

# The Solid-State Complex of *para*-Sulphonato-Calix[8]Arene Anion with Dimethylammonium Cations

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**Abstract:** The solid-state structure of the complex *para*-sulphonato-calix[8]arene – dimethylammonium – dimethylformamide shows the *para*-sulphonato-calix[8]arene anion in a pleated cone conformation with the inclusion of four dimethylammonium cations and the dimethylformamide positioned exo to the macrocycle.

**Key Words:** Solid-state, crystal structure, calix[8]arene, *para*-sulphonato-calix[8]arene, inclusion complex.

## INTRODUCTION

The calix[n]arenes due both to their ease of synthesis and selective chemical modification, [1] and their ability to complex with a wide range of substrates ranging from ions, [2] through small molecules, [3] to bio-active molecules, [4] and even to proteins, [5] are one of the most widely studied classes of organic host molecules [6].

Of growing interest over the last ten years has been the bioactivity of these molecules, [7] and in particular the water soluble calix[n]arenes where the greatest focus has been on the *para*-sulphonato-calix[n]arenes [8]. These molecules and their derivatives show strong selective binding for the amino-acids, [9] and for certain peptides, [10] more importantly they bind to proteins such as the Serum Albumins, [5] and the Prion protein [11]. In the last case the binding leads to enhanced detection of the pathogenic form of the prion, [12] responsible for such neurodegenerative diseases as Bovine Spongiform Encephalitis, Scrapie and nv-Creutzfeldt Jacobs Disease in humans [13]. The amplification of the detection of the prion increases with the size of the macrocycle, thus *para*-sulphonato-calix[4]arenes < *para*-sulphonato-calix[6]arenes < *para*-sulphonato-calix[8]arenes.

There is thus considerable interest in the determination of the structures of the *para*-sulphonato-calix[n]arenes and their complexes in the solid-state.

While *para*-sulphonato-calix[4]arenes have been widely studied, the solid-state properties of *p*-sulphonato-calix[8]arene (C8S) have been much less exploited due to its more challenging chemistry and the inherent difficulties in obtaining single crystals and authentication using X-ray diffraction data, coupled with their higher conformational flexibility. *para*-Sulphonato-calix[8]arene has theoretically a much larger molecular cavity than its smaller analogs and thus has great potential for enveloping large spherical guest

molecules such as fullerenes [14] or globular shaped metal complexes in water soluble thin films, [15] in catalysis and ion transport, [16, 17] or acting as a surfactant for nanoparticle stabilization, as well as its potential for protein complexation. Indeed models of certain sulphonato-calix[8]arenes show molecular diameters of 3 nm and above, comparable to small proteins [18].

The first structural study of *para*-sulphonatocalix[8]arene was reported by Raston *et al.* in 2005 [19]. The *para*-sulphonato-calix[8]arene molecule adopts a “pleated loop” conformation induced by the guest, 4,4'-dipyridine-*N,N'*-dioxide, here *para*-sulphonato-calix[8]arene does not possess a substantial molecular cavity and the conformation is similar to that found for *para*-*tert*-Bu-calix[8]arene, [20] and *para*-H-calix[8]arene [21]. In the presence of tetraphenylphosphonium and trivalent ytterbium cations, *para*-sulphonato-calix[8]arene forms large 2D porous structure [19]. The structure is complicated, consisting of pseudo molecular capsules of C8S forming an overall layered structure where the calixarenes are in bilayer arrangement. There are two kinds of criss-crossed large channels filled with water molecules and aquated ytterbium cations forming 2D porous structure.

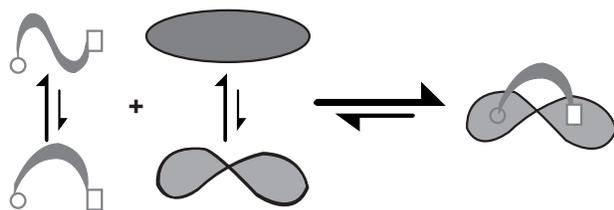
*para*-Sulphonato-calix[8]arene has been shown to form chalice-like cavity for the solid state inclusion of coordination complex tris(phenanthroline)cobalt(III) ([Co(phen)<sub>3</sub>]<sup>3+</sup>) in the presence of trivalent ytterbium cations [22]. The encapsulation of globular shaped [Co(phen)<sub>3</sub>]<sup>3+</sup> cation results in a disruption of the calixarene hydrogen bond network associated with the phenolic moieties, and the wrapping of the flexible host around the guest. Here, the conformation of the *para*-sulphonato-calix[8]arene is best described as a distorted version of the pleated loop conformation, with the phenolic hydrogen bond network breaking down such that a C<sub>2</sub> symmetrical chalice is formed that is similar to that found for a bismuth cluster complex of a *p-tert*-butylcalix[8]arene [23]. The lower rim of the chalice is ‘stitched’ together through the two hydrogen bonding interactions between the sulphonate group from one ring and phenolic oxygen atom

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from another ring in alternate conformation. The pre-organisation requirement of the calixarene in forming the complex results in the formation of large diameter, negatively charged channels within the crystal lattice.

