

Piling Up Pillar[5]arenes To Self-Assemble Nanotubes

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Dedicated to Prof. Virgil Percec on the occasion of his 70th birthday

Abstract: New liquid-crystalline pillar[5]arene derivatives have been prepared by grafting first-generation Percec-type poly(benzylether) dendrons onto the macrocyclic scaffold. The molecules adopt a disc-shaped structure perfectly suited for self-organization into a columnar liquid-crystalline phase. In this way, the pillar[5]arene cores are piled up, thus forming a nanotubular wire encased within a shell of peripheral dendrons. The capability of pillar[5]arenes to form inclusion complexes has been also exploited. Specifically, detailed binding studies have been carried out in solution with 1,6-dicyanohexane as the guest. Inclusion complexes have also been prepared in the solid state. Supramolecular organization into the Col_h mesophase has been deduced from X-ray diffraction data and found to be similar to that observed within the crystal lattice of a model inclusion complex prepared from 1,4-dimethoxypillar[5]arene and 1,6-dicyanohexane.

Pillar[5]arenes are *para*-cyclophane derivatives composed of five 1,4-disubstituted hydroquinone subunits connected by methylene bridges in their 2- and 5-positions.^[1,2] Since the first report on their one-step synthesis in 2008 by Ogoshi et al.,^[3] pillar[5]arenes have been used for many applications in the field of supramolecular chemistry.^[4-7] Owing to their cylindrical

structure, pillar[5]arenes have also been proposed as candidates to generate covalently linked tubular structures analogous to carbon nanotubes.^[8] In this respect, Stoddart and co-workers prepared oligomers by condensation of a pillar[5]arene AB monomer.^[8] As a result of the rigid mode of connection, the oligomeric products resemble tubular nanostructures.^[8] Moreover, the self-assembly of pillar[5]arene derivatives into tubular structures has also been observed in the solid state and in organogels through the occurrence of intermolecular hydrogen-bonding.^[9-11] As part of this research, we became interested in the preparation of pillar[5]arene derivatives having the appropriate shape for the self-organization into columnar liquid-crystalline phases. Whereas supramolecular lamellar organizations have been reported for liquid-crystalline pillar[5]arene derivatives,^[12-14] the self-organization of pillar[5]arene derivatives into tubular nanostructures within a columnar phase has, to our knowledge, not been achieved to date. A major problem associated with the design of columnar pillar[5]arene liquid-crystalline derivatives is related to the perpendicular orientation of their aromatic rings with respect to the plane of the macrocycle. Indeed, this orientation prevents the occurrence of intramolecular π - π interactions that could promote self-organization into columns, as observed for macrocyclic systems typically used for the design of columnar liquid crystals.^[15-18] To solve this problem, the pillar[5]arene core has to be functionalized with peripheral subunits programmed to promote their self-organization into a columnar liquid-crystalline material through appropriate hierarchical information transfer. In this respect, we propose to functionalize pillar[5]arene building blocks with Percec-type poly(benzylether) dendrons.^[19-21] We anticipate that the chemical information stored in the individual dendrons will force the compounds to adopt an appropriate conformation to mediate the self-organization of pillar[5]arene nanotubes within a columnar mesophase.

A first synthetic approach for the grafting of peripheral poly(benzylether) dendrons onto the pillar[5]arene scaffold was based on the acylation of decabromide **1**^[12] with carboxylates (Scheme 1). Treatment of **1** with an excess of *p*-dodecyloxybenzoic acid (**2**; 12 equiv) and K₂CO₃ (24 equiv) in DMF at 80 °C for 96 h gave compound **3** in 80% yield. The functionalization of pillar[5]arene **1** with dendron **4**^[22] was then performed under the same conditions. After workup and purification, compound **5** was obtained in 57% yield. A second series of compounds was prepared from decaazide **8** (Scheme 1). Compound **8** was obtained by reaction of decabromide **1** with sodium azide in DMF at room temperature, as described previ-

