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Preparation of Tris(spiroorthocarbonate) Cyclophanes as Back to Back Ditopic Hosts

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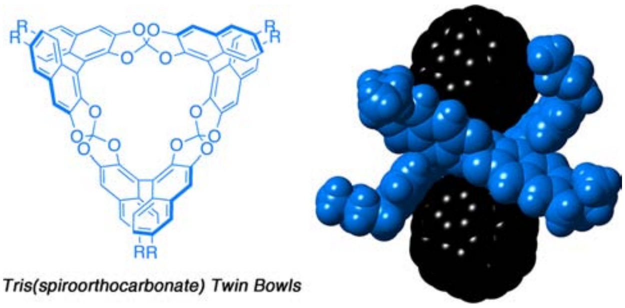
ABSTRACT



Twin-bowl-shaped tris(spiroorthocarbonate) cyclophanes were designed and prepared as ditopic hosts for electrically neutral or electron-rich guests. Preparation of the desired cyclophanes was achieved by cyclotrimerization of 2,2′,3,3′-tetrahydroxy-1,1′-binaphthyl (THB) via the transesterification of tetraphenyl orthocarbonate or dichlorodiphenoxymethane. In those reactions, bis(spiroorthocarbonate) cyclophane containing two THB units was also formed as the kinetically favored product. The spiroorthocarbonate twin bowl exhibited ditopic molecular recognition toward fullerene C_{60} in the crystalline state.

Continuing attention has been paid to the development of new host–guest and supramolecular systems for the construction of functional higher-order structures or nanomachineries, and for this purpose, various molecular recognition modules have been designed and prepared.[1] In particular, to construct higher-order, more complicated supramolecular architectures, multidentate molecular recognition is required. However, the association of a monotopic host and guest leads to the formation of only a 1:1 discrete complex. Therefore, the oligomerization of existing hosts, such as cyclodextrins[2−6] or calixarenes,[7−11] has been attempted in an effort to develop multitopic host modules that can be applied to the construction of functional higher-order structures. The development of host molecules possessing multiple molecular recognition sites within a single structural unit would be important to

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achieve simple and easy construction of the desired higher-order structures. In our previous research, we prepared tris(spiroborate)-type twin-bowl-shaped cyclophanes $\mathbf{1}^{3-}$ as ditopic host modules that could recognize two guests simultaneously within the cavities on both sides of their symmetry plane (Figure 1).[12] These cyclophanes were trianionic and could undergo intermolecular interaction with various cationic guest compounds. In the presence of ditopic cationic guests, iterative molecular recognition took place, resulting in the formation of an infinite one-dimensional array.

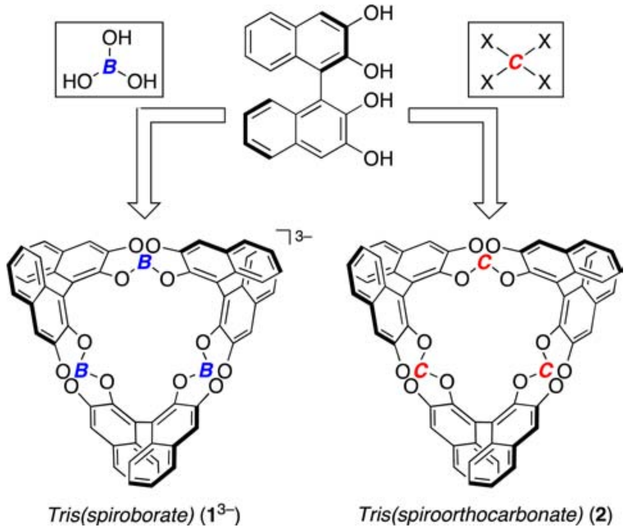
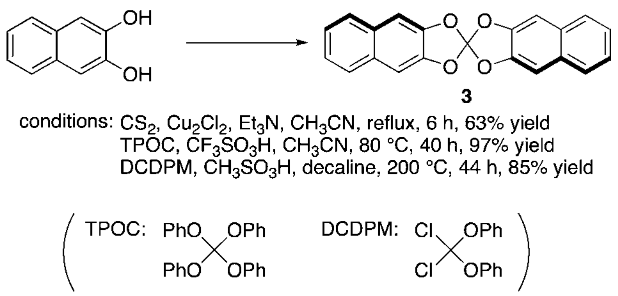


Figure 1. Chemical structures of tris(spiroborate) $\mathbf{1}^{3-}$ and tris(spiroorthocarbonate) **2**.