In the complex with bulky 1,2-cyclohexanediamine *p*-sulphonato-calix[8]arene adopts an inverted double cone conformation with two identical partial cones occupied by two guest cations. For the linear 1,4-butanediamine the host is in a conformation of almost planar macrocyclic rings with grooves occupied by elongated 1,4-butanediammonium cations. In the case of 1,4-butanediamine complex assemblies with channels are occupied by disordered methanol molecules are formed. However, perpendicular to these channels, two sets of cavities are generated. The first set of cavities represent channels of an oval geometry containing one butanediammonium cation in a folded conformation and disordered methanol molecules. The cavity walls are formed mainly of sulphonate groups and are therefore highly hydrophilic. The second set of square cavities intersects and connects the first set. The butanediammonium cations in an elongated form are located within these cavities, with the ammonium head groups pointing out of them. Calixarene molecules are held together *via* C-H...O hydrogen bonds between methylenic bridges and sulphonate groups (distances from 3.33(4) to 3.55(3) Å) [24].

It would appear that size or/and shape of the guest has the capacity to influence the shape of the *para*-sulphonato-calix[8]arene cavity adopted in the solid state. The mutually induced fit in host-guest complexes between conformationally flexible *para*-sulphonato-calix[8]arene and photolabile cholinergic ligands has been observed in solution [25]. Both the host and the guests adapted to each other and selected the higher energy but correct geometric conformers so that the guest could fit favorably into the cavity of the host to give diotopic binding of both the aromatic ring and the cationic ammonium moiety of the guest (guest host complex Fig. 1). This system with mutually induced fit represents an original example of adaptive supramolecular biomimetic chemistry.



**Fig. (1).** Adaptive supramolecular system of *para*-sulphonato-calix[8]arene with flexible guest molecule.

In this paper we present the solid-state structure of *para*-sulphonato-calix[8]arene with dimethylammonium cations.

## RESULTS AND DISCUSSION

The crystallographic data for the complex of *para*-sulphonato-calix[8]arene with dimethylammonium cations, derived from breakdown of dimethylformamide used as the crystallization solvent, are presented in Table 1. The asymmetric unit consists of half of the *para*-sulphonato-calix[8]arene molecule in the form of an anion carrying four

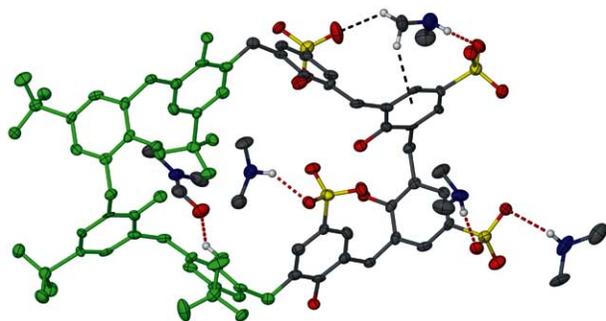
negative charges, four dimethylammonium cations named as X, Y, Z and W, and one DMF molecule (Fig. 2).

**Table 1.** Crystal Data and Structure Refinement for *Para*-Sulphonato-Calix[8]arene – Dimethylammonium – Dimethylformamide Complex [26, 27]

Molecular Formula	$(C_{56}H_{40}O_{32}S_8)^-(C_2H_8N)_8 \cdot (C_3H_7ON)_2$	
Formula weight	998.15	
Temperature	100(2) K	
Wavelength	0.71073 Å	
Crystal system	Triclinic	
Space group	P1	
Unit cell dimensions	a = 11.508(1) Å b = 12.816(1) Å c = 17.421(2) Å.	$\alpha = 74.999(7)^\circ$ $\beta = 89.037(6)^\circ$ $\gamma = 67.018(6)^\circ$
Volume	2274.5(4) Å <sup>3</sup>	
Z	1	
Density (calculated)	1.457 Mg·m <sup>-3</sup>	
Absorption coefficient	0.287 mm <sup>-1</sup>	
F(000)	1056	
Crystal size	0.20 × 0.20 × 0.10 mm <sup>3</sup>	
$\theta$ range for data collection	2.60 to 20.81°.	
Index ranges	-11 ≤ h ≤ 11, -12 ≤ k ≤ 12, -17 ≤ l ≤ 17	
Reflections collected	9241	
Independent reflections	4723 [R <sub>int</sub> = 0.113]	
Completeness to $\theta = 20.81^\circ$	99.2 %	
Absorption correction	None	
Refinement method	Full-matrix least-squares on F <sup>2</sup>	
Data / restraints / parameters	4723 / 0 / 599	
Goodness-of-fit on F <sup>2</sup>	0.93	
Final R indices [I > 2σ(I)]	R = 0.062, wR = 0.103	
R indices (all data)	R = 0.129, wR = 0.118	
Extinction coefficient	0.0024(5)	
Largest diff. peak and hole	0.26 and -0.30 e·Å <sup>-3</sup>	