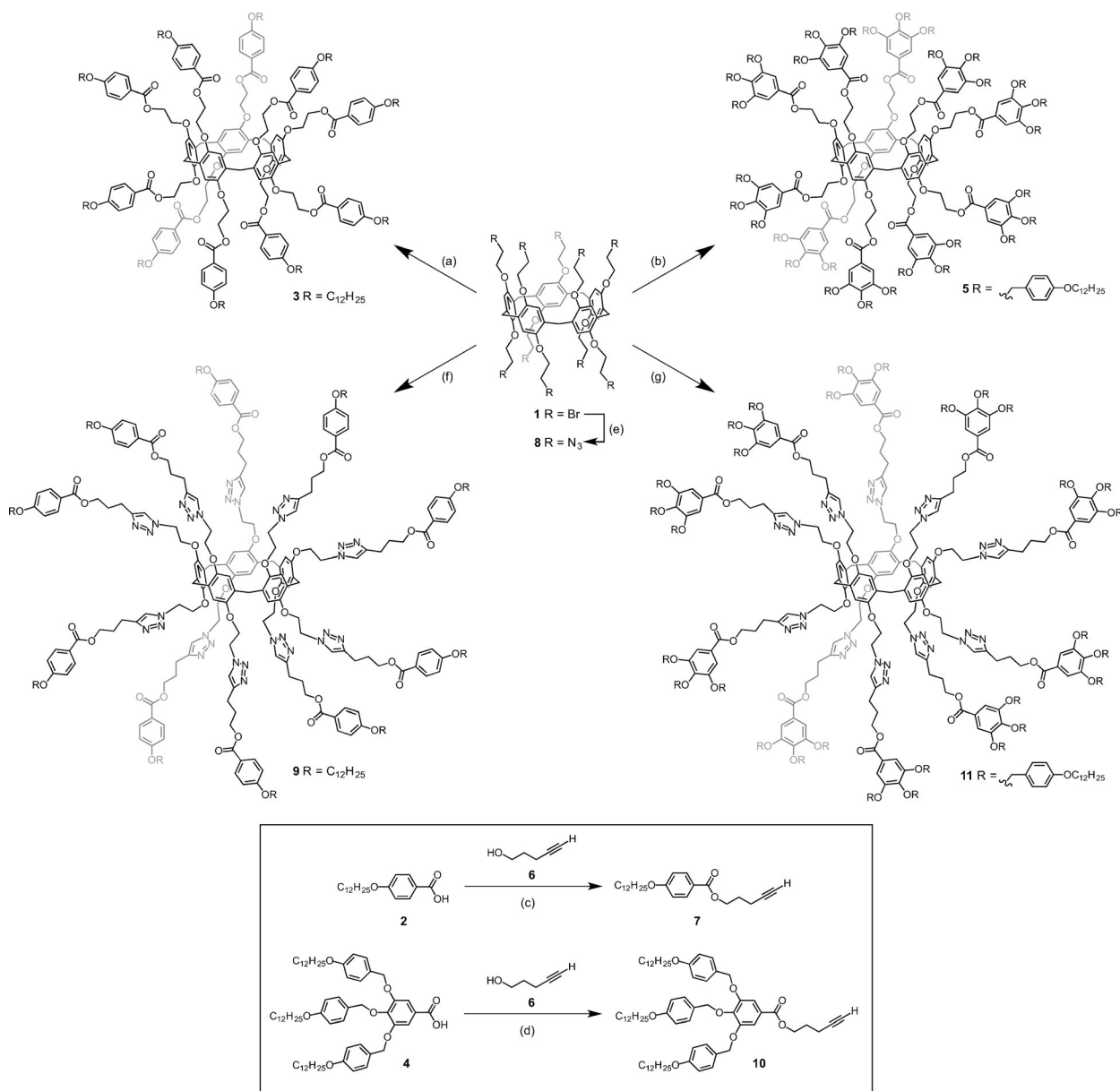
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Scheme 1. Preparation of the liquid-crystalline pillar[5]arene derivatives. Reagents and conditions: a) **1**, **2**, K_2CO_3 , DMF, $80^\circ C$ (80%); b) **1**, **4**, K_2CO_3 , DMF, $80^\circ C$ (57%); c) EDC, DPTS, CH_2Cl_2 , 0 to $25^\circ C$ (93%); d) EDC, DPTS, CH_2Cl_2 , 0 to $25^\circ C$ (81%); e) NaN_3 , DMF, $25^\circ C$ (95%); f) **7**, **8**, $CuSO_4 \cdot 5H_2O$, sodium ascorbate, CH_2Cl_2 , H_2O , $25^\circ C$ (85%); g) **8**, **10**, $CuSO_4 \cdot 5H_2O$, sodium ascorbate, CH_2Cl_2 , H_2O , $25^\circ C$ (76%).

