] and books[3] recently published on this topic. Because of the importance of anions in many biological and industrial processes, including environmental pollution, there are ongoing efforts to design and develop new synthetic receptors and sensors for the recognition of anions.

Of the many types of receptors for anion recognition currently known, those using highly directional hydrogen bonding interactions from amide, sulfonamide, urea and/or thiourea moieties[4] most efficiently complex anions. The tuneable shape of the calix[4]arene cavity can then operate as a molecular platform enabling an elaborated arrangement of functional groups in precisely defined mutual positions. As a result, calix[4]arene allows for the construction of highly preorganised anion receptors[5] possessing a cooperative effect of the various functional groups.

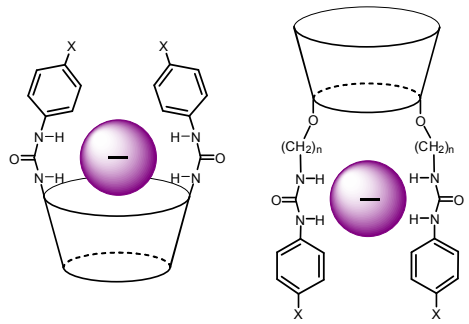

Fig. 1 General design of calix[4]arene-based ureido receptors for anion recognition.

Typical examples of calixarene-based anion receptors are depicted in Fig. 1. Calix[4]arene immobilised in the *cone* conformation is completed by neutral groups (such as ureido moieties) capable of hydrogen bonding interactions with anions. As shown in our previous work,[6] both the upper rim (aromatic subunits) and the lower rim (phenolic oxygens) of the calix[4]arene skeleton can be used for the design of receptors. The upper rim appended ureido functionality represents a diaryl urea motif which usually exhibits better results (in term of K_a values) than the corresponding alkyl aryl ureas on the lower rim (Fig. 1). In both cases, the complexation ability of the receptors can be enhanced by the introduction of electron-withdrawing groups onto the aryl moiety, but,

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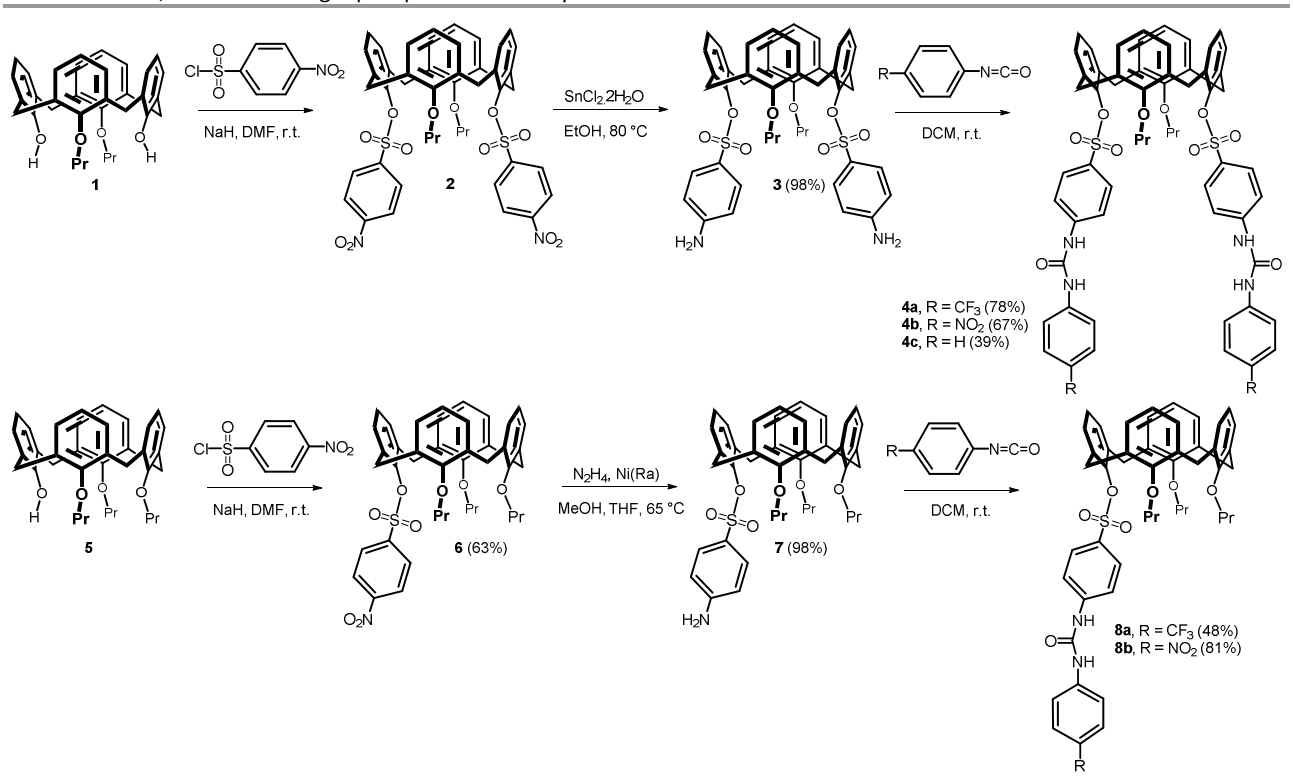
because of the design, this substitution can only be done on one side of the ureido moiety.

Recently, we reported a straightforward regioselective derivatization of the calix[4]arene skeleton based on protection/deprotection of the lower rim with nosyl (*p*-nitrobenzenesulfonyl) groups.[7] We realised that the nosyl group represents a suitable structural motif that (i) possesses a strongly electron-withdrawing substituent (-SO_3-), and (ii) enables the introduction of the diarylureido moiety onto the lower rim of calixarenes. In this paper we report on the synthesis and the complexation abilities of novel receptors based on the application of nosyl groups in the design of functional molecules capable of the recognition of biologically relevant anions, such as dihidrogenphosphate or carboxylates.

Results and discussion

Starting dipropoxycalix[4]arene **1**[8] was reacted with *p*-nitrobenzenesulfonyl chloride according to literature precedence[7c] (NaH/DMF, r.t.) to give sulfonylated compound **2** in 87% yield (Scheme 1). The nitro groups were then smoothly reduced by reaction of **2** with $SnCl_2 \cdot 2H_2O$ in refluxing EtOH. The corresponding amino derivative **3** was isolated in 98% yield. Finally, this compound was reacted (CH_2Cl_2, r.t.) with *p*-substituted phenyl isocyanates bearing electron-withdrawing substituents (CF_3, NO_2) or with phenyl isocyanate to give the target receptors **4a**-**4c** in good yields.



Scheme 1 Preparation of anion receptors based on calix[4]arene-urea conjugates.

To compare the complexation ability and to evaluate the cooperation effects of the two ureido clefts, the corresponding monosubstituted analogues **8a** and **8b** were prepared analogously. Thus, tripropoxy derivative **5** was reacted with nosyl chloride to give mononosylated calixarene **6** in 63% yield. Reduction with hydrazine and Raney nickel led to amino derivative **7** (98%) that was transformed into **8a** and **8b** by reaction with isocyanates in 48% and 81% yields, respectively.

