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Lithium-ion induced conformational change of 5,17-bis(9-fluorenyl)-25,26,27,28-tetrapropoxy calix[4]arene resulting in an egg-shaped dimeric clathrate

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Abstract

Synthesis and structural investigation of a 5,17-bis(9-fluorenyl)-25,26,27,28-tetrapropoxy calix[4]arene and its lithium complex salt that forms a dimeric clathrate with a molecule of solvent inside a cavity. At least three different interactions were identified as being responsible for the formation of the egg-shaped supramolecular assembly. © 2000 Elsevier Science Ltd. All rights reserved.

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Calixarenes are well known basket-shaped molecules easily prepared from 4-*t*-butylphenol and formaldehyde that together with their sister compounds, the rescorcinarenes, form versatile platforms for supramolecular host compounds.[1,2] The conformational behaviour of calix[4]arenes with four phenolic units joined by methylene groups has been thoroughly studied. When all four hydroxy groups are etherified and pointing in the same direction the so-called ‘cone’ conformation is obtained. Studies of tetraalkoxy-calix[4]arenes in solution show that two conformations with one or the other opposite pair of aromatic rings pinched together are in equilibrium.[3] Substituents such as carboxylic acids,[4] amides[5] and aryl groups[6] on the rings can influence the equilibrium between the conformers. The pinching closes the cavity and prohibits complexation of guest molecules. Two ways out of this dilemma have been investigated. Crown-ether type functionalisation of the phenolic units can constrain the geometry to open up the cavity.[3] Alternatively, binding a metal ion to the four oxygen atoms can impose C_{4v} symmetry on the calixarene skeleton. However, only a few cases are known where an alkali ion is bound to a simple calixarene ether.[7]

The present study shows how a lithium ion can similarly bind to the ether groups of a calix[4]arene to open up the structure. Two fluorenyl substituents placed opposite each other on the upper rim in the 5,17-positions are then allowed to have an efficient π–π overlap with another calix[4]arene forming

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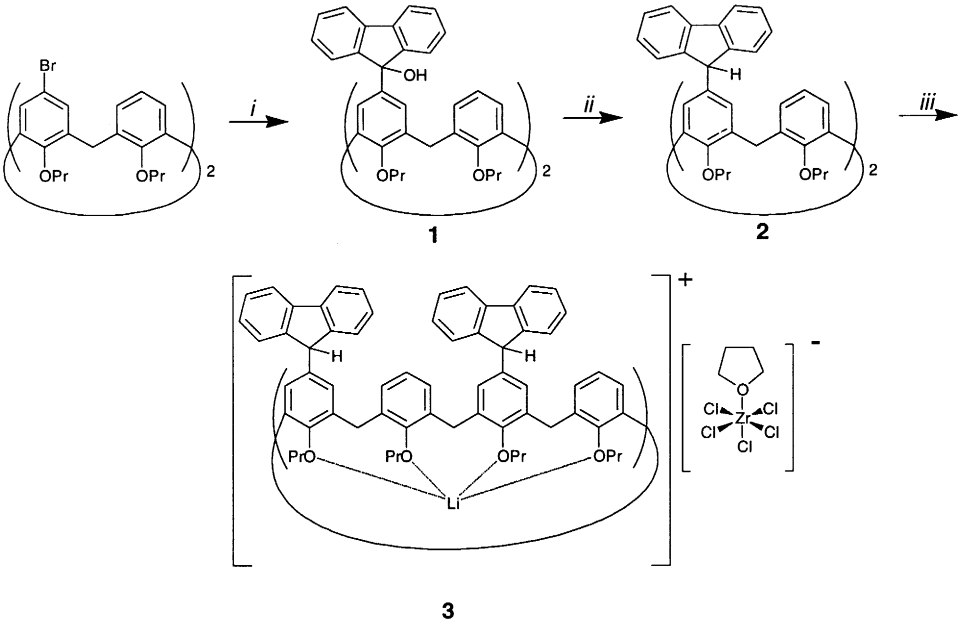
an egg-shaped cavity large enough to hold a solvent molecule of toluene. Syntheses of the substituted calix[4]arenes were carried out as shown in Scheme 1.



Scheme 1. (i) *t*-BuLi/THF/−78°C, 9-fluorenone/THF/rt (76%); (ii) Et_3SiH/TFA/rt (87%); (iii) (1) *t*-BuLi/THF, −78°C, (2) $ZrCl_4 \cdot 2THF$/THF/reflux