ously.^[13] The *p*-dodecyloxybenzoate moiety was equipped with a terminal alkyne group to allow its grafting onto clickable pillar[5]arene building block **8**. This was achieved by the reaction of **2** with 4-pentyn-1-ol (**6**) under esterification conditions using *N*-(3-dimethylaminopropyl)-*N'*-ethylcarbodiimide hydrochloride (EDC) and 4-(dimethylamino)pyridinium *p*-toluenesulfonate (DPTS). Compound **7** was thus obtained in 93% yield. The functionalization of pillar[5]arene **8** with **7** was performed under the typical Cu-catalyzed azide-alkyne cycloaddition (CuAAC) conditions reported by Sharpless^[23] ($CuSO_4 \cdot 5H_2O$ /sodium ascorbate/ CH_2Cl_2/H_2O). After purification by column chromatography on SiO_2 , compound **9** was isolated in 85% yield. Compound **11** was prepared by following the same synthetic strategy. Esterification of carboxylic acid **6**

afforded clickable dendron **10** in 81% yield. Reaction of **8** with an excess of **10** in the presence of $CuSO_4 \cdot 5H_2O$ and sodium ascorbate gave dendronized pillar[5]arene **11** in 76% yield. The structure and purity of compounds **3**, **5**, **9**, and **11** were confirmed by IR, 1H and ^{13}C NMR spectroscopies, mass spectrometry, and elemental analysis (see the Supporting Information).

Pillar[5]arenes exhibit interesting host-guest properties with electron-accepting molecules but also with simple alkyl-substituted guests.^[4-7] Thus, we became interested in preparing inclusion complexes from pillar[5]arene **3**, **5**, **9** and **11** (Scheme 1) in order to investigate the impact of guest incorporation. With this in mind, we selected 1,6-dicyanohexane as a guest molecule.^[24] In the solid state, dipole-dipole interactions are often observed between nitrile moieties of neighbor-

ing molecules oriented in an antiparallel fashion. This effect plays an important role in the supramolecular organization of liquid-crystalline nitrile derivatives, cyanobiphenyl or cyanoterphenyl derivatives being emblematic examples.^[25] In the case of inclusion complexes obtained from 1,6-dicyanohexane and pillar[5]arene derivatives **3**, **5**, **9** and **11** (see the Supporting Information), one may anticipate that the CN groups of neighboring inclusion complexes will give rise to intermolecular dipole–dipole interactions within the columnar stacks and thus stabilize the supramolecular organization. A model inclusion complex resulting from the association of 1,4-dimethoxypillar[5]arene^[3] (**12**) and 1,6-dicyanohexane (**13**) was also investigated. In this particular case, crystals suitable for X-ray crystal-structure analysis were obtained by slow diffusion of *n*-hexane into a CH₂Cl₂ solution of an equimolar mixture of **12** and **13**.^[26] The structure of the resultant complex [**13**⊂**12**] is shown in Figure 1.

