



Novel Linear Molecular Aggregation Tethered by Hydrogen-Bonded Interaction Within the Crystalline Calix[4]arene Derivatives[†]

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Abstract—Single crystals of two calix[4]arene derivatives, that is, 5,11,17,23-tetra-*tert*-butyl-25,27-bis[2-[*N*-(3-methoxy-4-methoxy-benzylidene)-amino]ethoxy]-26,28-dihydroxy calix[4]arene (**1**) and 5,11,17,23-tetra-*tert*-butyl-25,27-bis[2-[3-pyridine carbonyl-amino]ethoxy]-26,28-dihydroxy calix[4]arene (**2**), were prepared and their crystal structures have been determined by X-ray crystallographic study. As compared with calix[4]arene derivative **1** possessing C=N functional group, compound **2** bearing the NH group could form not only intermolecular hydrogen bonds between the hydrogen atom in NH group and the oxygen atom in C=O of an adjacent calix[4]arene molecule, but also intramolecular hydrogen bonds between the N—H···O=C moieties in solid state, giving a rare linear molecular aggregation.

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Introduction

It is well known that the calixarenes and their derivatives were taken as a family of receptors to bind selectively the inorganic/organic ions or molecules forming the host–guest complexes, which have been applied successfully to separate science and technology.¹ On the other hand, some functional calixarene derivatives can assemble or self-organize to form the nanometer structure supramolecular aggregations and/or molecular devices through the cooperative working of several weak intermolecular interactions.^{2,3} Therefore, a lot of effort has been contributed to the design and synthesis of functional calixarene derivatives in order to investigate the mechanism of molecular recognition and molecular assembly. It is noted that studies on hydrogen bonding interactions of calixarenes have been of growing interest to theoretical and experimental chemists, because it is one of important driving-forces in cooperative binding interactions. Recently, Rebek et al.⁴ have reported that the four urea functional groups attached on the wide rim of calixarene could aggregate to form the calixarene derivative's encapsulation by hydrogen bond interaction in solution.

Reinhoudt et al.⁵ have prepared rodlike nanostructure aggregation by hydrogen-bonding self-assembly. Nomura et al.⁶ have also found that calix[4]arene derivatives bearing amino acids could also form the aggregation through intermolecular and intramolecular hydrogen bonds. Beer et al. have reported the crystal structure of the 4-pyridyl analogue of **2**, which shows intermolecular and intramolecular hydrogen bonds between the NH···O=C moieties.⁷ More recently, we have described extensively, the interlocked 2-D supramolecular architecture of self-adhesive double-tailed 1,3-planar-2,4-upright-calix[4]arene.⁸ In the present study, we have synthesized two calix[4]arene derivatives possessing C=N (**1**) and NH (**2**) functional groups (Chart 1) and determined their crystal structures. It is of our particular interest to compare the molecular structures of two novel calix[4]arene derivatives in solid state, together with similar ones to those reported,⁷ which will serve our further understanding of this recently developing on the assemblies formed by calixarene derivatives through hydrogen bonds interaction, in order to design novel highly selective functional supramolecular systems.

Results and Discussion

It is usual to describe the cone conformation of the calix[4]arene with reference to the plane of four methyl-

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[†]Supporting information available. Positional and thermal parameters for non-hydrogen atoms, bond distances and angles of **1** and **2**.

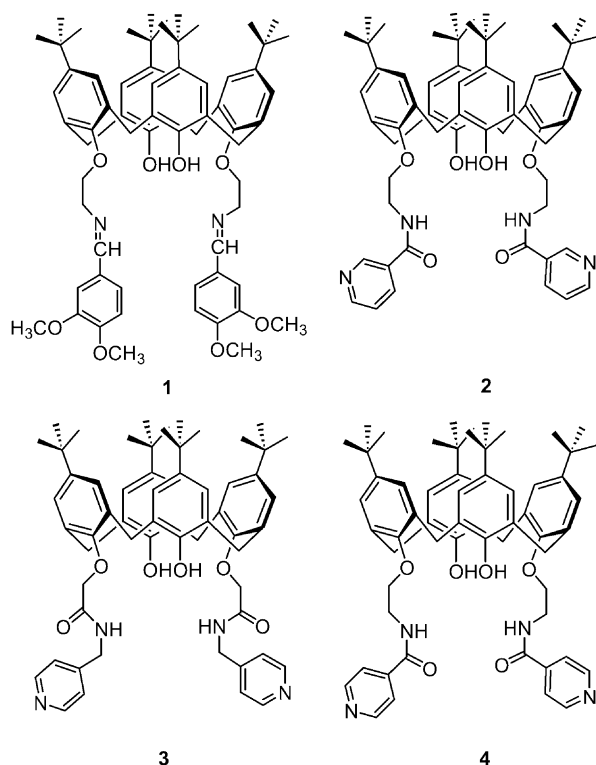


Chart 1.

