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Syntheses, Structures, and Anion-Binding Properties of Two Novel Calix[2]benzo[4]pyrroles

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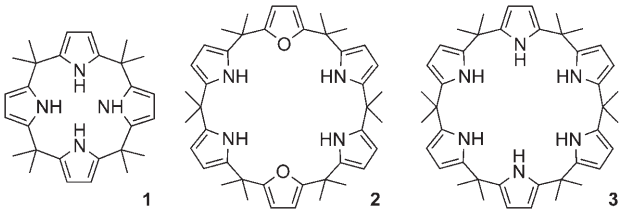
Abstract: Calix[2]benzo[4]pyrrole *m*-**6** and *p*-**6**, each containing two dipyrromethane moieties and two *m*-phenylene or *p*-phenylene units, respectively, were readily synthesised from pyrrole, 1,3- and 1,4-bis(1,1′-dimethylhydroxymethyl)benzene, (*m*-**4** and *p*-**4**, respectively) and acetone. Macrocycles *m*-**6** and *p*-**6** were tested as receptors for a selection of anions, such as acetate, dihydrogenphosphate and fluoride. The X-ray structures of *m*-**6** and *p*-**6** and those of the complexes *m*-**6**·F^-, *m*-**6**·Cl^- and *m*-**6**·CH_3COO^- (with an nBu_4N^+ counterion) were also determined.

Keywords: anions · calixpyrroles · host–guest systems · macrocycles · structure elucidation

Introduction

Calixpyrroles[1] are macrocycles made of pyrrole units linked at their 2,5-positions with quaternary carbon-atom bridges. Although structurally related to porphyrins, they have no hydrogen atoms at their *meso* positions and, therefore, they do not exhibit the typical chemistry of porphyrins.[2] Current interest in calixpyrroles is mostly related to their ability to act as molecular receptors for anions.[3] The initial discovery that calix[4]pyrrole **1** is capable of binding anions by means of multiple hydrogen bonds[1a] promoted considerable research on the use of pyrroles as building blocks for the assembly of both cyclic and acyclic anion-binding receptors,[4] such as a number of "hybrid" and "expanded" (i.e., containing more than four aromatic units) calixpyrroles.[5] Calix[4]-pyrroles in which some of the pyrrole units were replaced with furan and/or thiophene proved to be less-effective anion ligands overall than the "purely" pyrrole parent compound, although they did show interesting and varied selectivities.[5k] Similar results were reported for a comparison between calix[2]furan[4]pyrrole **2** and calix[6]pyrrole **3**.[5h,e]



However, benzo rings have the potential to form CH···anion hydrogen bonds,[6] and their inclusion in pyrrole-containing heterocalixarenes can be less detrimental to anion binding than the inclusion of either furan or thiophene. Although a study dealing with the replacement of some pyrrole rings with benzo units has been reported for the calix[4] systems,[5k] to the best of our knowledge there are no data for "hybrid" and "expanded" calixpyrroles containing benzo units. Here we report our initial studies on two representatives of these compounds.

Results and Discussion

Calix[2]-*m*-benzo[4]pyrrole (*m*-**6**) containing two dipyrromethane moieties and two *m*-phenylene units and its ana-

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logue *p*-**6**, in which the benzo rings have *p*-regiochemistry, were readily synthesised as outlined in Scheme 1. The bispyrrole intermediate *m*-**5** was prepared as described in the literature,[5g] and *p*-**5** was obtained by this same method.

The [2+2] macrocyclisation of *p*-**5** with acetone was optimised by testing various stoichiometric proportions of acetone and TFA (trifluoroacetic acid) in various solvents. The best yield of *p*-**6** (77% isolated by crystallisation from the crude reaction mixture with EtOAc/hexanes) was obtained by treating a 0.006 M solution of *p*-**5** in acetone/acetonitrile [1:12 (v/v)] with TFA (5 equiv). Because these conditions with *m*-**5** gave *m*-**6** in 50% yield, this reaction was not optimised further. The macrocyclic structures of *m*-**6** and *p*-**6** were evident from their ^{1}H and ^{13}C NMR spectra, which were consistent with time-averaged planar conformations. Both compounds gave single crystals by slow cooling of EtOAc/hexane (4:1) solutions.

The X-ray structure of *m*-**6** shows the macrocycle to have adopted a centrosymmetric rectangular box conformation (Figure 1), similar to that seen for the related calix[2]furan[4]pyrrole analogue.[5h] The C(6), C(14), C(6A) and C(14A) atoms define the corners of the rectangle and are perfectly coplanar; the lengths of the C(6)···C(14) and C(6)···C(14A) edges are ≈5.03 and 9.53 Å, respectively, and they subtend an angle of ≈83° at C(6). The front and back faces of the box are partially obscured by the C(25) and C(25A) methyl groups. The N(10) and aryl rings are steeply inclined to the plane of the macrocycle (by ≈81 and 70°, respectively); the N(10) and C(18) atoms are inclined inwards (towards the centre of the macrocycle) in each case. In contrast, the N(2) pyrrole ring is much less tilted: it is inclined by only ≈38° to the C(6)-C(14)-C(6A)-C(14A) plane with N(2) oriented towards the centre of the macrocycle. Although the N–H hydrogens do not appear to be involved in any significant intra- or intermolecular contacts, there is evidence for a pair of weak intramolecular C–H···π contacts between a C(25) methyl proton on one of the long edges of the rectangle and the aryl ring on the opposite edge, and vice versa, with a H···π distance of 3.12 Å and a C–H···π angle of 126°. The two unique pyrrole rings are each approached by a pyrrole C–H proton from a symmetry-related counterpart of the other ring. The N(2) ring is approached by the C(13)–H proton in an adjacent molecule (H···π = 3.02 Å, C–H···π = 159°), and the N(10) ring is approached by the C(4)–H proton in a different proximal macrocycle (H···π = 3.29 Å, C–H···π = 173°). The aryl ring is stacked with its centrosymmetrically related counterpart with mean interplanar and centroid···centroid separations of ≈3.48 and 4.01 Å, respectively, the two rings being perfectly parallel.

