Structures of Potassium encapsulated within the 1,3-Alternate Conformation of Calix[4]arenes†

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5,11,17,23-Tetra-*tert*-butyl-25,26,27,28-tetrakis(diethylcarbamoylmethoxy)calix[4]arene (L^1) has been synthesised in the 1,3-alternate conformation for the first time. Proton NMR complexation studies suggest that this molecule forms 1:1 and 2:1 complexes with potassium cations. A crystal structure determination has been performed on the 2:1 complex $[K_2L^1][CuCl_2][I_3]$, [monoclinic, space group $P2_1/n$, a = 13.972(6), b = 23.373(12), c = 25.271(12) Å, β = 102.5(1)°, Z = 4, R = 0.092 for 6501 'observed' reflections]. The structure of the 1:1 potassium complex of the related diamide, 5,11,17,23-tetra-*tert*-butyl-25,27-bis(diethylcarbamoylmethoxy)-26,28-dihydroxycalix[4]arene (L^2), $[KL^2][I_3]$, has also been elucidated [triclinic, space group $P\bar{1}$, a = 14.160(8), b = 16.326(10), c = 16.540(10) Å, α = 65.83(1), β = 67.37(1), γ = 88.87(1)°, Z = 2, R = 0.091 for 4976 'observed' reflections]. Remarkably, the calixarene is again found in the 1,3-alternate conformation, although ^{13}C NMR studies suggest that, in this case, the conformation is not maintained in solution. The co-ordination spheres of the potassium cations in both structures are similar, with a hitherto unobserved combination of close contacts to four oxygen atoms, and to two phenyl rings of the respective calix[4]arenes, Molecular mechanics calculations have been carried out to investigate the relative stabilities of the calixarene conformations.

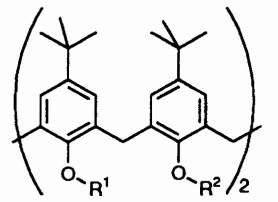
Calixarenes are a family of synthetic macrocyclic receptors consisting of cyclic arrays of phenol moieties linked by methylene groups.[1] They can be modified at the lower hydroxyl rim to produce a variety of novel ionophores for alkali- and alkaline-earth-metal cations.[2] The conformation of the calixarene has been shown to be important in controlling the selectivity of the receptor molecules. For example, the tetraamide (L^1) and tetraester (L^3) derivatives of *p-tert*-butylcalix[4]arene exhibit remarkable selectivity for Na^+ in the cone conformation,[3] whereas the partial-cone and 1,3-alternate conformers of the tetraester receptor show K^+ selectivity.[4] Despite the interest in this area,[5] there is a lack of structural information regarding the nature of the cation–calixarene complexes, especially for the less common conformers.

With particular regard to 1,3-alternate conformers of calix[4]arenes there are very few structurally characterised examples,[6,7] and to our knowledge none containing complexed metal cations. We report here the first X-ray crystallographic structural evidence of potassium cation complexes of 1,3-alternate calix[4]arenes, $[K_2L^1]^{2+}$ and $[KL^2]^+$.

Experimental

Syntheses.—5,11,17,23-Tetra-*tert*-butyl-25,27-bis(diethylcarbamoylmethoxy)-26,28-dihydroxycalix[4]arene (L^2) was synthesised by the literature method.[8]

5,11,17,23-Tetra-*tert*-butyl-25,26,27,28-tetrakis(diethylcarbamoylmethoxy)-calix[4]arene (L^1) in the 1,3-alternate conformation was prepared as follows. *p-tert*-Butylcalix[4]arene (2.5 g, 3.85 mmol) and K_2CO_3 (5.4 g, 38.5 mmol) were stirred in dry acetone for 2 h. 2-Chloro-*N,N*-diethylacetamide (5.7 g, 38.5 mmol) and KI (6.4 g, 38.5 mmol) were added and the mixture was heated to reflux for 5 d. The solvent was removed at reduced pressure, and the remaining solid extracted into



L^1 : $R^1 = R^2 = CH_2CONEt_2$
L^2 : $R^1 = H$, $R^2 = CH_2CONEt_2$
L^3 : $R^1 = R^2 = CH_2CO_2Et$

CH_2Cl_2 (3 × 100 cm^3). Hexane (100 cm^3) was added to the extracts, and the solution was left to evaporate, depositing 0.5 g of pale yellow crystals. (Subsequent crops of product gave L^1 in the cone conformation.) Dissolving a small amount of this solid in CH_2Cl_2, and adding excess $CuCl_2$ in ethanol gave a brown solution (suggesting the presence of I^-), from which deep red crystals of $[K_2L^1][Cu^ICl_2][I_3]$ **1**, slowly deposited (Found: Cu, 3.64; K, 4.95. Calc. for $C_{68}H_{100}Cl_2CuI_3K_2N_4O_8$ **1**: Cu, 3.75; K, 4.60%). The remainder of the sample was slurried in methanol (10 cm^3) and water (20 cm^3) and heated to reflux for 48 h. The white precipitate was filtered off, washed with water, and recrystallised from CH_2Cl_2–hexane to give 0.2 g (5% yield) of product (Found: C, 73.9; H, 9.45; N, 4.95. Calc. for $C_{68}H_{100}N_4O_8$: C, 74.1; H, 9.15; N, 5.10%). ^1H NMR (300 MHz, $CDCl_3$, 25 °C): δ 1.07 (t, *J* 6.6, 12 H, CH_2CH_3), 1.14 (t, *J* 6.6, 12 H, CH_2CH_3), 1.23 [s, 36 H, $C(CH_3)_3$], 3.17 (q, *J* 6.6, 8 H, CH_2CH_3), 3.38 (q, *J* 6.6 Hz, 8 H, CH_2CH_3), 3.63 (s, 8 H, CH_2), 4.36 (s, 8 H, OCH_2), 7.13 (s, 8 H, aromatic H). ^{13}C NMR (75 MHz, CD_2Cl_2): δ 12.99, 14.55 (CH_2CH_3), 31.57 [$C(CH_3)_3$], 33.89 [$C(CH_3)_3$], 37.61 (CH_2), 40.51, 41.92 (CH_2CH_3), 69.97 (OCH_2), 127.58 (aromatic CH), 132.59, 143.62, 155.11 (aromatic C), 168.12 (C=O).