*para*-Sulphonato-calix[8]arene adopts a conformation (Fig. 3) in which three of the phenolic rings point up from the mean plane of the molecule, three point down and the other two phenolic rings are self-included in the macrocyclic cavity forming intramolecular hydrogen bonds between phenolic oxygen atoms acting as donors and sulphonate oxygen atoms acting as acceptors with the distance of 2.855(6) Å. In this conformation the typical hydrogen bonding between vicinal hydroxyl groups does not exist.

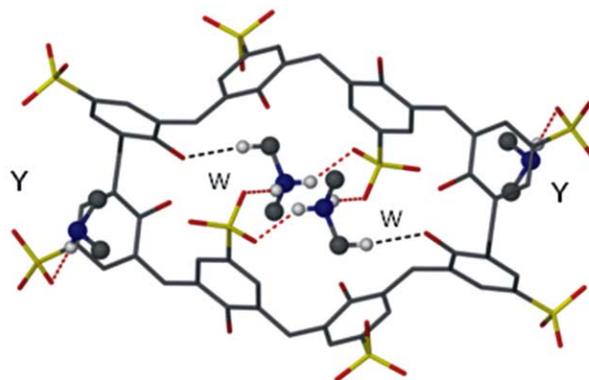
This centrosymmetric *para*-sulphonato-calix[8]arene conformation provides two pairs of identical binding sites for two dimethylammonium cations, **W** and two other dimethylammonium cations, **Y** leading to 1:4 host-guest inclusion stoichiometry (Fig. 4).



**Fig. (2).** Asymmetric unit of the *para*-sulphonato-calix[8]arene complex with dimethylammonium (symmetry-generated atoms in green).

Hydrogen bonding data is given in Table 2. Cations **Y** are located in the identical grooves formed by two phenolic rings pointing up and two phenolic rings pointing down and form hydrogen bond between ammonium nitrogen atom and sulphonate oxygen atom of the host with the distance of 2.820(7) Å. Cations **W** are situated between two included phenolic rings on each side of the macrocycle and form hydrogen bonds to the oxygen atoms of two sulphonate groups of 2.780(7) and 2.847(7) Å. The complexation is additionally

stabilized by C-H...O hydrogen bond (3.446(9) Å) between methyl carbon atom of the cation **W** and one of the phenolic oxygen atom of the host.

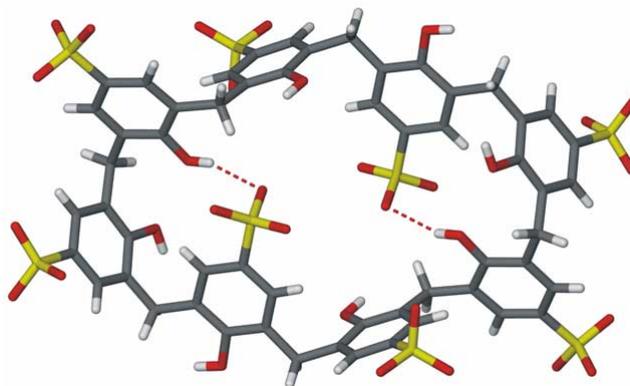


**Fig. (4).** Inclusion complex of *para*-sulphonatocalix[8]arene with dimethylammonium cations.

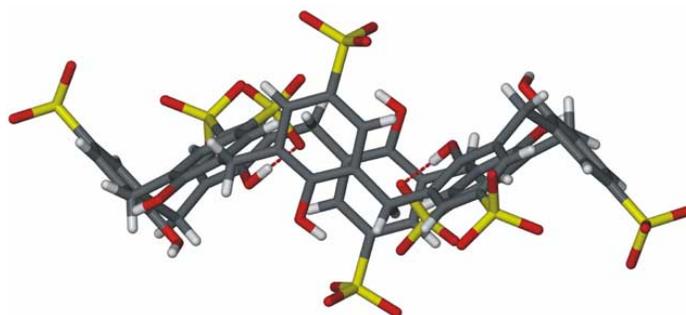
The cations **X** and **Z** are complexed between the neighboring *para*-sulphonato-calix[8]arene molecules by N-H...O hydrogen bonding. Both cations form one bifurcated hydrogen bond with two sulphonate oxygen atoms and one normal hydrogen bond also with sulphonate oxygen atom. The network of hydrogen bonds generated by all four crystallographically independent dimethylammonium cations is presented in Fig. (5).