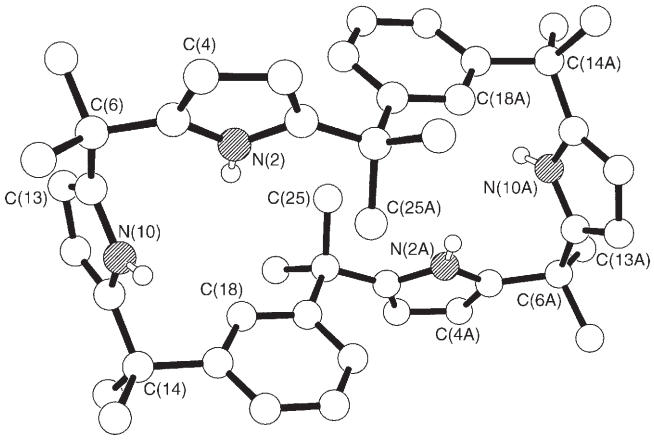
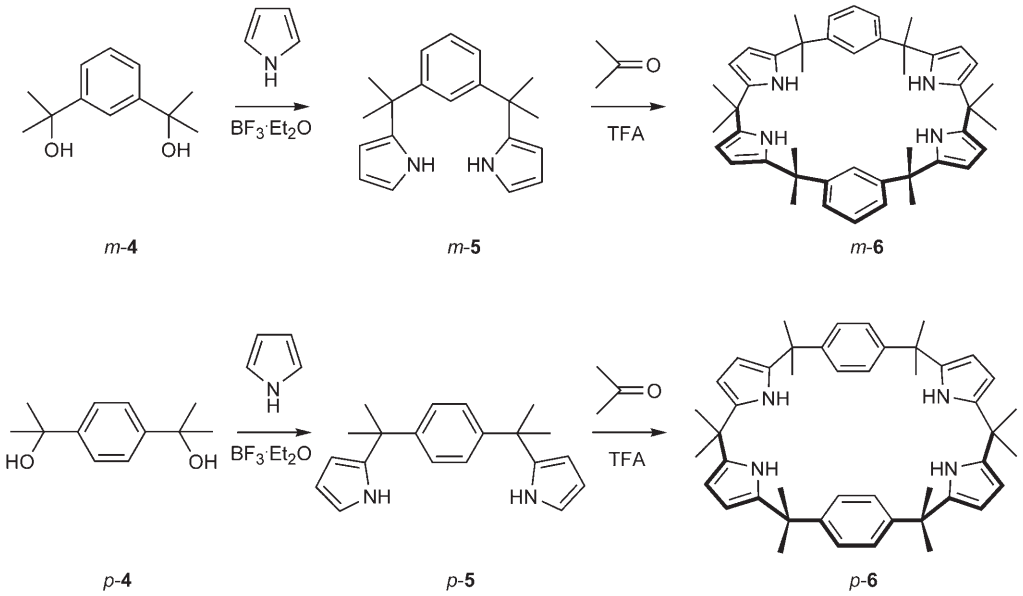


Figure 1. Molecular structure of the C_i-symmetric macrocycle *m*-**6**.

The X-ray analysis of crystals of *p*-**6** revealed the C_2-symmetric macrocycle to have a conformation resembling a twisted tennis-ball seam (Figure 2) similar to that of the re-



Scheme 1.

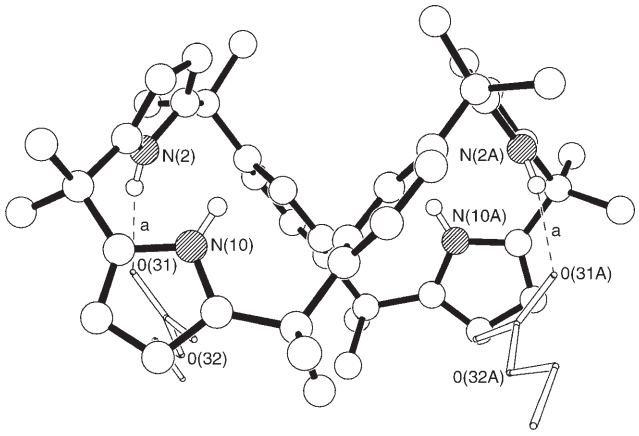


Figure 2. Molecular structure of the C_2-symmetric macrocycle *p*-**6** showing hydrogen bonding to the included ethyl acetate solvent molecules. Geometric data for the hydrogen bond (a) are N···O = 3.060(2) Å, H···O = 2.17 Å and N–H···O = 168°.

lated calix[6]pyrrole species[5h] (the C_2 axis runs vertically in Figure 2, bisecting the N(2)···N(2A) and N(10)···N(10A) vectors). Whilst the N–H group of the N(10) pyrrole ring is oriented inwards and does not participate in any noteworthy interactions, the N(2)–H group is oriented outwards and forms a hydrogen bond to the included ethyl acetate solvent molecule (N···O = 3.060(2) Å, H···O = 2.17 Å and N–H···O = 168°). Unlike the structure of the calix[6]pyrrole, here there is no guest species encapsulated within the macrocycle. The closest approach to the N(2) pyrrole ring is from an aryl proton on the neighbouring C_6H_4 ring with a H···π separation of 2.98 Å and a C–H···π angle of 123°. The H···π vector is inclined by only ≈55° to the pyrrole ring plane. The N(10) pyrrole ring is approached on one side by a methyl proton from the ethyl acetate solvent molecule (H···π = 2.68 Å, C–H···π = 137°) and on the other by an aryl proton in an adjacent macrocycle (H···π = 2.93 Å, C-H···π = 143°), the two interactions subtending an angle of ≈161° at the N(10) ring centroid. The closest approach to the aryl ring is from an isopropylidene methyl proton in a neighbouring macrocycle with a H···π separation of ≈3.40 Å and a C–H···π angle of ≈171°.