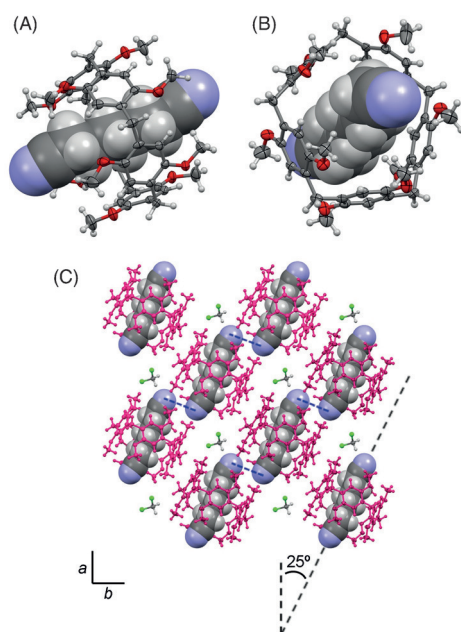


Figure 1. ORTEP plot of the X-ray crystal structure of [**13**⊂**12**] (thermal ellipsoids are shown at 50% probability level; N: blue, O: red, C: gray). For clarity, the 1,6-dicyanohexane guest is represented as a space-filling model and the cocrystallized CH₂Cl₂ molecules are omitted. A) Side view; B) top view; C) stacking within the [**13**⊂**12**](CH₂Cl₂) lattice (view down the crystallographic *c* axis).

Interestingly, supramolecular complex [**13**⊂**12**] crystallized as a conglomerate in the chiral orthorhombic space group C22₁. In other words, only one enantiomer of the pillar[5]arene macrocycle is present in the crystal lattice. Observation of the crystal lattice down the crystallographic *c* axis revealed that the [**13**⊂**12**] supramolecules are tilted by about 25° with respect to the crystallographic *a* axis and form parallel columns separated by CH₂Cl₂ molecules. Interestingly, nitrile groups of neighboring [**13**⊂**12**] supramolecules adopt an antiparallel orientation within these columns and their N atoms are separated by 5.159 Å (blue dashed line in Figure 1). Actually, the [**13**⊂**12**]

ensembles are self-organized in infinite supramolecular polymeric columns through dipole–dipole interactions between the nitrile functions of their 1,6-dicyanohexane subunits.

The liquid-crystalline and thermal properties of compounds **3**, **5**, **9**, and **11**, as well as supramolecular complexes [**13**⊂**3**], [**13**⊂**5**], [**13**⊂**9**] and [**13**⊂**11**], were investigated by polarized optical microscopy (POM), differential scanning calorimetry (DSC), and powder X-ray diffraction (XRD). Their thermal properties are collected in Table 1.

Table 1. Thermal properties deduced from POM and DSC investigations of the pillar[5]arene derivatives (**3**, **5**, **9**, and **11**) and the corresponding inclusion complexes ([**13**⊂**3**], [**13**⊂**5**], [**13**⊂**9**], and [**13**⊂**11**]).

Compound	Phase transition ^[a]	<i>T</i> [°C]	Δ <i>H</i> [kJ mol ⁻¹]
3	Cr→I	42	24.8
5	Col _h →I	130	17.7
9	<i>T</i> _g	44	
11	SmA→I	95	6.3
	Col _h →I	136	9.9
[13 ⊂ 3]	<i>T</i> _g ^[b]	50	
[13 ⊂ 5]	Col _h →I	123	21.9
[13 ⊂ 9]	<i>T</i> _g ^[b]	50	
[13 ⊂ 11]	Col _h →I	128	10.3

[a] Cr = crystalline solid; SmA = smectic A phase; Col_h = hexagonal columnar phase; I = isotropic liquid, *T*_g = glass transition temperature. Temperatures are given as the onset of the peak obtained during the second heating run. *T*_g values are determined during the first cooling run; approximate values. [b] The supramolecular complexes [**13**⊂**3**] and [**13**⊂**9**] are not thermally stable and irreversible phase separation was observed upon isotropization.

