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Novel Supramolecular Block Copolymer: A Polyrotaxane Consisting of Many Threaded α- and γ-Cyclodextrins with an ABA Triblock Architecture

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Chain-interlocked supramolecular structures such as rotaxanes and catenanes involving macrocycles have long been a fascinating topic in multidisciplinary chemistry.[1−6] Cyclodextrins (α-CD, *β*-CD, and γ-CD) are a series of cyclic oligosaccharides, consisting of 6, 7, and 8 α-D-glucopyranose units, respectively. Although their hydrophobic cavities have a similar depth of ca. 7.0 Å, the internal diameter of γ-CD (ca. 8.5 Å) is about twice that of α-CD (ca. 4.5 Å).[7,8] Since the first syntheses of polyrotaxanes with multiple α-CD rings threaded over a polymer chain,[9,10] such supramolecular structures have attracted tremendous interest[11−16] and inspired interesting exploitations for electronics[17−19] and biomedical[20−23] applications.

A block copolymer consists of two or more distinct blocks obtained from different monomers that are covalently linked together. Herein, we describe a strategic synthesis of a novel supramolecular "block copolymer"—a polyrotaxane with a triblock architecture. The block polyrotaxane consists of a middle block of multiple γ-CD rings and two flanking blocks of multiple α-CD rings, where all CD rings are threaded on the poly(ethylene oxide)−poly(propylene oxide)−poly(ethylene oxide) (PEO−PPO−PEO) triblock copolymer with two 2,4,6-trinitrophenyl groups capping the ends. Although the 2,4,6-trinitrophenyl group is only big enough to prevent the dethreading of small α-CD, the entrapped flanking α-CD blocks can eventually confine the middle γ-CD block and prevent the dethreading of γ-CD from the polymer chain, forming a chemically stable ABA triblock polyrotaxane.

Scheme 1 shows the procedures for the synthesis of the triblock polyrotaxane **5** and its control compound, the homopolyrotaxane **7** that contains only α-CD. The molecular characteristics of the starting PEO−PPO−PEO triblock copolymer **1** were determined by combination of GPC and ^{1}H NMR spectroscopy. Its composition was $m = 30$ and $n = 82$, with an ethylene oxide content of 80 wt %, while its total molecular weight data were $M_n = 8.97 \times 10^3$ and $M_w = 9.31 \times 10^3$, which were within the specifications given by the manufacturer.

The hydroxyl groups of **1** were activated with 1,1′-carbonyldiimidazole (CDI), followed by reaction with large excess of ethylenediamine to give the amino-terminated PEO−PPO−PEO triblock copolymer **2**. Addition of **2** into an aqueous solution of γ-CD resulted in the formation of the polypseudorotaxanes **3**, the inclusion complex (IC) formed between γ-CD and the PPO segments of **2**, since γ-CD can selectively form ICs with the bulky chain of PPO rather than the thinner PEO.[24] Reaction of **3** with sodium 2,4,6-trinitrobenzenesulfonate (TNBS) failed to give a polyrotaxane with γ-CD entrapped over the polymer chain, evidently because the 2,4,6-trinitrophenyl stopper is not big enough to prevent the dethreading of γ-CD (refer to Supporting Information).

The strategy to permanently entrap the threaded γ-CD over the polymer chain is to form two flanking α-CD polyrotaxane blocks and to cap the polymer ends with two 2,4,6-trinitrophenyl stoppers, which are big enough to prevent the dethreading of the smaller α-CD. This requires the formation of the polypseudorotaxanes **4**, wherein the γ-CD−PPO IC block is flanked by two α-CD−PEO IC blocks. It is practically impossible to isolate **4** from **3** because they both will dissociate if they are dissolved in solvents. For synthesis of the triblock polyrotaxane **5**, we first tried the addition of **3** into a saturated solution of α-CD, followed by adding TNBS into the solution to cap the ends of the polymer. However, the process failed to give **5**. Evidently, there was no formation of **4** under such conditions. Next, we tried to mix **3** with solid α-CD and allowed the mixture to stand at 80 °C in vacuum for 1 week, which could facilitate α-CD to thread onto the PEO segments to form **4** in solid state. We luckily found that addition of TNBS aqueous solution into the above solid gave a mixture of the triblock copolyrotaxane **5** (yield, 7%) and the non-interlocked thread polymer, together with the unconsumed α-CD, γ-CD, and TNBS. The product **5** could be isolated and purified based on its different solubility and molecular weight with respect to its components (refer to Supporting Information).