The anion-binding properties of *m*-**6** and *p*-**6** were explored by means of NMR titration experiments in DCM and compared with those of calix[2]furan[4]pyrrole **2**. The data obtained are summarised in Table 1, which includes the relevant binding constants (K_a) for calix[4]pyrrole **1**. This is included because it contains the same number of NH units as *m*-**6**, *p*-**6** and **2**. All anions were used as nBu$_4$N$^+$ salts.

The K_a value for the complexation of *m*-**6** with fluoride could not be determined at room temperature because the NH resonances disappeared upon addition of the salt. However, mixtures of *m*-**6** with nBu$_4$NF (various proportions) gave resolved ^{1}H NMR spectra at −65 °C consistent with the formation of a complex that was kinetically slow on the NMR timescale (K_a was too high to be calculated reliably). Three different NH resonances were observed for the complex (1:2:1 intensities with different couplings to fluoride). Only one of the two "isolated" benzo protons was shifted significantly (Figure 3). These features are consistent with the fluoride being off-centre within the macroring, thus, producing a dissymmetric structure.

Table 1. Association constants K_a[M^{-1}] for the 1:1 complexes of the nBu$_4$N$^+$ salts of the anions and macrocycles listed.[a]

	m-**6**	*p*-**6**	**1**	**2**
F^-	≈20000[b,c]	2246 ± 132	17170 ± 900[d]	57000 ± 9000[e]
Cl^-	4975 ± 372	no CIS	350[d]	1600 ± 570[f]
Br^-	296 ± 10	no CIS	10 ± 0.5[d]	61 ± 3[e]
I^-	no CIS	no CIS	< 10[d]	no CIS
CH_3COO^-	755 ± 33[g]	597 ± 236	547 ± 30[h]	34 ± 8
$H_2PO_4^-$	1711 ± 120[i]	no CIS	97 ± 4[d]	no CIS
HSO_4^-	no CIS	no CIS	< 10[d]	no CIS
NO_3^-	< 10	16 ± 0.4[c]	< 10[j]	no CIS

[a] Unless indicated otherwise, data were obtained by ^{1}H NMR titration and from the complexation-induced shifts (CIS) of the NH resonances in "anhydrous" CD_2Cl_2 at 20 °C. [b] NH resonances disappeared at 20 °C upon addition of the salt. [c] K_a value was estimated by competitive binding with *p*-**6** and **1**. [d] Data obtained by ^{1}H NMR titration in "anhydrous" CD_2Cl_2 reported in ref. [1a]. [e] Data from ref. [5h]. [f] From titration data based on the CIS observed for the pyrrole CH resonances (NH signals disappeared upon addition of the salt). [g] K_a value (95% confidence interval) was calculated for an "ideal unique" 1:1 complex from titration data obtained in competitive binding with **1** (see main text and Supporting Information). [h] Value previously reported (see ref. [1d]) is 668 M^{-1}. [i] Kinetically slow on the NMR timescale at 20 °C. [j] Data from ref. [4i].

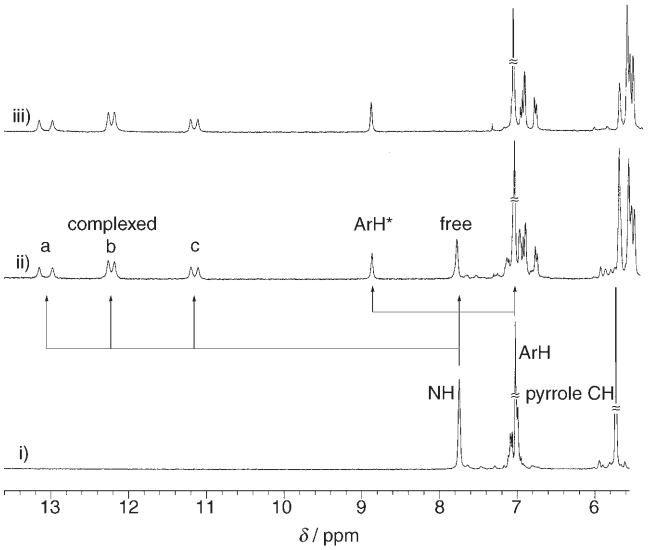


Figure 3. ^{1}H NMR spectra (CD_2Cl_2, −65 °C) of: i) *m*-**6**, 0.005 M, ii) *m*-**6**+nBu$_4$NF (1:0.77) and iii) *m*-**6**+nBu$_4$NF (1:1.81). The intensities and J(H,F) of the NH resonances of the complex (a, b and c) are 1:2:1 and 52, 22 and 27 Hz, respectively. ArH* accounts for only one of the "isolated" ArH protons of the complex. No free *m*-**6** is visible in iii).

The relative affinities of *m*-**6** and *p*-**6** for fluoride were investigated by direct competition experiments. Titration of a 1:1 mixture of *p*-**6** and nBu$_4$NF with *m*-**6** resulted in the displacement of fluoride from *p*-**6**•F$^-$, as indicated by the re-

gression of the complexation-induced shifts (CIS) of the NH protons of *p*-**6**. This regression was complete after the addition of just over one equivalent of *m*-**6**. Therefore, we estimate that the *m*-**6**·F^- complex is not less than ten times more stable than *p*-**6**·F^-. This conclusion is also supported by a competition experiment between *m*-**6** and **1**. In both experiments, the NH resonances remained too broad to determine reliably the ratios of the K_a values until nearly one equivalent of salt was added. However, it was evident that *m*-**6** is a marginally better fluoride ligand than **1**, hence, we can estimate K_a for *m*-**6**·F^- to be $\approx 20000\,M^{-1}$.