ene carbon atoms C(2), C(8), C(14), and C(20).¹⁰ As can be seen from Figures 1 and 2, phenyl rings 1 and 3 in compound 1, which have the substituted groups at the oxygen atoms at the bottom of the calixarene, are more nearly perpendicular to the methylene plane than the

unsubstituted rings 2 and 4. As compared with molecular structures of 3 and 4 reported,⁷ calix[4]arene derivatives 1 and 2 adopt a similar distorted cone conformation. The distortion can be seen from the least square planes calculations in Table 1, which show the interplanar angles between the phenyl rings and the plane of the four methylene carbon atoms. In all four cases the angles subtended by the unsubstituted rings 1 and 3 are between 22.2 and 47.8°, while the angles subtended by the substituted rings 2 and 4 range from 64.4 to 89.3°. Interestingly, the molecular structure of 2 among all four similar compounds reveals not only the least interplanar angle between the reference plane and one of the unsubstituted rings (22.2°), but also the largest for one of the substituted rings (89.3°).

It is significant that although four molecular structures are very analogous, different patterns of intermolecular and intramolecular hydrogen bonds are involved in solid state resulting in distinct aggregation. Hydrogen bonds around the lower rim of calix[4]arene between phenolic–OH groups extensively exist in this kind of calix[4]arene derivatives and stabilize the distorted cone conformation. The structure of 1 only involved these natural hydrogen bonds (Fig. 3). However, in 3 exists many other intramolecular weak interactions between amide groups and adjacent oxygen in addition the nitrogen atom of one the pyridine rings and an amide nitrogen, in which did not find the intermolecular hydrogen bonds.⁷ It is significant that 2 and 4 possess very similar structures, and allows us to examine the subtle difference arising from the different position substituted by the nitrogen atom in the pyridine ring. It is noted from Figure 4 and the results reported,⁷ only one

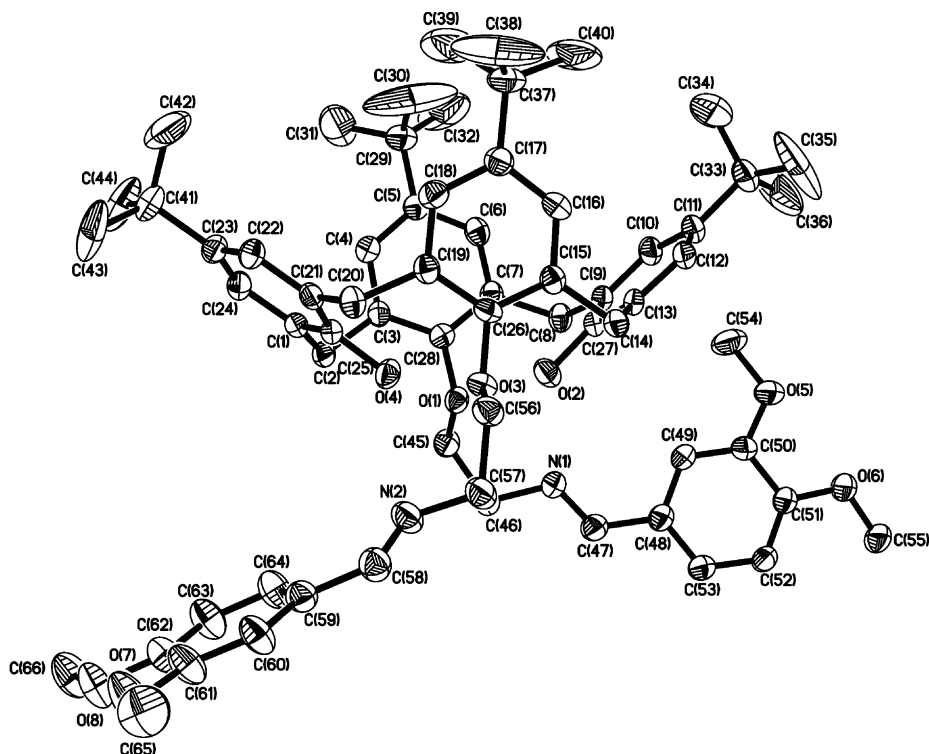


Figure 1. ORTEP representation of the molecular structure of 1. The intramolecular hydrogen bonds are shown: $d_{[O1...O2]}=2.777 \text{ \AA}$, $\Phi_{[O2-H2C...O1]}=167.9^\circ$; $d_{[O3...O4]}=2.947 \text{ \AA}$, $\Phi_{[O4-H4B...O3]}=168.0^\circ$.