The structures of the products were determined using the combination of NMR and HR MS techniques. Thus, the ^{1}H NMR spectrum of **4a** (in DMSO-d_6) reflected the expected C_{2v} symmetry of the cone conformation as demonstrated by the presence of the pair of characteristic doublets for equatorial and axial protons from -CH_2- bridging moieties at 3.02 and 4.05 ppm, possessing a typical geminal interaction constant J = 13.2 Hz. Also the presence of one triplet for the methyl (from propyl) at 0.69 ppm, together with two singlets from the NH bonds from the ureido moieties, is in line with the predicted structure. HR MS (Orbitrap) analysis of **4a** displayed a signal at 1215.3095, that was in good agreement with the calculated value (1215.3078) for the $[M+Na]^+$ ion.

Similarly, the ^{1}H NMR spectrum ($CDCl_3$) of **8a** clearly supported the lower symmetry of this compound. Thus, the presence of two pairs of doublets for the -CH_2- bridges moieties (2.90, 3.15, 4.15 and 4.40 ppm) corresponded to the expected C_s symmetry of the monosubstituted *cone* conformation.

The structure of **8b** was unequivocally confirmed by X-ray crystallography. It crystallised in the monoclinic system (CH_2Cl_2 - MeOH mixture), space group $P2_1/c$. Calix[4]arene adopted a

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distinctive *pinched cone* conformation (Fig 2a,b) with two phenyl rings (one of them bearing the ureido functional group) pointing inside the cavity. The corresponding interplanar angles Φ between the main plane of the molecule defined by the four carbon atoms of the CH_2 bridges and the phenolic subunits were 68.08° and 75.62°. The other two moieties pointed outside from the cavity (Φ.=151.28° and 139.38°).

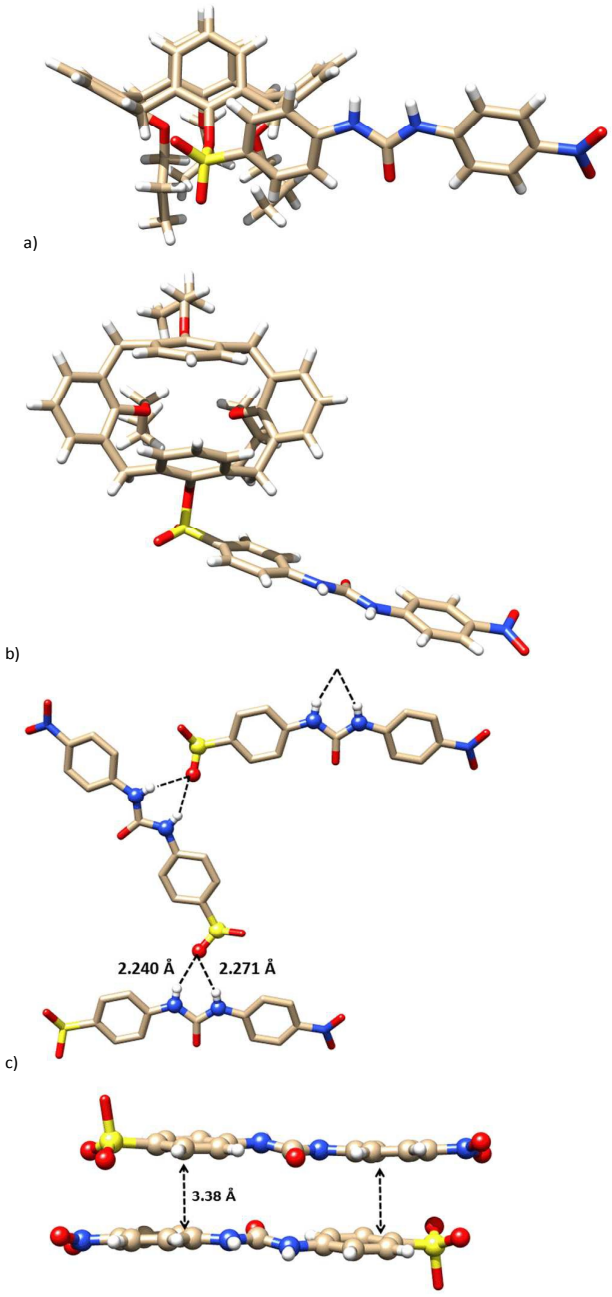

Fig. 2 Single crystal X-ray structures of compound **8b**: (a) side view, (b) from above the cavity, (c) packing motif showing hydrogen bonding interactions, (d) packing motif with π-π interactions (calixarene units were removed for better clarity).

The diaryl ureido part of **8b** is highly planar and it is clearly distorted out of the cavity. As follows from Fig 2a,b the long axis of the diaryl urea fragment is almost perpendicular to the vertical axis of the calix[4]arene molecule. The crystal packing of **8b** is characterised by an infinite assembly of molecules held together by hydrogen bonding interactions between the N-H bonds from the urea moieties and the oxygen atom (S=O) from sulfonate groups (Fig 2c). The corresponding N-H···O distances were 2.240 and 2.271 Å. Moreover, the planarized diaryl urea fragments formed dimers with an interplanar distance of 3.38 Å indicating the contribution of π-π interactions.

The complexation ability of novel ligands **4a-c** and **8a,b** towards selected anions was studied by standard ^{1}H NMR titration techniques. All anions used for titrations were in the form of tetrabutylammonium (TBA) salts to avoid possible complexation of bulky cations by the calixarene cavity. The selection of anions took into consideration various possible geometries, such as spherical (Cl^-), trigonal (NO_3^-, BzO^-, AcO^-) or tetragonal (HSO_4^-, $H_2PO_4^-$) shapes. The aliquots of anions were gradually added into the solution of ligands in DMSO-d_6 to obtain calixarene:anion ratios of up to 1:10-15.

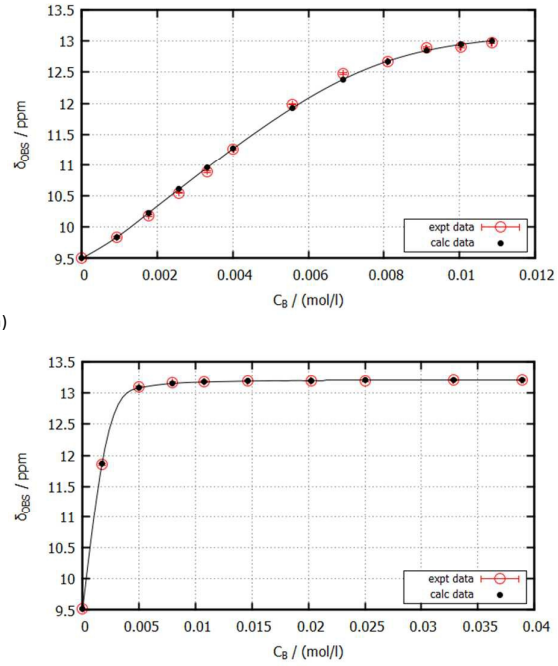

Fig 3 ^{1}H NMR titration curves of **4a** (a) and **8a** (b) with BzO^- (DMSO-d_6, 300 MHz, 298 K).