Compound $[KL^2][I_3]$ **2** was prepared as follows. A solution of L^2 in dichloromethane was treated with an excess of KI and I_2 in ethanol. Upon slow evaporation of the dichloromethane,

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† *Supplementary data available:* see Instructions for Authors, *J. Chem. Soc., Dalton Trans.*, 1994, Issue 1, pp. xxiii–xxviii.

Non-SI unit employed: cal = 4.184 J.

Table 1 Crystal and structure refinement data for $[K_2L^1][CuCl_2][I_3]\cdot1.5EtOH\cdot0.5H_2O$ **1** and $[KL^2][I_3]\cdot1.75EtOH\cdot1.75H_2O$ **2**

	1	**2**
Empirical formula	$C_{71}H_{110}Cl_2CuI_3K_2N_4O_{10}$	$C_{59.5}H_{92}I_3KN_2O_{9.5}$
M	1773.04	1407.20
T/K	293(2)	293(2)
Crystal system	Monoclinic	Triclinic
Space group	$P2_1/n$	$P\bar{1}$
a/Å	13.972(6)	14.160(8)
b/Å	23.373(12)	16.326(10)
c/Å	25.271(12)	16.540(10)
α/°	90	65.83(1)
β/°	102.5(1)	67.37(1)
γ/°	90	88.87(1)
U/Å^3	8056.2	3176
Z	4	2
D_c/Mg m^{-3}	1.47	1.48
μ/mm^{-1}	1.64	1.60
F(000)	3624	1438
Crystal size/mm	0.10 × 0.10 × 0.10	0.15 × 0.15 × 0.25
λ(Mo-Kα)/Å	0.7107	0.7107
θ range/°	1.66–24.00	1.66–24.00
Index ranges	$0 < h < 16, -26 < k < 27, -26 < l < 27$	$0 < h < 16, -18 < k < 18, -16 < l < 18$
Reflections collected	12737	8619
No. of reflections $[I > 3\sigma(I)]$	6501	4976
Refinement method	Full-matrix least-squares on F^2	
Parameters	875	693
Goodness-of-fit on F^2	1.134	1.112
Final R indices $[I > 3\sigma(I)]$	0.092	0.091
$R1$, $wR2$	0.1326, 0.3755	0.1492, 0.3349
Largest difference peak, hole/e Å^{-3}	1.45, −0.74	1.14, −2.03

Weighting scheme $w^{-1} = [\sigma^2(F_o^2) + (aP)^2 + bP]$ where $P = [\max(F_o^2, 0) + 2F_c^2]/3$; $a = 0.17, b = 41.20$ for **1**; $a = 0.24, b = 27.67$ for **2**.

deep red crystals precipitated in approximately 90% yield (Found: C, 51.3; H, 6.00; I, 31.4; K, 2.85; N, 2.20. Calc. for $C_{56}H_{78}I_3KN_2O_6$: C, 51.9; H, 6.05; N, 2.15; I, 29.4; K, 3.0%).

Structure Determinations.—Crystal data are given in Table 1, together with refinement details. Data for both crystals were collected at 293(2) K with Mo-Kα radiation using the MAR-research Image Plate System. The crystals were positioned 75 mm from the image plate. 120 Frames were measured at 2° intervals with a counting time of 5 min. Data analysis was carried out with the XDS program.[9] Both structures were solved using direct methods with the SHELXS 86 program.[10] In **1**, the $[K_2L^1]^{2+}$ cation was ordered and two different anions I_3^- and $CuCl_2^-$ were identified. In addition there was one discrete ethanol solvent molecule and a water–ethanol mixture each with half occupancy. In **2**, the $[KL^2]^+$ cation was ordered apart from one *tert*-butyl group for which two orientations of the methyl groups were identified and these were refined with 50% occupancy. There were several solvent molecules and these were identified as a discrete water molecule and a discrete ethanol molecule with full occupancy, a water molecule and an ethanol molecule with 50% occupany, as well as a superimposed water molecule and ethanol molecule (with the oxygen atom coinciding with the central carbon atom), which were refined each with 25% occupancy. For both structures, all non-hydrogen atoms in the cation and anions were given anisotropic thermal parameters apart from the disordered *tert*-butyl group in compound **2**. Hydrogen atoms on carbon were included in calculated positions. The two hydrogen atoms from the hydroxide groups in **2** could not be located and were omitted. For the solvent molecules in both structures, hydrogen atoms were omitted and all atoms refined isotropically. Full-matrix least-squares refinement on F^2 was carried out using the SHELXL program.[11] All calculations were carried out on a Silicon Graphics R4000 Workstation at the University of Reading. Atomic coordinates for **1** and **2** are given in Tables 2 and 3 respectively.

Additional material available from the Cambridge Crystallographic Data Centre comprises H-atom coordinates, thermal parameters and remaining bond lengths and angles.

