Organic LETTERS

Letter

pubs.acs.org/OrgLett

Multilayered Inclusion Nanocycles of Anionic Spiroborates

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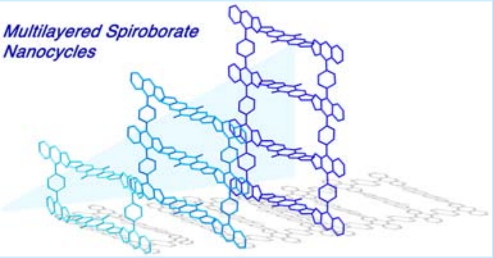
Supporting Information

ABSTRACT: Multilayered spiroborate nanocycles were prepared from tris- or tetrakis(dihydroxynaphthalene) and tetrahydroxyanthraquinone as pillar and crossbar units via the reversible formation of a spiroborate linkage. The four-layered spiroborate nanocycle recognized two cationic aromatic guests simultaneously and exhibited the ability to form a supramolecular one-dimensional array by combining with methyl viologen dimer as the ditopic guest.



Constant attention has been given to the development of nanometer-sized cyclophanes as building blocks for functional higher order structures.[1] Cyclic cationic oligopyridinium type cyclophanes, which have been continuously investigated by Stoddart and co-workers[2] and acknowledged as the representative of this class, have been applied to various supramolecular systems, such as molecular shuttles[3] or other mechanically bound macromolecules.[4] Sessler and co-workers reported the cationic cyclophane named "Texas-sized" molecular box and applied it to the construction of various mechanically interlocked systems.[5] As an example of electrically neutral cyclophanes, pillar[*n*]arenes have recently been developed by Ogoshi and co-workers, and their molecular recognition behavior has been well studied.[6,7] To further extend the chemistry of these cyclophanes, multiple analogues bearing various shapes and sizes were designed and prepared, and their molecular recognition behavior was precisely investigated. On the other hand, only a few examples of cyclophanes possessing plural cavities have been reported.[8,9] These compounds would exhibit multitopic molecular recognition and are therefore expected to play various roles in the construction of higher order nanostructures, such as supramolecular polymers and network structures, or other topologically fixed functional macromolecules.

Previously, we have reported the preparation of tris(spiroborate) cyclophanes from bis(dihydroxynaphthalene)s and boric acid in a self-organization manner.[10] These cyclic spiroborates are trianionic and well recognize such cationic guest compounds as $[Ir(tpy)_2]^{3+}$ (tpy; 2,2′:6′,2″-terpyridine) iteratively to form supramolecular polymers. More recently, we have demonstrated the construction of spiroborate nanocycles $\mathbf{1}^{4-}$ in which two kinds of bis(dihydroxyarene) components, 1,4-phenylenebis(1-(2,3-dihydroxynaphthalene)) and 2,3,6,7-tetrahydroxy-9,10-anthraquinone, were involved as pillar and crossbar units (Figure 1).[11] These nanocycles exhibited molecular recognition behavior toward cationic aromatic guests due to their anionic nature and shape persistence. These characteristics enable them to construct a nestable, ring@ring supramolecular structure by combination with cationic tetrapyridinium cyclophane. The association mode of the spiroborate nanocycles could be controlled by adjusting their sizes and shapes. On the basis of this background, we next planned to develop new spiroborate nanocycles bearing plural cavities, which are expected to exhibit molecular recognition behavior toward multiple guest cations. Herein we will discuss the preparation and structural analysis of multilayered spiroborate nanocycles.