Although DMSO is an example of a highly competitive solvent towards hydrogen bonding interactions, the addition of anion aliquots led to pronounced downfield shifts of the ureido NH signals, demonstrating strong complexation under fast exchange conditions. Thus, the addition of benzoate anion to a solution of **8a** in DMSO-d_6 resulted in huge complexation induced shifts (CIS) of both ureido NH protons from 9.5 to ca 13.2 ppm (see Fig. 3b). The corresponding Job plot[9] analyses of **8a** and **8b** revealed the formation of complexes with 1:1

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stoichiometry for all anions measured (see Fig. 4 for **8b**/ BzO^- system). The corresponding complexation constants, collected in Table 1, were determined by analysing the binding isotherms obtained from the CIS values of NH ureido protons using the original nonlinear curve-fitting program (OPIUM).[10]

Table 1. Binding constants of receptors **4** and **8** toward selected anions[a] (^{1}H NMR titration, 300 MHz, DMSO-d_6, 298 K)

Compound	BzO^-	AcO^-	NO_3^-	HSO_4^-	$H_2PO_4^-$	Cl^-
4a	20 ± 3 [b]	27 ± 7 [b]	2.4 ± 0.3 [b]	7 ± 0.7 [b]	135 ± 54 [b]	2.7 ± 0.4 [b]
4b	108 ± 44 [b]	79 ± 17 [b]	1.5 ± 0.4 [b]	0.5 ± 0.1 [b]	210 ± 16 [b]	4 ± 0.4 [b]
4c	22 ± 6 [b]	29 ± 3 [b]	0.12 ± 0.03 [b]	0.17 ± 0.05 [b]	95 ± 6 [b]	0.34 ± 0.07 [b]
8a	5000 ± 160	9400 ± 520	≈ 0	97 ± 5	>>3·10^4	105 ± 5
8b	12700 ± 720	9400 ± 760	120 ± 10	250 ± 22	>>3·10^4	140 ± 10

[a] All anions used as TBA salts. [b] 1:2 stoichiometry (calix:anion), given as $(K_1 \cdot K_2)/10^5$.

As documented by Table 1, spherical Cl^- was only relatively weakly bound by **8b** (K_{Cl} = 140 M^{-1}), the same is true for trigonal NO_3^- and tetrahedral HSO_4^- with the complexations constants K_{NO3} = 120 M^{-1} and K_{HSO4} = 250 M^{-1}, respectively. On the other hand, planar carboxylates like BzO^- and AcO^- formed much stronger complexes (K_{BzO^-} = 12700 M^{-1}, K_{AcO^-} = 9400 M^{-1}). Surprisingly, the strongest binding was observed for the $H_2PO_4^-$ anion. In this case, the NMR titration experiments were found to reach the borderlines of applicability of this method for the evaluation of the complexation constants.[11] As the titrations were carried out at millimolar concentration of receptors **8a** or **8b**, the values of the K_{H2PO4} could be assigned only approximately[12] as >>3·10^4 M^{-1}.

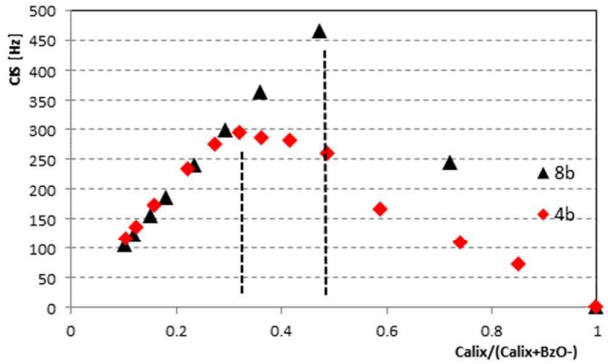

Fig 4 Job plot for **8b**/BzO^- and **4b**/BzO^- systems (^{1}H NMR titration, DMSO-d_6, 300 MHz, 298 K).

The complexation with bis-urea derivatives **4a-c** resulted in the formation of complexes with a 1:2 stoichiometry (calix:anion) as confirmed by the Job plot analyses for all anions used. Consequently, the ^{1}H NMR titration experiments led to evaluation of the overall binding constants K (defined by stepwise binding constants K_1 and K_2 as $K = K_1 \times K_2$). As shown in Table 1 there are several general trends: (i) receptor **4c** without an electron-withdrawing substituent possesses the lowest K values as compared to those of **4a** (CF_3) or **4b** (NO_2) with the exception of carboxylates where the affinities of **4a** and **4c** were more or less comparable. (ii) **4a** and **4b** show extremely high overall constant towards $H_2PO_4^-$ (K_{H2PO4^-} = 1.35·10^7 and 2.1·10^7, respectively). (iii) by way of contrast, the Cl^-, NO_3^- and HSO_4^- exhibit lower overall complexations constants K and are relatively weakly bound by ditopic receptors **8a**-**8b**.

As the complexation of $H_2PO_4^-$ was in fact too strong to be reliably measured by NMR techniques, we have carried out UV/vis titration experiments using nitro and trifluoromethyl derivatives **4a**, **4b**, **8a** and **8b**. The low concentration of the host molecules (< 10^{-5} mol·l^{-1}) allowed for the assignment of both the overall and the stepwise constants that are collected in Table 2. In both cases the corresponding nitro derivatives exhibited stronger complexation ability for the dihydrogenphosphate anion. All four receptors possessed very high complexation constants (K_1 > 4.5·10^4 M^{-1}), despite the fact that DMSO is a highly competitive solvent towards hydrogen bonding interactions.

Table 2. Binding constants of receptors **4a,b and 8a,b** towards $H_2PO_4^-$ (UV/vis titrations,[a] DMSO, 298 K).

Compound	K_1	K[c]
4a	7.7 x 10^4 ± 3.4 x 10^3	7.3 x 10^6± 3.7 x 10^5
4b	3.5 x 10^5± 1.1 x 10^4	3.0 x 10^7 ± 9.0 x 10^6
8a	4.5 x 10^4 ± 9.3 x 10^2	na[b]
8b	1.8 x 10^5 ± 2.9 x 10^3	na[b]

[a] TBA salt used. [b] na = not applicable. [c] $K = K_1 \times K_2$.

Conclusions

The introduction of nosyl moieties onto the lower rim of the calix[4]arene skeleton led to compounds immobilised in the *cone* conformations. Subsequent reduction of the nitro group and reaction with aryl isocyanates enabled the construction of new calixarene-based ligands for anion recognition. As proven by NMR and UV/vis titration experiments, the *N,N'*-diarylurea moieties substituted at both *para* positions with electron-withdrawing substituents represent very efficient tools for the complexation of selected anions (AcO^-, BzO^-, $H_2PO_4^-$) even in a highly competitive solvent like DMSO-d_6.