Results and Discussion

The tetraamide L^1 has been previously reported only in the cone conformation,[3] and indeed, the reaction of 2-chloro-*N*,*N*-diethylacetamide with *p*-*tert*-butylcalix[4]arene in the presence of various alkali-metal carbonates gave the product in predominantly the cone conformation. This contrasts with the synthesis of the tetraester L^3, where varying the alkali-metal cation allows significant control over the conformer distribution.[4] Nevertheless, employing potassium carbonate as the base gave rise to a quantity of L^1 in the 1,3-alternate conformation, which was purified by fractional crystallisation in the presence of potassium iodide. X-Ray quality crystals of the dipotassium complex of L^1 were produced after testing for the presence of iodide with $CuCl_2$, giving a mixed I_3^-–$CuCl_2^-$ salt of the $[K_2L^1]^{2+}$ cation. The 1,3-distally substituted diamide[8] (L^2) was also found to bind potassium, and X-ray quality crystals of a 1 : 1 complex were isolated as the I_3^- salt. Unlike the tetrasubstituted calixarene, L^2 is not conformationally locked, and hence the influence of the potassium cation on the conformation of the calixarene is of interest.

The structures of both complexes consist of discrete cations, anions and several solvent molecules. The two cations $[K_2L^1]^{2+}$ in **1** and $[KL^2]^+$ in **2** are shown in Figs. 1 and 2 together with the atomic numbering scheme. Other views of the cavity are shown in Fig. 3. Both structures show the calix[4]arene in the 1,3-alternate conformation. The potassium ions (two of them in **1** and one in **2**) have similar environments (Table 4), being bonded to four oxygen atoms with distances in the ranges 2.58–2.69, 2.56–2.68 Å for the two K^+ cations in **1** and 2.64–2.71 Å for the cation in **2**. In all three cases the four oxygen atoms are directed into the cavity and form an approximately square-planar environment for the metal ions. Indeed the KO_4 moieties are all planar with a maximum deviation of 0.10 Å. This structure contrasts with the structure

Table 2 Atomic coordinates (× 10^4) for $[K_2L^1][CuCl_2][I_3]\cdot1.5EtOH\cdot0.5H_2O$ **1**

Atom	*x*	*y*	*z*	Atom	*x*	*y*	*z*
I(1)	2 459(1)	8 166(1)	690(1)	C(31)	−644(11)	7 698(7)	−684(6)
I(2)	3 211(2)	7 197(1)	218(1)	C(32)	−1454(13)	7 694(7)	−500(6)
I(3)	1 704(2)	9 127(1)	1 162(1)	C(33)	−2 259(11)	7 355(8)	−699(6)
Cu(1)	261(3)	10 618(1)	−2 803(1)	C(34)	−2 207(12)	7 020(8)	−1 141(6)
Cl(1)	−1 098(7)	10 915(4)	−3 080(4)	C(35)	−1 407(10)	7 004(7)	−1 341(5)
Cl(2)	1 592(6)	10 289(4)	−2 537(4)	C(36)	−613(10)	7 317(7)	−1 102(6)
K(2)	729(3)	7 861(2)	−2 073(2)	C(300)	−3 167(13)	7 380(9)	−461(6)
K(3)	−2 509(3)	8 283(2)	−1 664(2)	C(301)	−4 005(15)	7 651(12)	−850(10)
C(11)	−2 051(12)	8 583(6)	−2 896(6)	C(302)	−3 049(18)	7 682(14)	56(9)
C(12)	−2 944(13)	8 805(7)	−2 873(7)	C(303)	−3 417(16)	6 755(10)	−334(8)
C(13)	−3 065(10)	9 262(6)	−2 555(7)	O(350)	240(8)	7 249(5)	−1 276(4)
C(14)	−2 266(12)	9 501(7)	−2 233(7)	C(351)	839(12)	6 791(8)	−992(7)
C(15)	−1 374(14)	9 287(6)	−2 222(6)	C(352)	1 674(13)	6 713(10)	−1 251(9)
C(16)	−1 259(11)	8 862(7)	−2 583(6)	O(353)	1 853(10)	7 069(7)	−1 560(6)
C(100)	−4 036(13)	9 516(7)	−2 548(8)	N(354)	2 182(11)	6 259(9)	−1 087(8)
C(101)	−4 046(16)	10 111(9)	−2 683(14)	C(355)	1 998(16)	5 857(11)	−713(10)
C(102)	−4 299(20)	9 409(18)	−2 023(13)	C(356)	1 393(22)	5 361(12)	−963(16)
C(103)	−4 838(18)	9 257(13)	−2 981(12)	C(357)	2 995(18)	6 146(11)	−1 325(11)
O(150)	−341(8)	8 693(4)	−2 633(4)	C(358)	3 929(18)	6 303(14)	−980(10)
C(151)	−68(14)	9 007(9)	−3 054(8)	C(37)	216(11)	8 043(8)	−447(5)
C(152)	880(18)	8 709(11)	−3 139(9)	C(41)	260(14)	9 182(7)	−1 518(6)
O(153)	1 282(11)	8 366(8)	−2 867(7)	C(42)	1 209(12)	9 140(7)	−1 544(7)
N(154)	1 155(16)	8 953(12)	−3 537(12)	C(43)	1 851(10)	8 790(7)	−1 221(7)
C(155)	732(22)	9 455(12)	−3 881(10)	C(44)	1 472(13)	8 446(7)	−892(5)
C(156)	350(42)	9 315(21)	−4 367(14)	C(45)	508(11)	8 454(8)	−841(6)
C(157)	2 026(52)	8 602(22)	−3 745(17)	C(46)	−98(14)	8 836(6)	−1 154(6)
C(158)	2 720(30)	8 855(19)	−3 507(19)	C(47)	−444(12)	9 558(7)	−1 881(7)
C(17)	−1 929(11)	8 076(7)	−3 252(6)	C(400)	2 892(14)	8 816(8)	−1 274(8)
C(21)	−1 105(12)	6 863(6)	−2 307(6)	C(401)	3 481(17)	8 592(23)	−831(19)
C(22)	−378(12)	6 665(7)	−2 512(7)	C(402)	3 218(15)	9 411(12)	−1 247(16)
C(23)	−141(11)	6 896(8)	−2 969(6)	C(403)	3 039(18)	8 570(24)	−1 750(17)
C(24)	−640(11)	7 367(6)	−3 182(6)	O(450)	−1 017(8)	8 877(5)	−1 072(4)
C(25)	−1 385(12)	7 604(6)	−2 999(6)	C(451)	−1 103(11)	9 260(8)	−661(8)
C(26)	−1 628(11)	7 303(6)	−2 567(7)	C(452)	−2 141(14)	9 255(7)	−606(7)
C(27)	−1 387(12)	6 600(7)	−1 803(6)	O(453)	−2 720(9)	9 009(6)	−915(5)
C(200)	623(12)	6 602(8)	−3 207(8)	N(455)	−2 346(10)	9 566(7)	−205(6)
C(201)	1 379(31)	6 391(28)	−2 872(16)	C(456)	−1 656(16)	9 875(10)	199(10)
C(202)	1 097(34)	6 992(13)	−3 408(24)	C(457)	−3 378(16)	9 579(11)	−150(10)
C(203)	220(24)	6 242(20)	−3 609(18)	C(458)	−3 867(18)	10 049(13)	−489(11)
O(250)	−2 458(8)	7 478(5)	−2 404(4)	C(459)	−1 347(17)	9 540(13)	694(13)
C(251)	−3 315(12)	7 174(7)	−2 709(7)	C(600)	−107(39)	5 796(24)	−110(22)
C(252)	−4 175(11)	7 459(9)	−2 537(7)	C(601)	−422(38)	6 238(25)	216(22)
O(253)	−4 090(8)	7 812(6)	−2 192(5)	C(602)	362(38)	6 629(22)	514(20)
N(254)	−5 002(11)	7 276(8)	−2 817(7)	C(701)*	2 873(73)	5 093(41)	712(37)
C(255)	−5 934(16)	7 497(12)	−2 670(10)	C(702)*	2 362(54)	5 278(31)	939(28)
C(256)	−6 125(21)	7 156(13)	−2 266(13)	O(700)*	2 134(49)	4 635(28)	891(25)
C(257)	−5 158(14)	6 849(10)	−3 231(8)	O(800)*	1 270(61)	4 967(33)	600(31)
C(258)	−5 399(23)	7 064(14)	−3 786(10)				