When electrically neutral or electron-rich guest molecules were used, however, cyclic spiroborate $\mathbf{1}^{3-}$ could not realize similar iterative molecular recognition because of electrostatic repulsion between the two adjacent spiroborates. In order to achieve such molecular recognition toward those guests, we had to employ ditopic host modules without an electric charge. Accordingly, we planned to exchange the boron atom at the spiro center with a group 14 element. Among them, a carbon center was chosen to construct an electrically neutral spiro linkage to avoid the formation of a hypervalent structure.[13] Herein we report the preparation of tris(spiroorthocarbonate) cyclophanes **2** as electrically neutral ditopic hosts (Figure 1).

Scheme 1. Preparation of Spiroorthocarbonate **3**



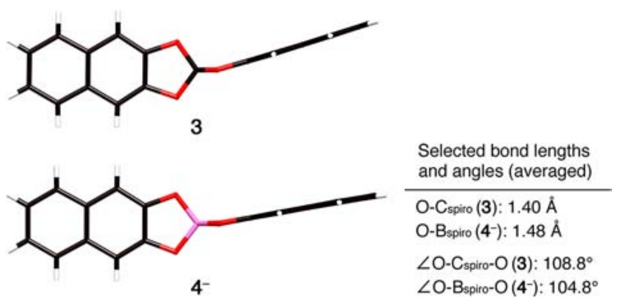


Figure 2. Crystal structures of spiroorthocarbonate **3** (top) and spiroborate $\mathbf{4}\cdot PPh_4$ (bottom). Counterions and solvent molecules are omitted for clarity.

The formation of the spiroorthocarbonate linkage was first attempted with 2,3-dihydroxynaphthalene. The use of carbon disulfide as the spirocarbon source led to the formation of the spiroorthocarbonate structure in 63% yield in the presence of copper(I) chloride and triethylamine in acetonitrile at 100 °C (Scheme 1).[13a] Transesterification could also be employed in this synthesis. No product was afforded when dimethyl carbonate, diphenyl carbonate, or tetramethyl orthocarbonate was used as the carbon source. On the other hand, spiroorthocarbonate was obtained in 33% yield by treatment with tetraphenyl orthocarbonate (TPOC) and a catalytic amount of trifluoromethanesulfonic acid (1 mol %) in toluene at 100 °C, and the yield was improved to 97% when the reaction was carried out in acetonitrile at 80 °C. The reaction also proceeded with the use of dichlorodiphenoxymethane (DCDPM) as the carbon source in decaline in the presence of methanesulfonic acid as the catalyst, although a relatively high temperature (200 °C) was required (85% yield).

Crystallographic analysis of spiroorthocarbonate **3** revealed that the average length of $O{-}C_{spiro}$ bonds was 1.40 Å, which was smaller than that of $O{-}B_{spiro}$ bonds