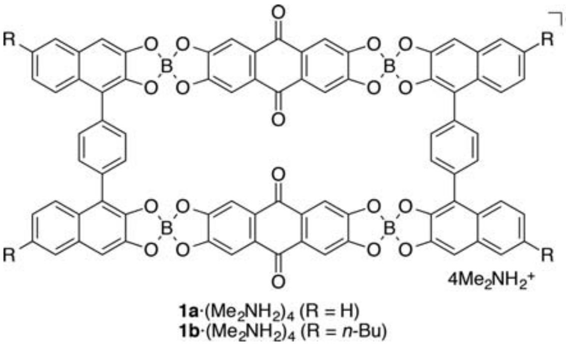


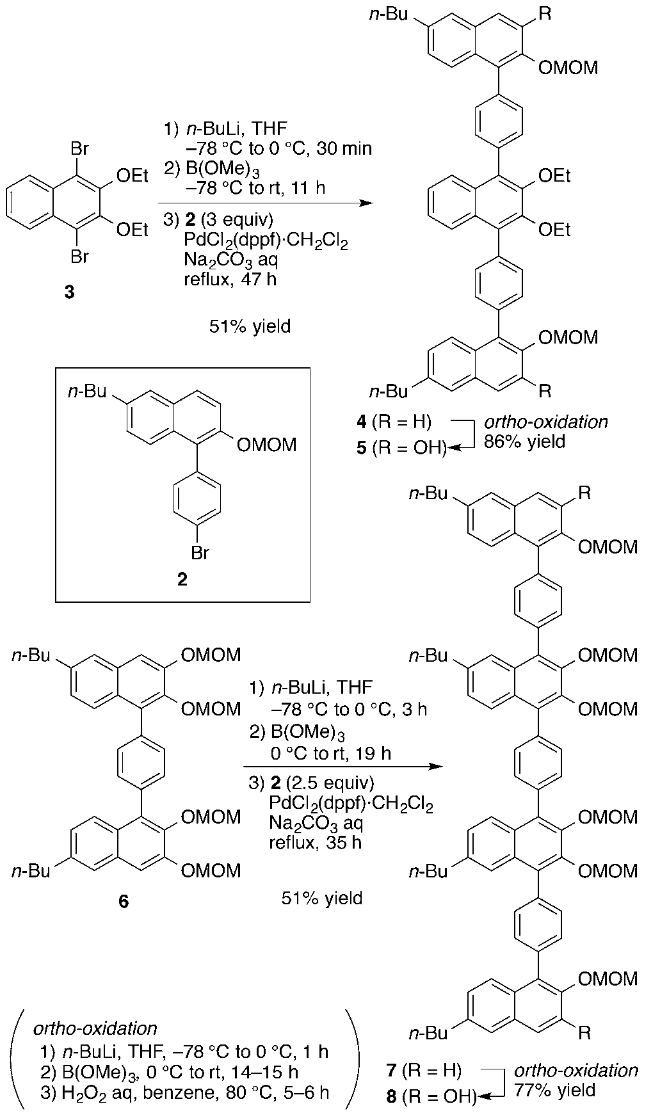
Figure 1. Chemical structure of $\mathbf{1}\cdot(Me_2NH_2)_4$.

In order to extend the nanocycles to the multilayered system, tris- and tetrakis(2,3-dioxynaphthalene)s **5** and **8** were newly designed as multidentate pillar unit precursors (Scheme 1). The