The solid-state structure of the fluoride complex *m*-**6**·F^- revealed two independent complexes (**I** and **II**) with the fluoride anion sitting in the plane of the four pyrrole N–H nitrogen atoms in each case; a geometry that differs from the perching arrangement seen for *m*-**6**·Cl^- (see below). The $\{N_4F\}$ atoms are coplanar to within ≈ 0.02 Å in complex **I** and ≈ 0.01 Å in complex **II** (complex **I** is shown in Figure 4,

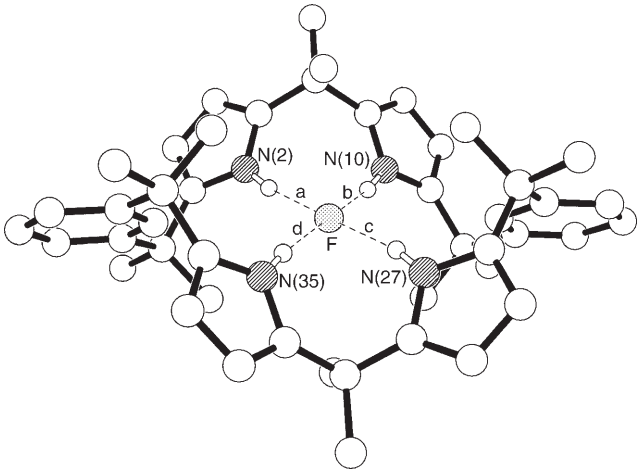


Figure 4. Molecular structure of one (**I**) of the two independent "macrocycle and encapsulated anion" complexes present in the crystals of *m*-**6**·F^-. Hydrogen-bonding geometries N···F, H···F [Å] and N–H···F [°], respectively, are: a) 2.917(3), 2.03, 170; b) 2.922(4), 2.04, 166; c) 2.890(3), 2.00, 169; d) 2.918(3), 2.03, 171.

and complex **II** in Figure S3 in the Supporting Information). The complexes, which have essentially the same geometry,[7] each have molecular C_S symmetry about a plane that includes the fluorine atom and is perpendicular to the N_4F plane, bisecting the N(2)···N(10) and N(27)···N(35) vectors. The only intermolecular macrocycle···macrocycle contact of note[8] is a centrosymmetric π–π stacking interaction involving the C_6 ring located between the N(2) and N(35) pyrrole rings of complex **I** (mean interplanar and centroid···centroid separations of ≈ 3.78 and 4.06 Å, respectively).

In the presence of Cl^-, the ^{1}H NMR spectrum of *m*-**6** shows significant CISs not only for the NH resonances, but also for the aryl C–H units (from $\delta = 7.08$ to $\delta = 8.10$ ppm), which appear to be involved in the binding of the anion.[9] However, in the solid state (see below), this interaction seems less relevant. Of those indicated in Table 1, receptor *m*-**6** is the best ligand for Cl^-, whereas *p*-**6** does not show any interaction with Cl^-.

The X-ray structure of *m*-**6**·Cl^- reveals that the encapsulation of a chloride anion results in the macrocycle adopting a conformation that resembles a tennis-ball seam (Figure 5)

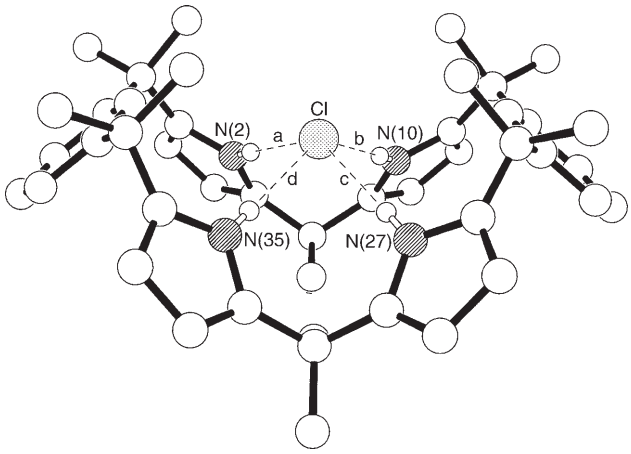


Figure 5. Molecular structure of the macrocycle and the encapsulated anion present in the crystals of *m*-**6**·Cl^-. Hydrogen-bonding geometries N···Cl, H···Cl [Å] and N–H···Cl [°], respectively, are a) 3.3816(15), 2.49, 172; b) 3.3254(14), 2.43, 173; c) 3.4216(14), 2.52, 178; d) 3.4241(14), 2.53, 174.