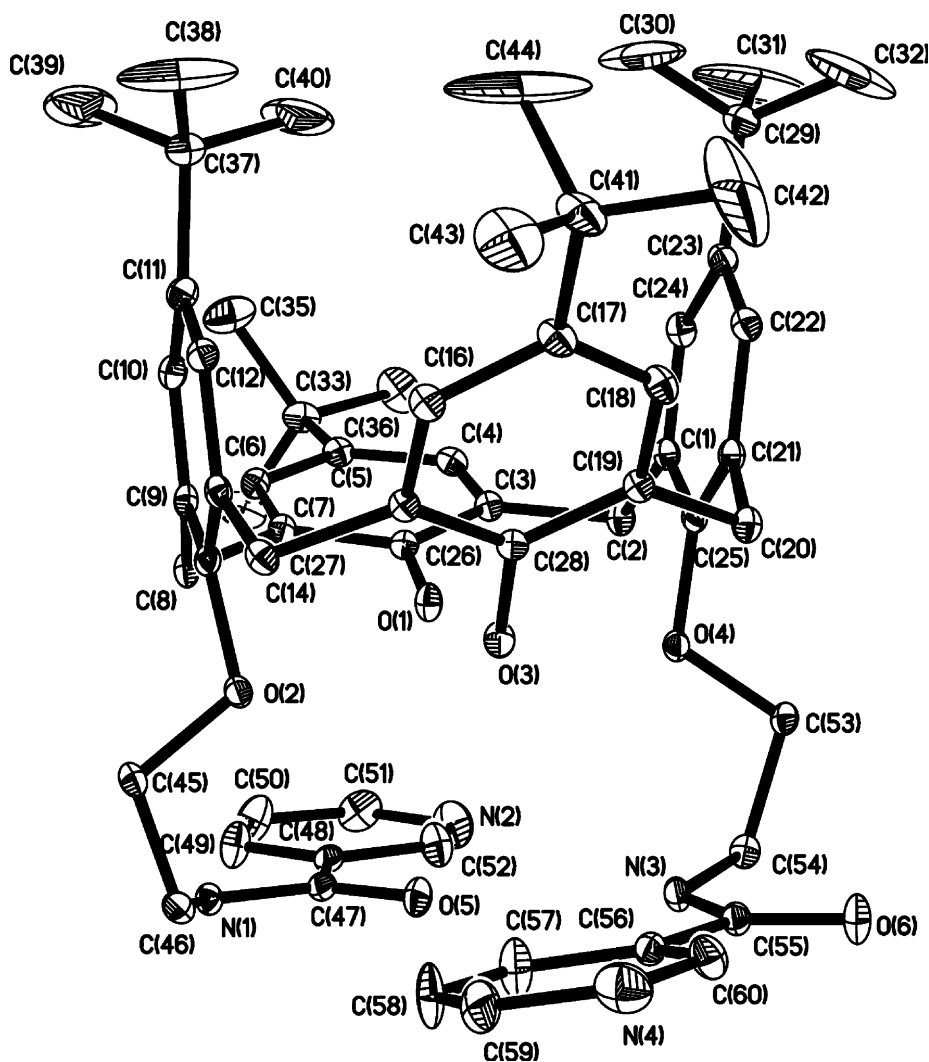


Figure 2. ORTEP representation of the molecular structure of **2**. The intramolecular hydrogen bonds are shown: $d_{[O1...O4]}=2.777 \text{ \AA}$, $\Phi_{[O1-H1B...O4]}=168.0^\circ$; $d_{[O2...O3]}=2.914 \text{ \AA}$, $\Phi_{[O3-H3B...O2]}=169.9^\circ$.

