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A Benzo-21-Crown-7/Secondary Ammonium Salt [*c*2]Daisy Chain

Bo Zheng, Mingming Zhang, Shengyi Dong, Jiyong Liu, and Feihe Huang*

Department of Chemistry, Zhejiang University, Hangzhou 310027, P. R. China

fhuang@zju.edu.cn

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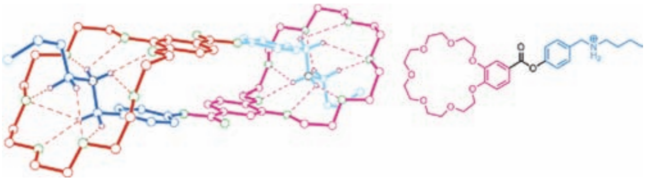
ABSTRACT



A [*c*2]daisy chain has been constructed from a heteroditopic monomer based on the benzo-21-crown-7/secondary ammonium salt recognition motif as shown by single crystal X-ray analysis. It has been further demonstrated that the complexation behavior of this heteroditopic monomer in solution can be controlled by changing the solution pH or adding/removing K$^+$.

During the past decades, supramolecular chemistry has developed rapidly with the purpose of mimicking nature and going beyond that to facilitate the construction of supramolecular structures with novel topologies and/or important functions.[1] Threaded structures, as a kind of unique and interesting supramolecular structure, have played a significant role in the development of supramolecular chemistry due to their wide application in the fabrication of molecular machines,[2] supramolecular polymers,[3] and other functional supramolecular systems.[4] [*c*2]Daisy chains, fundamental threaded structures, are cyclic interwoven dimers. They have been often constructed from the dimerization of AB-type plerotopic monomers with two self-complementary units A (host) and B (guest). Various host−guest recognition motifs have been applied for the preparation of threaded structures.[5−10] Stoddart and coworkers prepared the first [*c*2]daisy chain, which was based on the dibenzo-24-crown-8 (DB24C8)/secondary ammonium salt recognition motif.[6a] Later, they also applied crown ether/paraquat recognition motifs to fabricate [*c*2]daisy chains.[6b] [*c*2]Daisy chains were further capped

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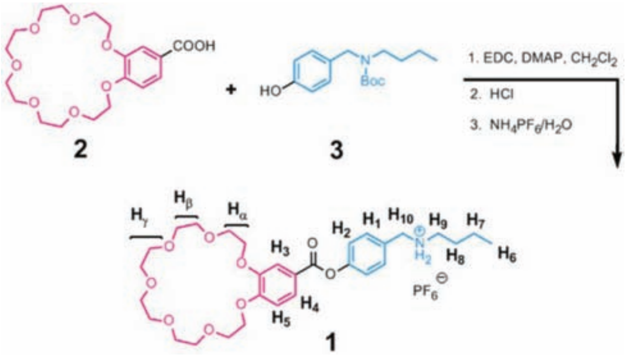
with bulky stoppers by different strategies, such as "Wittig-exchange" of stoppers and a "threading-followed-by-swelling" approach, to afford mechanically interlocked threaded structures.[7] Given the intrinsic extended and contracted property of [*c*2]daisy chains, they are excellent building blocks for the construction of artificial molecular muscles. For example, Stoddart et al. introduced an extra binding site, an *N*,*N*′-dialkylated-4,4′-bipyridinium unit, into the first [*c*2]daisy chain and constructed an acid−base-controllable molecular muscle.[8] Coutrot and co-workers synthesized a dimannosyl[*c*2]daisy chain with two binding sites for the DB24C8 ring to locate and it also showed pH-switchable muscle-like movements.[9] By utilizing functionalized [*c*2]daisy chain-type molecular muscles as the monomers during polymerization reactions, the pH-controlled muscle-like movements were incorporated into mechanically interlocked polymers for the development of smart materials and functional nanomachinery.[10] All of these studies have opened bright prospects for [*c*2]daisy chains.

In 2007, we reported that secondary dialkylammonium salts could thread into the cavity of benzo-21-crown-7 (B21C7) to form threaded structures.[11] Compared with that of DB24C8, the cavity of B21C7 is smaller, so it not only binds secondary dialkylammonium salts more efficiently but also calls for smaller and simpler stoppers such as benzene rings during the construction of mechanically interlocked threaded structures. Moreover, the synthesis of B21C7 is convenient. Owing to these virtues, the B21C7/secondary ammonium salt recognition motif has been widely used to fabricate various threaded structures by not only us but also other research groups.[12] However, to the best of our knowledge, no daisy chain has been constructed based on this recognition motif. Herein we report the preparation of a self-complementary monomer **1** (Scheme 1) and its formation of a [*c*2]daisy chain in the solid state based on the B21C7/secondary ammonium salt recognition motif.