rather than the rectangular box conformation seen for the empty macrocycle (Figure 1). The chloride is held in place by hydrogen bonds to all four of the pyrrole N–H atoms (the N···Cl distances range between 3.3254(14) and 3.4241(14) Å). That the chloride ion perches (by ≈ 1.09 Å) on top of the plane of the four pyrrole nitrogen atoms (which are coplanar to better than 0.01 Å) is reminiscent of the encapsulation of chloride and bromide by calix[6]pyrrole **3**.[5h] The adjacent aryl protons are not in close proximity to the chloride (H···Cl distances of ≈ 3.09 and 3.14 Å) with noticeably nonlinear C–H···Cl angles of ≈ 117 and 116°, respectively.[10] Adjacent molecules are held together by a series of four cooperative C–H···π hydrogen bonds and a π–π stacking interaction (see Figure S7 in the Supporting Information). The C(18) aryl ring of one molecule stacks with the C(43) aryl ring in a symmetry-related counterpart with mean interplanar and centroid···centroid separations of ≈ 3.16 and 3.92 Å, respectively; the two rings being inclined by $\approx 5°$. The stacking is such that two of the aryl protons of the C(43) ring of the neighbouring molecule form C–H···π interactions with the N(2) and N(35) pyrrole rings (H···π = 3.00 Å, C–H···π = 149°, and H···π = 2.91 Å, C–H···π = 153°, respectively), and two of the aryl protons of the C(18) ring form C–H···π interactions with the N(10) and N(27) pyrrole rings of the neighbouring molecule (H···π = 2.87 Å, C–H···π = 153°, and H···π = 2.77 Å, C–H···π = 158° respectively). This results in the formation of chains of molecules along the direction of the crystallographic *b* axis.

The NH resonances in the ^{1}H NMR of *m*-**6** became very broad on addition of acetate at room temperature. At

−30 °C these signals became clearly visible as two pairs of singlets each having 1:1 intensity (at $\delta = 12.27$ and 11.40, and $\delta = 10.37$ and 8.10 ppm), labelled L and M, respectively, in Figure 6. In the presence of 0.5 equivalents of acetate, M is ≈4 times more intense than L. As the amount of acetate increased, this proportion decreased (to M:L≈1.3 with 2.5 equivalents of salt). These spectral features indicate the presence of more than one complex. However, *m*-**6** (0.005 M) appears to be nearly 100 % complexed in the presence of 1.2 equivalents of acetate. This strong binding and the presence of various types of complexes hampered the evaluation of a binding constant. However, we believe that the M resonances refer to a dominant mode of complexation that is compatible with the structural features in the X-ray crystal structure of the host–guest complex formed between *m*-**6** and acetate (see below).

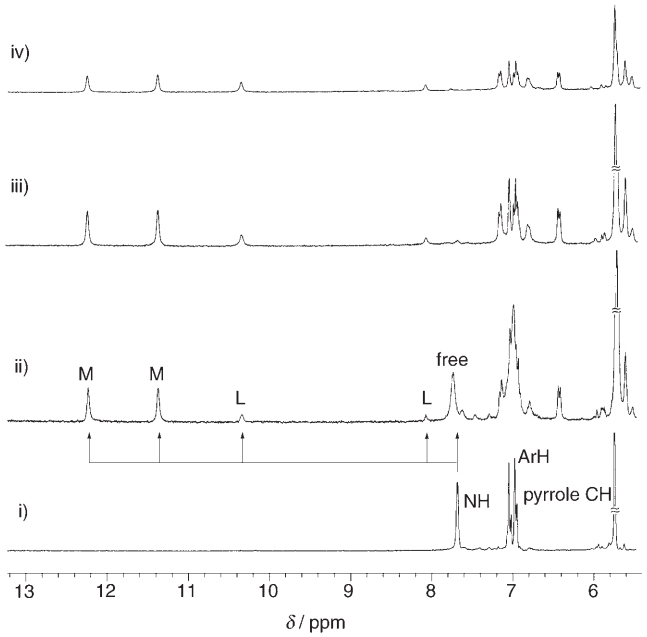


Figure 6. CIS in ^{1}H NMR spectra of *m*-**6** upon addition of $CH_3COOnBu_4N$ at −30 °C: i)–iv) 0, 0.5, 1.2 and 2.5 equivalents of added salt, respectively; each pair of M and L resonances always have 1:1 intensities, the M:L ratios in ii)–iv) are 3.8, 2.1 and 1.3, respectively.

To compare the overall affinities of *m*-**6** and **1** for acetate, we assumed *m*-**6** forms a single ideal 1:1 complex with this anion. Therefore, a 1:1 mixture of *m*-**6** and **1** was used in a ^{1}H NMR titration with acetate. Because the NH resonances of *m*-**6** disappeared upon addition of the salt, only the CISs of **1** were used. Nonlinear least-square fitting of these data for the system of equations comprising a) the expressions of the 1:1 equilibrium constants of each receptor, b) the mass balance relations and c) the well-known equation[11] that correlates the observed δ value to the degree of complexation (used to determine the concentration of **1**·CH_3COO^-), gave a K_a value of 755 M^{-1} for *m*-**6** (Table 1).[12] In this calculation we used the limiting chemical shift determined for the NH resonances of **1** in the absence of competing receptors (1:1, K_a value of 547 ± 30 M^{-1}, see Table 1).[13]

Titration data of receptor *p*-**6** with acetate were consistent with the kinetically fast formation of a 1:1 complex and a K_a value that is equivalent to that for **1**·CH_3COO^-, but which is also considerably higher than that of **2**·CH_3COO^-. Competitive binding experiments with *m*-**6**, *p*-**6** and acetate were hampered by excessive broadening of the NH resonances of both receptors. Acetate was complexed with equal strength by *p*-**6** and **1**.

The X-ray structure of *m*-**6**·CH_3COO^- (Figure 7) shows the macrocycle to have adopted a C_s-symmetric conformation with the encapsulated acetate anion sitting on the crystallographic mirror plane. The anion is held within the macrocycle by N−H···O hydrogen bonds to all four of the pyrrole N−H groups, each of the acetate oxygen atoms being linked to two of the N−H donors (the N···O distances are 2.805(3) and 2.764(3) Å).[14] The aryl rings are oriented approximately parallel to the plane of the acetate (inclined by ≈7°), such that there are a pair of π–π stacking interactions. The delocalised COO^- moiety is sandwiched between the two C_6 rings with mean interplanar and centroid···C(31) separations of ≈3.55 and 3.58 Å, respectively. The two aryl···C(31) vectors subtend an angle of ≈173° at C(31). There are no intercomplex interactions of note.