* Population 0.5.

of L^1 in the cone formation which has the four ethereal oxygens directed into the cavity with the four carbonyl oxygens directed outwards.[12] It is interesting, however, that in the structure of $[KL^1]^+$ where the calix[4]arene has the cone conformation, all eight oxygen atoms are directed inwards and form bonds to the potassium at distances which range from 2.71 to 2.74 Å.[12] The structure is highly disordered but the main features can be discerned.

In the present structures, however, the calix[4]arenes are in the 1,3-alternate conformation which, in each case, permits close contacts between the potassium ion and two phenyl rings. The close contacts are listed in Table 4. In both cases the metal ions interact with two phenyl rings of the calix at distances in **1** of 3.24–3.51, 3.26–3.51 Å for K(2) and 3.18–3.47, 3.23–3.54 Å for K(3) and in **2** of 3.22–3.43, 3.22–3.51 Å for K(1). This combination of K···O and K···Ph interactions is unique but there are precedents for the interaction of metal cations with phenyl rings.[13–15] Examples involving calixarenes are the monocaesium derivative of *p*-*tert*-butylcalix[4]arene[16] where the metal atom is bound to the four phenyl rings, and the monocaesium derivative of bis(homooxa)-*p*-*tert*-butyl-calix[4]arene (7,13,19,25-tetra-*tert*-butyl-27,28,29,30-tetrahydroxy-2,3-dihomo-3-oxacalix[4]arene),[17] where the metal interacts with only two phenyl rings. For precedents of the potassium ion bonding to phenyl rings, a notable example can be found in the structure of $K[Nd(OC_6H_3Pr^i{}_2\text{-}2,6)_4]$, where the potassium ion is bonded to one oxygen atom [K–O 2.760(9) Å], and two phenyl rings, with K–C contacts in the range 3.097–3.473 Å.[18] Another comparable structure is $KBPh_4$, where the K^+ cation is bound to four arene rings with an average K–C distance of 3.29 Å.[19]

The occurrence of the 1,3-alternate conformation is one of the most interesting features of these two structures. Molecular mechanics calculations with a variety of force fields[20,21] show that it has a higher energy than other conformations for the calix[4]arene, although the relative order of stability can be affected by substituents on the OH groups. These calculations are validated by the experimental rarity of the conformation. The only previous detailed crystallographic studies have been observed with substituted calix[4]arenes. One example has

Table 3 Atomic coordinates (× 10^4) for $[KL^2][I_3]\cdot 1.75EtOH\cdot 1.75H_2O$ **2***