The strategy used to prepare the target molecule **1** is based on the esterification reaction between **2** and **3** (Scheme 1). Benzo-21-crown-7 acid **2** was prepared from methyl 3,4-dihydroxybenzoate and hexaethylene glycol ditosylate in two steps with a reasonable overall yield.[12g] The other substrate **3** was synthesized from 4-hydroxybenzaldehyde and butan-1-amine. After the esterification reaction of **2** and **3**, the *tert*-butoxycarbonyl protective group was removed and the counterion was exchanged from chloride to hexafluorophosphate to afford monomer **1**.[11,13]

Scheme 1. Synthesis of Monomer **1**



We obtained single crystals suitable for X-ray crystallography by slowly evaporating a CH_2Cl_2/MeOH solution of **1**. Interestingly, X-ray crystallographic analysis of **1** reveals that one monomer seems smart and prefers finding another one to form a [*c*2]daisy chain in the solid state (Figure 1, top). In the dimer structure, the secondary ammonium salt moiety of one monomer is located in the B21C7 ring of the other one and this threading is driven by four [$N^+{-}H\cdots O$] (**a**, **b**, **c**, and **d** in Figure 1) and five [$C{-}H\cdots O$] (**e**, **f**, **g**, **h**, and **i** in Figure 1) hydrogen bonds. Similar to a previously reported [2]rotaxane based on the same recognition motif (Figure S9, left),[11] all the oxygen atoms of the polyether ring of B21C7 and the ammonium and closest methylene hydrogens participate in these hydrogen bonds. However, what is different here is that, besides these hydrogen bonds, this threading is also driven by the face-to-face π-stacking interaction between the benzene ring of the B21C7 host moiety and the benzene ring of the ammonium salt guest unit. These two aromatic rings are almost parallel with a ring plane/ring plane inclination of 4.89°. Possibly due to the cooperative effect of hydrogen bonds and face-to-face π-stacking interactions and the rigid linkage between the two aromatic rings of the monomer, which results in the intermolecular complexation other than intramolecular self-complementary complexation, the [*c*2]daisy chain structure forms in the solid state. Interestingly, in the packing structure, supramolecular arrays are obtained from the [*c*2]daisy chains driven by face-to-face π-stacking interactions.

Matrix-assisted laser desorption ionization time-of-flight (MALDI-TOF) mass spectrometry was employed to study compound **1** (Figure S10). The resultant spectrum

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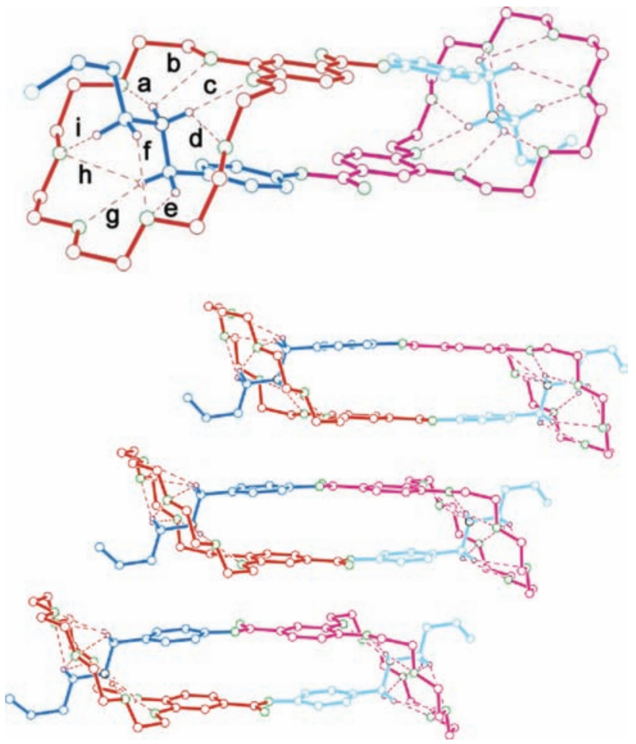