As shown in Fig. (6), the overall structure reveals the layered character of the packing. There are no distinct hydrophobic and hydrophilic layers in the structure. The struc-

(a)



(b)

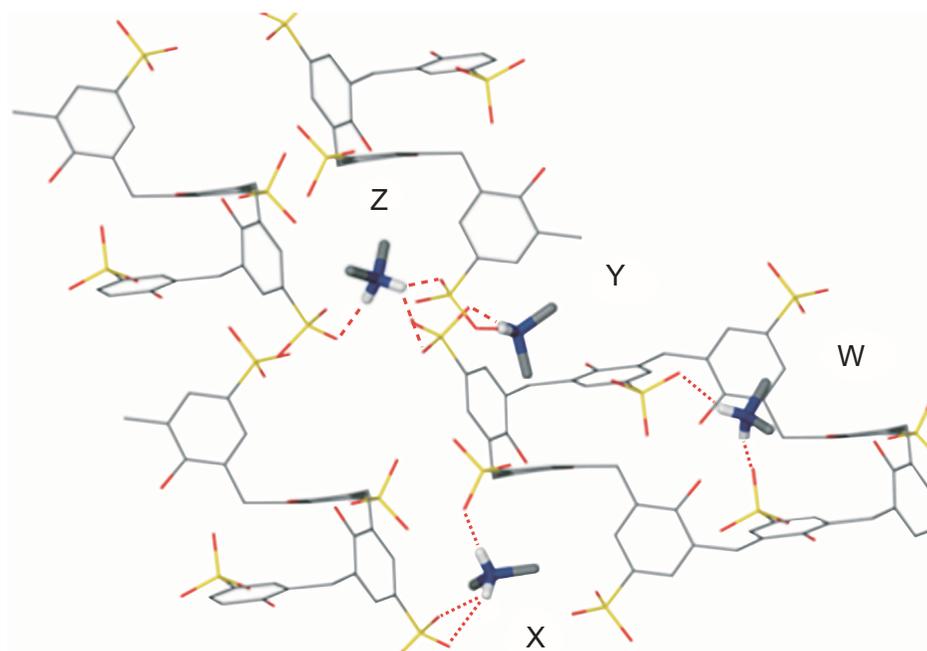


**Fig. (3).** *para*-Sulphonato-calix[8]arene conformation in the dimethylammonium complex: (a) top view; (b) side view.

**Table 2.** Hydrogen Bonding Data for *Para*-Sulphonato-Calix[8]Arene – Dimethylammonium Complex (Å and °)

D-H...A	d(D-H)	d(H...A)	d(D...A)	<(D-H...A)
O(1B)-H(1B)...O(3A) <sup>2</sup>	0.84	1.94	2.708(7)	150.6
O(1D)-H(1D)...O(1S) <sup>1</sup>	0.84	1.91	2.590(6)	136.5
O(1A)-H(1A)...O(3C)	0.84	2.07	2.856(6)	154.9
O(1C)-H(1C)...O(2D) <sup>3</sup>	0.84	2.05	2.701(6)	133.7
N(1X)-H(1X1)...O(2A)	0.92	1.81	2.723(7)	169.9
N(1X)-H(1X2)...O(2B) <sup>4</sup>	0.92	2.05	2.795(8)	137.2
N(1X)-H(1X2)...O(3B) <sup>5</sup>	0.92	2.41	3.112(8)	133.5
N(1Z)-H(1Z1)...O(3D) <sup>6</sup>	0.92	1.94	2.764(7)	147.5
N(1Z)-H(1Z1)...O(2B)	0.92	2.61	3.086(8)	112.5
N(1Z)-H(1Z2)...O(3B) <sup>7</sup>	0.92	1.96	2.864(7)	168.2
N(1Y)-H(1Y1)...O(4B)	0.92	1.90	2.820(7)	172.6
N(1Y)-H(1Y2)...O(2D) <sup>6</sup>	0.92	1.88	2.789(8)	170.0
N(1W)-H(1W1)...O(4C)	0.92	1.97	2.780(7)	146.1
N(1W)-H(1W2)...O(3C) <sup>1</sup>	0.92	1.97	2.847(7)	159.6

(1) -x,-y,-z-1; (2) x-1,y,z; (3) x-1,y+1,z; (4) -x+1,-y,-z; (5) x+1,y-1,z; (6) x,y+1,z; (7) -x,-y+1,-z.