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Experimental

Materials and instrumentations

All chemicals were purchased from commercial sources and used without further purification. Solvents were dried and distilled using conventional methods. Melting points were measured on Heiztisch Mikroskop-Polytherm A (Wagner & Munz, Germany) and are not corrected. NMR spectra were performed on Varian Gemini 300 (^{1}H: 300 MHz, ^{13}C: 75 MHz), Varian Unity Inova 500 (^{1}H: 500 MHz, ^{13}C: 125 MHz, ^{19}F 470 MHz), and on Bruker Avance III^{TM} (^{1}H: 500 MHz, ^{13}C: 125 MHz). spectrometers. Deuterated solvents used are indicated in each case. Chemical shifts (δ) are expressed in ppm and are referenced to the residual solvent signal or TMS as an internal standard as indicated; coupling constants (*J*) are in Hz. Signal assignments were supported by ^{1}H–^{1}H COSY, ^{1}H–^{13}C HMQC, ^{1}H–^{13}C HMBC and ^{1}H–^{1}H NOESY 2D NMR and 1D ^{1}H-DPFGSE NOE experiments using the standard pulse sequences provided by Bruker and Varian. The right position of chemical shift of CF_3 carbon of receptor **8a** was determined using the ^{13}C-^{19}F gHSQC pulse sequence provided by Varian. The HRMS analyses were performed using ESI on a LTQ Orbitrap Velos (Thermo Scientific) spectrometer equipped with an Orbitrap detector. The IR spectra were measured on an FT–IR spectrometer Nicolet 740 or Bruker IFS66 spectrometers equipped with a heatable Golden Gate Diamante ATR–Unit (SPECAC) in KBr. 100 Scans for one spectrum were co–added at a spectral resolution of 4 cm^{-1}. The purity of substances and the courses of the reactions were monitored by TLC using TLC aluminium sheets with Silica gel 60 F_{254} (Merck) and analysed at 254 and/or 365 nm. Preparative TLC chromatography was carried out on 20 × 20 cm glass plates covered by Silica gel 60 GF_{254} (Merck).

Titration experiments

The UV-Vis titration experiments were carried out using Cintra 20 spectrometer (GBC Scientific Equipment Ltd.). The starting concentration of the calixarene-based receptors in DMSO was held in the region $4{\cdot}10^{-6}$ - $2{\cdot}10^{-5}$ mol/l. Tetrabutylammonium phosphate solution in DMSO was added in portions into the UV cuvette until at least 10 equiv. of the anion was added. All UV spectra were taken in the wavelength region from 200 to 700 nm, with steps of 0.48 nm. The stability constants of the resulting complexes were evaluated by employing the freeware program OPIUM,[10] using the whole parts of absorption curves where the changes in absorbance were the most significant. For each calixarene derivative, the appropriate computational model was chosen according to the Job plot. In the case where the 1:2 stoichiometry model was used, both the values of K_1 (for 1:1 binding) and *K* (overall) were obtained.

The ^{1}HNMR titration measurements were performed in DMSO-d_6 at concentrations of ~$1{\cdot}10^{-3}$ mol/l. The concentration of calixarene receptors was held constant to avoid potential problems with changes of chemical shifts induced by dilution. The stability constants and their errors were evaluated using the self-made computation program ESTAC.

Synthesis

Starting compounds **1** and **5** were prepared exactly according to recently published procedures.[8,13]

25,27-bis(*p*-nitrophenylsulfonyl)-26,28-dipropoxy-calix[4]arene (2)

A mixture of 26,28-dipropoxy-calix[4]arene-25,27-diol **1** (5.00 g, 9.80 mmol) and sodium hydride (1.1 g, 27.50 mmol, 60% suspension in mineral oil) was stirred for 30 min at 0 °C in anhydrous DMF (200 ml). Then, *p*-nitrobenzenesulfonyl chloride (8.70 g, 38.3 mmol, 97% purity) was added and the reaction mixture was stirred at room temperature for 7 days. The resulting mixture was acidified with 1M HCl (aq) and extracted with CH_2Cl_2 (3 × 100 ml). The combined organic layers were washed with water (300 ml), brine (300 ml) and dried over $MgSO_4$. Organic solvent was removed under reduced pressure, and the oily residue was dissolved in CH_2Cl_2 (30 ml) and precipitated by addition of methanol (150 ml). The precipitate was filtered off, washed with methanol and dried to give 7.58 g of title compound **2** as a yellowish powder (87%).

^{1}H NMR ($CDCl_3$, 300 MHz, 298 K) δ (ppm): 8.40 (d, 4H, *J* = 8.8 Hz, Ar-H), 8.15 – 7.96 (m, 4H, *J* = 8.49 Hz, Ar-**H**), 7.07 (d, 4H, *J* = 7.9 Hz, Ar-**H**), 6.91 (t, 2H, *J* = 7.5 Hz, Ar-**H**), 6.40 (t, 2H, *J* = 7.6 Hz, Ar-**H**), 6.19 (d, 4H, *J* = 7.6 Hz, Ar-**H**), 3.98 (d, 4H, *J* = 13.8 Hz, Ar-**CH_2**-Ar); 3.81 (t, 4H, *J* = 8.4 Hz, -OCH_2-), 2.83 (d, 4H, *J* = 13.8 Hz, Ar-**CH_2**-Ar), 1.96 – 1.74 (m, 4H, -CH_2-**CH_2**-CH_3), 0.87 (t, 6H, *J* = 7.47 Hz, -CH_2-**CH_3**). All characterizations including ^{13}C NMR, IR and MS spectra are in agreement with previously published data.[7]

25,27-bis(*p*-aminophenylsulfonyl)-26,28-dipropoxy-calix[4]arene (3)

A 100 mL flask was charged with compound **2** (1.00 g, 1.14 mmol) and ethanol (50 ml). The mixture was heated to obtain a clear solution and then $SnCl_2.2H_2O$ (2.60 g, 11.6 mmol) was added. The reaction mixture was stirred at 80 °C for 4 days. The reaction was quenched by pouring the mixture into ice water which was basified to pH 9-10 using 1M aq. KOH. The aqueous phase was extracted with CH_2Cl_2 (3 x 25 mL), the combined organic layers were washed with saturated solution of NaCl, dried over $MgSO_4$ and the solvent was evaporated *in vacuo* to yield 0.91 g (98%) of the title compound as a yellowish powder, m.p.: 140-147 °C. ^{1}H NMR ($CDCl_3$, 400 MHz, 298 K) δ (ppm): 7.62 (d, 2H, *J* = 8.8 Hz, Ar-**H**), 7.07 (d, 4H, *J* = 7.3 Hz, Ar-**H**), 6.90 (t, 2H, *J* = 7.3 Hz, Ar-**H**), 6.67 (d, 4H, *J* = 8.7 Hz, Ar-**H**), 6.34 (t, 2H, *J* = 7.7 Hz, Ar-**H**), 6.16 (d, 4H, *J* = 7.6 Hz, Ar-**CH_2**-Ar), 4.14 (d, 4H, *J* = 13.8 Hz, Ar-**CH_2**-Ar), 3.85 - 3.71 (m, 4H, -O-**CH_2**-CH_2-), 2.93 (d, 4H, *J* = 14.4 Hz, Ar-**CH_2**-Ar), 1.91 – 1.72 (m, 4H, O-CH_2-**CH_2**-), 0.80 (t, 6H, *J* = 7.47 Hz, -CH_2-**CH_3**). ^{13}C NMR ($CDCl_3$, 100 MHz, 298 K) δ (ppm): 157.6, 151.7, 144.3, 136.4, 134.5, 130.6, 129.1, 127.9, 124.9, 122.3, 113.8, 110.0, 76.5, 31.9, 22.9, 9.8. IR (KBr) ν (cm^{-1}): 3386; 1625; 1355; 1168. HRMS-ESI ($C_{46}H_{46}N_2O_8S_2$) *m/z* (% int.) calcd.: 841.25878 $[M+Na]^+$, found: 841.25941 $[M+Na]^+$ (100)..

