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Pillararenes, A New Class of Macrocycles for Supramolecular Chemistry

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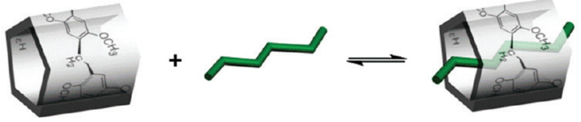
CONSPECTUS

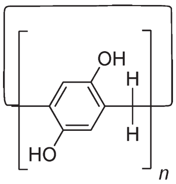


Because of the importance of novel macrocycles in supramolecular science, interest in the preparation of these substances has grown considerably. However, the discovery of a new class of macrocycles presents challenges because of the need for routes to further functionalization of these molecules and good host–guest complexation. Furthermore, useful macrocylic hosts must be easily synthesized in large quantities. With these issues in mind, the recently discovered pillararenes attracted our attention. These macrocycles contain hydroquinone units linked by methylene bridges at para positions. Although the composition of pillararenes is similar to that of calixarenes, they have different structural characteristics. One conformationally stable member of this family is pillar[5]arene, which consists of five hydroquinone units. The symmetrical pillar architecture and electron-donating cavities of these macrocycles are particularly intriguing and afford them with some special and interesting physical, chemical, and host–guest properties. Due to these features and their easy accessibility, pillararenes, especially pillar[5]arenes, have been actively studied and rapidly developed within the last 4 years.

In this Account, we provide a comprehensive overview of pillararene chemistry, summarizing our results along with related studies from other researchers. We describe strategies for the synthesis, isomerization, and functionalization of pillararenes. We also discuss their macrocyclic cavity sizes, their host–guest properties, and their self-assembly into supramolecular polymers. The hydroxyl groups of the pillararenes can be modified at all positions or selectively on one or two positions. Through a variety of functionalizations, researchers have developed many pillararene derivatives that exhibit very interesting host–guest properties both in organic solvents and in aqueous media. Guest molecules include electron acceptors such as viologen derivatives and (bis)imidazolium cations and alkyl chain derivatives such as *n*-hexane, alkanediamines, *n*-octyltrimethyl ammonium, and neutral bis(imidazole) derivatives. These host–guest studies have led to the fabrication of (pseudo)rotaxanes or poly(pseudo)rotaxanes, supramolecular dimers or polymers, artificial transmembrane proton channels, fluorescent sensors, and other functional materials.

Introduction

It is of continuing interest to design and synthesize novel macrocyclic host molecules because of their important roles in supramolecular chemistry. The successful examples include crown ethers,[1−3] cyclodextrins,[4] cucurbiturils,[5] calixarenes,[6−8] and their structurally similar scaffolds.[9−11] Currently a new class of [1_n]paracyclophanes[12,13] is growing with similar composition but different structural features compared with calixarenes. This new class of macrocyclic molecules are made up of hydroquinone units linked by methylene bridges at *para* positions. Their descriptive name "pillararene" was coined by Tomoki Ogoshi in 2008.[14]



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Pillar[*n*]arenes (*n* = 5, 6, 7) have some advantages compared with traditional hosts. First, they are highly

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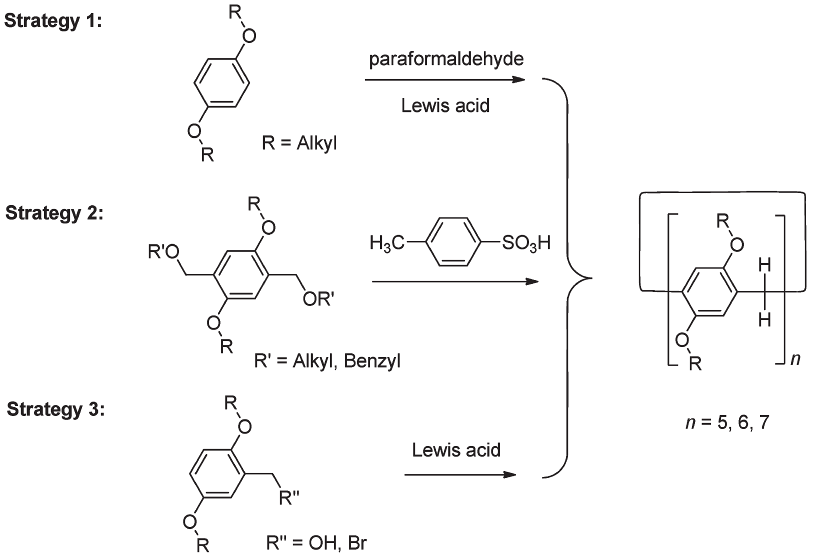
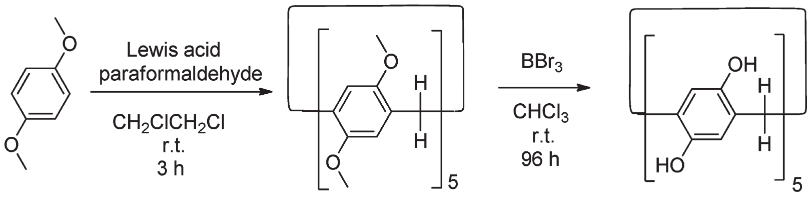
SCHEME 1. Three Synthetic Strategies for Pillararenes



SCHEME 2. Synthesis of DMpillar[5]arene (**2**) and Pillar[5]arene (**1**)



2 **1**

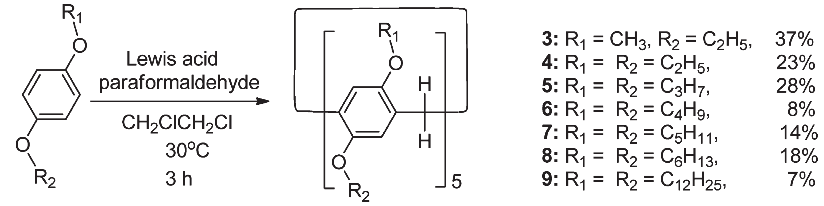
symmetrical and rigid compared with crown ethers and calixarenes, and this affords their selective binding to guests. Second, they are easier to functionalize with different substituents on all of the benzene rings or selectively on one or two positions than cucurbiturils, which enables tuning of their host–guest binding properties. Third, they are easily soluble in organic solvents, which makes them good and necessary supplements to water-soluble cucurbiturils and cyclodextrins with similar cavity sizes. These features and their rigid electron-rich cavity make them good candidates as host molecules for various electron-deficient guests or other neutral molecules such as viologen derivatives, (bis)-imidazolium cations, *n*-hexane, alkanediamines, *n*-octyltrimethyl ammonium, and neutral bis(imidazole) derivatives. Pillararenes with good host–guest properties can further self-assemble and be applied in the fabrication of (pseudo)rotaxanes or poly(pseudo)rotaxanes, supramolecular dimers or polymers, artificial transmembrane proton channels, fluorescent sensors, or other functional materials. Therefore, soon after their invention, this new type of host has attracted great attention and been reviewed recently.[15]

Now mainly based on our own work on pillararenes, as well as the work from other groups, we provide an Account of the growth of pillararene-based chemistry, which will highlight recent advances in the synthetic strategies, conformational characteristics, host–guest binding properties, and self-assembly of pillararenes.