Figure 1 shows the ^{1}H NMR spectra of the triblock polyrotaxane **5** and other control compounds. The polypseudorotaxanes **6** and **3** are ICs of **2** with α-CD and γ-CD, respectively. They will dissociate when dissolved in solvents. Their peaks appear basically the same as their respective components (Figure 1, b compared with a, and e with d). However, the peaks of the triblock polyrotaxanes **5** and the polyrotaxane **7** are much more broadened with respect to their free components (Figure 1c,f). This is due to the restricted motion of the interlocked molecules. The peaks of α-CD in Figure 1c clearly correspond to those of α-CD in Figure 1a,b. In contrast, the peaks for CDs in Figure 1f generally appear in pairs, with one set corresponding to α-CD and another to γ-CD. Particularly, H(1) of α-CD and H(1′) of γ-CD are clearly separate without overlapping. The results indicate that the triblock polyrotaxane **5** consists of both interlocked γ-CD and α-CD.

The compositions of the triblock polyrotaxane **5** and the polyrotaxane **7** were obtained from the ^{1}H NMR spectra. In **5**, there are about 11 γ-CD rings threaded over the PPO segments, which are flanked and entrapped by two α-CD blocks, each containing about 8 α-CD rings threaded over the PEO segments and capped by the 2,4,6-trinitrophenyl end groups. The molar ratio of PO unit to γ-CD (m/x) is 2.8, which is close to 2:1, the stoichiometry of γ-CD−PPO inclusion complex, indicating that most of the PPO block is covered by γ-CD in the triblock polyrotaxane **5**. However, the molar ratios of EO unit to α-CD (n/y) is 9.7, which means only about 20% of the PEO block is covered by α-CD in **5**. The coverage is relatively low, since it was reported that about 50% of PEO segments were covered by α-CD in the polyrotaxane formed by α-CD and PEO of M_n 3350.[9] The low coverage rate may be caused by the incomplete threading of α-CD over the flanking PEO blocks because the process was carried out in solid state. In addition, the

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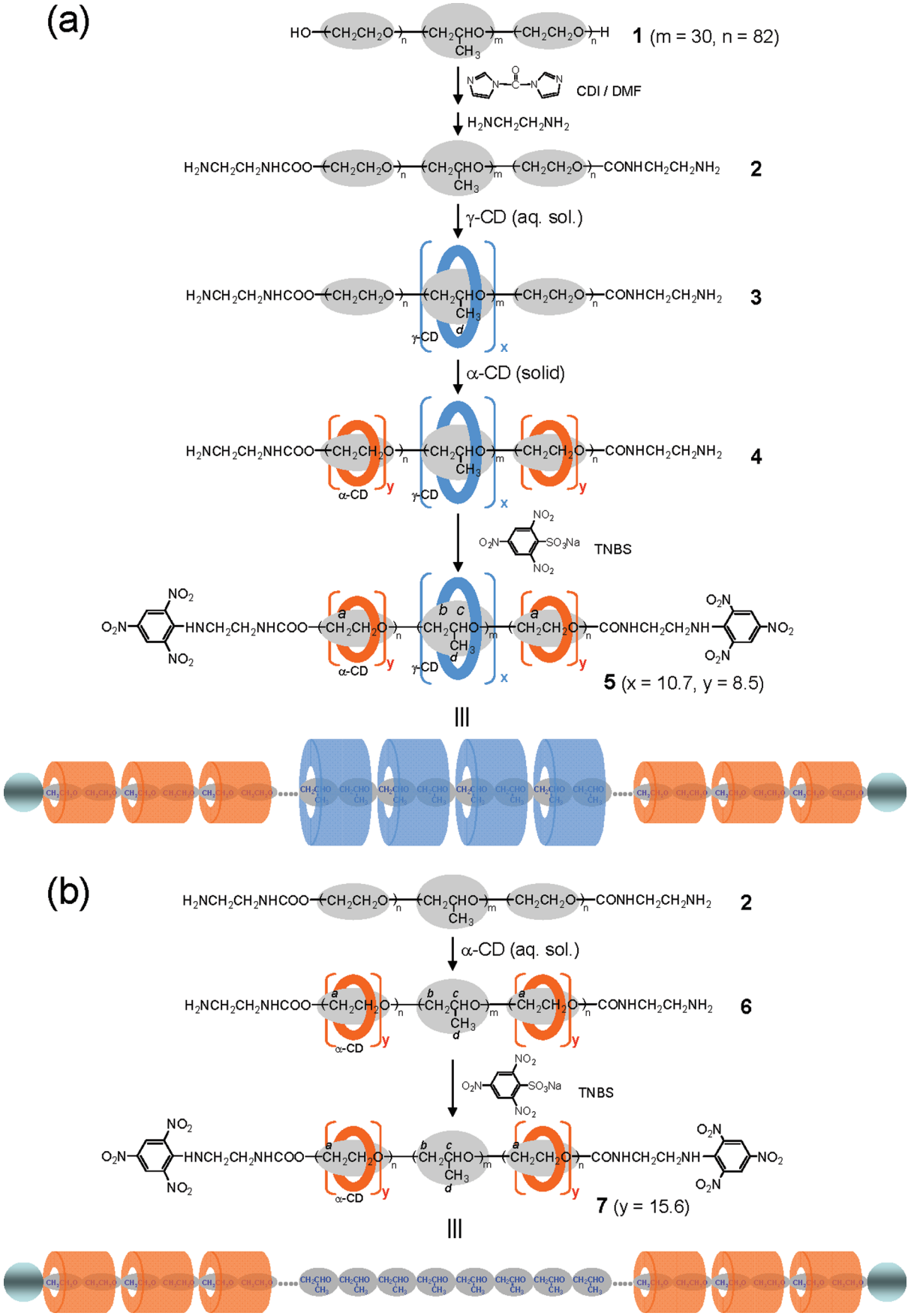
Scheme 1. Synthesis Procedures for Triblock Copolyrotaxanes 5 (a) and Polyrotaxane 7 (b)[a]