25,27-bis(4-(*p*-trifluormethylphenylureido)-phenylsulfonyl)-26,28-dipropoxycalix[4]arene (4a)

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A 10 mL flask charged with amino derivative **3** (100 mg, 0.12 mmol) and 2 mL of CH_2Cl_2 was degassed with argon for 5 min. Then, *p*-trifluormethylphenyl isocyanate (114 mg, 0.61 mmol) was added and the mixture was stirred for 2 days at room temperature under an inert atmosphere. The reaction was quenched with 2 ml of MeOH and the mixture was stirred for 2 hours. The solvents was removed under reduced pressure and the residue was purified by column chromatography on silica gel (eluent: CH_2Cl_2:MeOH = 100:1) to give 110 mg of product **4a** (78%) as a colourless microcrystals, m.p. > 300 °C. ^{1}H NMR (DMSO-d_6, 300 MHz, 298 K) δ (ppm): 9.51 (s, 2H, N-**H**), 9.31 (s, 2H, N-**H**), 7.80 (m, 8H, Ar-**H**), 7.66 (m, 8H, Ar-**H**), 7.18 (d, 4H, *J* = 7.3 Hz, Ar-**H**), 6.89 (t, 2H, *J* = 7.3 Hz, Ar-**H**), 6.46 (t, 2H, *J* = 7.6 Hz, Ar-**H**), 6.28 (d, 4H, *J* = 7.6 Hz, Ar-**H**), 4.05 (d, 4H, *J* = 13.2 Hz, Ar-**CH_2**-Ar), 3.64 (t, 4H, *J* = 8.5 Hz, -O-**CH_2**-), 3.02 (d, 4H, *J* = 13.2 Hz, Ar-**CH_2**-Ar), 1.70 (m, 4H, -CH_2-**CH_2**-CH_3), 0.71 (t, 6H, *J* = 7.3 Hz, -CH_2-**CH_3**),. ^{13}C NMR (DMSO-d_6, 75 MHz, 298 K) δ (ppm): 156.8, 151.9, 145.4, 143.3, 142.9, 135.5, 134.2, 129.6, 129.2, 127.9, 127.3, 126.1, 125.0, 122.7, 122.6, 122.2, 118.3, 118.0, 76.0, 31.1, 22.4, 9.5. ^{19}F NMR (DMSO-d_6, 282 MHz): δ = -60.89. IR (KBr) ν (cm^{-1}): 3372; 1723; 1168. HRMS-ESI ($C_{62}H_{54}F_6N_4O_{10}S_2$) *m/z* (% int.) calcd.: 1215.30778 $[M+Na]^+$, found: 1215.30946 $[M+Na]^+$ (100).

25,27-bis(4-(*p*-nitrofenylureido)-phenylsulfonyl)-26,28-dipropoxycalix[4]arene (4b)

The same procedure as described for the preparation of compounds **4a** starting from derivative **2** (116 mg, 0.141 mmol), dry CH_2Cl_2 (1O ml), and *p*-nitrophenyl isocyanate (116 mg, 0.705 mmol). The crude product was purified by precipitation from MeOH/CH_2Cl_2 mixture to yield 94 mg (67%) of **4b** as a yellow powder, m.p: 280 – 286 °C. ^{1}H NMR (DMSO-d_6, 300 MHz, 298 K) δ (ppm): 9.63 (s, 4H, N-**H**), 8.22 (m, 4H, Ar-**H**), 7.82 (m, 8H, Ar-**H**); 7.73 (m, 4H, Ar-**H**), 7.32 (d, 4H, *J* = 7.6 Hz, Ar-**H**), 6.90 (t, 2H, *J* = 7.6 Hz, Ar-**H**), 6.46 (t, 2H, *J* = 7.3 Hz, Ar-**H**), 6.28 (d, 4H, *J* = 7.3 Hz, Ar-**H**), 4.06 (d, 4H, *J* = 13.5 Hz, Ar-**CH_2**-Ar), 3.64 (t, 4H, *J* = 7.9 Hz, -**OCH_2**), 3.02 (d, 4H, *J* = 13.8 Hz, Ar-**CH_2**-Ar), 1.70 (m, -OCH_2-**CH_2**-), 0.71 (t, 6H, *J* = 7.3 Hz, -CH_2-**CH_3**). ^{13}C NMR (DMSO-d_6, 75.4 MHz, 298 K) δ (ppm): 156.5, 151.6, 145.7, 145.1, 143.3, 141.6, 135.9, 134.2, 129.6, 129.2, 127.9, 127.6, 125.12, 125.09, 122.7, 118.2, 117.9, 76.0, 31.1, 22.4, 9.5. IR (KBr) ν (cm^{-1}): 3352, 1724, 1542, 1332, 1195, 1170. MS-ESI ($C_{60}H_{56}N_6O_{14}S_2$) *m/z* (% int.) calcd.: 1164.34777 $[M+NH_4]^+$, 1169.30316 $[M+Na]^+$, 1185.27710 $[M+K]^+$, found: 1164.34770 $[M+NH_4]^+$ (30), 1169.30241 $[M+Na]^+$ (100), 1185.27647 $[M+K]^+$ (10).

25,27-bis(4-(phenylureido)phenylsulfonyl)-26,28-dipropoxycalix[4]arene (4c)

Phenyl isocyanate (0.15 g, 1.26 mmol) was added to the solution of amine **1** (0.15 g, 0.02 mmol) dissolved in dry THF (15 mL) under an inert atmosphere of nitrogen. The resulting mixture was stirred for 7 days, poured into water (60 mL) and extracted with CH_2Cl_2 (3 x 20 mL). The combined organic layers were washed with brine, dried over $MgSO_4$ and evaporated to dryness. The mixture was purified by flash column chromatography (Al_2O_3; CH_2Cl_2/MeOH = 160:1), first eluent was used to remove impurities and the second eluent (CH_2Cl_2/MeOH = 1:1) gave the pure product **4c** as slightly brown solid in 39% yield (75 mg), m.p: 219.3 – 220.5 °C. ^{1}H NMR (DMSO-d_6, 400 MHz, 298 K) δ (ppm): 9.40 (s, 2H, N-**H**), 8.91 (s, 2H, N-**H**), 7.80-7.74 (m, 8H, Ar-**H**), 7.47 (d, ^3J = 7.83 Hz, 4H, Ar-**H**), 7.30 (t, ^3J = 8.00 Hz, 4H, Ar-**H**), 7.17 (d, ^3J = 7.83 Hz, 4H, Ar-**H**), 7.01 (t, ^3J = 7.43 Hz, 2H, Ar-**H**), 6.89 (t, ^3J = 7.63, 2H, Ar-**H**), 6.45 (t, ^3J = 7.63, 2H, Ar-**H**), 6.28 (d, ^3J = 7.43, 4H, Ar-**H**), 4.05 (d, ^2J = 13.69 Hz, 4H; Ar-**CH_2**-Ar *ax*), 3.65 (t, ^3J = 8.41 Hz, 4H; O**CH_2**), 3.02 (d, ^2J = 13.69 Hz, 4H; Ar-**CH_2**-Ar *eq*), 1.74–1.64 (m, 8H; OCH_2**CH_2**), 0.72 (t, ^3J = 7.44 Hz, 6H; **CH_3**) ppm. ^{13}C NMR ($CDCl_3$/CD_3OD = 7:1, v/v, 100 MHz, 298 K) δ (ppm): 161.28, 156.63, 149.22, 148.05, 142.20, 140.02, 138.27, 132.01, 133.64, 132.82, 131.90, 129.02, 127.20, 126.32, 123.24, 121.57, 80.40, 35.72, 26.77, 13.54 ppm, (C=O signal was not clearly visible). IR (KBr) ν (cm^{-1}): 2924, 1665, 1594, 1447, 1173. MS-ESI ($C_{60}H_{56}N_4O_{10}S_2$) *m/z* (% int.) calcd.: 1079.33301 $[M+Na]^+$, found: 1079.33374 $[M+Na]^+$ (100).