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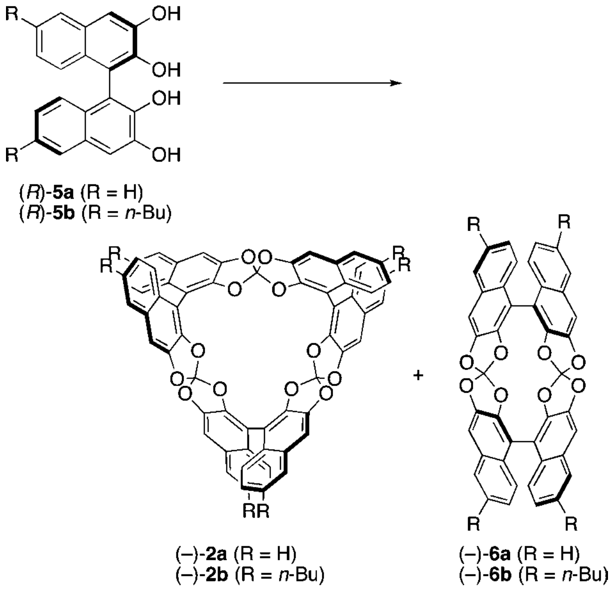
of corresponding spiroborate 4^- (1.48 Å), and therefore, the average bond angle of $O-C_{spiro}-O$ in **3** (108.8°) was larger than that of $O-B_{spiro}-O$ in 4^- (104.8°) (Figure 2). These differences might affect the rigidity of the molecular structure around the spiro center.

Scheme 2. Preparation of Cyclic Spiroorthocarbonates **2** and **6**



(*R*)-**5a** (R = H)
(*R*)-**5b** (R = *n*-Bu)

(−)-**2a** (R = H)
(−)-**2b** (R = *n*-Bu)

(−)-**6a** (R = H)
(−)-**6b** (R = *n*-Bu)

conditions	yield (%) of **2a**/**6a**	yield (%) of **2b**/**6b**
CS_2, Cu_2Cl_2, Et_3N CH_3CN, reflux, 6 h	0/0	–
TPOC, CH_3SO_3H decaline, 200 °C, 15 h	5/10	1/4
DCDPM, CH_3SO_3H toluene, reflux, 16 h	2/13	8/17

Using the optimized reaction conditions, we next constructed spiroorthocarbonate cyclophanes from 2,2′,3,3′-tetrahydroxy-1,1′-binaphthyl (THB, **5**) (Scheme 2). Treatment of **5a** with carbon disulfide in the presence of copper(I) chloride and triethylamine gave no cyclization product. On the contrary, spiroorthocarbonate cyclophanes were formed when TPOC or DCDPM was employed as the carbon source in the presence of an acid catalyst. ^1H NMR and ESI-MS analyses revealed that the cyclization of **5a** with the spiroorthocarbonate linkage mainly gave dimer **6a** as the major product and trimer **2a** as the minor one, in contrast to the formation of spiroborate cyclophane $\mathbf{1}^{3-}$. This indicated that the equilibrium for the formation of the spiroorthocarbonate linkage was not sufficiently activated to afford thermodynamically favored trimer **2a** under those reaction conditions. A polymeric product and kinetically favored dimer **6a** were predominantly afforded, and the yield of trimer **2a** remained low. When the reaction was carried out with TPOC in decaline at 200 °C in the presence of methanesulfonic acid, cyclic spiroorthocarbonate dimer **6a** and trimer **2a** were obtained in 10% and 5% yield, respectively. Spiroorthocarbonate cyclophanes **2b** and **6b** bearing six butyl groups at the 6-position of the naphthalene ring were also prepared with the same procedure (1% and 4% yield, respectively), and slightly improved yields were observed when DCDPM was used as the carbon source in toluene (8% and 17% yield, respectively).

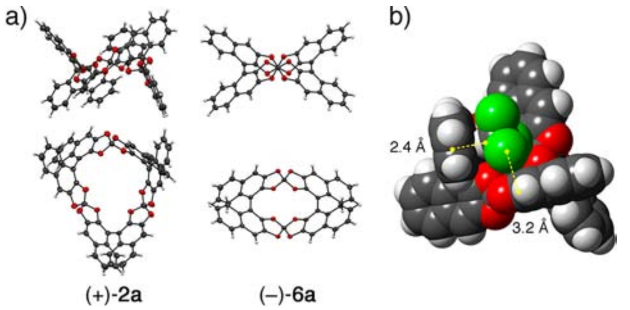


Figure 3. (a) ORTEP drawings of spiroorthocarbonate (+)-**2a** and (−)-**6a**. Front and top views. Thermal ellipsoids are shown in 50% probability. Solvent molecules are omitted for clarity. (b) Crystal structure of (+)-**2a**·$CHCl_3$ drawn in the space-filling model.