No liquid-crystalline behavior could be observed for **3**. The only event detected for this compound was the formation of an isotropic melt at 42 °C. In contrast, compound **9** gave rise to the formation of a liquid-crystalline phase that cleared at 95 °C. No typical texture could be observed by POM for compound **9**, even by annealing the sample for several hours near the isotropization temperature. However, the X-ray diffraction patterns recorded for **9** were typical of a smectic-type organization (see the Supporting Information). Compound **9** adopt a tubular shape suited for the self-organization into a layered phase. Such a behavior was already observed for previous liquid-crystalline pillar[5]arene derivatives.^[12–14] Mesomorphic properties were also observed for pillar[5]arene derivatives **5** and **11**. Whereas the clearing temperatures were evidenced by DSC in both cases, no glass transitions could be clearly observed. For both **5** and **11**, POM observations revealed the formation of columnar phases upon cooling the samples from the isotropic phase into the liquid-crystalline one (see the Supporting Information).

Supramolecular complexes [**13**⊂**3**] and [**13**⊂**9**] were not thermally stable and no liquid-crystalline behavior was detected for these compounds. In both cases, a clear phase separation was observed by POM as soon as the samples reached the liquid state. In contrast, inclusion complexes [**13**⊂**5**] and [**13**⊂**11**] were found to be thermally stable and no phase separation was observed, even on repeated heating–cooling cycles.

In both cases, DSC thermograms revealed a reversible transition from a liquid-crystalline phase into an isotropic liquid. It can be noted that the birefringent fluids of the supramolecular complexes [13C5] and [13C11] were more viscous when compared to those of **5** and **11**. Finally, the optical textures observed for [13C5] and [13C11] were characteristic of columnar phases (see the Supporting Information).

The X-ray patterns unambiguously confirmed that the mesophases of **5**, **11**, [13C5], and [13C11] are columnar hexagonal (Col_h) in nature. In all cases, three sharp maxima were observed in the small-angle region (Table 2). The reciprocal ratio of the

Compound	<i>a</i> [Å] ^[a]	<i>d</i> _{exp} [Å]	<i>d</i> _{cal} [Å]	<i>hkl</i>	<i>h</i> [Å] ^[b]
5	50.0	43.2	43.3	100	8.3
		25.3	25.0	110	
		21.5	21.7	200	
		4.45 ^[c]			
11	58.9	51.2	51.0	100	6.4
		29.4	29.4	110	
		25.3	25.5	200	
		4.4 ^[c]			
[13C5]	49.3	42.8	42.7	100	8.6
		24.7	24.65	110	
		21.2	21.3	200	
		4.4 ^[c]			
[13C11]	57.8	50.0	50.1	100	6.7
		29.0	28.9	110	
		25.0	25.0	200	
		4.4 ^[c]			

[a] Hexagonal lattice constant calculated from the observed spacing as $a = 2(d_{100} + 3^{1/2}d_{110} + 4^{1/2}d_{200})/(3\sqrt{3})$. [b] Calculated thickness of the molecular disk, assuming a density $\rho = 1 \text{ g cm}^{-3}$ [$h = 10 \times M / (6.023 \times (\sqrt{3}/2) \times a^2)$]; *M* = molecular mass. [c] Diffuse maximum.

three peaks is $1:\sqrt{3}:\sqrt{4}$, corresponding to the (1 0), (1 1) and (2 0) reflections of a two-dimensional hexagonal lattice of packed columns. Apart from these reflections, a broad diffuse halo is also detected in the large-angle region of the patterns, corresponding to the interferences between the molten hydrocarbon chains. The diffuse character of this scattering and the absence of other reflections confirm the liquid-crystalline nature of the mesophases. Importantly, the measured lattice parameter (*a*) follows the trend of the pillar[5]arene-dendron spacer length when going from **5** to **11**. Similar *a* values are also obtained when comparing the pillar[5]arene derivatives (**5** and **11**) with their inclusion complexes ([13C5] and [13C11], respectively). The measured lattice parameters (*a*) are consistent with the dimensions of the molecules deduced from molecular modeling studies (see the Supporting Information). As shown in Figure 2, one molecule forms an entire disk in which the central pillar[5]arene core is surrounded by 10 dendrons forming a ring with all 30 alkyl chains pointing out of the disc. Indeed, the discotic conformation adopted by the system re-