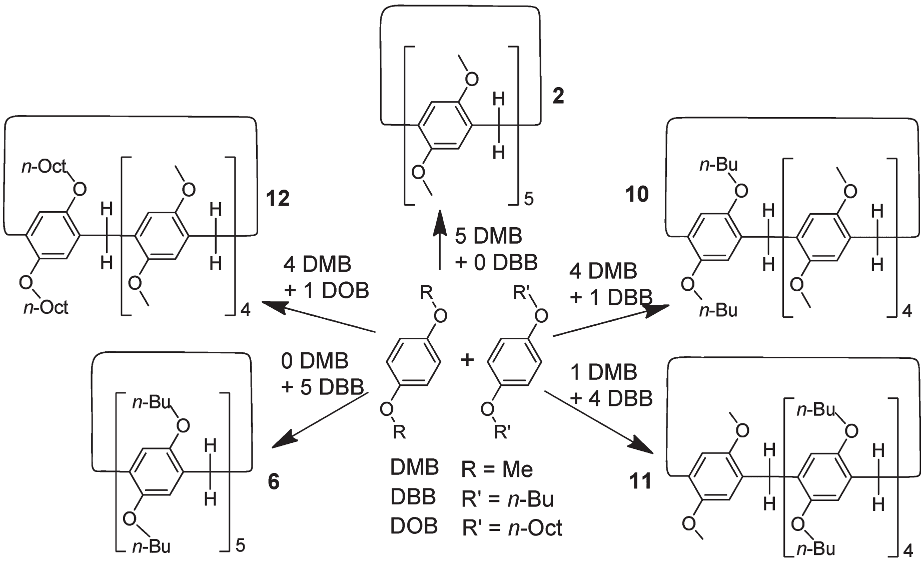
Synthesis

For the synthesis of pillararenes, three strategies have thus far been employed (Scheme 1). The first is the Lewis acid catalyzed condensation of 1,4-dialkoxybenzene and paraformaldehyde. The second is the condensation of 1,4-dialkoxy-2,5-bis(alkoxymethyl)benzene catalyzed by *p*-toluenesulfonic acid. The third is cyclooligomerization of 2,5-dialkoxybenzyl alcohols or 2,5-dialkoxybenzyl bromides with an appropriate Lewis acid as the catalyst. With these methodologies, pillar[5]arenes, pillar[6]arenes and pillar[7]arenes can be obtained. In the word "pillar[*n*]arene", the letter "*n*" means the number of the hydroquinone units. For example, pillar[5]arene means a cyclopentamer with five hydroquinone units.

SCHEME 3. Synthesis of Alkyl-Substituted Pillar[5]arenes



SCHEME 4. Preparation of Copillar[5]arenes by Oligomerization of Different Hydroquinone Diethers



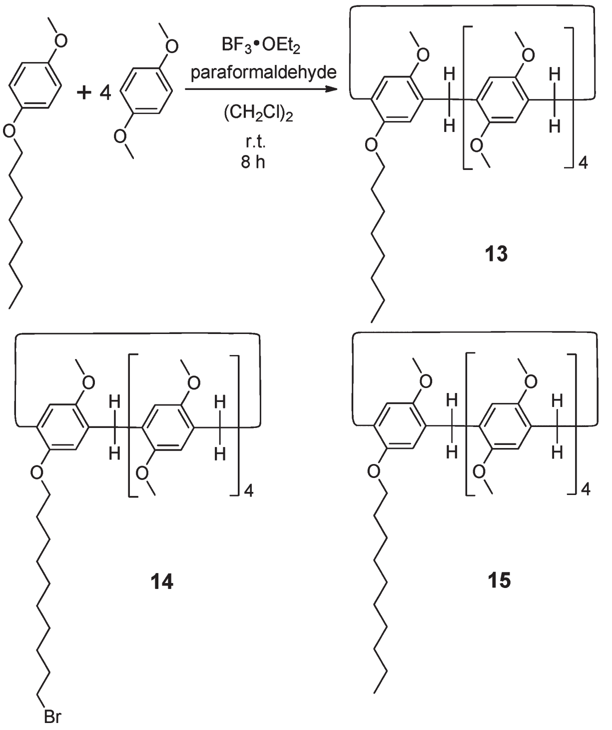
The synthesis of pillar[5]arene, **1**, was reported by Ogoshi et al. in 2008.[14] By condensation of 1,4-dimethoxybenzene with paraformaldehyde and an appropriate Lewis acid as a catalyst, the symmetrical 1,4-dimethoxypillar[5]arene (DMpillar[5]arene), **2**, was selectively obtained (Scheme 2). Various Lewis acids were used for this reaction, and with $BF_3 \cdot O(C_2H_5)_2$, the cyclic pentamer was selectively obtained in 22% yield. Then pillar[5]arene, **1**, was obtained by deprotection of the methoxy groups of DMpillar[5]arene with a total yield of 7%. Subsequently, to reveal the conformational characteristics of pillar[5]arene, the same research group synthesized a series of pillar[5]arene derivatives **3**−**9** with different alkyl groups and found that long alkyl substituents tended to suppress the cyclization reaction (Scheme 3).[16,17]

Recently, our group invested effort in synthesis of copillar[5]arenes containing different repeating units. By using the above reaction conditions, three copillar[5]arenes **10**−**12** were successfully prepared by co-oligomerization of different monomers (Scheme 4).[18] From a mixture of 4 equiv of 1,4-dimethoxybenzene (DMB) per equiv of 1,4-dibutoxybenzene (DBB), copillar[5]arene **10** was obtained in 16% yield. By changing the ratio or the composition of the two comonomers, other copillar[5]arenes **11** and **12** were isolated.

By co-oligomerization of 4 equiv of DMB and 1 equiv of 1-methoxy-4-(octyloxy)benzene, copillar[5]arene **13** was obtained in 9% yield (Scheme 5).[19] This macrocycle was designed as a monomer for the fabrication of supramolecular polymers. Later, for the investigation of self-assembly behavior of pillararenes, copillar[5]arenes **14** and **15** were also designed and synthesized.[20] During this time period, a similar synthetic approach was conceived to prepare copillar[5]arene **16**, which was substituted with an azide group and functionalized through copper-catalyzed azide−alkyne cycloaddition (CuAAC; Scheme 6).[21−23] More recently, more copillar[5]arenes were synthesized in high yields by Cao et al. via strategy 1 in Scheme 1 using $FeCl_3$ as the catalyst.[24]

Recently Ogoshi et al. improved the preparation of DMpillar[5]arene **2** by using excess paraformaldehyde (3 equiv of paraformaldehyde per equiv of 1,4-dimethoxybenzene). As a result, they successfully obtained DMpillar[5]arene, **2**, in a short time (3 min) and in high yield (71%) and pillar[5]arene, **1**, almost in quantitative yield.[25] Via this improved preparation method, pillar[5]arenes carrying chiral substituents at both rims were synthesized to investigate their molecular chirality.[26]

SCHEME 5. Synthesis of Copillar[5]arene **13** and Chemical Structures of Copillar[5]arenes **14** and **15**



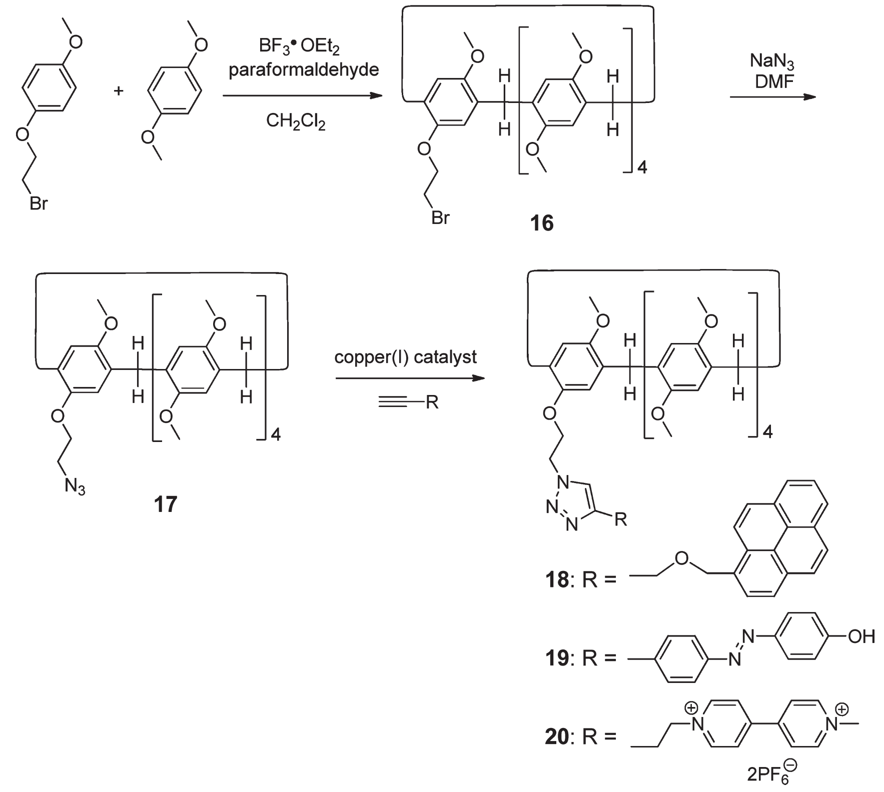
On the other hand, Cao et al. changed the synthetic methodology and found a surprising reaction involving 1,4-diethoxy-2,5-bis(benzyloxymethyl)benzene with catalytic amounts of *p*-toluenesulfonic acid.[27,28] The yields of pillar[5]arenes were improved to 75%–95%. Furthermore, pillar[6]arenes **21** and **22** were prepared in 8%–11% (Scheme 7).