Figure 1. Ball-stick views of the X-ray structure of $\mathbf{1_2}$ (top) and the packing structure of $\mathbf{1}_2$ (bottom). PF_6 counterions, and hydrogens except the ones involved in hydrogen bonding were omitted for clarity. B21C7 parts are red or magenta, secondary ammonium salt parts are blue or light blue, hydrogens are purple, oxygens are green, and nitrogens are black. Hydrogen-bond parameters in the dimer structure: H···O distances (Å), C(N)···O distances (Å), C(N)−H···O angles (deg): **a**, 2.46, 2.92, 131; **b**, 2.17, 2.91, 151; **c**, 2.25, 2.98, 130; **d**, 2.11, 3.12, 148; **e**, 2.61, 3.50, 138; **f**, 2.30, 3.28, 153; **g**, 2.71, 3.16, 109; **h**, 2.64, 3.40, 147; **i**, 2.41, 3.19, 150. Face-to-face π-stacking parameters in the dimer structure: centroid−centroid distance (Å), 3.64; ring plane/ring plane inclination (deg), 4.89. Face-to-face π-stacking parameter in the packing structure: centroid−centroid distance (Å), 3.69.

revealed the existence of the dimer structure of **1**: *m*/*z* 1123.49 (25%), corresponding to $[\mathbf{1}_2 - HPF_6 - PF_6]^+$. The other main peaks at 562.29 (100%), 584.24 (98%), and 600.20 (57%), corresponding to $[\mathbf{1} - PF_6]^+$, $[\mathbf{1} - HPF_6 + Na]^+$, and $[\mathbf{1} - HPF_6 + K]^+$, respectively, were also observed.

^{1}H NMR studies provided important insights into the complexation behavior of **1** in solution. Since the ammonium centers were preferentially solvated by the highly polar solvent molecules,[6c,11] the spectrum recorded in CD_3SOCD_3 (Figure S5) showed relative clear peaks and the peaks could be assigned as the uncomplexed monomer **1**. While the spectrum became complicated in less polar CD_3COCD_3 (Figure S11, spectrum b), it can be rationalized by ascribing it to the formation of the interwoven complexes. Owing to the slow-exchanging system of this recognition motif, the spectrum exhibited in an even more intricate way. By employing ^{1}H−^{1}H COSY experiments (Figure S12) and comparison of the spectra of B21C7 and a model secondary ammonium salt (Figures 2 and S11), the signals of **1** in CD_3COCD_3 were identified. The signals of protons H_1, H_2, H_4, H_6, H_7, H_8, H_9, and H_{10} were divided into two sets. Aromatic protons H_1, H_2, and H_4 shifted upfield due to the shielding effect of the aromatic rings associated with the other units in the oligomers of **1**. The assignment and correlation of the peaks were further validated by a NOESY spectrum of **1** (Figure S13). Strong correlations were observed between the protons adjacent to secondary ammonium H_9 and the protons of the polyether macrocyclic ring, suggesting that secondary ammonium salt moiety NH_2^+ is located in the center of the macrocyclic ring.

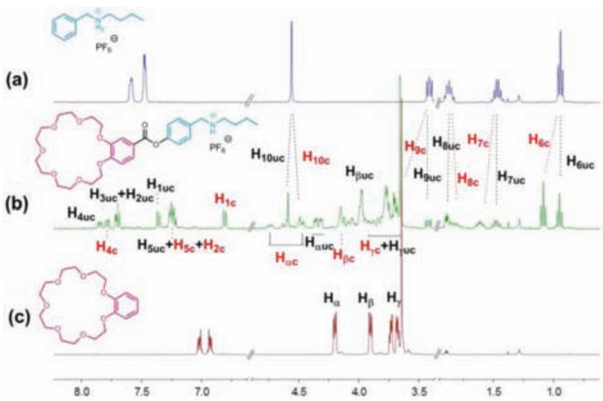

Figure 2. Partial ^{1}H NMR spectra (400 MHz, acetone-d_6, rt) of (a) 8.00 mM model secondary ammonium salt, (b) 8.00 mM **1**, and (c) 8.00 mM B21C7. “c” and “uc” denote complexed and uncomplexed species, respectively.

The chemically driven uncomplexing and recomplexing processes were further investigated. The spectra for acid/base controlled complexation are shown in Figure 3.[14] Upon addition of an excess of triethyl amine to the solution of **1** in CD_3COCD_3, the B21C7/secondary ammonium salt complexation was destroyed due to the deprotonation of NH_2^+. Correspondingly, no complexed signals were found in spectrum b. After the addition of an excess of CF_3COOD to this solution to protonate the amine groups, threaded structures formed again; spectrum c was almost identical to spectrum a except the additional peaks of $[Et_3NH]^+$. These reversible changes upon the addition of acid and base represent the possibility that the complexation behavior of **1** could be controlled by the change of the pH value. Additionally, the polyether ring of B21C7 can bind alkali caions strongly. We then checked whether the complexation behavior of **1** could be controlled by addition and removal of K^+ in solution (Figure 4).[15] When 1 mol equiv of KPF_6 was added to a solution of **1** in CD_3COCD_3, the polyether ring was occupied by K^+, driving the NH_2^+ unit to slide out of the cavity of B21C7; the spectrum of **1** became clear (spectra a and b in Figure 4).