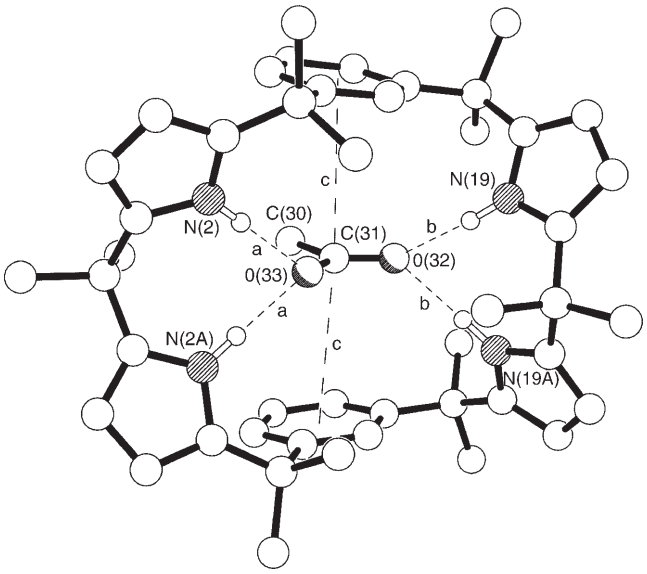


Figure 7. Molecular structure of the C_s-symmetric macrocycle and encapsulated anion present in the crystals of *m*-**6**·CH_3COO^-. Hydrogen-bonding geometries N···O, H···O [Å] and N−H···O [°], respectively, are a) 2.805(3), 1.91, 178; b) 2.764(3), 1.87, 173, and the π–π interactions (c) have mean interplanar and centroid···C(31) separations of ≈3.55 and 3.58 Å, respectively (aryl and acetyl planes are inclined by ≈7°).

The ^{1}H NMR spectrum of *m*-**6** with dihydrogen phosphate revealed the kinetically slow formation of a complex exhibiting two different NH resonances (at $\delta = 12.27$ and 11.85 ppm), which were sufficiently sharp at room temperature (20 °C) to provide a means to calculate a K_a value of

$1711 \pm 120\,M^{-1}$ for the 1:1 complex. Unlike the analogous acetate complex, there was no evidence of the formation of different complexes as a function of the amount of added salt.

These spectral features suggest a binding geometry similar to that observed in the solid state for the corresponding acetate complex. Molecular models indicate the potential for additional stabilisation by means of OH··π interactions between the hydroxy groups of the dihydrogenphosphate anion and the aromatic benzo rings. Unfortunately, attempts to obtain crystals of the *m*-**6**·$H_2PO_4^-$ complex were unsuccessful.

Receptor *p*-**6** displayed no CIS with $H_2PO_4^-$. No interaction could be detected for HSO_4^- with either *m*-**6** or *p*-**6**; however, NO_3^- was weakly bound by both receptors.

The anion-binding properties of *m*-**6**, *p*-**6**, **1** and **2** were also tested by means of ESI MS (negative mode).[15] However, upon mixing solutions of the receptors in CH_2Cl_2/CH_3CN (1:1) with solutions (various stoichiometric proportions) of the anions given in Table 1 (with a nBu_4N^+ counterion), the only supramolecular complexes that could be detected were those with chloride. This can be explained by the fact that under the experimental ESI conditions, CH_2Cl_2 becomes a good source of chloride and, because this anion is present in excess, it displaces any other of the tested anions from the receptors.[15c]

Conclusion

This study demonstrates that hybrid-expanded calixpyrroles *m*-**6** and *p*-**6** can be synthesised and purified very easily from readily available starting materials at low cost, which is a key issue for future practical and commercial applications. Although chemically very similar, these two macrocycles have considerably different anion-binding properties. Overall, *m*-**6** is a better anion ligand than *p*-**6**. In fact, among the tested anions, *p*-**6** binds only fluoride and acetate to an appreciable extent. However, with the exclusion of fluoride, the selectivity of *p*-**6** towards acetate is remarkably higher than that observed for *m*-**6**. For *p*-**6** there is a "shape" mismatch with spherical or tetragonal anions (fluoride is too small to be substantially affected by this factor), thus, only the planar Y-shaped acetate and nitrate are bound (the latter weakly) by this receptor. The kinetically slow formation of the *m*-**6**·$H_2PO_4^-$ complex is intriguing because the corresponding association constant is relatively small.

The original idea that the replacement of the furan rings of calix[2]furan[4]pyrrole **2** with benzo rings would lead to improved anion binding was confirmed for all of the anions tested, with the exception of fluoride. On the basis of this observation, we are currently pursuing the synthesis of analogues of *m*-**6** that have electron-withdrawing groups on the benzo rings. These are expected to exhibit improved anion binding relative to *m*-**6** because of the increased acidity of the CH unit between the two *meta* positions and/or by means of anion···π interactions with the electron-deficient aryl ring.[16] Finally, *m*-**6** proved to be a better anion receptor than **1** towards all of the anions tested, with the exception of iodide and hydrogen sulfate. For this reason, it may be a more convenient starting material than **1** for the construction of optical anion sensors by functionalisation with appropriate chromophores.[17]

Experimental Section

General methods and instrumentation: Acetonitrile was distilled from CaH_2. Pyrrole was distilled before use. All other chemicals were standard reagent grade and were used without further purification. All air-sensitive and/or moisture-sensitive reactions were conducted under an inert atmosphere. Thin-layer chromatography was carried out by using Merck SiO_2 $60F_{254}$ plastic plates. Compounds were visualised with vanillin or by examination under UV light. Column chromatography was conducted by using silica gel (Aldrich, 230–400 mesh, 60 Å). ^{1}H NMR and ^{13}C NMR spectra were recorded in $CDCl_3$ or CD_2Cl_2 by using a Varian Gemini 300 spectrometer at 300 and 75 MHz, respectively. Melting points were determined by using a Kofler hot-stage apparatus, and are not corrected.