Most recently, another facile and efficient preparation of pillar[*n*]arenes (*n* = 5 or 6) was achieved in our group via cyclooligomerization of 2,5-dialkoxybenzyl alcohols or 2,5-dialkoxybenzyl bromides with an appropriate Lewis acid as the catalyst at room temperature (Scheme 8).[29] The mechanism for this cyclooligomerization is presumed to be a Friedel–Crafts alkylation.[30] Using this method, pillar[*n*]arenes (*n* = 5, 6) having different alkoxy substituents were prepared successfully.

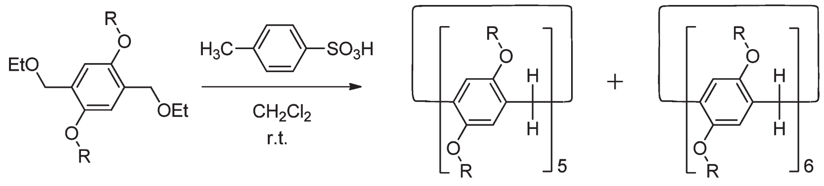
Functionalization

Functionalized pillararenes are necessary for molecular recognition and self-assembly. Pillararenes containing functional groups, such as alkyl-substituted pillar[5]arenes[16,17]

SCHEME 6. Synthesis of Copillar[5]arenes **16**–**20**

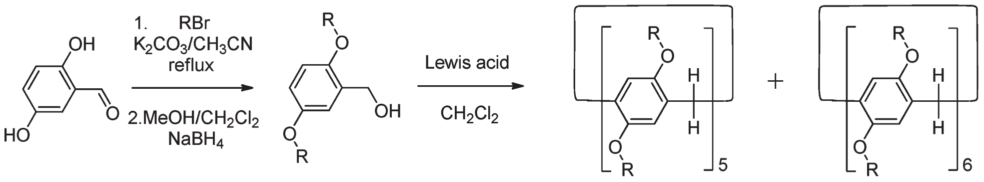


SCHEME 7. Synthesis of Pillar[5]arenes and Pillar[6]arenes from 1,4-Diethoxy-2,5-bis(alkoxymethyl)benzene



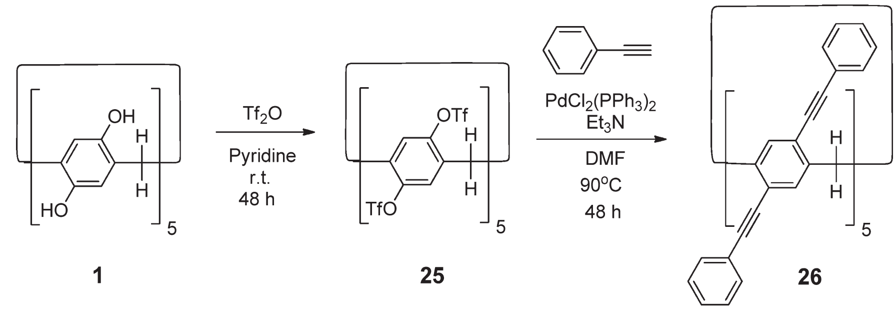
2: R = CH_3, 95%;
4: R = C_2H_5, 89%; **21**: R = C_2H_5, 8%;
6: R = C_6H_{13}, 86%; **22**: R = C_8H_{17}, 11%.

SCHEME 8. Synthesis of Pillar[*n*]arenes from the Condensation of 2,5-Dialkoxybenzyl Alcohols



7: R = C_5H_{11}, 41%;
8: R = C_6H_{13}, 43%;
23: R = C_8H_{17}, 14%; **24**: R = C_8H_{17}, 13%.

SCHEME 9. Synthesis of DPhEpillar[5]arene, **26**



and copillar[5]arenes,[18−24] were synthesized directly from reactants with various substituents. In fact, the other method for the construction of functionalized pillararenes is based on chemical modification of the parent macrocyclic rings.[31−38] Take copillar[5]arene **16**, for example (Scheme 6), the bromo group is reactive for chemical manipulations and was substituted with an azide group to obtain compound **17** and then functionalized through CuAAC to get copillar[5]arenes **18**−**20**.

For parent macrocyclic pillar[*n*]arenes, reactive and transformable hydroxyl groups, which provide a unique platform for further chemical modification and functionalization, exist. Ogoshi et al. synthesized a new fluorescent pillar[5]arene **26** modified with phenylethynyl groups (Scheme 9), which showed temperature- and solvent-responsive blue-green emission.[31]

By introduction of carboxylate anions at both rims, pillararenes can be made soluble in aqueous media.[32] By hydrolysis of ethoxycarbonyl-substituted pillar[5]arene **27** under basic conditions and neutralization to the ammounium salt, water-soluble pillar[5]arene **29** was obtained (Scheme 10); its interesting host−guest properties in aqueous media will be described in the following section.

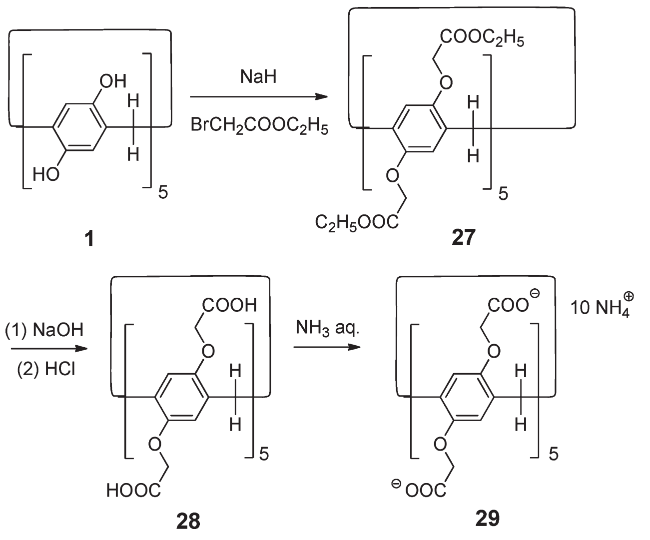
Other water-soluble pillar[5]arenes were investigated by the Hou group[33] and our group.[34] An amine-substituted pillar[5]arene **33** and a trimethylammonium-substituted pillar[5]arene **34** have been synthesized through modification of pillar[5]arene **31**, which was afforded by derivation from ethoxycarbonyl-substituted pillar[5]arene **27** through several steps, or simply by condensation of 1,4-dialkoxybenzene and paraformaldehyde (Scheme 11).

Functionalization of pillar[5]arene using "click" chemistry provides an extremely simple method to prepare various functional group-modified pillar[5]arenes.[21−23,35] To attach functional groups via the click reaction, an intermediate alkynylated pillar[5]arene **35** was prepared by etherification (Scheme 12). Then the coupling reactions between **35** and azide compounds were examined to obtain the target products **36**−**38**.