[a] DMF: *N*,*N*-dimethylformamide; CDI: 1,1′-carbonyldiimidazole; CD: cyclodextrin; TNBS: sodium 2,4,6-trinitrobenzenesulfonate.

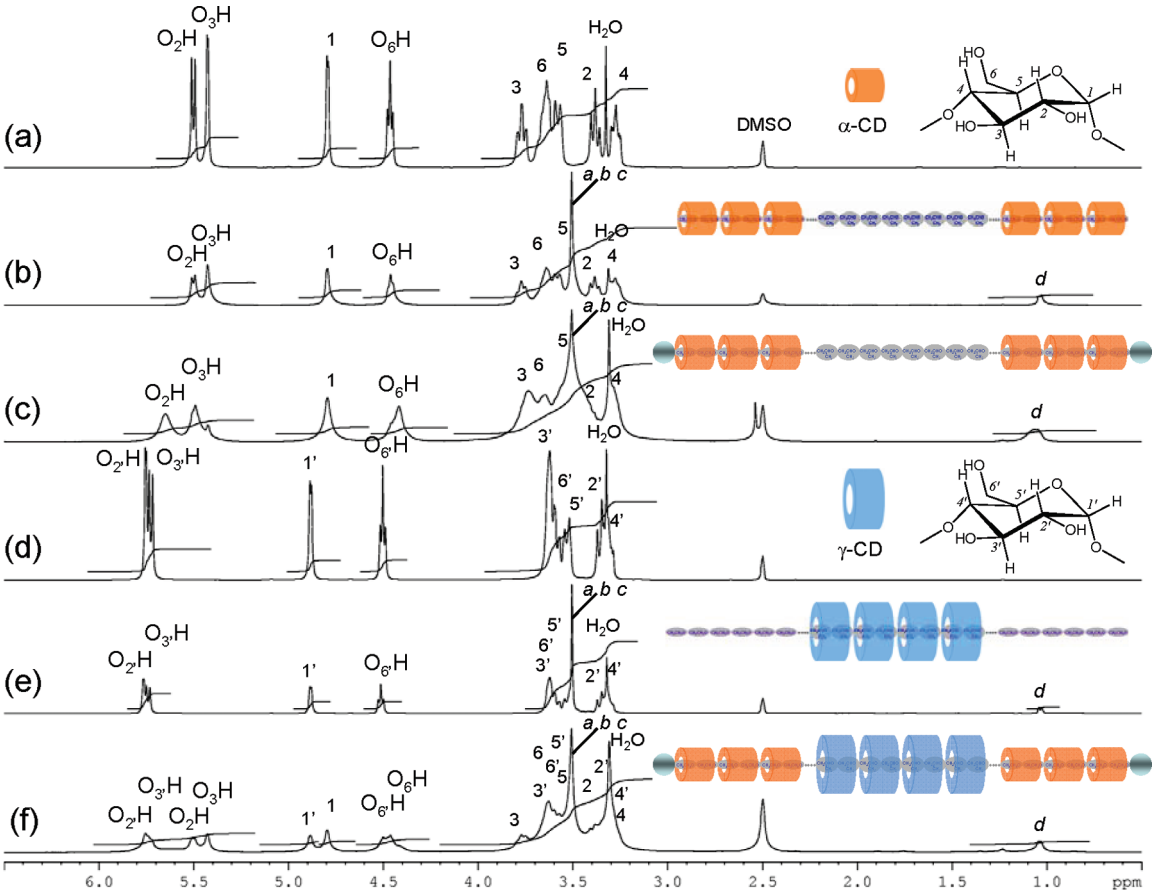


Figure 1. 400 MHz ^{1}H NMR spectra of (a) α-cyclodextrin (α-CD), (b) polypseudorotaxane **6**, (c) polyrotaxane **7**, (d) γ-CD, (e) polypseudorotaxane **3**, and (f) triblock copolyrotaxane **5** in DMSO-d_6. Refer to Scheme 1 for the definitions of these compounds.

threading of α-CD may be hindered by the IC domains formed by γ-CD and the middle PPO block. However, theoretically, only one α-CD threaded over each flanking PEO block will be enough to prevent the dethreading of the sandwiched γ-CD rings. It is thought that the low yield of the triblock polyrotaxane **5** (7%) was the result of the difficulty of α-CD threading onto the PEO segments of the polypseudorotaxane **3**. We are currently studying how the reaction conditions will affect the yield as well as the number of α-CD threaded over each flanking PEO block. On the other hand, in the polyrotaxane **7**, there are about 16 α-CD rings threaded over each flanking PEO block, with the molar ratio of EO unit to α-CD (n/y) of 5.3, which means about 40% of each PEO block is covered by α-CD in **7**. It should be noted that the process converting polymer **2** to IC **6** was carried out in aqueous solution. The 40% coverage is very close to the case in the polyrotaxane formed by α-CD and PEO of M_n 3350 (50% coverage).