**Fig. (5).** Hydrogen bonding generated by the four independent dimethylammonium cations.

ture is stabilised by a number of C-H... $\pi$  interactions, given in Table 3.

## CONCLUSION

In the complex with the small dimethylammonium cations *para*-sulphonato-calix[8]arene adopts an intermedi-

ate conformation between the double inverted cone and the almost planar macrocyclic ring with three of the phenolic rings pointing up from the mean plane of the molecule, three pointing down and the other two of the phenolic rings being self-included in the macrocyclic cavity. In this conformation typical hydrogen bonding between neighboring phenolic

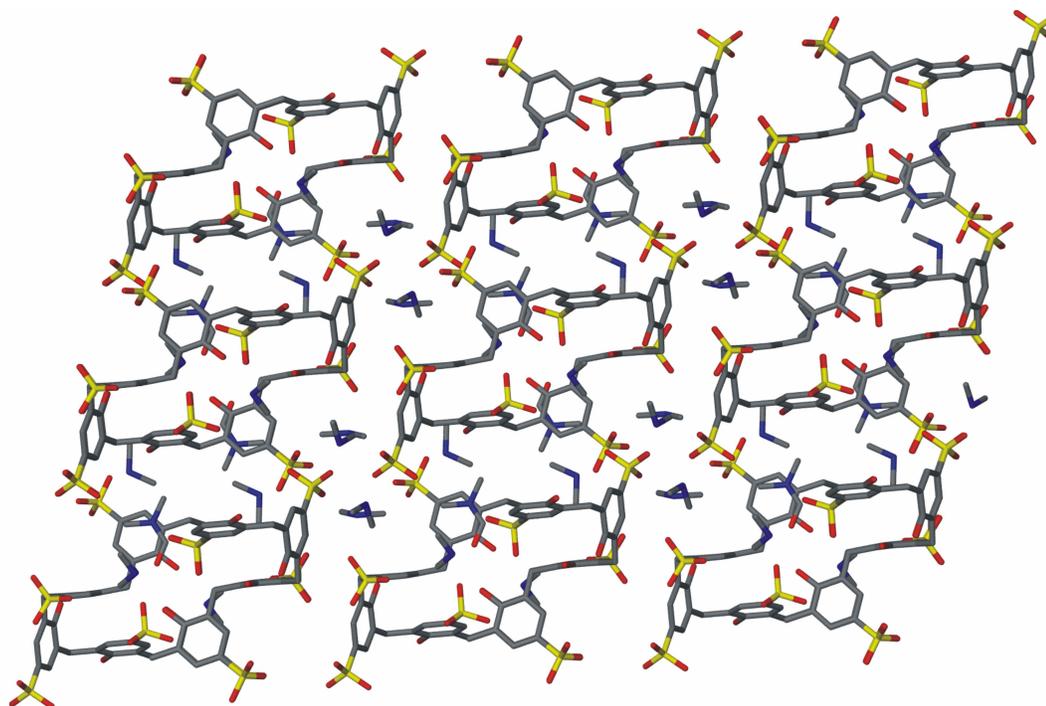


Fig. (6). Molecular packing of the *para*-sulphonato-calix[8]arene–dimethylammonium complex along the *a* axis.

Table 3. C–H... $\pi$  Interactions for *Para*-Sulphonato-Calix[8]Arene – Dimethylammonium ( $\text{\AA}$  and  $^\circ$ ), where Cg1, Cg2 and Cg3 are the Centroids of the Benzene Rings (C1A–C6A), (C1B–C6B) and (C1C–C6C), Respectively

C–H... $\pi$	d(C–H)	d(H...Cg)	d(C...Cg)	$\angle(\text{C–H...Cg})$
C3S–H3S3...Cg1 <sup>i</sup>	0.98	2.96	3.415(9)	110
C2X–H2X1...Cg2	0.98	2.87	3.760(8)	152
C1Z–H1Z3...Cg3 <sup>ii</sup>	0.98	2.83	3.722(9)	151

(i)  $-1+x,y,z$ ; (ii)  $-x,1-y,-z$ .

rings does not exist. In this complex *para*-sulphonato-calix[8]arene complex host includes dimethylammonium cations, while dimethylformamide molecules are complexed *exo* to the cavity.

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