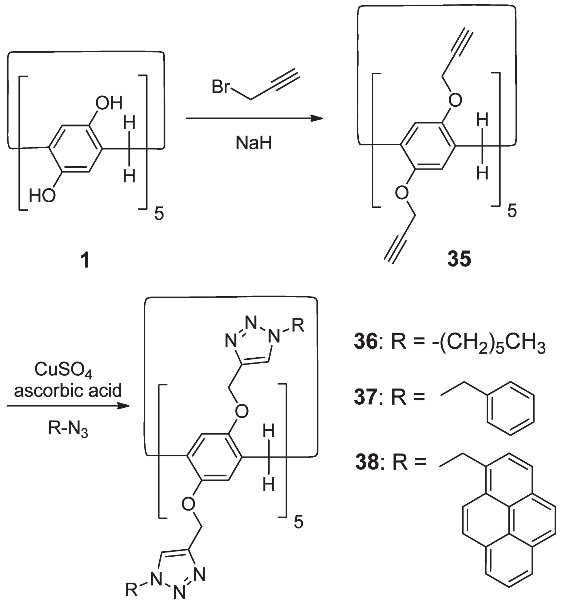
In addition to the mono-macrocyclic pillararene molecules, functionalization can also afford a pillararene dimer, which is composed of two pillararene units linked by a chain.[36−38] For this purpose, we have successfully synthesized pillar[5]arene dimer **39** linked by a single aliphatic chain (Scheme 13).[36] It is a necessary supplement to the pillararene family and opens a way for studies of pillararene dimers. With a different methodology, other pillar[5]arene dimers were synthesized by linking monodeprotected pillar[5]arene[39,40] with different dihalide derivatives.[37,38]

Besides the functionalization of pillararenes, other reactions of pillararenes have been examined, for example, the

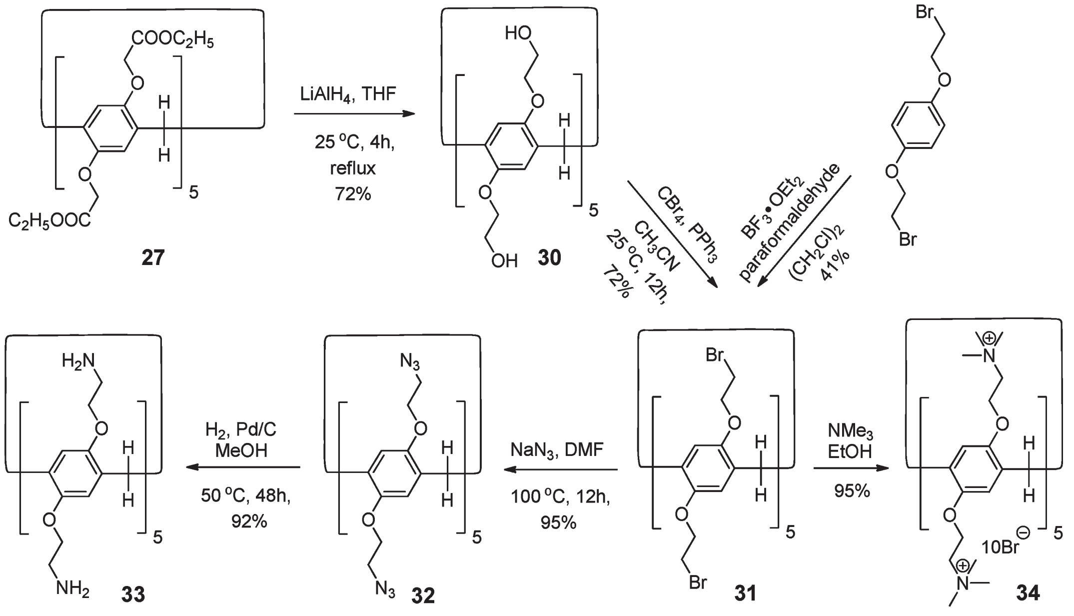
SCHEME 10. Synthesis of Water-Soluble Pillar[5]arene **29**



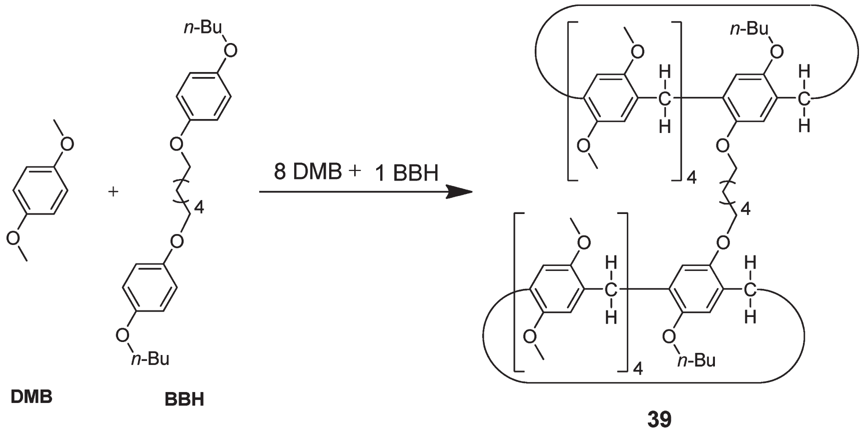
SCHEME 12. Synthesis of Pillar[5]arenes **36**−**38** by Click Reactions



SCHEME 11. Synthesis of Water-Soluble Pillar[5]arenes **33** and **34**



SCHEME 13. Synthesis of Pillar[5]arene Dimer **39**



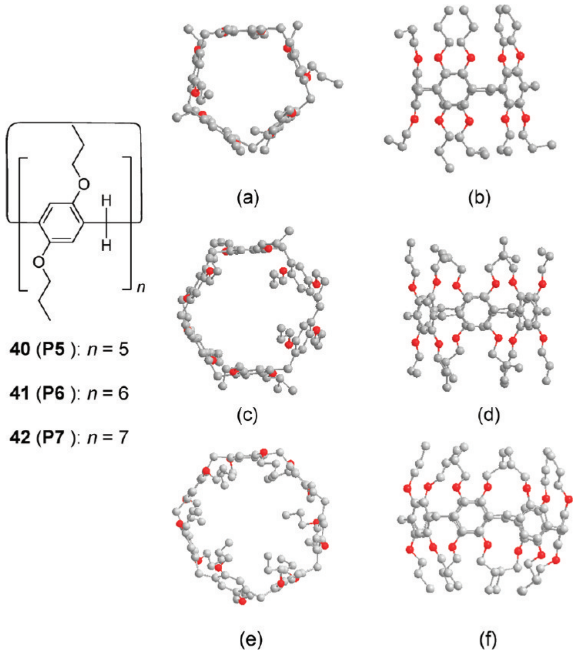
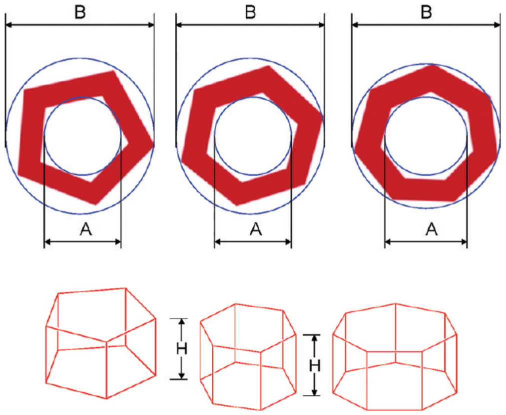


FIGURE 1. Crystal structures of **P5** (a, b) and **P6** (c, d) and the minimized energy structure of **P7** (e, f). Hydrogens were omitted for clarity.