Atom	*x*	*y*	*z*	Atom	*x*	*y*	*z*
I(1)	2 257(1)	3 313(1)	6 986(1)	C(201)	−4 232(16)	8 034(32)	10 773(18)
I(2)	3 481(1)	4 436(1)	7 316(1)	C(202)	−4 229(20)	7 093(21)	10 079(30)
I(3)	1 105(2)	2 172(1)	6 587(2)	C(203)	−4 358(17)	8 554(23)	9 233(20)
K(1)	1 783(2)	8 072(2)	7 036(2)	C(300)	3 124(10)	10 392(11)	4 515(11)
C(11)	618(10)	5 895(10)	8 609(10)	C(301)	3 855(37)	9 884(35)	4 807(38)
C(12)	−64(10)	6 278(12)	9 107(10)	C(302)	3 315(40)	10 704(36)	3 430(37)
C(13)	230(9)	6 837(10)	9 471(9)	C(303)	3 160(41)	11 292(35)	4 634(45)
C(14)	1 248(11)	6 887(12)	9 346(12)	C(311)	3 561(27)	10 330(26)	5 266(26)
C(15)	1 934(11)	6 474(12)	8 917(10)	C(312)	3 819(27)	10 038(25)	3 848(26)
C(16)	1 604(9)	5 989(10)	8 535(10)	C(313)	3 133(28)	11 448(24)	4 025(30)
C(17)	−525(11)	7 258(12)	10 015(10)	C(401)	−3 062(21)	5 912(22)	6 543(20)
C(21)	−1 076(10)	7 891(11)	9 459(10)	C(400)	−2 789(11)	5 559(10)	7 401(12)
C(22)	−2 142(10)	7 716(11)	9 841(10)	C(402)	−3 021(21)	4 497(19)	7 910(22)
C(23)	−2 732(10)	8 194(12)	9 356(11)	C(403)	−3 412(18)	5 955(33)	7 997(35)
C(24)	−2 130(10)	8 904(11)	8 425(11)	C(251)	833(12)	9 416(12)	8 455(14)
C(25)	−1 077(9)	9 108(9)	8 017(9)	C(252)	1 980(12)	9 510(12)	8 099(13)
C(26)	−562(8)	8 606(9)	8 556(9)	N(254)	2 444(13)	10 117(16)	8 302(17)
C(27)	−501(10)	9 852(10)	6 993(12)	O(253)	2 516(12)	9 150(11)	7 589(11)
C(31)	278(10)	9 585(10)	6 284(9)	C(255)	3 592(22)	10 594(18)	7 616(24)
C(32)	10(9)	8 901(9)	6 082(9)	C(256)	3 977(26)	9 843(31)	8 210(33)
C(33)	738(9)	8 673(10)	5 436(9)	C(257)	1 846(16)	10 542(20)	8 903(21)
C(34)	1 723(9)	9 153(9)	4 940(9)	C(258)	1 607(23)	9 966(25)	9 969(27)
C(35)	2 037(9)	9 881(9)	5 092(10)	C(451)	2 076(10)	6 477(10)	5 896(11)
C(36)	1 267(10)	10 059(11)	5 783(10)	C(452)	3 132(11)	7 021(11)	5 531(10)
C(37)	443(11)	7 911(10)	5 202(11)	O(453)	3 227(8)	7 565(8)	5 831(8)
C(41)	−122(10)	7 014(10)	6 084(10)	N(454)	3 910(8)	6 801(10)	4 941(9)
C(42)	−1 104(10)	6 693(10)	6 283(10)	C(455)	4 969(12)	7 327(14)	4 631(15)
C(43)	−1 693(10)	5 902(10)	7 150(11)	C(456)	5 483(14)	6 813(21)	5 232(16)
C(44)	−1 206(10)	5 457(11)	7 721(11)	C(457)	3 813(22)	6 476(22)	3 665(19)
C(45)	−197(10)	5 797(10)	7 501(10)	C(458)	3 845(14)	6 129(16)	4 619(16)
C(46)	388(10)	6 585(12)	6 667(9)	O(400)	4 715(14)	5 586(13)	7 644(13)
C(47)	260(10)	5 276(10)	8 226(10)	O(700)	860(27)	5 915(24)	4 400(22)
O(150)	−1 078(7)	6 127(9)	9 230(8)	C(701)	1 133(35)	5 075(32)	4 886(34)
O(250)	500(6)	8 790(7)	8 179(6)	C(702)	340(35)	4 743(27)	5 802(26)
O(350)	−981(6)	8 487(8)	6 560(7)	O(500)	−2 896(20)	1 323(19)	7 436(19)
O(450)	1 356(6)	6 850(7)	6 463(7)	C(501)	−2 154(35)	1 508(43)	7 719(42)
C(100)	3 046(10)	6 556(12)	8 817(12)	C(502)	−2 717(74)	1 909(80)	8 363(74)
C(101)	3 757(12)	7 002(21)	7 836(16)	O(800)	−1 022(61)	2 961(57)	8 424(58)
C(102)	3 210(15)	6 991(20)	9 378(21)	O(600)	−1 956(71)	2 055(90)	9 149(82)
C(103)	3 267(13)	5 569(15)	9 213(15)	C,O(601)	−2 705(24)	2 046(23)	8 778(24)
C(200)	−3 842(12)	8 019(15)	9 807(12)	C(602)	−2 024(86)	2 053(131)	7 868(62)

* Occupation parameters O(500), C(501), C(502) 0.5, O(800) 0.5, O(600), C(602) 0.25, C,O(601) 0.5, C(301), C(302), C(303), C(311), C(312), C(313) 0.5.

different groups alternating at the bottom of the cone, *viz.* ethoxycarbonylmethoxy and bis(2-pyridylmethoxy),[6] and the other has a 15-crown-5 ring bridging two opposite ethereal oxygen atoms.[7]