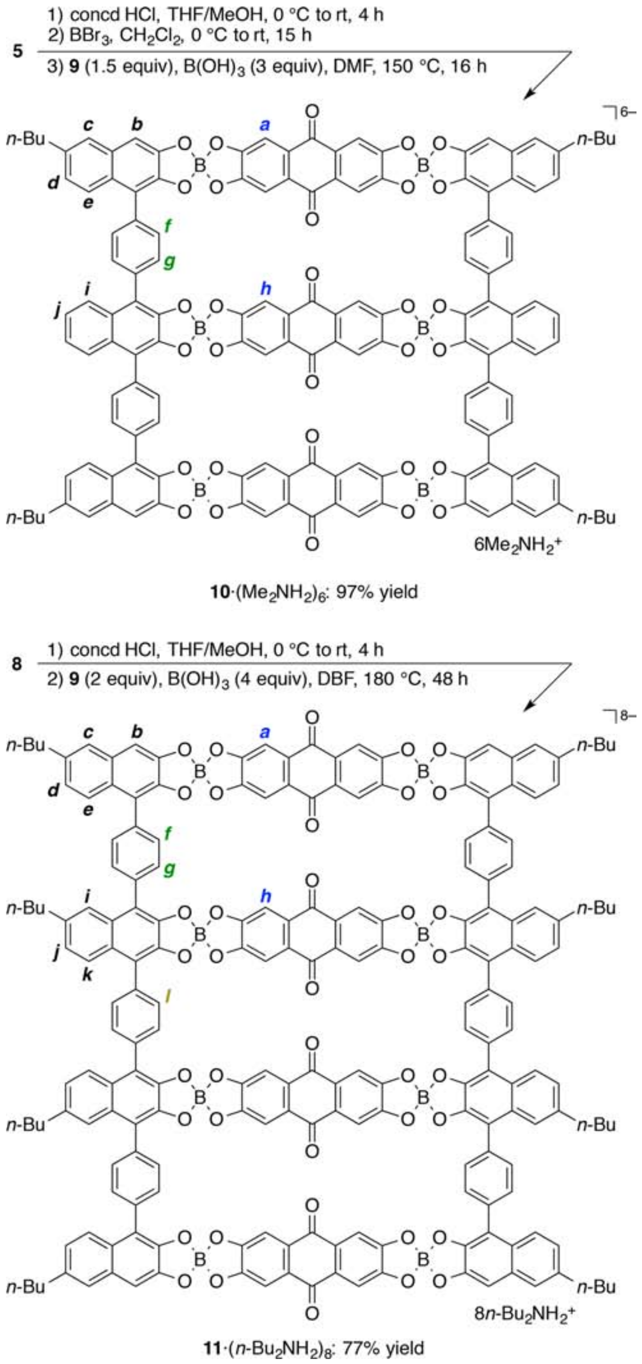
Received: April 4, 2015
Published: April 27, 2015

DOI: 10.1021/acs.orglett.5b00974
Org. Lett. 2015, 17, 2466−2469

Scheme 1



Scheme 2



preparation of **5** was carried out by the use of 1,4-dibromo-2,3-diethoxynaphthalene (**3**) as the starting material. One-pot diborylation and Suzuki–Miyaura coupling reaction with bromide **2** afforded tris(naphthalene) **4**. The introduction of hydroxyl groups at the 3-positions of both terminal naphthalene moieties gave **5**. In a similar manner, **8** could be obtained from phenylenebis(di(methoxymethoxy)naphthalene) **6** as the starting material. In this case, double ortho-lithiation was involved in the transformation and subsequent diborylation and cross-coupling with **2** gave tetrakis(naphthalene) **7**. Ortho-oxidation at the 3-positions of the terminal naphthalene moieties afforded **8**.

Construction of the multilayered spiroborate nanocycles was examined by the use of **5** and **8** as precursors of the pillar units (Scheme 2). Tris(dioxynaphthalene) **5** was previously deprotected by treating with BBr$_3$ and HCl, and then mixed with 1.5 equiv of 2,3,6,7-tetrahydroxy-9,10-anthraquinone (**9**) and 3 equiv of boric acid in DMF. After being stirred at 150 °C for 16 h, the reaction mixture almost converged into the sole product, **10**·(Me$_2$NH$_2$)$_6$, indicating that this 11-component reaction proceeded in a self-organization manner. On the other hand, the reaction of **8**, previously deprotected by HCl, with 2 equiv of **9** and 4 equiv of boric acid, did not lead to complete convergence even after heating at 180 °C for 48 h in *N*,*N*-di-*n*-butylformamide (DBF). After reprecipitation from DBF/Et$_2$O, the desired four-layered spiroborate nanocycle **11**·(*n*-Bu$_2$NH$_2$)$_8$ was obtained in 77% isolated yield.

The structures of these nanocycles were confirmed by ^{1}H NMR, MS, and finally X-ray crystallographic analysis (Figure 2).[12] According to their crystal structures, the distance between two adjacent anthraquinone planes on one side of the cavity of **10**$^{6-}$ was estimated to be 7.6 Å, similar to that of **1a**$^{4-}$. This indicated that slight deflection of the whole framework allowed the nanocycle to vary its cavity size over a certain range. This tendency was more obvious for **11**$^{8-}$, in which both its terminal cavities had a similar size to that of **10**$^{6-}$, whereas the size of the

