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per-Hydroxylated Pillar[6]arene: Synthesis, X-ray Crystal Structure, and Host–Guest Complexation

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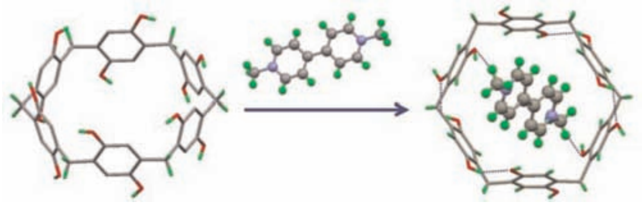
ABSTRACT



A *per*-hydroxylated pillar[6]arene was prepared. Single-crystal X-ray analysis demonstrated that its molecules are arranged in an up-to-down manner to form infinite channels in the solid state. Its host–guest complexation with a series of bispyridinium salts in solution was further investigated. It was found that the *per*-hydroxylated pillar[6]arene could form a 1:1 complex with paraquat in acetone with an association constant of 2.2 × 10^2 M^{-1}. This complex is a [2]pseudorotaxane as shown by its crystal structure, which is the first pillar[6]arene-based host–guest complex crystal structure.

It has been demonstrated that the arrival of any new generation of macrocycles can accelerate the development of supramolecular chemistry and provide new opportunities for material science.[1] Pillar[*n*]arenes, including pillar[5]arenes and pillar[6]arenes, recently appeared in the supramolecular world. Because of their rigid symmetrical pillar architecture, they have exhibited unique binding abilities to various organic guests and displayed fascinating

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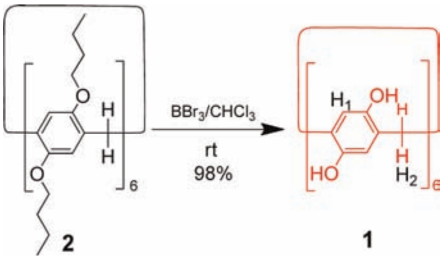
properties in the preparation of supramolecular polymers,[3d] daisy chains,[3e] chemosensors,[7a] and other interesting supramolecular systems.[2−7] However, although the host−guest chemistry of pillar[5]arenes has been well studied,[2−7] the host−guest chemistry of pillar[6]arenes has been rarely explored. The only study is the host−guest complexation between a *per*-isobutylated pillar[6]arene with *n*-octyltriethyl ammonium hexafluorophosphate reported by us in 2010.[3b] In the present work, we made the *per*-hydroxylated pillar[6]arene, studied its host−guest complexation with a series of bispyridinium salts, and obtained not only the crystal structure of the *per*-hydroxylated pillar[6]arene but also the first pillar[6]arene-based host−guest complex crystal structure, one of the complex between the *per*-hydroxylated pillar[6]arene and paraquat.

The synthetic method for the *per*-hydroxylated pillar[6]arene **1** is shown in Scheme 1. Compound **2** was synthesized according to a previously reported procedure.[6c] After removal of the butyl groups of **2** with boron tribromide (BBr_3) in chloroform, **1** was obtained as a white solid. A single crystal of **1** suitable for X-ray analysis was grown by slow evaporation of its acetone solution. The crystal structure of **1** had a high symmetry with a hexagonal axis (Figure 1). The phenolic units were found to be disordered over two sites (50: 50) even at low temperature (173 K). The same to the *per*-isobutylated pillar[6]arene,[3b] the *per*-hydroxylated pillar[6]arene **1** also possesses a pillar structure with a methylene bridge angle of 115.33°. The radius of the incircle of the hexagonal cavity is about 6.6 Å, which produces a larger cavity compared to the *per*-hydroxylated pillar[5]arene, for which the corresponding value is about 4.7 Å (based on the van der Waals radii of atoms).[2e] Hydrogen bonds are formed in an end to end manner between the well arranged hydroxyl groups. Interestingly, a close-packed arrangement of **1** molecules in the crystal structure is observed, in which **1** molecules are stacked in an up-to-down manner to form infinite channels (b and c in Figure 1).