^{1}H NMR tritations: The *n*-tetrabutylammonium salts were dried in a vacuum oven for a least 24 h. Solvents were used as supplied in sealed ampoules, and care was taken to minimise exposure to moisture. However, trace amounts of water could not be removed owing to the extremely hydrophilic nature of the salts. Because water has been demonstrated to lower the values of the observed binding constants, the data given in Table 1 should be considered to be the minimum observable value if operating under strictly anhydrous conditions. The anions were added as measured volumes of solution ($\approx 0.035\,M$) in CD_2Cl_2 to a solution of the macrocycle under investigation ($0.005\,M$) in the same solvent (0.7 mL), and the total volume was kept constant by evaporation with anhydrous nitrogen. After each addition, the stoichiometric ratios between the salt and macrocycle were also redetermined from the resonance intensities of the host pyrrole protons versus those of the *n*-tetrabutylammonium cation. Quantitative ^{1}H NMR integrations were obtained by the use of appropriate pulse delays in all cases. The data were processed by using the WinEQNMR[18] program and gave the reported K_a values for the 1:1 complexation model. For binding processes that were kinetically slow on the NMR timescale, the K_a values were determined from the ratios of the intensities of bound and free species.[11] No analysis of experimental errors was conducted, and the errors quoted in Table 1 are those related to the fitting calculation alone. However, measurements were reproducible within 15%.

The new compounds gave ESI mass spectra that were consistent with the proposed structures. ESI mass spectra were acquired by using a Mariner ESI-TOF instrument (resolution >7000) (Applied Biosystems, Framingham, MA, USA) with CH_2Cl_2/CH_3CN (negative-ion mode). Accurate mass measurements were recorded by performing ESI. In all cases, differences between measured and calculated masses were less than 10 ppm. Comparisons between measured and calculated isotopic patterns were also performed.

1,3-Bis[1′-(pyrrol-2-yl)-1′,1′-(dimethyl)methyl]benzene (*m*-5): This compound was prepared as described in ref. [5g].

1,4-Bis[1′-(pyrrol-2-yl)-1′,1′-(dimethyl)methyl]benzene (*p*-5): A mixture of pyrrole (14 mL) and 1,4-bis(1,1′-dimethylhydroxymethyl)benzene (2 g, 10.3 mmol) was degassed by bubbling with argon for 5 min, and BF_3·Et_2O (1.27 mL, 10.3 mmol) was added. The mixture was stirred for 30 min at RT, diluted with CH_2Cl_2 (20 mL) and quenched by the addition of aqueous NaOH (0.1 N, 20 mL). The organic layer was separated, extracted with water, dried ($MgSO_4$) and concentrated. The resulting brown oil was subjected to column chromatography (hexane/EtOAc 4:1) to give a white solid as the major fraction, which was crystallised from hexane/EtOAc (4:1) to give *p*-**5** (30%). M.p. 164–166 °C; ^{1}H NMR ($CDCl_3$): $\delta = 1.67$ (s, 12H, CH_3), 6.10–6.12, 6.13–6.17 and 6.64–6.66 (3m, 3×2H, pyrrole-CH), 7.15 (s, 4H, benzo-CH), 7.68 ppm (br s, 2H, NH);

Table 2. Crystal data, data collection and refinement parameters for compounds *p*-**6**, *m*-**6**, *m*-**6**·F^-, *m*-**6**·Cl^- and *m*-**6**·CH_3COO^-.[a]

Data	*p*-**6**	*m*-**6**	*m*-**6**·F^-	*m*-**6**·Cl^-	*m*-**6**·CH_3COO^-
formula	$C_{46}H_{56}N_4$	$C_{46}H_{56}N_4$	$[C_{46}H_{56}N_4{\cdot}F^-](C_{16}H_{36}N^+)$	$[C_{46}H_{56}N_4{\cdot}Cl^-](C_{16}H_{36}N^+)$	$[C_{46}H_{56}N_4{\cdot}C_2H_3OO^-](C_{16}H_{36}N^+)$
solvent	$2\,C_4H_8O_2$	–	$0.75\,C_6H_{14}$	$CH_2Cl_2{\cdot}C_4H_8O_2{\cdot}C_6H_{14}$	C_6H_{14}
formula weight	841.16	664.95	991.04	1202.06	1052.62
colour, habit	colourless blocks	colourless needles	colourless blocks	colourless plates	colourless blocks
crystal size [mm^3]	$0.17\times0.13\times0.08$	$0.27\times0.07\times0.04$	$0.11\times0.08\times0.06$	$0.28\times0.13\times0.03$	$0.36\times0.31\times0.21$
T [K]	173	173	173	173	173
crystal system	monoclinic	monoclinic	monoclinic	monoclinic	tetragonal
space group	$C2/c$ (no. 15)	$P2_1/n$ (no. 14)	$P2_1/c$ (no. 14)	$P2_1/n$ (no. 14)	$P\bar{4}2_1m$ (no. 113)
a [Å]	25.076(3)	7.0634(4)	23.8427(18)	16.5509(17)	20.051(2)
b [Å]	10.0222(10)	26.3820(13)	13.9176(14)	18.024(3)	–
c [Å]	20.280(2)	10.0535(5)	39.047(3)	24.900(4)	15.9085(7)
α [°]	–	–	–	–	–
β [°]	109.320(9)	90.325(4)	103.884(6)	106.825(11)	–
γ [°]	–	–	–	–	–
V [$Å^3$]	4809.8(8)	1873.41(17)	12578.6(18)	7109.8(17)	6395.8(9)
Z	4[b]	2[c]	8[d]	4	4[e]
ρ_{calcd} [$g\,cm^{-3}$]	1.162	1.179	1.047	1.123	1.093
radiation	$Cu_{K\alpha}$	$Cu_{K\alpha}$	$Cu_{K\alpha}$	$Cu_{K\alpha}$	$Mo_{K\alpha}$
μ [mm]	0.566	0.519	0.471	1.510	0.065
2θ max [°]	142	142	130	142	64
unique reflns	4551	3547	20792	13639	11004
obsd reflns $\lvert F_o\rvert > 4\sigma(\lvert F_o\rvert)$	3270	3166	8352	7860	6617
parameters	298	234	1316	711	409
R_1, wR_2[f]	0.051, 0.136	0.039, 0.099	0.060, 0.136	0.041, 0.099	0.089, 0.212