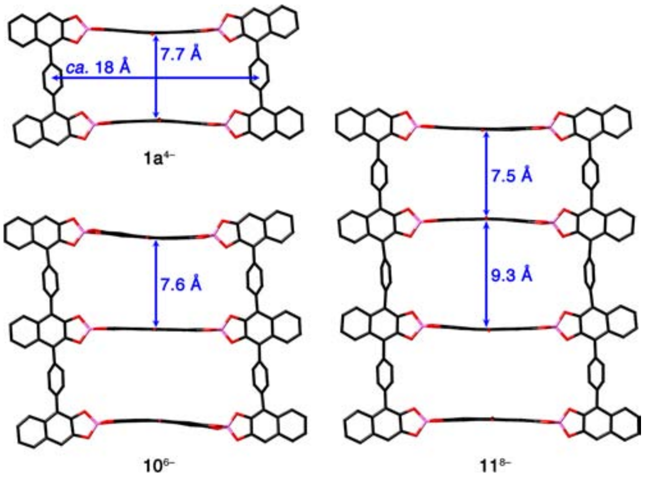


Figure 2. Crystal structures of spiroborate nanocycles **1a**·(TBA)$_4$, **10**·(TBA)$_6$, and **11**·(n-Bu$_2$NH$_2$)$_8$ (TBA: tetra(n-butylammonium). Hydrogen atoms, n-butyl groups on **10**$^{6-}$ and **11**$^{8-}$, counterions, and solvent molecules are omitted for clarity.

central cavity was found to be 9.3 Å, ca. 2 Å larger than that of the terminal cavities. These three cavities might exhibit different molecular recognition behavior to each other.

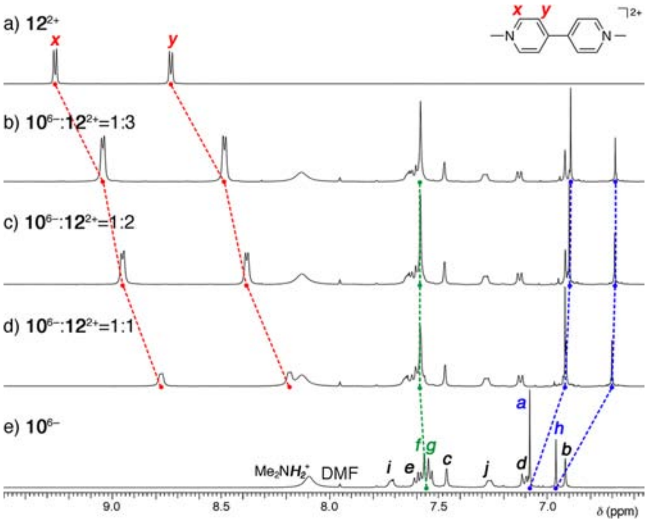


Figure 3. Partial ^{1}H NMR spectra (500 MHz, 25 °C in DMSO-d_6) of (a) **12**·(BF$_4$)$_2$ (1 mM), (b) **12**·(BF$_4$)$_2$ (3 mM) and **10**·(Me$_2$NH$_2$)$_6$ (1 mM), (c) **12**·(BF$_4$)$_2$ (2 mM) and **10**·(Me$_2$NH$_2$)$_6$ (1 mM), (d) **12**·(BF$_4$)$_2$ (1 mM) and **10**·(Me$_2$NH$_2$)$_6$ (1 mM), and (e) **10**·(Me$_2$NH$_2$)$_6$ (1 mM).

The molecular recognition mode of the multilayered spiroborate nanocycles was evaluated by using methyl viologen (**12**·(BF$_4$)$_2$) as the cationic aromatic guest. From the ^{1}H NMR spectrum of the mixed solution of the three-layered nanocycle **10**·(Me$_2$NH$_2$)$_6$ and **12**·(BF$_4$)$_2$ in DMSO-d_6, it was found that all the proton signals of **12**$^{2+}$ were largely shifted upfield (Figure 3). For **10**$^{6-}$, the signals assigned to the anthraquinone protons (a and h) were significantly shifted upfield, whereas the proton signals of the phenylene linkages (f and g) exhibited a downfield shift. These shifts indicated that the molecular recognition occurred inside the cavity, not just electrostatic association outside the spiroborate nanocycle.[11] The association ratio of **10**$^{6-}$ and **12**$^{2+}$ was determined to be 1:1 by the Job plot (Figure S1, Supporting Information). The two cavities of **10**$^{6-}$ were not identical to each other in the recognition of **12**$^{2+}$ probably because of the induced fit of one cavity toward **12**$^{2+}$ and the consequent negative allosterism upon recognition of the second **12**$^{2+}$.