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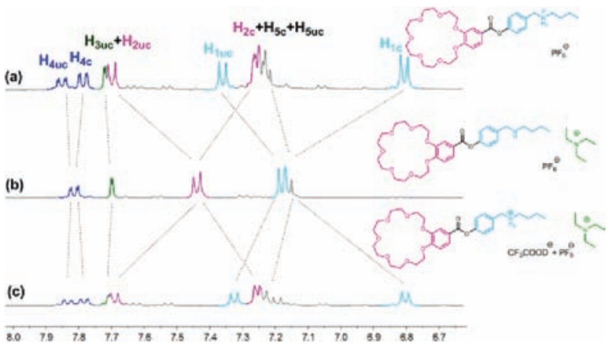

Figure 3. Partial ^{1}H NMR spectra (400 MHz, acetone-d_6, rt) of (a) 8.00 mM **1**, (b) 8.00 mM **1** and 24.0 mM Et_3N, and (c) 8.00 mM **1**, 24.0 mM Et_3N, and 32.0 mM CF_3COOD.

However, after 1 mol equiv of benzo-18-crown-6 (B18C6) was subsequently added, the B21C7/secondary ammonium salt complexation recovered (spectrum c in Figure 4) since K^+ bound B18C6 more strongly. Accordingly, the complexed peaks were observed again and the spectrum almost recovered to the original state (spectra a and c, Figure 4). This dual-responsive property of the complexation between the B21C7 moiety and the secondary ammonium salt unit makes the [*c*2]daisy chain a good candidate to construct stimuli-responsive artificial systems through suitable engineering because it can be easily contracted and extended by changing the chemical environment.

In summary, we constructed a [*c*2]daisy chain in the solid state based on the benzo-21-crown-7/secondary ammonium salt recognition motif. X-ray single crystal analysis shows that it is stabilized by multiple [$N^+{-}H\cdots O$] and [$C{-}H\cdots O$] hydrogen bonds and face-to-face π-stacking interactions. In the packing structure, the [*c*2]daisy chains further form supramolecular arrays driven by face-to-face π-stacking interactions. By combination of various techniques, such as MALDI-TOF mass spectrometry, ^{1}H NMR, COSY, and NOESY, the complexation behavior of **1** in the gaseous state and solution were studied. The dual-responsive property of the complexation between the B21C7 moiety and the secondary ammonium salt unit makes the [*c*2]daisy chain a good candidate to construct stimuli-responsive artificial systems through suitable engineering. Although the B21C7/secondary ammonium salt recognition motif is a young member of host–guest systems, the preparation of threaded structures based on it has been launched because of the easy preparation of B21C7 derivatives, good host–guest binding, and easy availability of stoppers for the B21C7 ring. The proper modification of monomer **1** can be employed to construct more advanced and smart supramolecular structures. In the future, further exploration is needed to reveal the relationship between the structures of monomers and the properties and functions of the resultant supramolecular architectures.

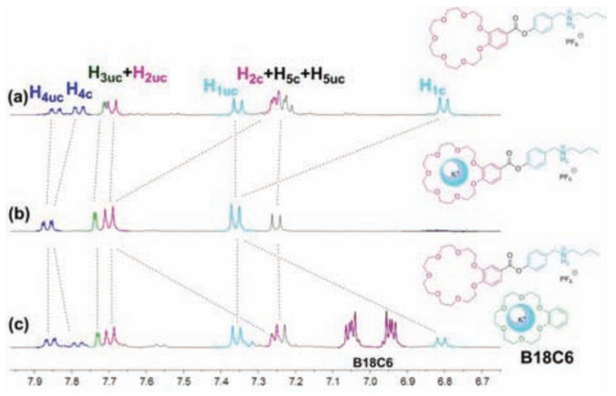

Figure 4. Partial ^{1}H NMR spectra (400 MHz, acetone-d_6, rt) of (a) 8.00 mM **1**, (b) 8.00 mM **1** and 8.00 mM KPF_6, and (c) 8.00 mM **1**, 8.00 mM KPF_6, and 8.00 mM B18C6.

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Supporting Information Available. Synthetic procedures, characterizations, and other materials. This material is available free of charge via the Internet at http://pubs.acs.org.