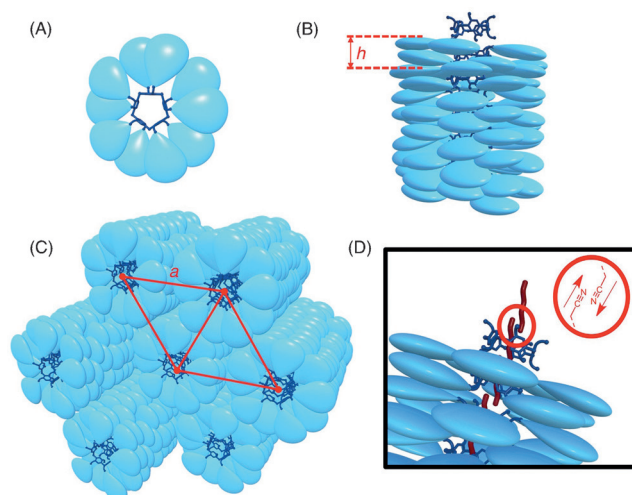


Figure 2. Schematic representations of A) compound **5** or **11** (dark blue: pillar[5]arene core, pale blue: peripheral dendrons); B) the columnar stacks of compound **5** or **11**; C) the supramolecular arrangement of compound **5** or **11** into the hexagonal columnar phase; D) the columnar stacks of the inclusion complexes [13C5] and [13C11] (dark red: 1,6-dicyanohexane guest).

sults from the self-assembling capabilities of the peripheral dendrons through the establishment of intramolecular inter-dendron π - π and van der Waals interactions.^[19–21] The dendronized pillar[5]arene derivatives form columns composed of stacked molecular disks (Figure 2A,B). The pillar[5]arene cores located at the center of the column are piled up, thus forming a nanotubular wire parallel to the column directive vector. Finally, these columnar assemblies are organized into a hexagonal array in the Col_h phase (Figure 2C). For all of the compounds, the molecular thicknesses along the column axis (*h*) were estimated on the basis of the X-ray data (Table 2). The *h* values estimated in the four cases are larger than those typically observed in classical disk-like systems and are consistent with the proposed model for the Col_h phase. The stacking distances *h* found for **5** and [13C5] are, however, significantly larger than those of **11** and [13C11]. In the case of **11** and [13C11], the linker connecting the dendron to the macrocyclic core is longer, thus introducing a higher conformational flexibility and thus the possibility of a flatter arrangement of the molecule. The estimated molecule thicknesses *h* are also slightly larger for [13C5] and [13C11] than for their respective free pillar[5]arenes **5** and **11**. At the same time, the lattice constants *a* measured for the inclusion complexes are slightly smaller. This effect results from the space demand of the 1,6-dicyanohexane guests located in the middle of the macrocycle (Figure 2D). In this way, the 1,6-dicyanohexane moieties contribute to making the complex thicker, and hence the lattice constant smaller, to preserve the density. This model for the supramolecular organization of [13C5] and [13C11] is similar to the infinite polymeric columns observed within the crystal lattice of [13C12]. Moreover, the existence of dipole-dipole interactions between neighboring guest molecules in the center of the columns should contribute to rigidify the supramolecular columns. This effect may explain the very high viscosity ob-

served for the birefringent fluids of inclusion complexes [13C5] and [13C11].

In conclusion, we have described the self-assembly of pillar[5]arene derivatives into tubular nanostructures within columnar phases. Interestingly, the formation of columnar assemblies occurs not only in the presence of a guest molecule, but also in the absence of a guest molecule, despite the generated free volume. This work therefore represents an important step towards preparation of a new class of organic nanotubes.

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Keywords: inclusion complexes · liquid crystals · pillar[5]arenes · self-assembly · supramolecular chemistry

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- [26] CCDC 1438988 ([13C12]) contains the supplementary crystallographic data for this paper. These data are provided free of charge by The Cambridge Crystallographic Data Centre.