25-(*p*-nitrophenylsulfonyl)-26,27,28-dipropoxy-calix[4]arene (6)

A mixture of 26,27,28-tripropoxy-calix[4]arene **5** (0.466 g, 0.868 mmol) and sodium hydride (0.138 g, 3.47 mmol, 4 equivs, 60% suspension in mineral oil) was stirred for 30 min at 0 °C in anhydrous DMF (25 ml). Then, *p*-nitrobenzenesulfonyl chloride (0.77 g, 3.47 mmol, 4 equivs, 97% purity) was added and the reaction mixture was stirred at room temperature for 5 days. The resulting mixture was acidified with 1 M aq. HCl (50 ml) and extracted with CH_2Cl_2 (3 × 50 ml). The combined organic layers were washed with water (100 ml), brine (100 ml), and dried over $MgSO_4$. Organic solvent was removed *in vacuo*, and the oily residue was dissolved in CH_2Cl_2 (20 ml) and precipitated by the addition of methanol (100 ml). The filtration of precipitate yielded 0.404 g of title compound **6** as a yellow powder (63%), m.p: 280 – 286 °C. ^{1}H NMR (DMSO-d_6, 300 MHz, 298 K) δ (ppm): 9.63 (s, 4H, N-**H**), 8.22 (m, 4H, Ar-**H**), 7.82 (m, 8H, Ar-**H**); 7.73 (m, 4H, Ar-**H**), 7.32 (d, 4H, *J* = 7.6 Hz, Ar-**H**), 6.90 (t, 2H, *J* = 7.6 Hz, Ar-**H**), 6.46 (t, 2H, *J* = 7.3 Hz, Ar-**H**), 6.28 (d, 4H, *J* = 7.3 Hz, Ar-**H**), 4.06 (d, 4H, *J* = 13.5 Hz, Ar-**CH_2**-Ar), 3.64 (t, 4H, *J* = 7.9 Hz, -O**CH_2**), 3.02 (d, 4H, *J* = 13.8 Hz, Ar-**CH_2**-Ar), 1.70 (m, -OCH_2**CH_2**-), 0.71 (t, 6H, *J* = 7.3 Hz, -CH_2**CH_3**). ^{13}C NMR (DMSO-d_6, 75.4 MHz, 298 K) δ (ppm): 156.5, 151.6, 145.7, 145.1, 143.3, 141.6, 135.9, 134.2, 129.6, 129.2, 127.9, 127.6, 125.12, 125.09, 122.7, 118.2, 117.9, 76.0, 31.1, 22.4, 9.5. IR (KBr) ν (cm^{-1}): 3352, 1724, 1542, 1332, 1195, 1170. MS-ESI ($C_{60}H_{56}N_6O_{14}S_2$) *m/z* (% int.) calcd.: 1169.30316 $[M+Na]^+$, found: 1169.30241 $[M+Na]^+$ (100).

25-(*p*-aminophenylsulfonyl)-26,27,28-tripropoxy-calix[4]arene (7)

Nitro derivative **6** (0.31 g) was dissolved in MeOH:THF (1:1) mixture and a catalytic amount (10 mg) of Raney nickel was added. The reaction mixture was heated to 65 °C and hydrazine hydrate (0.5 ml) was added. The mixture was stirred for 10 min at the same temperature, then cooled to rt and filtered through a short pad of celite. Evaporation of the filtrate gave 0.291 g of product **7** (98%) as an off-white powder, m.p.: 172-174 °C. ^{1}H NMR ($CDCl_3$, 300 MHz, 298 K) δ (ppm): 7.61 (d, 2H, *J* = 8.6 Hz, Ar-**H**), 7.12 (d, 2H, *J* = 7.0 Hz, Ar-

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H), 7.06 (d, 2H, *J* = 7.4 Hz, Ar-**H**), 6.91 (t, 2H, *J* = 7.4 Hz, Ar-**H**), 6.64 (d, 2H, *J* = 8.6 Hz, Ar-**H**), 6.38 (t, 2H, *J* = 7.4 Hz, Ar-**H**), 6.20 (m, 2H, Ar-**H**), 6.10 (d, 2H, *J* = 7.4 Hz, Ar-**H**), 4.43 (d, 2H, *J* = 13.3 Hz, Ar-**CH$_2$**-Ar), 4.32 (s, 2H, -**NH$_2$**), 4.19 (d, 2H, *J* = 14.1 Hz, Ar-**CH$_2$**-Ar), 4.05 (td, 2H, J^1 = 11.0 Hz, J^2 = 5.5 Hz, CH_2-**CH_2**-CH_3), 3.84 (td, 2H, J^1 = 11.0 Hz, J^2 = 5.5 Hz, -CH_2-**CH_2**-CH_3), 3.66 (t, 2H, *J* = 6.7 Hz, O-**CH_2**-CH_2), 3.16 (d, 2H, *J* = 13.7 Hz, Ar-**CH_2**-Ar), 2.95 (d, 2H, *J* = 13.7 Hz, Ar-**CH_2**-Ar), 1.88 (m, 6H, -CH_2-CH_2-**CH_3**), 1.10 (t, 3H, *J* = 7.4 Hz, -CH_2-**CH_3**), 0.86 (t, 3H, *J* = 7.4 Hz, -CH_2-**CH_3**). ^{13}C NMR ($CDCl_3$, 75 MHz, 298 K) δ (ppm): 157.7, 155.0, 151.8, 144.4, 136.9, 136.3, 134.7, 132.9, 130.6, 129.3, 128.6, 127.8, 127.3, 124.9, 123.7, 121.9, 113.6, 76.5, 76.4, 31.9, 30.8, 23.4, 22.9, 10.8, 9.8. IR (KBr) ν (cm^{-1}): 3384, 2960, 2964, 2360, 2339, 1623; 1594; 1455; 1088; 767. HRMS-ESI ($C_{43}H_{47}NO_6S$) *m/z* (% int.) calcd.: 728.30163 $[M+Na]^+$, 744.27472 $[M+K]^+$, found: 728.30194 $[M+Na]^+$ (100), 744.27557 $[M+K]^+$ (25).