Some structural features of the 1,3-alternate conformation have been established from the former structure[6] and also from molecular mechanics calculations. (The presence of the crown has distorted the conformation of the calix[4]arene in the second structure.[7]) The four phenyl rings are far more upright relative to the cone axis than in the other conformations. Thus in the former crystal structure,[6] the four phenyl rings intersect the plane of the four methylene groups at angles of 93.5, 100.4, 101.4 and 106.1°. Also of interest, the Ph–CH_2–Ph angles are enlarged to values of 112.9, 114.8, 114.9, 115.0°. In the present structures these trends are also observed. Thus the angles between the phenyl rings and the plane of the methylene atoms are 103.9, 103.8, 104.7, 112.33° in **1** and 103.2, 106.5, 99.0, 97.6° in **2**. Note that the smaller angles in **2** are for the phenyl rings enclosing the potassium cation. In both structures, the KO_4 plane is almost perpendicular to the plane of the four methylene groups (angles of intersection 88.2, 86.6° in **1** and 87.8° in **2**). In addition the angles at the methylene groups are also extended as values of 117.4, 116.2, 113.4, 118.2° in **1** and 115, 117, 115, 112° in **2** are found.

Investigations of the solution structure of these complexes were carried out using ^1H and ^{13}C NMR. Addition of K^+ to a solution of 1,3-alternate L^1, in 5:1 CD_3CN–CD_2Cl_2, causes the evolution of new peaks in the ^1H NMR spectrum, consistent with the formation of an asymmetric 1:1 complex, and then the symmetric 2:1 complex (Fig. 4), as has been found with the analogous tetraester L^3.[4] Addition of 2 equivalents of K^+ gave complete formation of the 2:1 complex, indicating the stability constant is high under the conditions used. Addition of K^+ to a solution of L^2, on the other hand, produces a gradual shift in the resonances consistent with the formation of a 1:1 complex, from which a stability constant of 380 ± 40 $dm^3 mol^{-1}$ was calculated.[22] It is possible that the preorganisation of L^1 in the 1,3-alternate conformation enhances the binding of K^+, compared with the conformationally mobile L^2.

These results do not give sufficient information regarding the conformation of the calixarene in solution. However, it has been shown that this can be determined from the chemical shift of the linking methylene carbon in the ^{13}C NMR spectrum, regardless of the solvent used or the substituents on the calixarene; $\delta \approx 37$ indicates a 1,3-alternate conformation and $\delta \approx 32$ indicates a cone.[23] Thus for uncomplexed 1,3-alternate L^1, the methylene carbon resonance was observed at δ 37.22, and in the presence of potassium cations, at δ 37.97. Uncomplexed L^2, however, exhibits a value of δ 32.47 suggesting that the bis-substituted calixarene assumes a cone conformation. Addition of a large excess of potassium cations to the solution causes only a small shift in the methylene carbon resonance to δ 31.64, despite

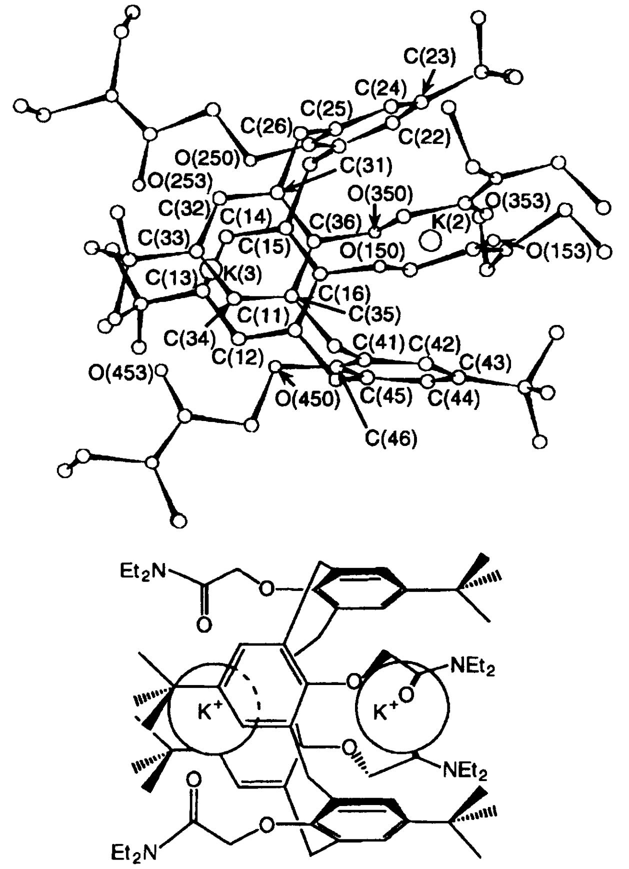

Fig. 1 The $[K_2L^1]^{2+}$ cation in **1** together with the atomic numbering scheme and a schematic diagram showing the environment of the K^+ cations