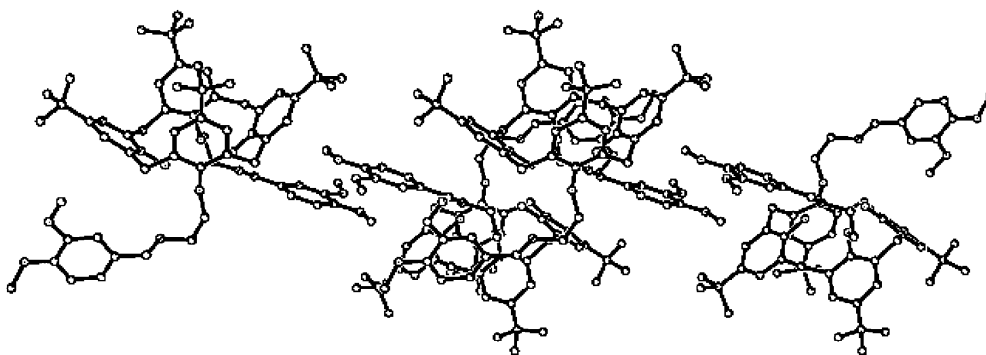


Figure 3. Crystal packing of **1**.

of the amide nitrogen atom in compounds **2** and **4** forms intramolecular hydrogen bonds with the carbonyl oxygen atom in the other arm, except for intrinsic intramolecular hydrogen bonds between lower rim oxygen atoms, entirely differing from the amide nitrogen atom in **3** to form intramolecular hydrogen bonds with an oxygen atom at the lower rim. On the other hand, although the second amide nitrogen atom in **2** and **4** is involved in an

intermolecular hydrogen bond to an adjacent molecule, the binding ability of intermolecular interaction organized by hydrogen bonds is different. As can be seen from Table 2, intermolecular hydrogen bonds of **2** become much shorter than that of **4** (from 3.136 to 2.952 Å). This means stronger intermolecular hydrogen bond interactions are formed for **2**, directly resulting in the stabilization of the linear molecular aggregation.

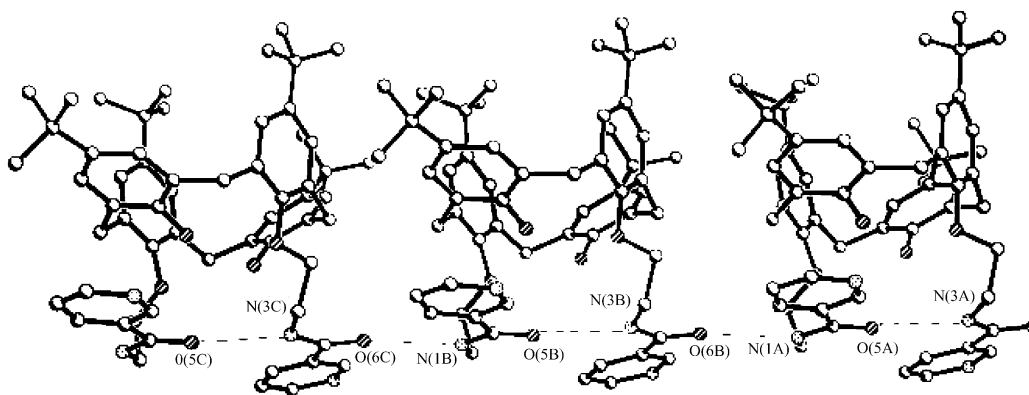


Figure 4. Linear molecular aggregation of **2**. The intramolecular and intermolecular hydrogen bonds are shown: $d_{[N(3C)\cdots O(5C)]}=2.958$ Å, $\Phi_{[N(3C)-H(3CC)\cdots O(5C)]}=150.9^\circ$; $d_{[O(6C)\cdots N(1B)]}=2.952$ Å, $\Phi_{[N(1B)-H(1BB)\cdots O(6C)]}=157.0^\circ$.

Comparing the four similar structures of calix[4]arene derivatives, it is found that compounds **2** and **4**, possessing very similar side arms could form ‘hand-by-hand’

Table 1. Least squares planes angles of intersection ($^\circ$) are given between the four phenyl rings and the plane of the four methylene atoms

	Structure			
	1	2	3	4
Ring 1	38.6	22.2	48.0	42.7
Ring 2	81.0	75.2	64.4	81.1
Ring 3	43.2	42.4	47.8	39.1
Ring 4	82.5	89.3	72.6	87.0

Table 2. Hydrogen bond distances/Å

	Structure	
	2	4
O(1) \cdots O(4)	2.777	3.270
O(2) \cdots O(3)	2.947	2.908
N(3C) \cdots O(5C)	2.958	2.963
O(6C) \cdots N(1B)	2.952	3.136