25-(4-(*p*-trifluoromethylphenylureido)-phenylsulfonyl)-26,27,28-tripropoxycalix[4]arene (8a)

Using the same procedure as described for the preparation of compounds **4a**, starting from **7** (92.5 mg, 0.131 mmol) and *p*-trifluoromethylphenyl isocyanate (61.4 mg, XXX mmol, 2.5 equiv.) were reacted in dry DMF (2 mL). The crude product was purified by preparative TLC using CH_2Cl_2 as eluent to yield 56 mg (48%) of **8a** as an off white powder, m.p: 148 – 152 °C. ^{1}H NMR ($CDCl_3$, 500 MHz, 298 K) δ (ppm): 7.79 (d, 2H, *J* = 8.3 Hz, Ar-**H**), 7.58 (d, 4H, *J* = 8.45 Hz, Ar-**H**, 7.53 (d, 2H, *J* = 8.5 Hz, Ar-**H**), 7.20 (bs, 1H, N-**H**), 7.11 (dd, 2H, J^1 = 7.5 Hz, J^2 = 1.6 Hz, Ar-**H**), 7.01 (dd, 2H, J^1 = 7.5 Hz, J^2 = 1.3 Hz, Ar-**H**), 6.89 (t, 2H, *J* = 7.5 Hz, Ar-**H**), 6.40 (t, 1H, *J* = 7.6 Hz, Ar-**H**), 6.19 (d, 2H, *J* = 7.7 Hz, Ar-**H)**, 6.14 (m, 1H, Ar-**H**), 6.08 (d, 2H, *J* = 7.5 Hz, Ar-**H**), 4.41 (d, 2H, *J* = 13.3 Hz, Ar-C**H$_2$**-Ar), 4.14 (d, 2H, *J* = 13.8 Hz, Ar-C**H$_2$**-Ar), 4.06 (m, 2H, -OCH**H**), 3.79 (m, 2H, -OCH**H**), 3.65 (t, 2H, *J* = 7.4 Hz, -OC**H$_2$**), 3.15 (d, 2H, *J* = 13.5 Hz, Ar-C**H$_2$**-Ar), 2.89 (d, 2H, *J* = 13.9 Hz, Ar-C**H$_2$**-Ar), 1.8-1.6 (m, 6H, -OCH_2**CH_2-**), 1.07 (t, 3H, *J* = 7.4 Hz, -CH_2**CH_3**), 0.84 (t, 6H, *J* = 7.5 Hz, -CH_2**CH_3**). ^{13}C NMR ($CDCl_3$, 125 MHz, 298 K) δ (ppm): 157.6, 155.0, 151.0, 144.2, 144.0, 140.9, 136.9, 135.9, 134.6, 132.9, 129.9, 129.6, 129.4, 128.5, 128.1, 127.3, 126.4 (q, *J* = 3.9 Hz), 125.5 (q, *J* = 32.9Hz), 125.4, 123.9 (q, *J* = 271.2Hz), 122.0, 121.9, 119.3, 118.3, 76.8, 76.5, 31.9, 30.9, 23.5, 23.0, 10.8, 9.8. ^{19}F NMR ($CDCl_3$, 282 MHz): δ = -62.10. IR (KBr) ν (cm^{-1}): 3383, 2903, 2360, 1958, 1538, 1323, 1167, 1068, 771. MS-ESI ($C_{51}H_{51}F_3N_2O_7S$) *m/z* (% int.) calcd.: 915.32613 $[M+Na]^+$, 931.30007 $[M+K]^+$, found: 915.32629 $[M+Na]^+$ (100), 931.29834 $[M+K]^+$ (25).

25-(4-(*p*-nitrophenylureido)-phenylsulfonyl)-26,27,28-tripropoxycalix[4]arene (8b)

Using the same procedure as described for the preparation of compounds **4a**, starting derivative **7** (55.5 mg, 0.079 mmol) and *p*-nitrophenyl isocyanate (32.3 mg, 0.197 mmol, 2.5 equiv.) were reacted in dry DMF (5 mL). The crude product was purified by column chromatography on silica gel (eluent: petroleum ether : ethyl acetate = 3:1 v/v) to yield 35 mg (81%) of **8b** as a yellow powder, m.p: 275 – 278 °C. ^{1}H NMR (DMSO-d_6, 300 MHz, 298 K) δ (ppm): 8.22 (s, 1H, N-**H**), 8.20 (s, 1H, N-**H**), 7.84 (m, 4H, Ar-**H**), 7.74 (d, 2H, *J* = 9 Hz, Ar-**H**), 7.13 (m, 4H, Ar-**H**), 6.88 (t, 2H, *J* = 7.4 Hz. Ar-**H**), 6.46 (t, 2H, *J* = 7.8 Hz, Ar-**H**), 6.27 (d, 2H, *J* = 7.8 Hz, Ar-**H**), 6.17 (m, 2H, Ar-**H**), 6.09 (d, 2H, *J* = 7.8 Hz, Ar-**H**), 4.30 (d, 2H *J* = 12.9 Hz, Ar-**CH$_2$**-Ar), 4.11 (d, 2H, *J* = 13.3 Hz, Ar-**CH$_2$**-Ar), 3.91 (dt, 2H, J^1 = 10.6 Hz, J^2 = 5.5 Hz, O-**CH_2**-CH_2-), 3.71 (dt, 2H, J^1 = 10.6 Hz, J^2 = 5.5 Hz, O-**CH_2**-CH_2-), 3.58 (t, 2H, *J* = 6.3 Hz, O-**CH_2**-CH_2-), 3.17 (d, 2H, *J* = 12.9 Hz, Ar-**CH_2**-Ar), 3.02 (d, 2H, *J* = 14.1 Hz, Ar-**CH_2**-Ar), 1.79 (m, 8H,-CH_2-**CH_2**-CH_3), 1.05 (t, 3H, *J* = 7.4 Hz, -CH_2-**CH_3**), 0.78 (t, 6H, *J* = 7.4 Hz, -CH_2-**CH_3**). ^{13}C NMR (DMSO-d_6, 100 MHz, 298 K) δ (ppm): 157.03, 154.61, 151.67, 145.73, 145.73, 145.08, 143.36, 141.46, 136.24, 135.50, 134.42, 132.55, 129.64, 128.58, 127.74, 127.17, 125.15, 122.26, 121.63, 118.63, 117.93, 76.79, 75.95, 23.03, 22.49, 10.71, 9.61. IR (KBr) ν (cm^{-1}): 3358, 2961, 2923, 2350, 1727, 1593, 2638, 1498, 2332, 1303, 1195, 1170, 1088, 1004, 857, 768. MS-ESI ($C_{51}H_{51}F_3N_2O_7S$) *m/z* (% int.) calcd.: 892.32382 $[M+Na]^+$, 908.29776 $[M+K]^+$, found: 892.32367 $[M+Na]^+$ (100), 908.29712 $[M+K]^+$ (40).