Scanning tunneling microscopy (STM) is a convenient method for visualizing the nanostructures of CD-based polyrotaxanes.[25] Figure 2 shows the STM image of the triblock polyrotaxane **5** in 2D and 3D modes. Five long-chain and nanometer-sized wires, corresponding to the triblock polyrotaxane **5**, are distributed homogeneously on the graphite (HOPG) substrate. According to the size and shape (Figure 2b), each peak in the middle segments of one wire corresponds to a γ-CD unit, while each peak in the flanking segments corresponds to an α-CD unit. The number of α-CD and γ-CD threaded on one wire agrees well with the number determined by ^{1}H NMR spectroscopy. Hence, the STM images provide a visual evidence for the formation of the triblock polyrotaxane **5**.

In conclusion, a novel supramolecular triblock polyrotaxane was synthesized, which consists of the middle block of multiple

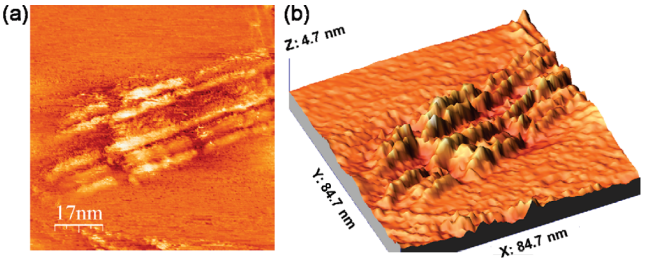


Figure 2. 2D (a) and 3D (b) scanning tunneling microscopy images of triblock polyrotaxane **5**.

γ-CD rings and two flanking blocks of multiple α-CD rings, where all the CDs are threaded over a polymer chain with two moderately bulky stoppers to prevent the dethreading of the small α-CD: the flanking α-CD blocks further serve as "stoppers" to prevent the dethreading of the large γ-CD rings in the middle. This is the first example of a polyrotaxane having such an ABA triblock architecture formed by two different types of CDs. The strategy may be extended to copolyrotaxane syntheses with other macrocycles, and such copolyrotaxanes may be promising precursors for designing advanced materials with interesting functional properties.

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Supporting Information Available: Experimental details. This material is available free of charge via the Internet at http://pubs.acs.org.

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