Table 3. Data collection and processing parameters for compounds **1** and **2**

Compound	1	2
Empirical formula	$C_{66}H_{82}N_2O_8$	$C_{60}H_{72}N_4O_6$
Formula weight	1031.34	945.22
Temperature	293(2) K	293(2) K
Wavelength	0.71073 Å	0.71073 Å
Crystal system, space group	Monoclinic, P2(1)/c	Triclinic, P-1
Unit cell dimensions	$a=20.98(3)$ Å $\alpha=90^\circ$ $b=17.52(2)$ Å $\beta=113.21(2)^\circ$ $c=18.03(2)$ Å $\gamma=90^\circ$	$a=10.158(4)$ Å $\alpha=94.811(6)^\circ$ $b=13.317(4)$ Å $\beta=97.347(6)^\circ$ $c=19.899(6)$ Å $\gamma=94.218(4)^\circ$
Volume	$6091(13)$ Å ³	$2650.5(15)$ Å ³
Z, Calculated density	4, 1.125 Mg/m ³	2, 1.184 Mg/m ³
Absorption coefficient	0.073 mm ⁻¹	0.076 mm ⁻¹
F(000)	2224	1016
Crystal size	0.30×0.25×0.20 mm	0.30×0.25×0.20 mm
Theta range for data collection	1.06–25.03 $^\circ$	1.94–25.03 $^\circ$
Reflections collected/unique	25022 / 10746 [R(int)=0.0895]	10976/9254 [R(int)=0.0270]
Refinement method	Full-matrix least-squares on F ²	Full-matrix least-squares on F ²
Data/restraints/parameters	10746 / 0 / 686	9254 / 0 / 631
Goodness-of-fit on F ²	0.940	1.053
Final R indices [I > 2sigma(I)]	R ₁ =0.0695, wR ₂ =0.1615	R ₁ =0.0746, wR ₂ =0.1944

one-dimensional infinite self-assembly, while calix[4]arene derivatives **1** and **3** only show the discrete molecular structures. Furthermore, we validated that the subtle difference arising from the different position substituted by the nitrogen atom in the pyridine ring could lead to different binding ability between calixarene units. The above results indicated that the hydrogen bonds play an important role in molecular aggregation and highly ordered supramolecular architecture, which prompts us to design a route to the supramolecular assembly based on functional synthetic receptors, so as to further understand sophisticated biological systems.

Experiment

General

The melting points were measured by an XT-4 apparatus without correction. ¹H NMR spectrum was recorded at 300 MHz in CDCl₃, using tetramethylsilane as an internal reference. Elemental analysis was performed on a Perkin–Elmer 2400C instrument.

Materials

Starting materials were commercially available unless otherwise noted. The 5,11,17,23-tetra-*tert*-butyl-25,27-bis(aminoethoxy)-26,28-dihydroxy-calix[4]-arene was synthesized according to the literature procedures.¹¹

Synthesis

Compound **1** was prepared by the reaction of *p*-*tert*-butylcalix[4]arene amine and aldehyde according to the reported procedure.⁹ Compound **2** was prepared as follows: a sample of 1,3-distally substituted *p*-*tert*-butylcalix[4]arene amine (0.27 mmol) was added to a mixture of the 3-pyridinecarbonyl chloride (0.54 mmol) and triethylamine (0.6 mL) in dry CH₂Cl₂ (10 mL) under stirring. The mixture was continuously stirred at room temperature for 4 h, after removal of the solvent, the residue was recrystallized from methanol to obtain white pure calix[4]arene amide derivative (**2**) in 86% yield; mp 270–272 °C; ¹H NMR δ 9.26 (s, 2H, OH), 8.66 (d, *J* = 7.8 Hz, 2H, PyH), 8.57 (t, *J* = 5.5 Hz, 2H, NH), 8.32 (d, *J* = 6.6 Hz, 2H, PyH), 8.02 (s, 2H, PyH), 7.30 (m, 2H, PyH), 7.04 (s, 4H, ArH), 6.92 (s, 4H, ArH), 4.23 (d, *J* = 14.4 Hz, 4H, ArCH₂Ar), 4.12 (br, 4H, OCH₂), 3.79 (m, 4H, NCH₂), 3.37 (d, *J* = 14.4 Hz, 4H, ArCH₂Ar), 1.26 (s, 18H, C(CH₃)₃), 1.05 (s, 18H, C(CH₃)₃); anal. calcd for C₆₀H₇₂N₄O₆: C, 76.24; H, 7.68; N, 5.93. Found: C, 76.13; H, 7.42; N, 5.80.

X-ray structure analysis

A single crystal study was performed on a Siemens SMART CCD area detector. Crystal data and structure refinement for **1** and **2** are shown in Table 3.

Acknowledgements

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