Crystallographic measurements

The structure 8b was measured using D8 VENTURE with Cu-Kα (λ = 1.54054 Å) radiation at 180 K. The structure was in monoclinic system, $P2_1/c$ space group with lattice parameters *a* = 21.5008 (10) Å, *b* = 12.8677 (6) Å, *c* = 16.1684 (7) Å, *β* = 91.2161 (19) °, *Z* = 4, *V* = 4472.2 (4) Å^3, D_c = 1.292 g cm^{-3}, μ(Cu-Kα) = 1.14 mm^{-1}. The data reduction and absorption correction were done with Apex3 software.[14] The Structure was solved by direct methods[15] and refined by full matrix least squares on F squared value using Crystals software[16] to final values *R* = 0.085 an R_w = 0.193 using 8114 independent reflections (Θ_{max} = 68.3 °), 624 parameters and 74 restrains. The MCE software[17] was used for visualization of electron density maps. The positions of disordered functional groups were found in difference Fourier maps; the bond lengths and angles were restrained. The overall occupancy of the disordered functional groups was constrained to 1. According to common practice the hydrogen atoms attached to the carbon atoms were placed geometrically with U_{iso}(H) in the range of 1.2-1.5 U_{eq} of parent atom (C). The structure was deposited into Cambridge Structural Database under number CCDC 1471641.

Acknowledgements

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Notes and references

1 For books on calixarenes, see: (a) C. D. Gutsche Calixarenes An introduction 2nd Edition, The Royal Society of Chemistry, Thomas Graham House, Cambridge, 2008. (b) J. Vicens, J. Harrowfield, L. Backlouti, Eds. Calixarenes in the Nanoworld, Springer, Dordrecht, 2007. (c) L. Mandolini, R. Ungaro, Calixarenes in Action, Imperial College Press, London, 2000.

2 For some recent selected reviews on anion recognition, see: (a) P. A. Gale, *Chem. Commun.* 2011, **47**, 82. (b) I. Ravikumar, P. Ghosh, *Chem. Soc. Rev.* 2012, **41**, 3077. (c) M. Wenzel, J. R.

View Article Online
DOI: 10.1039/C6NJ01271J

Hiscock, P. A. Gale, *Chem. Soc. Rev*. 2012, **41**, 480. (d) N. Busschaert, C. Caltagirone, W. Van Rossom, P. A. Gale, *Chem. Rev.*, 2015, **115**, 8038. (e) V. Blazek Bregovic, N. Basaric, K. Mlinaric-Majerski, *Coord. Chem. Rev.* 2015, **295**, 80. (f) M. J. Langton, C. J. Serpell, P. D. Beer, *Angew. Chem. Int. Ed.* 2016, **55**, 1974.

3 K. Bowman-James, A. Bianchi, E. Garcia-Espana, (Eds) *Anion Coordination Chemistry*, Wiley-VCH Verlag, 2012. (b) P. A. Gale, W. Dehaen, (Eds.) *Anion Recognition in Supramolecular Chemistry* in Topics in Heterocyclic Chemistry, Vol. 24, Springer Verlag, 2010. (c) R. Vilar, (Ed.) *Recognition of Anions* in Structure and Bonding, Vol. 129, Springer Verlag, 2008.

4 See e.g.: (a) V. Amendola , L. Fabbrizzi, L. Mosca, *Chem. Soc. Rev*. 2010, **39**, 3889. (b) P. Dydio, D. Lichosyt, J. Jurczak, *Chem. Soc. Rev.* 2011, **40**, 2971. (c) M. O. Odago, A. E. Hoffman, R. L. Carpenter, D. C. T. Tse, S.-S. Sun, A. J. Lees, *Inorg. Chim. Acta*, 2011, **374**, 558.

5 For selected reviews on calixarene-based receptors for anions, see: (a) B. Mokhtari, K. Pourabdollah, *Asian J. Chem*. 2013, **25**, 1. (b) R. Joseph, C. P. Rao, *Chem. Rev.* 2011, **111**, 4658. (c) E. A. Shokova, V. V. Kovalev, *Russ. J. Org. Chem*. 2009, **45**, 1275 (d) E. A. Shokova, V. V. Kovalev, *Russ. J. Org. Chem.* 2009, **45**, 1275. (e) P. Lhotak, *Top. Curr. Chem*. 2005, **255**, 65. (f) S. E. Matthews, P. D. Beer, *Supramol. Chem*. 2005, **17**, 411.

6 (a) K. Flidrova, M. Tkadlecova, K. Lang, P. Lhotak, *Dyes and Pigments*, 2012, **92**, 668. (b) K. Flidrova, M. Tkadlecova, K. Lang, P. Lhoták, *Tetrahedron Lett*. 2012, **53**, 678. (c) P. Curinova, I. Stibor, J. Budka, J. Sykora, K. Lang, P. Lhotak, *New J. Chem.* 2009, **33**, 612. (d) J. Kroupa, I. Stibor, M. Pojarová, M. Tkadlecova, P. Lhotak, *Tetrahedron* 2008, **64**, 10075. I. Stibor, J. Budka, V. Michlová, M. Tkadlecová, M. Pojarová, P. Curinova, P. Lhotak, *New J. Chem.* 2008, **32**, 1597.

7 7(a) O. Hudecek, P. Curinova, J. Budka, P. Lhoták, *Tetrahedron* 2011, **67**, 5213-5218; (b) O. Hudecek, J. Budka, V. Eigner, P. Lhotak, *Tetrahedron* 2012, **68**, 4187. (c) O. Hudecek, J. Budka, H. Dvorakova, P. Curinova, I. Cisarova, P. Lhoták, *New J. Chem.* 2013, **37**, 220.

8 S. Kennedy, S. J. Dalgarno, *Chem. Commun.* 2009, **35**, 5275.

9 Z. D. Hill, P. MacCarthy, *J. Chem. Educ.* 1986, **63**, 162.

10 The binding constants were calculated using the computer program OPIUM (Kyvala M.) freely available at: http://www.natur.cuni.cz/~kyvala/opium.html.

11 P. Thordarson, *Chem. Soc. Rev.* 2011, **40**, 1305.

12 It is well known that the NMR measurements below 20% and above 80% complexation ratio (x) yield uncertain values. In the case where $[\mathbf{8a}]_0 \cong 1$ mM as an example, the complexation ratio between 0.2 and 0.8 corresponds to *K* values between 300 and 20 000 M^{-1}. For more details, see: K. Hirose in *Analytical Methods in Supramolecular Chemistry*, Ch. Schalley (Ed.), Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, 2007.

13 A. Dondoni, C. Ghiglione, A. Marra, M. Scoponi, *J. Org. Chem.* 1998**, 63**, 9535.

14 Bruker (2015). APEX3, SAINT. Bruker AXS Inc., Madison, Wisconsin, USA.

15 A. Altomare, G. Cascarano, C. Giacovazzo, A. Guagliardi, M. C. Burla, G. Polidori, M. Camalli, *J. Appl. Cryst.* 1994, **27**, 435.

16 P. W. Betteridge, J. R. Carruthers, R. I. Cooper, K. Prout, D. J. Watkin, *J. Appl. Cryst.* 2003, **36**, 1487.

17 J. Rohlicek, M. Husak, *J. Appl. Cryst.* 2007, **40**, 600.

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Graphical Abstract

Calix[4]arenes Containing Ureido Functionality on the Lower Rim as Highly Efficient Receptors for Anion Recognition

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Calix[4]arenes bearing diaryl urea moieties with electron-withdrawing substituents on both sides represent very efficient tools for the complexation of selected anions (AcO^-, BzO^-, $H_2PO_4^-$) even in highly competitive solvents such as DMSO-d_6.