Scheme 1. Synthesis of the *per*-Hydroxylated Pillar[6]arene **1**



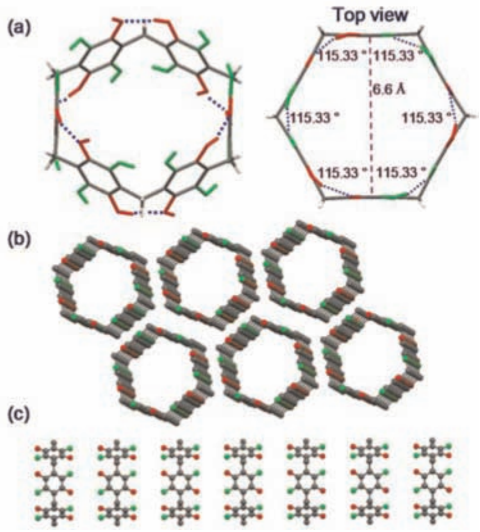


Figure 1. Crystal structure of **1**: (a) two views of **1**; (b) packing mode of **1** in the solid state; (c) partial structure of an infinite channel in 1D. Solvents are omitted for clarity. The disordered hydroxyl groups are depicted by green and red atoms (50:50, either set is independently occupied).

The electron-donating hydroxy donors are aligned around the cavity of **1**, implying that **1** might be a good host for electron-accepting guests. Thus, its recognition possibilities to some bispyridinium salts[8] and analogues (Figure 2) were investigated by ^{1}H NMR. Unlike the *per*-hydroxylated pillar[5]arene, which was mixed with paraquat $\mathbf{G_1}$ in acetone to give precipitation,[5a] the *per*-hydroxylated pillar[6]arene **1** was mixed with $\mathbf{G_1}$ in acetone to give a clear solution. Addition of 1.0 equiv of paraquat $\mathbf{G_1}$ to a solution

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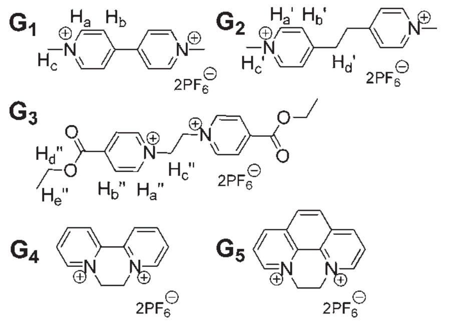

Figure 2. Chemical structures of organic salt guests G_1−G_5.

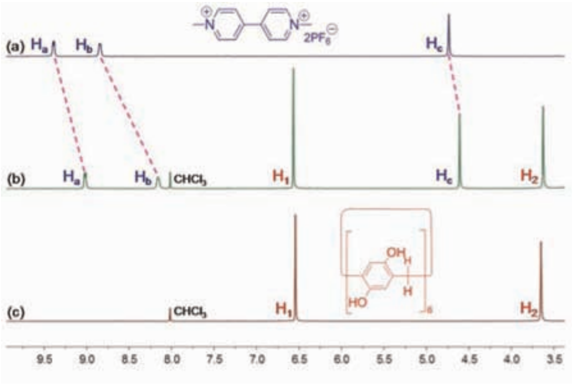

Figure 3. ^{1}H NMR spectra (400 MHz, acetone-d_6, 298 K): (a) 0.500 mM G_1; (b) 0.500 mM **1** and G_1; (c) 0.500 mM **1**.

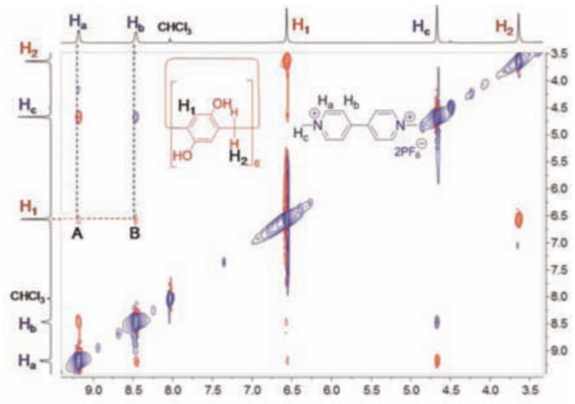

Figure 4. 2D NOESY NMR spectrum (400 MHz, acetone-d_6, 298 K, mixing time = 1.0 s) of 0.500 mM **1** and G_1.