TABLE 1. Calculated Structural Parameters for **40**, **41**, and **42** Based on van der Waals Radii of the Atoms



	A^c (Å)	B^c (Å)	H (Å)^d	V (Å^3)^e
P5 (**40**)^a	4.7	13.5	7.8	152
P6 (**41**)^a	6.7	15.2	7.8	302
P7 (**42**)^b	8.7	16.9	7.8	493

[a] Based on X-ray crystal structures reported here. [b] Based on the minimized energy model of **P7**. [c] Based on the diameter of the inscribed circle or the circumcircle of the regular pentagon, the regular hexagon, or the regular heptagon. [d] Based on the distance between the two oxygen atoms on the same benzene ring. [e] Based on the volume of the regular pentagonal pillar, hexagonal pillar, or heptagonal pillar.

oxidation of pillar[5]arene **4**.[27] When compound **4** was treated with $(NH_4)_2[Ce(NO_3)_6]$, the pillarquinone was produced, representing the first cyclooligomeric quinone.[41] Another example is the reaction of DMpillar[5]arene, **2**, with *N*-bromosuccinimide (NBS) in acetone to afford bis(4-bromo-2,5-dimethoxyphenyl)-methane. Nitration of **2** with nitric acid gave bis(4-nitro-2,5-dimethoxyphenyl)methane.[42]

Structures

Investigation of the structural features of novel hosts is extremely important because their structural features influence their host–guest binding properties. Being different from the basket-shaped structures of the *meta*-bridged calixarenes, pillar[5]arenes have unique, symmetrical architectures.[43] X-ray crystal structure of 1,4-dipropoxypillar-[5]arene (DPpillar[5]arene) **40** confirmed that **40** was a pentagon from the upper view and a pillar structure from the side view (Figure 1).[44] The average angle between the two bridging carbon–carbon bonds is 108°, which is very close to the normal bond angle of the sp^3 carbon atom, 109°28′. Therefore, DPpillar[5]arene is conformationally stable. The diameter of the internal cavity of DPpillar[5]arene was ~4.7 Å (Table 1), which is close

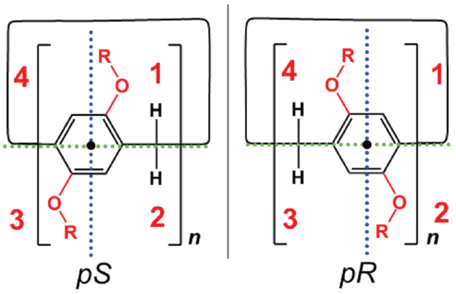


FIGURE 2. The *pS*- and *pR*-conformations of pillar[*n*]arenes.

to that of cucurbit[6]uril (~5.8 Å)[45] and α-cyclodextrin (~4.7 Å).[46]

As shown by the crystal structure of DPpillar[6]arene **41** reported by our group,[44] it has a hexagon-like cyclic structure and the diameter of its internal cavity is ~6.7 Å, analogous to cucurbit[7]uril (~7.3 Å)[45] and β-cyclodextrin (~6.0 Å).[46] We also obtained the DPpillar[7]arene **42**.[44] With the minimized energy structure of **42**, it is found that DPpillar[7]arene has a heptagonal pillar structure and the diameter of its internal cavity is ~8.7 Å, analogous to cucurbit[8]uril (~8.8 Å)[45] and γ-cyclodextrin (~7.5 Å).[46] Cucurbiturils and cyclodextrins are usually insoluble in organic solvents. Thus the organic solvent soluble pillararenes are good and necessary supplements to the corresponding cucurbiturils and cyclodextrins with similar cavity sizes.

Calixarenes have separable conformers due to the rotation of the phenolic unit. For pillararenes, which are also made up of phenolic units, conformational freedom still remains in their cavity. Up to now, all of the symmetric pillar[5]arenes have two equivalent most stable conformations (*pS* and *pR*) in their crystal structures (Figure 2). If they are conformationally fixed, the two conformers should be enantiomers. Therefore, investigation of the factors that affect the rotation of phenolic unit is not only helpful for understanding the interconversion between *pS* and *pR* forms[26] but also affords the route to control the rotational motion and subsequently obtain the isolation of the enantiomers.[47] On the other hand, if the hydroquinone unit was etherified with two different substituents, the pillararene should not only have conformational isomers but also constitutional isomers. This is another aspect to investigate.

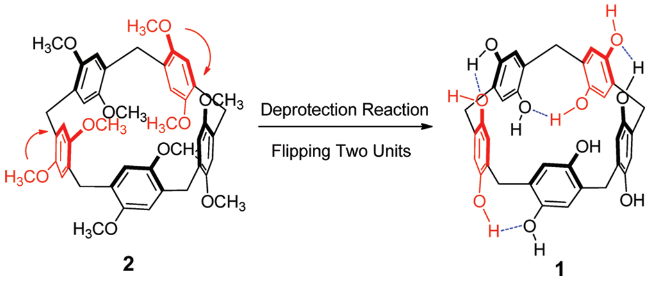


FIGURE 3. Conformations of DMpillar[5]arene, **2**, and pillar[5]arene, **1**, in the crystalline state. Blue dashed lines denote the intramolecular O−H···O hydrogen bonds.

The rotational behavior of pillar[5]arenes largely depends on the intramolecular H-bonding interactions, substituents, temperature, solvent, and addition of the guest. Being different from the conformation of DMpillar[5]arene **2**,[14] the flipping of two phenolic units in pillar[5]arene **1** was observed both in the solid state and in solution at low temperatures due to the intramolecular hydrogen bonds between OH groups and other interactions (Figure 3).[25,48] A similar phenomenon involving intramolecular hydrogen bond effects on the conformational characteristics is observed in cyclodextrins.[49]

Furthermore, when pillar[5]arene, **1**, interacted with dioctylviologen salt and formed the host−guest complex, the rotational movement was slow on the NMR time scale under −30 °C and almost prohibited under −60 °C.[48] In other words, the dioctylviologen salt acted as a "braking agent" for the rotation.

Modification of pillar[5]arene can also affect the conformations. The conformational characteristics of the pillar[5]arene derivatives with alkyl groups of different lengths were investigated by variable-temperature ^{1}H NMR measurements.[17] As their length increased, the alkyl substituents packed at the upper and lower rims and thus lowered the conformational freedom of the pillar[5]arenes.[17,18,32,35]

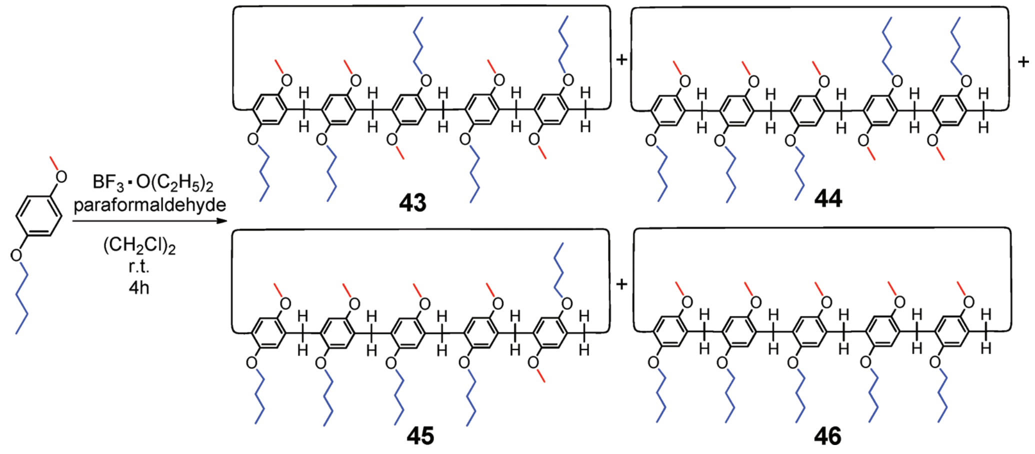
As stated above, there may exist constitutional isomers if the pillar[5]arenes have different substituents at the two rims. It was demonstrated by us that the four constitutional isomers **43**−**46** of an non-symmetric pillar[5]arene (BMpillar[5]arene) can be prepared and successfully separated by column chromatography (Scheme 14).[28,50]

Host−Guest Binding Properties

Pillar[*n*]arenes ($n = 5, 6, 7$) have some advantages compared with traditional hosts. First, they are highly symmetrical and rigid compared with crown ethers and calixarenes, and this affords their selective binding to guests. Second, they are easier to functionalize with different substituents on the benzene rings than cucurbiturils, which enables tuning of their host−guest binding properties.