[a] Details in common: graphite-monochromated radiation, refinement based on F^2. [b] Molecule has crystallographic C_2 symmetry. [c] Molecule has crystallographic C_i symmetry. [d] Two independent molecules. [e] Molecule has crystallographic C_S symmetry. [f] $R_1=\Sigma\,||F_o|-|F_c||/\Sigma|F_o|$; $wR_2=\{\Sigma[w(F_o^2-F_c^2)^2]/\Sigma[w(F_o^2)^2]\}^{1/2}$; $w^{-1}=\sigma^2(F_o^2)+(aP)^2+bP$.

^{13}C NMR ($CDCl_3$): $\delta=30.0$, 38.8, 104.2, 107.6, 116.6, 126.0, 140.4, 146.7 ppm.

Calix[2]-*m*-benzo[4]pyrrole (*m*-6): TFA (778 mg, 6.82 mmol) was added to a mixture of *m*-**5** (400 mg, 1.36 mmol) and acetone (17 mL) in anhydrous acetonitrile (200 mL) at 0 °C. The mixture was stirred at RT for 1.5 h, neutralised with NaOH (0.1 M) and then concentrated and extracted with CH_2Cl_2 (50 mL). The organic phase was separated, washed with aq. $NaHCO_3$ (2×50 mL), dried ($MgSO_4$) and concentrated. The residue was crystallised from hexane/EtOAc (4:1) to give *m*-**6** (225 mg, 50%). M.p. 206–208 °C; ^1H NMR ($CDCl_3$): $\delta=1.52$ (s, 12H, CH_3), 1.53 (s, 24H, CH_3), 5.83–5.86 (m, 8H, pyrrole-CH), 7.01–7.11 (m, 8H, benzo-CH), 7.67 ppm (br s, 4H, NH); ^1H NMR (CD_2Cl_2): $\delta=1.41$ (s, 12H, CH_3), 1.50 (s, 24H, CH_3), 5.76–5.81 (m, 8H, pyrrole-CH), 6.88–6.98 (m, 6H, benzo-CH), 7.08 (s, 2H, benzo CH), 7.48 ppm (br s, 4H, NH); ^{13}C NMR ($CDCl_3$): $\delta=29.8$, 29.8, 35.6, 39.2, 103.0, 103.9, 123.6, 123.6, 124.1, 127.9, 138.5, 139.5, 148.9 ppm.

Calix[2]-*p*-benzo[4]pyrrole (*p*-6): TFA (973 mg, 8.53 mmol) was added to a mixture of *p*-**5** (500 mg, 1.70 mmol) and acetone (21 mL) in anhydrous acetonitrile (250 mL) at 0 °C. The mixture was stirred at RT for 2 h and then neutralised with NaOH (0.1 M). The white solid was filtered and crystallised from hexane/EtOAc (4:1) to give *p*-**6** (510 mg, 77%). M.p. 209 °C; ^1H NMR ($CDCl_3$): $\delta=1.54$ (s, 12H, CH_3), 1.56 (s, 24H, CH_3), 5.84–5.88 (m, 8H pyrrole-CH), 6.98 (s, 8H, benzo-CH), 7.25 ppm (br s, 4H, NH); ^1H NMR (CD_2Cl_2): $\delta=1.50$ (s, 12H, CH_3), 1.52 (s, 24H, CH_3), 5.79–5.84 (m, 8H, pyrrole-CH), 6.96 (s, 8H, benzo-CH), 7.26 ppm (br s, 4H, NH); ^{13}C NMR ($CDCl_3$): $\delta=30.3$, 30.3, 35.1, 35.1, 102.5, 103.8, 125.8, 137.9, 139.2, 146.8 ppm.

X-ray crystallography: Table 2 summarises the crystallographic data for compounds *m*-**6**, *p*-**6**, *m*-**6**·F^-, *m*-**6**·Cl^- and *m*-**6**·CH_3COO^-. Data were collected by using Oxford Diffraction PX Ultra (*m*-**6**, *p*-**6**, *m*-**6**·F^- and *m*-**6**·Cl^-) and an Xcalibur 3 diffractometers (*m*-**6**·CH_3COO^-), and the structures were refined based on F^2 by using the SHELXTL and SHELX-97 program systems.[19] The absolute structure of *m*-**6**·CH_3COO^- could not be unambiguously determined by either *R*-factor tests ($R_1^+=0.0889$, $R_1^-=0.0889$) or by the Flack parameter ($x^+=+0.4(19)$, $x^-=+0.6(19)$). CCDC 603345 (*m*-**6**), 603346 (*p*-**6**), 603347 (*m*-**6**·Cl^-), 603348 (*m*-**6**·CH_3COO^-) and 603349 (*m*-**6**·F^-) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from the Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

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