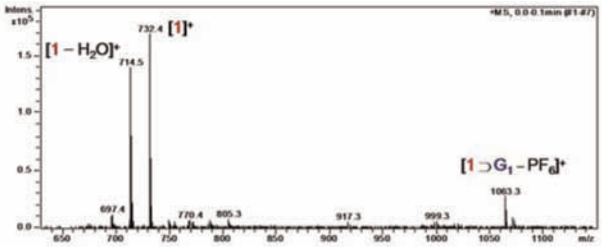

Figure 5. Electrospray ionization mass spectrum of an equimolar mixture of **1** and G_1.

of **1** in acetone-d_6 led to the signals of α-pyridinium protons H_a, β-pyridinium protons H_b, and *N*-methyl protons H_c on G_1 shifting upfield by 0.37, 0.69, and 0.13 ppm, respectively (Figure 3). These chemical shift changes indicated that the complexation of **1** with G_1 took place in solution. The 2D ^{1}H NMR NOESY spectrum of an equimolar mixture of **1** and G_1 showed correlations (**A** and **B** in Figure 4) between the signal of phenyl protons H_1 of **1** and that of α-pyridinium protons H_a and between the signal of phenyl protons H_1 and that of β-pyridinium protons H_b, also indicating the formation of a complex between **1** and G_1. Electrospray ionization mass spectrometry (ESI MS) of an equimolar mixture of **1** and G_1 exhibited a peak at m/z = 1063.3 (Figure 5), corresponding to $[1 \supset G_1 - PF_6]^+$, which revealed a 1:1 stoichiometry for the complexation between **1** and G_1. This 1:1 stoichiometry was confirmed by a mole ratio plot based on proton NMR data of α-pyridinium protons H_a of G_1 (Figure S7, Supporting Information). The 1:1 complexation stoichiometry between the *per*-hydroxylated pillar[6]arene **1** and paraquat G_1 is in sharp contrast with the previously reported 1:2 complexation stoichiometry between the *per*-hydroxylated pillar[5]arene and paraquat G_1.[5a] This complexation stoichiometry difference should be due to the cavity size difference between these two macrocycles. The association constant (K_a) of $1 \supset G_1$ was measured by a ^{1}H NMR titration experiment to be $(2.2 \pm 0.3) \times 10^2$ M^{-1} in acetone (Figure S6, Supporting Information).

Further evidence for the formation of a 1:1 complex between **1** and G_1 was from X-ray analysis of a single crystal grown by slow diffusion of *n*-pentane into an equimolar acetone solution of **1** and G_1. The resultant crystal structure (Figure 6) showed that G_1 threaded through the cavity of **1** to form a [2]pseudorotaxane in the solid state. To the best of our knowledge, this is the first pillar[6]arene-based host−guest complex crystal structure. Although there were several reports on the complexation between the *per*-hydroxylated pillar[5]arene and paraquat, the corresponding complex crystal structure was not reported.[2,5a,7b] The complexation of G_1 decreased the disorder of the phenolic units of **1** and made the pillar structure slightly disturbed. In the [2]pseudorotaxane, hydrogen bonds between hydroxyl groups were also observed. Two hydrogen bonds (**a** and **b** in Figure 6a) were formed between *N*-methyl hydrogens H_c of G_1 and the oxygen atoms of **1**, which contributed to the stabilization of the [2]pseudorotaxane in the solid state. Face-to-face π-stacking interactions were not observed between the phenylene rings of **1** and the pyridinium rings of paraquat, presumably in order to maximize the hydrogen bonding interactions between the host