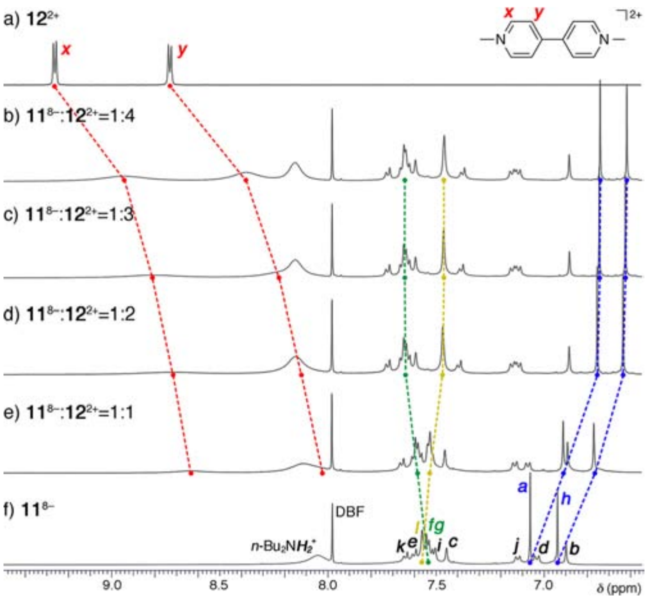


Figure 4. Partial ^{1}H NMR spectra (500 MHz, 25 °C in DMSO-d_6) of (a) **12**·(BF$_4$)$_2$ (0.5 mM), (b) **12**·(BF$_4$)$_2$ (2 mM) and **11**·(n-Bu$_2$NH$_2$)$_8$ (0.5 mM), (c) **12**·(BF$_4$)$_2$ (1.5 mM) and **11**·(n-Bu$_2$NH$_2$)$_8$ (0.5 mM), (d) **12**·(BF$_4$)$_2$ (1 mM) and **11**·(n-Bu$_2$NH$_2$)$_8$ (0.5 mM), (e) **12**·(BF$_4$)$_2$ (0.5 mM) and **11**·(n-Bu$_2$NH$_2$)$_8$ (0.5 mM), and (f) **11**·(n-Bu$_2$NH$_2$)$_8$ (0.5 mM).

The molecular recognition behavior of four-layered nanocycle **11**·(n-Bu$_2$NH$_2$)$_8$ was also examined. Significant upfield shifts were again observed for the proton signals of **12**$^{2+}$ and the two anthraquinone proton signals of **11**$^{8-}$ (a and h) in their mixed solutions (Figure 4). The proton signals assigned to both ends of the phenylene linkages of **11**$^{8-}$ (f and g) were slightly shifted downfield, whereas a small upfield shift was observed for the signals of the central phenylene linkage (l). This implies that the terminal cavities and the central cavity exhibited different molecular recognition behavior to each other. The Job plot showed that the association ratio of **11**$^{8-}$ and **12**$^{2+}$ was 1:2 (Figure S2, Supporting Information). On the basis of these results, it could be concluded that two **12**$^{2+}$ molecules were simultaneously recognized at the terminal cavities of **11**$^{8-}$, whereas the central cavity was kept vacant. As was shown in the case of **10**$^{6-}$, the incorporation of **12**$^{2+}$ into one cavity induced a negative allosteric effect on the adjacent cavity due to the slight mismatch between the sizes of the cavities and the guest.