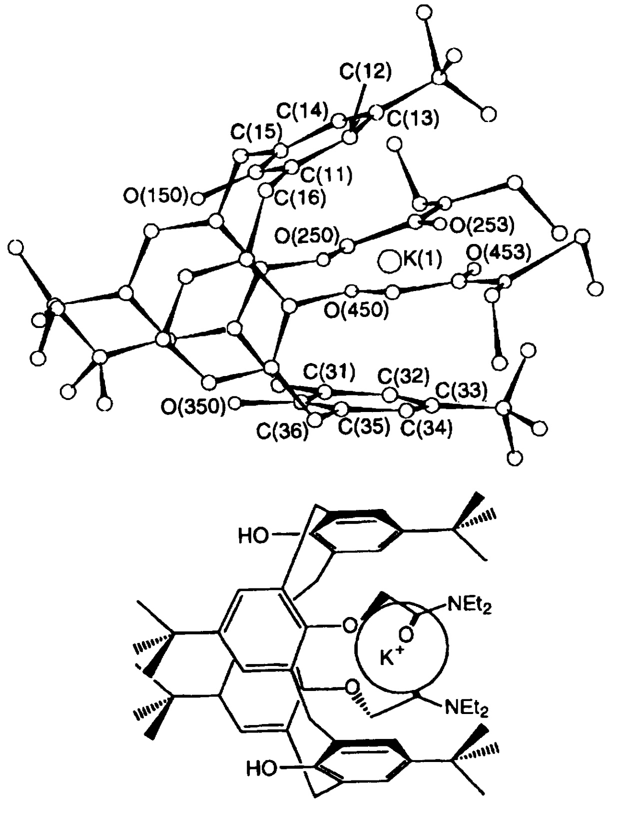

Fig. 2 The $[KL^2]^+$ cation in **2** together with the atomic numbering scheme and a schematic diagram showing the environment of the K^+ cation

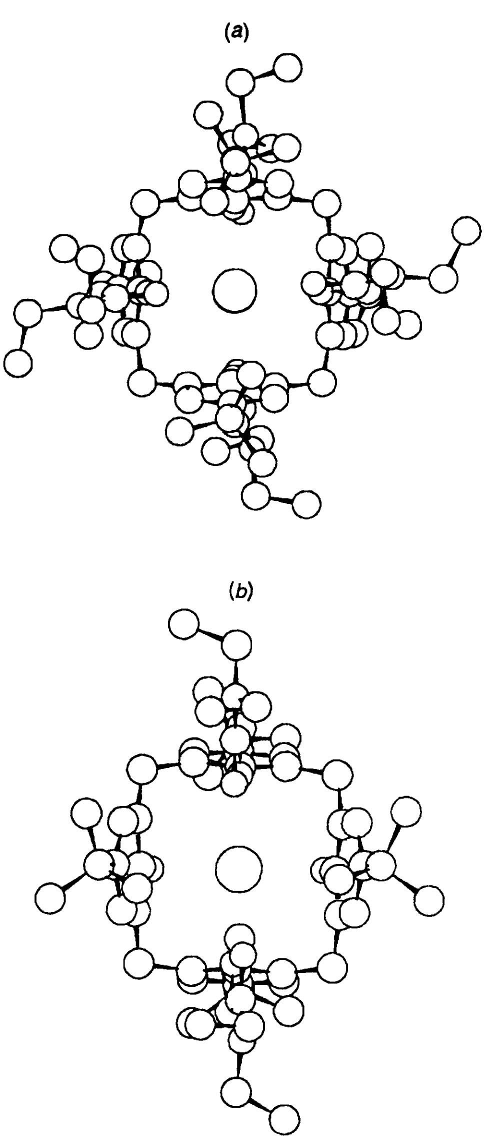

Fig. 3 Views looking down the channel of the calix[4]arene in (*a*) the $[K_2L^1]^{2+}$ cation in **1**, and (*b*) the $[KL^2]^+$ cation in **2**

causing significant changes in other regions of the ^{13}C NMR spectrum, consistent with continued predominance of the cone conformation. Hence, it appears that factors such as solvation energy and/or crystal packing forces may be responsible for the change in conformation observed from solution to the solid state.

Molecular mechanics calculations have been carried out to investigate further the relative stabilities of the two structures L^1 and L^2 both with and without the presence of K^+ cations. Calculations were carried out using the CERIUS software package[24] with the Dreiding force field. Calculations were carried out on the cone conformation and the 1,3-alternate conformation for L^1, L^2, $[KL^2]^+$ and $[K_2L^1]^{2+}$ and the results are shown in Table 5. As in the published work using MM3[21] and Amber,[20] this force field finds the cone conformation to be at a lower energy than the 1,3-alternate conformation with the unsubstituted hydroxide groups at the lower rim of the calixarene, and this is consistent with the experimental rarity of the 1,3-alternate conformation. However when two amide groups are added to create L^2, then the energies of the two conformations become comparable (cone 202.5 kcal mol^{-1} and 1,3-alternate 203.5 kcal mol^{-1}) while the presence of one potassium ion increases the difference between the two conformations to 15.4 kcal mol^{-1} with the 1,3-alternate the most stable. Clearly in the cone conformation the potassium will be

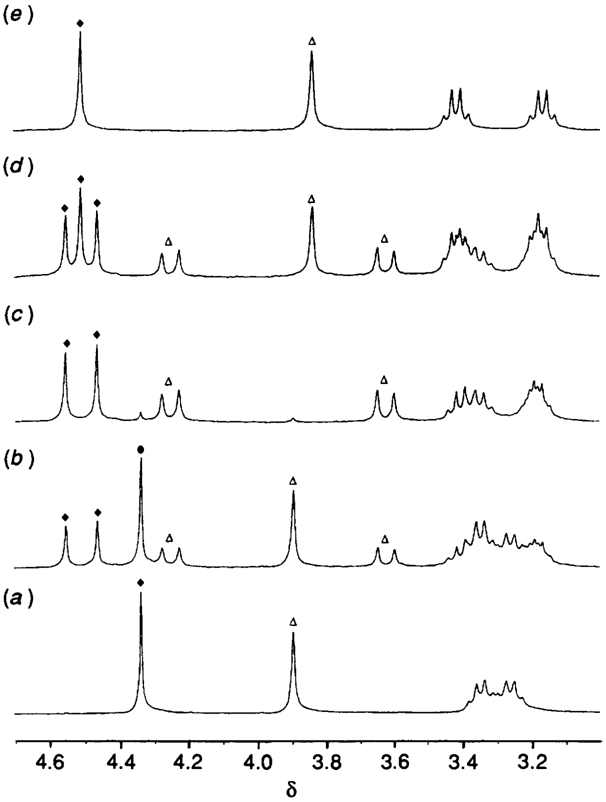

Fig. 4 Partial ^1H NMR spectrum of L^1 in 5:1 CD_3CN–CD_2Cl_2 (*a*), and the spectra obtained upon addition of 0.5 (*b*), 1.0 (*c*), 1.5 (*d*) and 2.0 (*e*) equivalents of KPF_6. (Δ) linking CH_2 resonances and (◆) OCH_2CO resonances

bonded to six oxygens of the calixarene in a somewhat strained environment, while in the 1,3-alternate conformation (as in the crystal structure), the metal environment will consist of four oxygen atoms and the two phenyl rings.