Pillar[5]arene, **1**, without any modifications is composed of the electron-donor hydroquinone and has ionophores at both ends. Thus, it exhibits interesting host−guest properties

SCHEME 14. Synthesis of Four Constitutional Isomers **43**–**46** of BMpillar[5]arene



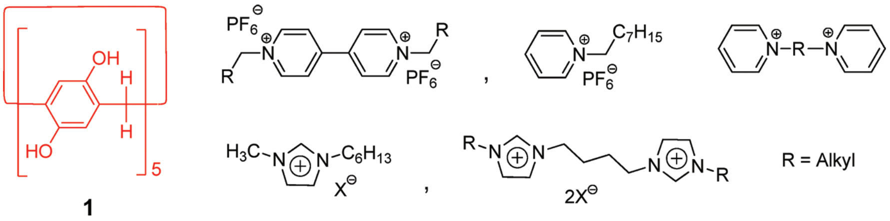


FIGURE 4. Structures of pillar[5]arene, **1**, and guest molecules.

with electron-accepting molecules such as viologen and pyridinium derivatives,[14,51,52] imidazolium cations,[53] and bis(imidazolium) dications[54] in organic media (Figure 4). The Ogoshi and Li groups have presented the binding behavior of paraquats and bis(pyridinium) derivatives by pillar[5]arene **1**.[14,51] Li et al. have investigated the binding modes and complexation stoichiometry for the two types of guests in detail and found that pillar[5]arene, **1**, formed 2:1 external host–guest complexes with *N*,*N*′-dialkyl-4,4′-bipyridiniums, while it forms 1:1 pseudorotaxane-type inclusion complexes with methylene [–$(CH_2)_n$–]-linked bis(pyridinium) derivatives possessing appropriate chain lengths.

Some alkyl-substituted pillar[5]arenes exhibit host–guest properties similar to pillar[5]arene, **1**. Take BMpillar[5]arene, for example; four constitutional isomers of BMpillar[5]arene **43**–**46** were prepared by our group.[50] It is interesting that although the four isomers have the same equilateral pentagonal pillar cavity, they have different arrangements of substituents, which determine their different binding abilities with *n*-octyltrimethyl ammonium hexafluorophosphate to form a [2]pseudorotaxane. Ogoshi et al. used the similar trimethyl ammonium moiety to prepare the monofunctionalized pillar[5]arene **47**, which formed a self-inclusion complex in $CDCl_3$, whereas in acetone-d_6 dethreading of the guest moiety took place (Figure 5).[39]

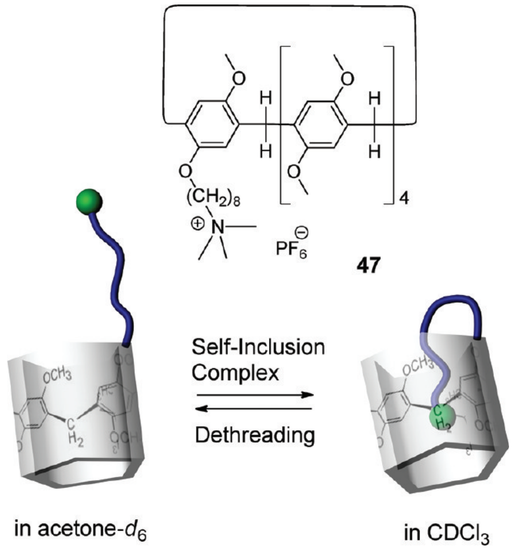


FIGURE 5. Solvent-dependent supramolecular structural change of **47**.

Along with charge transfer interactions occurring between the electron-rich cavities of the pillar[5]arenes and the encircled electron-deficient guest molecules, $C{-}H\cdots\pi$ interactions provide main driving forces for the formation of inclusion complexes, as confirmed by us during the preparation of copillar[5]arenes.[18] We found interestingly that an *n*-hexane molecule was symmetrically included in the cavity of homopillar[5]arene **6** or the copillar[5]arene **12** to form a pseudorotaxane, driven by multiple C$-$H$\cdots\pi$ interactions (Figure 6).

Mainly based on C$-$H$\cdots\pi$ interactions, uncharged aliphatic amines were encapsulated in the cavity of DMpillar[5]arene **2** recently. This binding motif was further explored in the preparation of a [2]rotaxane (Figure 7).[21] Furthermore, utilizing multiple C$-$H$\cdots\pi$ interactions and C$-$H$\cdots$O(N) hydrogen bonds, simple alkyl-substituted pillar[5]arenes also form stable interpenetrated complexes with neutral bis(imidazole) guests (Figure 8).[55]

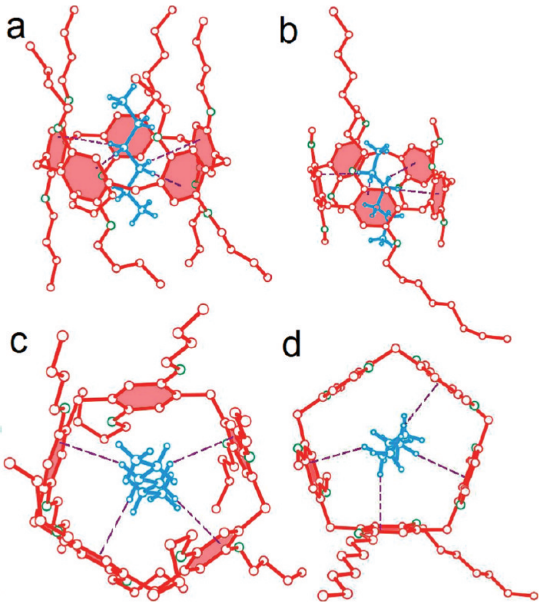


FIGURE 6. Views of the crystal structures of **6**$\supset$*n*-C_6H_{14} (a, c), and **12**$\supset$*n*-C_6H_{14} (b, d). Hydrogens on **6** and **12** were omitted for clarity; **6** and **12** are red, oxygen atoms are green, and *n*-hexane molecules are blue. The purple dotted lines indicate C$-$H$\cdots\pi$ interactions.

All of the above host$-$guest complexes are formed in organic media, which results from the poor solubility of pillar[5]arene in aqueous media and limits the development of host$-$guest chemistry of pillar[5]arene. In order to solve this problem, water-soluble pillar[5]arenes were prepared.[32$-$34,56] In 2010, Ogoshi et al. synthesized the water-soluble pillar[5]arene **29** containing 10 negatively charged carboxylate groups, which binds cationic viologen salts in water. Subsequently, the water-soluble pillar[5]arene **33** containing neutral amino groups was prepared by Hou et al.; it encapsulates linear diacids in neutral, alkaline, and acidic conditions.

Recently a cationic pillar[5]arene **34** bearing trimethylammonium groups on both two rims has been synthesized by us and revealed to bind sodium 1-octanesulfonate in aqueous media, forming a [2]pseudorataxane mainly driven by hydrophobic and electrostatic interactions (Figure 9).[34] With the negatively charged carboxylatopillar[5]arene **28**, the binding behavior of substituted 1,4-bis(pyridinium)-butane derivatives has been investigated in aqueous phosphate buffer solution, and in some cases [2]pseudorotaxanes with large association constants ($>10^5$ M^{-1}) were formed.[56]

The association constants, K_a (M^{-1}), of pillar[5]arene derivatives and their typical guests are listed in Table 2. It is shown that the K_a values of the pillar[5]arene hosts and the surveyed guests changed from 10^2 to 10^6 L/mol. Different driving forces between pillar[5]arenes and different guests such as charge transfer interactions, C$-$H$\cdots\pi$ interactions, hydrogen bonding interactions, and hydrophobic and

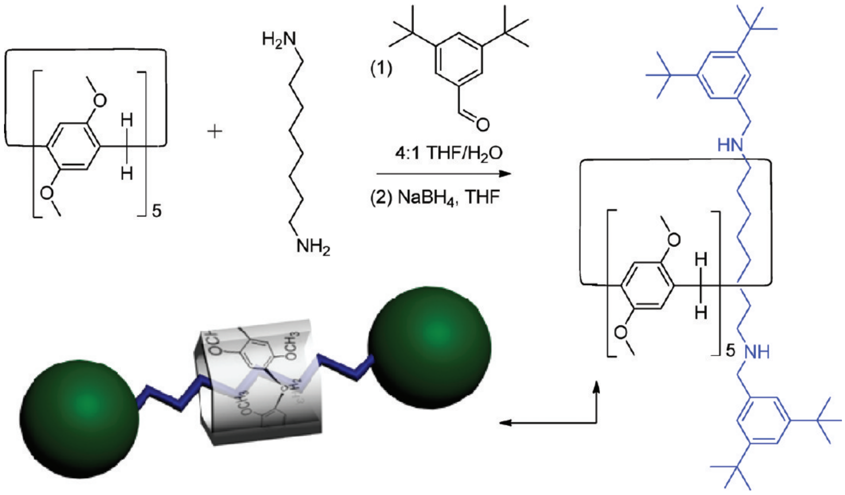


FIGURE 7. Formation of a [2]rotaxane with DMpillar[5]arene **2** as the ring component.