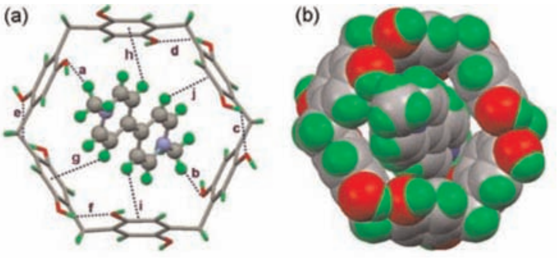

Figure 6. Crystal structure of $\mathbf{1}\supset\mathbf{G_1}$. PF_6^- counterions and solvent molecules were omitted for clarity. (a) Stick model for **1** and ball-and-stick model for $\mathbf{G_1}$; (b) space-filling model (top view). Hydrogen bond parameters: H···O distance (Å), C···O distance (Å), C–H···O angle (deg): a, 2.63, 3.30, 127.4; b, 2.63, 3.30, 127.4; c, 2.27, 2.71, 114.1; d, 1.95, 2.70, 152.0; e, 2.27, 2.71, 114.1; f, 1.95, 2.70, 152.0. Edge-to-face π-stacking parameters: C-centroid distance (Å) and H-centroid distance (Å): g, 3.70, 2.98; h, 3.74, 3.08; i, 3.74, 3.08; j, 3.70, 2.98. Color codes: carbon, gray; nitrogen, blue; oxygen, red; hydrogen, green.

and guest. This is in sharp contrast with the reported complexes between bisphenylene crown ethers and paraquat, in which face-to-face π-stacking interactions between the host and guest were always observed in the solid state.[8a–d] However, the edge-to-face π-stacking interactions were observed (**g**–**j** in Figure 6a), which also assisted the stabilization of the [2]pseudorotaxane structure in the solid state.

For bispyridinium salts $\mathbf{G_2}$ and $\mathbf{G_3}$, 1:1 host–guest complexes also formed, which were confirmed by ^{1}H NMR and ESI MS (Figures S9–S16, Supporting Information) (Figure 7). After complexation, the upfield shifts of bridge methylene protons H_d' and H_c'' on $\mathbf{G_2}$ and $\mathbf{G_3}$ demonstrated that these guests threaded through the cavity of the *per*-hydroxylated pillar[6]arene **1** to form pseudorotaxanes. The K_a values of the 1:1 complexes based on these guests toward **1** were measured to be smaller than 20 M^{-1}, indicating weak binding between them. The organic salts with wider sizes, such as $\mathbf{G_4}$ and $\mathbf{G_5}$, are impossible to thread into the cavity, although the 1:1 complexes were still detected by ESI MS (Figures S17–S27, Supporting Information).

In summary, we have successfully synthesized the *per*-hydroxylated pillar[6]arene and obtained its single crystal structure, which was a regular hexagon. The X-ray crystallographic analysis showed that the pillar[6]arene molecules were arranged in an up-to-down manner to form infinite channels in the solid state. The pillar[6]arene could bind bispyridinium salts in acetone to form [2]pseudorotaxanes. The crystal structure of the complex between **1** and paraquat $\mathbf{G_1}$ showed that the presence of the guest in the cavity of **1** twisted the regular hexagonal structure, but it also destroyed the disorder. The easy availability of the *per*-hydroxylated pillar[6]arene makes these newly established host–guest recognition motifs applicable in the design and preparation of new functional supramolecular systems, including mechanically interlocked threaded structures.

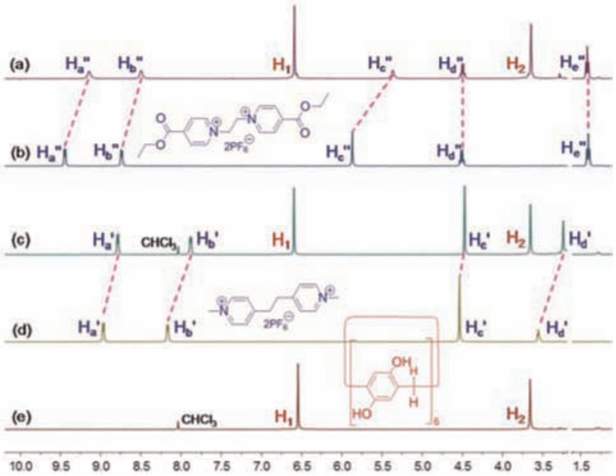

Figure 7. ^{1}H NMR spectra (400 MHz, acetone-d_6, 298 K) of (a) 0.500 mM $\mathbf{G_3}$ + 0.500 mM **1**; (b) 0.500 mM $\mathbf{G_3}$; (c) 0.500 mM $\mathbf{G_2}$ + 0.500 mM **1**; (d) 0.500 mM $\mathbf{G_2}$; (e) 0.500 mM **1**.

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Supporting Information Available. Compound characterization, synthetic details, determination of association constants, and other materials.This material is available free of charge via the Internet at http://pubs.acs.org.

The authors declare no competing financial interest.