5,17-Dibromo-calix[4]arene tetrapropoxyether was lithiated with *t*-BuLi in THF in a halogen–metal exchange reaction and subsequently reacted with fluorenone to produce 5,17-bis(9-hydroxy-fluoren-9-yl)-calix[4]arene ether **1**. Reduction of **1** with $HSiEt_3$ proceeded smoothly to give the 5,17-bis(9-fluorenyl)-calixarene **2**. It was expected that deprotonation at the 9-positions in both fluorene moieties followed by reaction with $ZrCl_4$ would result in the formation of a bis-fluorenyl zirconocene dichloride system placed upon the calix[4]arene platform. Crystals of the salt **3** were harvested from the solution and analysed by X-ray crystallography which showed that the product was instead a lithium complex of the calixarene **2** with the protons in the 9-fluorenyl groups intact and zirconium pentachloride coordinated with THF present as counter ions. Anions of this type, although unusual, have been observed previously.[8] The observed product may be explained by a partial cleavage of the calixarene ether functions with the Lewis acid $ZrCl_4$:

$$\mathrm{ArOPr} + 2\mathrm{ZrCl_4} \rightarrow \mathrm{ArOZrCl_3} + \mathrm{ZrCl_5^-} + \mathrm{Pr^+} \qquad (1)$$

The propyl cation can decompose to give a proton that neutralises the lithium salt of the fluorenyl moiety. These reactions would then have created the ionic species found in the salt **3**. Zirconium tetrachloride induced cleavage of the ether groups was demonstrated by dissolving about 10 mg each of tetrapropoxy calix[4]arene and $ZrCl_4$ in deuterobenzene and two drops of THF in a sealed NMR tube. The reaction was run at 350 K overnight and almost total conversion to calixarenes with three or two propoxy groups was observed by ^1H NMR. A sample was then analysed by MALDI-TOF mass spectroscopy which showed peaks corresponding to cleavage of four, two or one propoxy ether groups.

Calixarene **2** crystallises without solvent in a conformation with the aryl groups holding the fluorenyl moieties pinched together while the fluorenyl groups themselves are bent outwards away from the calixarene centre. The angles between the fluorenyl planes are 81.22(4)° giving rise to a zig-zag interdigitation between layers of calixarenes of opposite orientation (see Fig. 1). In the structure of the salt **3** a dramatic change has occurred in the calixarene on complexation with the lithium ion. There is no pinching of the calixarene skeleton forcing the fluorenyl groups outwards and into a plane inclined with respect to the C_{2v} axis. This feature allows dimerisation to occur with an interplanar fluorenyl–fluorenyl distance of about 4.15(5) Å giving rise to a substantial intermolecular π–π overlap. Dimers incorporating solvent molecules have been constructed from calixarenes relying on hydrogen bonding interactions.[9] Due to the more open calixarene structure, an egg-shaped cavity is formed in the dimer large enough to hold a disordered toluene molecule. The crystal structure of the salt **3** is then a simple packing of the egg-shaped dimers interspersed with solvent toluene and tetrahydrofuran pentachlorozirconate anions.

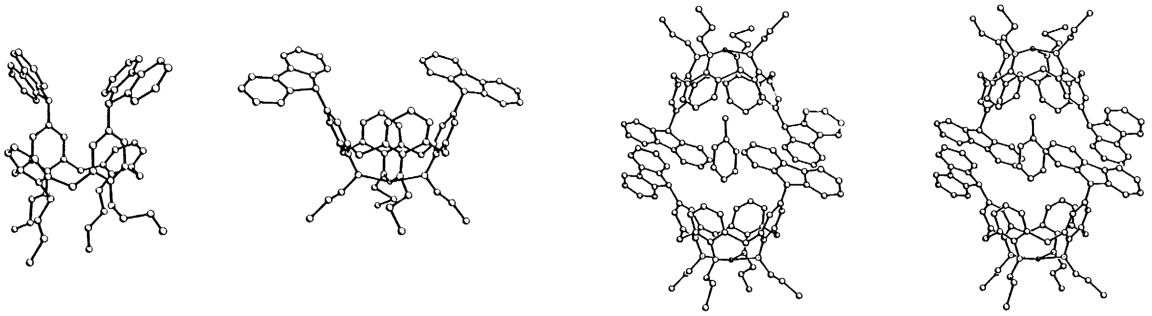


Fig. 1. The molecular conformation of compounds **2** (left) and **3** (middle). In compound **2** the well-known pinched cone conformation is observed with the fluorenyl substituents together. In compound **3** however a lithium ion is bound between oxygen atoms of the propoxy groups. This forces the calixarene into the cone conformation (pseudo C_{4v}). Subsequently, the fluorenyl groups are splayed outwards allowing for dimerisation. To the right is shown a stereoview of the dimer clathrate with the lithium ions bound between oxygen atoms of the propoxy groups and the included toluene solvent molecule.

In summary, the present study demonstrates how three different interactions, namely ion-binding, π–π interactions and solvent inclusion, gives rise to an egg-shaped clathrate in the solid state.