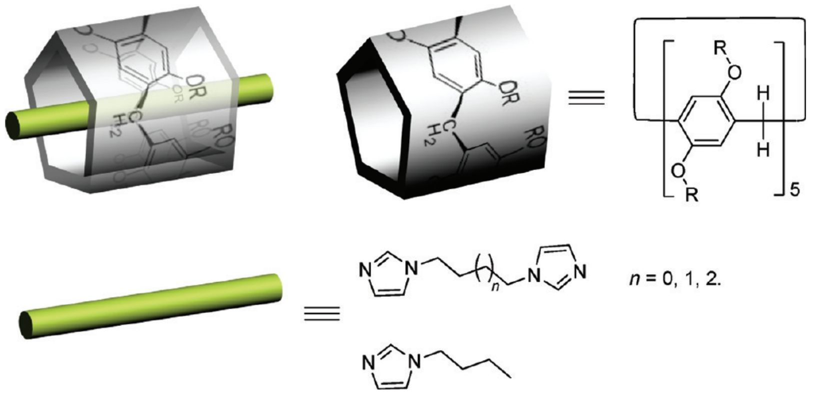


FIGURE 8. Representation of interpenetrated complexes between pillar[5]arenes and neutral guests.

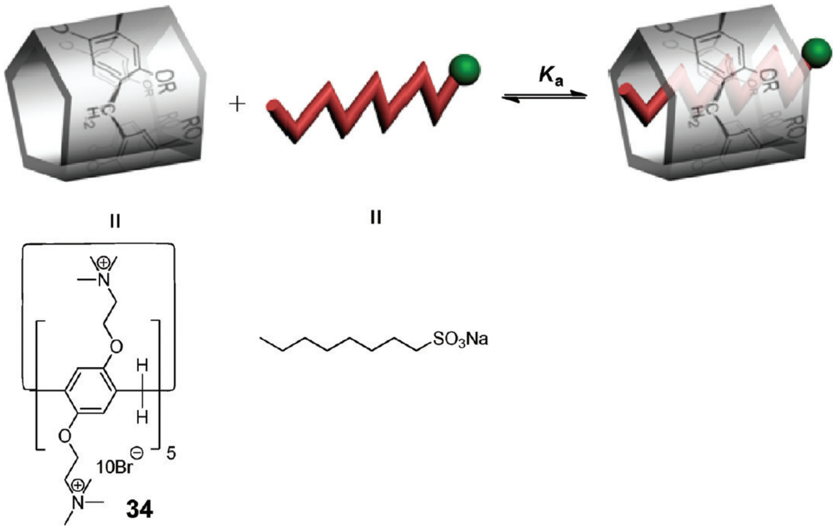


FIGURE 9. The formation of a host–guest complex from pillar[5]arene **34** and sodium 1-octanesulfonate in water.

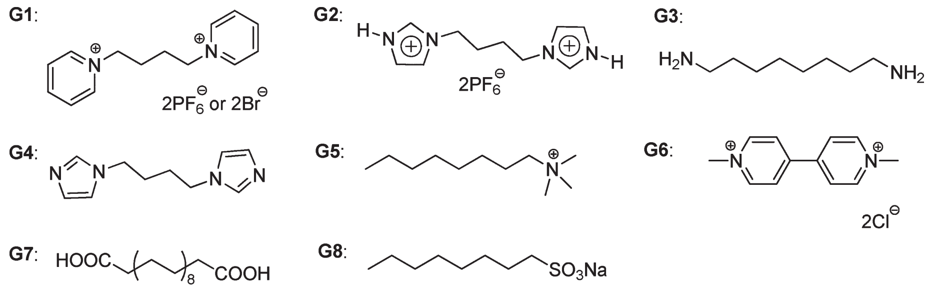
electrostatic interactions, affect the association affinity. In addition, the K_a values are also dependent on solvent, experimental method, and substituent groups on host or guest molecules. On the other hand, host–guest complexes with lower K_a values might not limit their potential applications.[57] For example, the supramolecular polymer and mirror image cyclic dimer can be self-assembled driven by C–H···π interactions, which will be described in the following section.

Although many guest molecules have been investigated for pillar[5]arenes, the host–guest chemistry of pillar[6]arenes and pillar[7]arenes has rarely been explored. We investigated the complexing properties of DIBpillar[6]arene[43] and DPpillar[6]arene[44] with *n*-octyltrimethylammonium hexafluorophosphate and found that both formed 1:1 complexes in chloroform, while DIBpillar[5]arene, DPpillar[5]arene, and DPpillar[7]arene showed no or weak complexation with the same guest due to their smaller or bigger cavity sizes.

Self-Assembly

The host–guest chemistry of pillar[5]arene with *n*-hexane can be used in the preparation of supramolecular polymers.[19] We designed and constructed linear supramolecular polymers based on easily available copillararene monomers **13**, driven by quadruple C–H···π interactions (Figure 10). It was demonstrated by a combination of various techniques that the formation of the supramolecular polymer is highly dependent on the temperature and monomer concentration. After this work, two new copillar[5]arenes, **14** and **15**, were prepared. We found that **14** forms a mirror image cyclic dimer in the solid state, while **15** forms linear supramolecular structures, *pS* and *pR* separated arrays, in the solid state (Figure 11). This research

TABLE 2. Association Constants (K_a) for 1:1 Inclusion Complexation of Pillar[5]arenes with Guests **G1**–**G8**



host–guest	K_a (M^{-1})	solvent	method
1–**G1**[51]	$(4.5 \pm 0.4) \times 10^2$	DMSO	UV/vis experiments
1–**G2**[54]	$(3.1 \pm 0.5) \times 10^3$	1:1 $(CD_3)_2CO/CDCl_3$	^1H NMR experiments
2–**G3**[21]	70 ± 10	$CDCl_3$	^1H NMR titration
2–**G3**[21]	$(3.6 \pm 0.3) \times 10^4$	1:1 $MeCN/H_2O$	fluorescence experiments
4–**G4**[55]	$(2.0 \pm 0.4) \times 10^4$	$CDCl_3$	^1H NMR experiments
43–**G5**[50]	$(6.3 \pm 0.3) \times 10^3$	$CDCl_3$	^1H NMR titration
29–**G6**[32]	$(8.2 \pm 1.7) \times 10^4$	H_2O	fluorescence experiments
33–**G7**[33]	1.5×10^4	D_2O	^1H NMR titration
34–**G8**[34]	$(1.3 \pm 0.9) \times 10^4$	D_2O	^1H NMR titration
28–**G1**[56]	$(1.1 \pm 0.2) \times 10^6$	aqueous phosphate buffer solution	fluorescence experiments

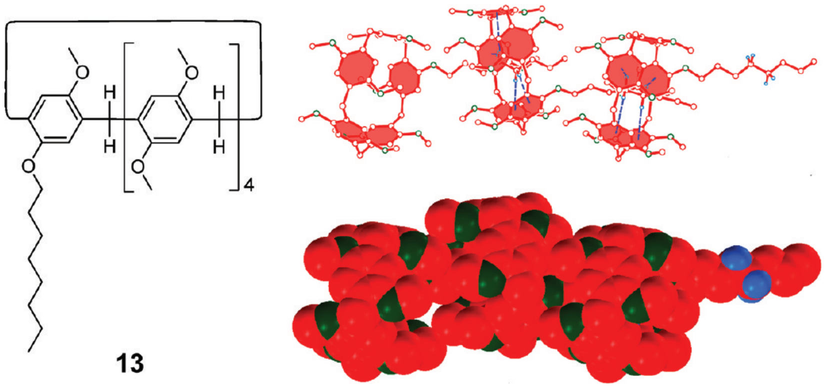


FIGURE 10. Structure of copillar[5]arene **13** and two views of the linear supramolecular polymers in the solid state.