The structures of these spiroorthocarbonate cyclophanes were unambiguously determined by X-ray crystallographic analysis.[14] Trimer **2a** exhibited a twin bowl structure, identical to spiroborate $\mathbf{1}^{3-}$, in which the three naphthalene planes were positioned in such a way as to form one bowl-shaped cavity (Figure 3a). In its crystal, trimer **2a** incorporated one chloroform molecule in one of its two cavities. The distances of one chlorine atom and a hydrogen atom from the naphthalene plane were 3.2 and 2.4 Å, respectively, indicating the existence of halogen−π and CH−π interactions between **2a** and chloroform (Figure 3b). On the other hand, spiroorthocarbonate dimer **6a** had a ditopic propeller-like structure that was composed of two highly distorted THB units. In the crystal structure, four five-membered rings containing the spirocarbon were bent along the spiro linkage direction. The flexibility of the spiroorthocarbonate linkage would allow the formation of the dimer structure. In contrast to spiroorthocarbonate trimer **2a**, dimer **6a** no longer has a crown-ether-like cavity at the center of the molecule.

The association of spiroorthocarbonate trimer **2b** with fullerene C_{60} could be observed by X-ray crystallographic analysis (Figure 4).[14] It was found that one **2b** recognized two C_{60} in both cavities, and the complexation was stabilized by multivalent $\pi-\pi$ interaction between one C_{60} and the three naphthalene rings of **2b**. The distance between the centers of the two C_{60} recognized at both sides of the single molecule of **2b** was found to be 13.0 Å. This indicates that spiroorthocarbonate trimer **2b** may act as a molecular connecting module toward two C_{60} molecules, which glue

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[14] CCDC 929028 ((+)-**2a**), 929029 ((−)-**6a**), 929030 (*rac*-**2b**·$(C_{60})_2$), and 929084 (*rac*-**2b**·$(C_{70})_2$) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.au.uk/data_request/cif.

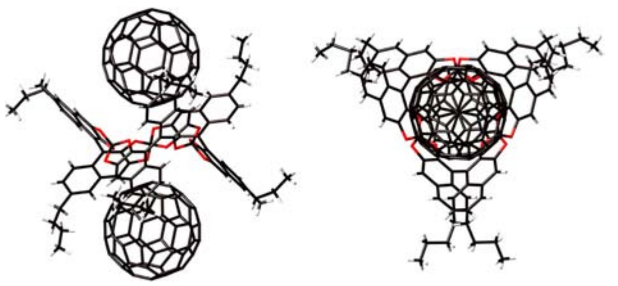

Figure 4. Crystal structure of *rac*-**2b**$\cdot$(C_{60})$_2$. Front (left) and top (right) views.

to each other to produce a C_{60} dimer through noncovalent interaction.[15]

In conclusion, spiroorthocarbonate cyclophanes were designed as electrically neutral ditopic host compounds that glued two electrically neutral guest compounds to each other. The synthesis was carried out via transesterification of THB (**5**) and orthocarbonate derivatives in the presence of methanesulfonic acid as the acid catalyst. Cyclic spiroorthocarbonates were obtained as a mixture of trimer **2** and dimer **6**, and their precise structures were determined by X-ray crystallographic analysis. The molecular recognition mode of **2b** was evaluated with fullerene C_{60} as an electrically neutral guest by X-ray analysis, and it was found that the two fullerenes were recognized by a single molecule of **2b**.

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Supporting Information Available. Detailed experimental procedures for synthesis and characterization of all new compounds and X-ray diffraction data in the form of a CIF file. This material is available free of charge via the Internet at http://pubs.acs.org.

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(15) Almost identical complexation was observed in the cocrystal of **2b** and C_{70}, although the crystal structure refinement of *rac*-**2b**$\cdot$(C_{70})$_2$ was not fully completed due to the low crystal quality (see Figure S1).

The authors declare no competing financial interest.