Experimental procedure: 1. To a solution of 5,17-dibromo-calix[4]arene tetrapropoxyether[10] (13.32 mmol) in THF was added *t*-BuLi (60 mmol) at −78°C. A solution of 9-fluorenone (60 mmol) in THF was added and the mixture stirred overnight at ambient temperature. Methanol was added and the mixture evaporated to dryness, the solid was dissolved in CH_2Cl_2, washed with water, dried and evaporated to an oil. The oil was taken up in boiling $CHCl_3$ followed by addition of hexane. The yellow suspension was placed in the freezer for two hours and then filtered. The white product was washed with 20 cm^3 *n*-hexane and dried (9.62 g, 76% yield); mp: ca. 260°C (dec.); δ_H (250 MHz, $CDCl_3$): 7.63 (d, 4H, J=7.1 Hz, Ar), 7.25–7.41 (m, 12H, Ar), 7.03 (s, 4H, Ar), 6.32 (m, 2H, Ar), 6.17 (d, 4H, J=7.5 Hz, Ar), 4.55 (d, 4H, J=13.2 Hz, CH_2), 3.86 (t, 4H, J=7.9 Hz, OCH_2), 3.67 (t, 4H, J=7.0 Hz, OCH_2), 3.03 (d, 4H, J=13.2 Hz, CH_2), 2.58 (s, 2H, OH), 1.80–1.93 (m, 8H, CH_2), 1.01 (t, 6H, J=7.4 Hz, CH_3), 0.88 (t, 6H, J=7.4 Hz, CH_3); δ_C (62.9 MHz, $CDCl_3$): 157.0, 155.5, 150.3, 139.5, 135.8, 133.8, 128.8, 128.2, 127.5, 126.1, 125.9, 125.0, 122.1, 120.0, 83.5, 76.7, 31.0, 23.4, 23.1, 10.6, 10.0.

2. To the nearly black solution of **1** (8.51 g, 8.93 mmol) in TFA was added dropwise Et_3SiH (4.17 g, 35.72 mmol) at ambient temperature under argon. The mixture was stirred for one hour. The reaction mixture was evaporated to dryness and the solid was treated with 100 cm^3 boiling CH_3OH. The mixture was left in the freezer to crystallise the product which was filtered and washed with CH_3OH and dried (7.16 g, 87% yield); mp: ca. 260°C (dec.) [found: C, 86.19; H, 7.24. $C_{66}H_{64}O_4$ requires C, 86.05; H, 7.00%]; δ_H (250 MHz, $CDCl_3$): 7.74 (d, 4H, Ar), 7.24–7.37 (m, 12H, Ar), 6.68 (s, 4H, Ar), 6.35 (m, 6H, Ar), 4.89 (s, 2H, CH), 4.37 (d, 4H, J=13.2 Hz, CH_2), 3.86 (t, 4H, J=7.7 Hz, OCH_2), 3.71 (t, 4H, J=7.0 Hz, OCH_2), 3.03 (d, 4H, J=13.2 Hz, CH_2), 1.89 (q, 8H, J=7.4 Hz, CH_2), 1.02 (t, 6H, J=7.4 Hz, CH_3), 0.91 (t, 6H, J=7.4 Hz, CH_3); δ_C (62.9 MHz, $CDCl_3$): 156.4, 155.7, 148.1, 140.9, 136.0, 134.0, 133.9, 128.5, 127.6, 127.1, 127.0, 125.3, 122.2, 119.7, 76.7, 76.6, 53.9, 30.9, 23.3, 23.1, 10.6, 10.0. Crystal data: $C_{66}H_{64}O_4$; M=921.17, monoclinic space group $P2/c$, a=24.944(5), b=10.351(2), c=19.888(4) Å, β=91.90(3)°, V=5132.2(18) Å^3, Z=4, D_c=1.192 g cm^{-3}, T=120(2) K, μ=0.072 cm^{-1}, wR_2=0.1284 (8494 independent reflections), R=0.0438 [$I>2\sigma(I)$].

3. To a solution of 1.09 mmol **2** (1.00 g) in THF was added *t*-BuLi (2.28 mmol, 1 equiv.+5%) at −78°C under argon. The solution was stirred for 15 min at −78°C followed by stirring for another hour at ambient temperature. The coloured solution was slowly cannulated into a solution of $ZrCl_4\cdot 2THF$ (0.91 g, 2.40 mmol) in THF at room temperature. After the addition, the mixture was refluxed overnight. The solution was evaporated to dryness using a flow of argon to exclude moisture. The solid was treated with toluene and filtered using Schlenk techniques. The filtrate was evaporated to half its original volume and left at ambient temperature for several days to crystallise. Crystal data: $C_{84}H_{88}Cl_5LiO_5Zr$, M=1452.95, triclinic space group P1, a=13.832(3), b=17.564(4), c=18.546(4) Å; α=70.71(3), β=91.90(3), γ=71.23(3)°; V=3928.1(14) Å^3, Z=2, D_c=1.228 g cm^{-3}, T=120(2) K, μ=0.359 cm^{-1}, wR_2=0.3609 (12285 independent reflections), R=0.1131 [$I>2\sigma(I)$].

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