provides a facile approach to control the self-assembly mode of self-complementary copillar[5]arene monomers between cyclic dimers and linear supramolecular polymers. In addition, a self-complexing copillar[5]arene **20** was reported recently.[23]

Based on the interactions between pillar[5]arene, **1**, and viologen units, new polypseudorotaxanes and polyrotaxanes composed of pillar[5]arene, **1**, and viologen polymer were successfully prepared with extremely high yields by capping the chain ends with adamantyl moieties (Figure 12).[58,59] Besides its electron-donating property, pillar[5]arene **1** also possesses reducing ability, which was used to fabricate polyaniline-based polypseudorotaxanes.[60]

A new type of organic nanotubes has been assembled from pillar[5]arenes **1** and **27** in the solid state.[61] The water in the nanotubes of **27** offer selective proton conductance. Subsequently, a new class of artificial transmembrane proton channels from mono- and dimeric pillar[5]arene derivatives **27** and **48** have been developed by Hou and coworkers.[62] The new channels conduct protons through water in the pillar[5]arene backbones, the first examples of synthetic water-wire-based proton channels (Figure 13).

Recently, based on monofunctionalized pillar[5]arene **19**, a polymacrocycle that can self-assemble into a dynamic, smart clicked surface was prepared.[22] This assembly can switch between vesicles and solid particles through exposure to visible and UV light. This means

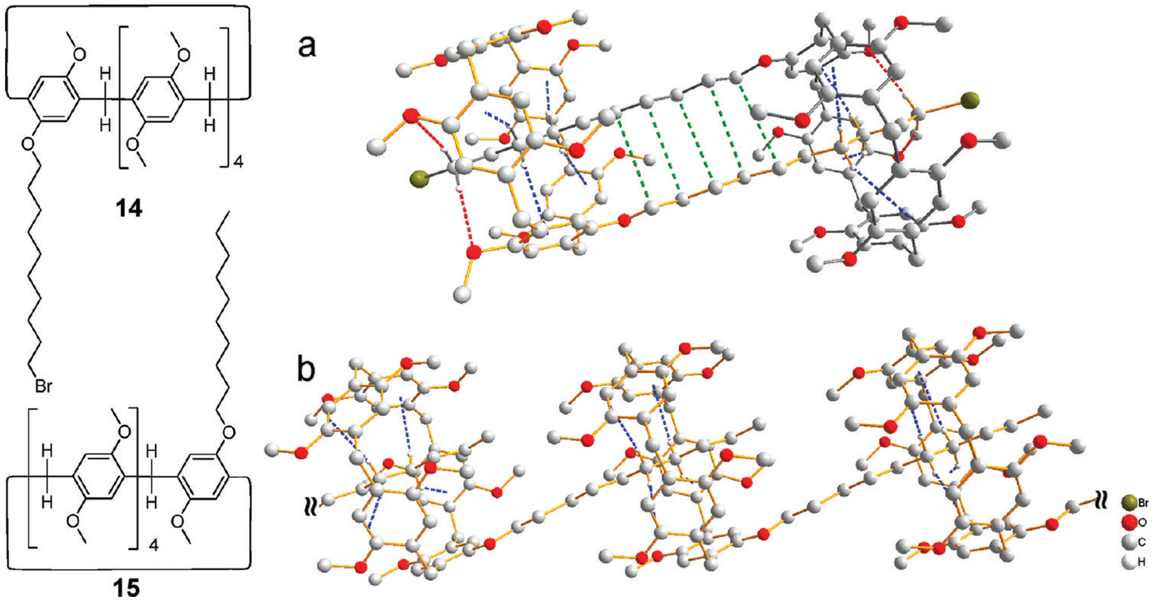


FIGURE 11. Ball-and-stick views of a mirror image cyclic dimer (a) from **14** and a *pS*-supramolecular polymer (b) from **15** in the solid state. Hydrogen atoms related to the C−H···π interactions and C−H···O interactions are included.

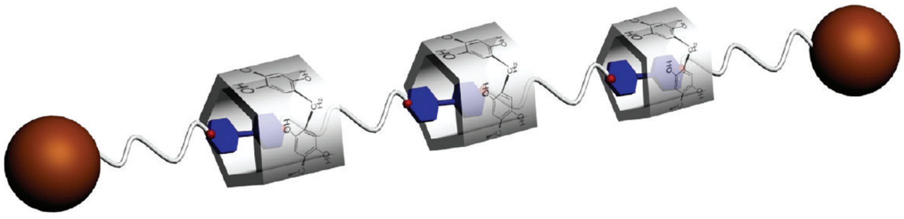


FIGURE 12. A pillar[5]arene-based polyrotaxane.

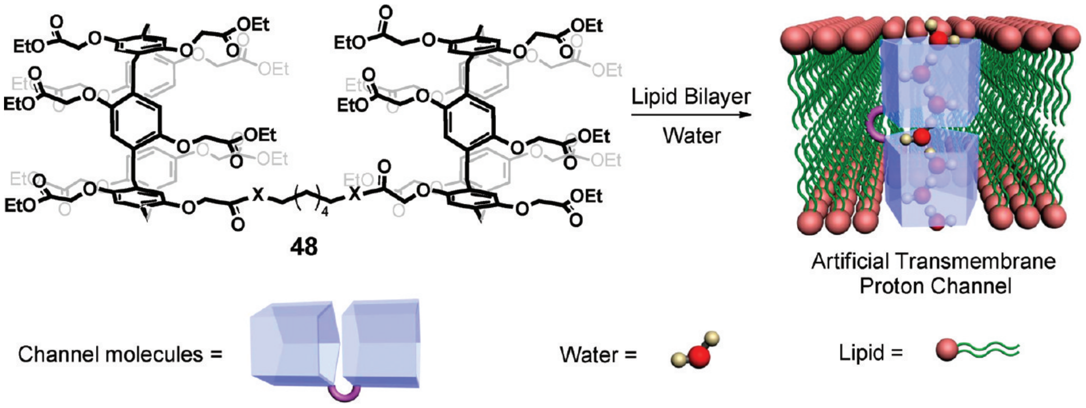


FIGURE 13. Structure of **48** and the artificial transmembrane proton channel.

that photoresponsive pillararenes have potential applications in UV sensors and functional materials.

Conclusions and Perspectives

As novel macrocyclic host molecules in supramolecular chemistry, pillararenes have attracted a remarkable level of attention during the past few years. Since the discovery of convenient and practical methods for the syntheses of pillar[5]arenes, studies on their modification and development of the functions have been expanded. Thus a large number of diverse pillararenes are now readily available. The studies of pillararenes have focused not only on the shape and cavity sizes of the macrocycles but also on the rotation of the repeating units, which results in conformational isomers and also sometimes constitutional isomers. Furthermore, the applications of pillararenes in host–guest complexation with electron-deficient or neutral molecules and their self-assembly properties have been explored. These studies have not only afforded the basis and evidence for understanding this new generation of macrocycles but also provided new opportunities and challenges for further investigation as the chemistry of pillararenes is just in its infancy. For pillar[5]arenes, facile synthetic strategies provide powerful tools to prepare numerous diverse functionalized pillar[5]arene derivatives and develop their potential applications in fabrication of molecular machines and devices and more sophisticated supramolecular architectures. On the other hand, discovery of new synthetic methodologies for pillar[6]arenes and pillar[7]arenes to improve their yields and thus development of their host–guest chemistry and self-assembly properties can also be anticipated in the future. Last but not least, exploration of new members of pillararenes family such as pillar[8]arenes and expansion of their potential applications in supramolecular chemistry are also required in further investigation.

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FOOTNOTES

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The authors declare no competing financial interest.

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