By contrast, in structure L^1 with four amide groups, the 1,3-alternate conformation is favoured by 7.1 kcal mol^{-1} presumably because the four amide groups are sterically crowded at the bottom of the cone. As has been shown previously[12] in a complex formed with one potassium ion $[KL^1]^+$, the cone conformation is favoured because the metal can be bonded to all eight oxygen atoms in a square anti-prismatic environment. The cone conformation cannot, however, accommodate two metal ions, in contrast to the 1,3-alternate conformation as shown in the structure of **1**.

As shown in Fig. 3, one potassium ion (in **2**) or two (in **1**) are found in the 'tube-shaped' cavity of the calixarene. We carried out molecular mechanics calculations to establish the range of metal size that could be encapsulated within this tube. A metal with a specific radius was placed within the cavity and the resulting structure was minimised. A subsequent plot of metal radius against the energy of the molecule showed that over a range of 0.9 Å in size, there was only 5.2 kcal mol^{-1} difference in energy. This result is compatible with the work of Ikeda and Shinkai[5] who report the presence of a Ag^+ cation within the 1,3-alternate conformation, as the radius of the silver ion is significantly smaller at 1.29 Å than the K^+ ion at 1.52 Å.[25] We would therefore anticipate that a range of metal ions could be found to stabilise the 1,3-alternate conformation.

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Table 4 Environment of the potassium cations in **1** and **2**; distances in Å, angles in °

In $[KL^2]^+$, **2**		In $[K_2L^1]^{2+}$, **1**			
K(1)–O(453)	2.64(2)	K(2)–O(353)	2.58(1)	K(3)–O(253)	2.56(1)
K(1)–O(253)	2.67(2)	K(2)–O(153)	2.59(1)	K(3)–O(453)	2.60(1)
K(1)–O(450)	2.70(2)	K(2)–O(150)	2.67(1)	K(3)–O(250)	2.66(1)
K(1)–O(250)	2.71(2)	K(2)–O(350)	2.69(1)	K(3)–O(450)	2.68(1)
K(1)–C(31)	3.39(3)	K(2)–C(21)	3.47(2)	K(3)–C(11)	3.39(2)
K(1)–C(32)	3.43(3)	K(2)–C(22)	3.28(1)	K(3)–C(12)	3.23(1)
K(1)–C(33)	3.31(3)	K(2)–C(23)	3.24(1)	K(3)–C(13)	3.18(1)
K(1)–C(34)	3.22(3)	K(2)–C(24)	3.26(1)	K(3)–C(14)	3.24(1)
K(1)–C(35)	3.25(3)	K(2)–C(25)	3.40(1)	K(3)–C(15)	3.31(2)
K(1)–C(36)	3.31(3)	K(2)–C(26)	3.51(2)	K(3)–C(16)	3.47(2)
K(1)–C(11)	3.39(3)	K(2)–C(41)	3.42(2)	K(3)–C(31)	3.47(2)
K(1)–C(12)	3.51(3)	K(2)–C(42)	3.28(1)	K(3)–C(32)	3.30(2)
K(1)–C(13)	3.44(3)	K(2)–C(43)	3.26(1)	K(3)–C(33)	3.23(1)
K(1)–C(14)	3.27(3)	K(2)–C(44)	3.26(1)	K(3)–C(34)	3.25(1)
K(1)–C(15)	3.22(3)	K(2)–C(45)	3.40(1)	K(3)–C(35)	3.38(1)
K(1)–C(16)	3.23(3)	K(2)–C(46)	3.51(1)	K(3)–C(36)	3.54(1)
O(453)–K(1)–O(253)	114.6(6)	O(353)–K(2)–O(153)	117.4(4)		
O(453)–K(1)–O(450)	56.8(6)	O(353)–K(2)–O(350)	58.0(4)		
O(453)–K(1)–O(250)	172.2(7)	O(353)–K(2)–O(150)	176.2(5)		
O(253)–K(1)–O(450)	169.7(7)	O(153)–K(2)–O(350)	174.6(5)		
O(253)–K(1)–O(250)	58.4(7)	O(153)–K(2)–O(150)	58.9(4)		
O(450)–K(1)–O(250)	130.5(7)	O(150)–K(2)–O(350)	125.8(5)		
		O(253)–K(3)–O(453)	115.8(5)		
		O(253)–K(3)–O(250)	58.9(5)		
		O(253)–K(3)–O(450)	172.3(6)		
		O(453)–K(3)–O(250)	173.6(5)		
		O(453)–K(3)–O(450)	56.9(5)		
		O(250)–K(3)–O(450)	128.5(5)		

Table 5 Molecular mechanics calculations on L^1 and L^2. Lowest energy conformation given in kcal mol^{-1}

	Cone	1,3-Alternate
L^1	271.5	264.4
L^2	202.5	203.5
$[K_2L^1]^{2+}$	Not applicable	294.3
$[KL^2]^+$	229.2	213.8

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