The ditopic molecular recognition mode of **11**$^{8-}$ could be applied to the construction of a supramolecular one-dimensional array as a higher order architecture. In order to realize iterative molecular recognition, we employed methyl viologen dimer **13**·(PF$_6$)$_4$ bearing an octamethylene linkage between the two pyridinium nitrogens (Figure 5a).[13] Dynamic light scattering (DLS, 1.0 mg/mL in DMF) analysis revealed that the mixture of **1b**·(Me$_2$NH$_2$)$_4$ and **12**·(BF$_4$)$_2$ afforded the hydrodynamic diameter (D_H) of 1.8 nm in DMF, and similar D_Hs were observed in the DMF solutions of **1b**·(Me$_2$NH$_2$)$_4$ + **13**·(PF$_6$)$_4$ and **11**·(n-Bu$_2$NH$_2$)$_8$ + **12**·(BF$_4$)$_2$ (3.1 and 2.5 nm,

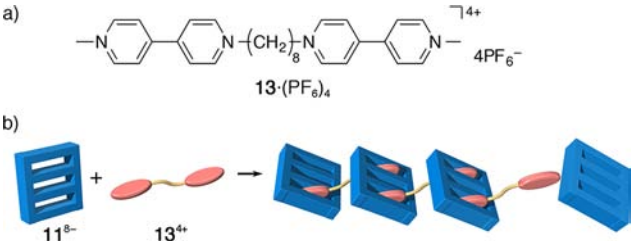


Figure 5. Chemical structure of methyl viologen dimer $\mathbf{13}\cdot(PF_6)_4$ (a) and a schematic representation of a supramolecular array composed of $\mathbf{11}^{8-}$ and $\mathbf{13}^{4+}$ (b).

respectively) (Figure S3, Supporting Information). On the other hand, the mixture of $\mathbf{11}\cdot(n\text{-}Bu_2NH_2)_8$ and $\mathbf{13}\cdot(PF_6)_4$ gave a D_H value of 6.1 nm, and this value was increased to 14.8 nm by reprecipitation with methanol. These results indicated that only the combination of ditopic host and ditopic guest led to the formation of a supramolecular array (Figure 5b). This array formation was confirmed by cold spray ionization mass spectrometry (CSI-MS).[14] When a mixture of $\mathbf{11}\cdot(n\text{-}Bu_2NH_2)_8$ and $\mathbf{13}\cdot(PF_6)_4$ in DMF was sprayed in the negative-ion mode at ambient temperature, characteristic signals were observed at m/z = 1257.7, 1509.5, and 1999.6, which were assigned to the associates assigned to $\mathbf{11}^{8-}:\mathbf{13}^{4+}$ = 1:1, 2:2, and 2:3, respectively (Figure S4, Supporting Information).

In summary, we have prepared three- and four-layered spiroborate nanocycles by the combination of oligo(dihydroxynaphthalene)s and tetrahydroxyanthraquinone as pillar and crossbar units in the presence of boric acid. Single-crystal X-ray diffraction analysis showed that these multilayered nanocycles possessed rectangular cavities that could vary their sizes over a certain range by deflection of the anthraquinone planes. The molecular recognition mode of the multilayered nanocycles was investigated by using methyl viologen as the cationic aromatic guest. The three-layered nanocycle exhibited inclusion behavior only toward a single guest, whereas the four-layered one recognized two guests simultaneously in its cavities. The ditopic molecular recognition ability of the four-layered nanocycle was applied to the construction of a supramolecular one-dimensional array by combining with methyl viologen dimer as the ditopic guest. The formation of the array structure was confirmed by DLS and CSI-MS analysis.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Detailed experimental procedures for the synthesis and characterization of all new compounds, DLS data, CSI-MS data of the mixture of $\mathbf{11}\cdot(n\text{-}Bu_2NH_2)_8$ and $\mathbf{13}\cdot(PF_6)_4$, and X-ray diffraction data of $\mathbf{10}\cdot(TBA)_6$ and $\mathbf{11}\cdot(n\text{-}Bu_2NH_2)_8$ in the form of single-crystal X-ray crystallographic information files (CIF). This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This work was supported by The Hirao Taro Foundation of the Konan University Association for Academic Research. We thank Drs. N. Mizuno and S. Baba (Japan Synchrotron Radiation Research Institute (JASRI)) for invaluable help in data collection in the X-ray analysis of $\mathbf{10}\cdot(TBA)_6$. Synchrotron radiation experiment was performed at the BL38B1 stations of SPring-8 with the approval of JASRI (Proposal No. 2014B1423).

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