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COMMUNICATION

Pillar[5]arene-based Nonionic Polyrotaxanes and a Topological Gel Prepared from Cyclic Host Liquids

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We synthesize nonionic polymer-based polyrotaxanes in solvent systems based on pillar[5]arene cyclic host liquids. Using a reactive liquid, pillar[5]arene enabled synthesis of a nonionic topological gel.

Polyrotaxanes, in which many cyclic compounds are threaded onto a linear polymeric chain, have attracted much attention because the cyclic components move and rotate freely on the linear polymeric chain.¹ Harada and coworkers first reported polyrotaxanes consisting of cyclodextrin (CD) wheels and linear nonionic polymers such as poly(ethylene glycol),² poly(propylene glycol)³ and polytetrahydrofuran (PTHF).⁴ Other types of polyrotaxanes using different host molecules such as crown ethers⁵ and cucurbiturils⁶ have subsequently been reported. These host molecules form stable host-guest complexes with positively charged molecules, producing polyrotaxanes with linear cationic polymer chains. Pillar[5]arenes (**Fig. 1**),⁷⁻¹⁰ which were first reported by our group in 2008,⁷ also form stable host-guest complexes with cationic molecules. On the basis of the host-guest complexation of pillar[5]arene (**Fig. 1**) with cationic guest molecules,⁷⁻¹⁰ we successfully synthesized a novel polyrotaxane composed of pillar[5]arene wheels and linear cationic viologen polymer.¹⁰

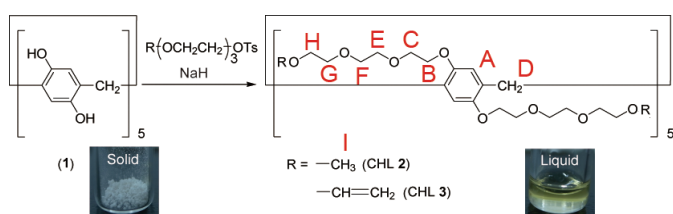


Fig. 1 Pillar[5]arene-based cyclic host liquids produced by modification with tri(ethylene oxide) chains.

Nearly all polyrotaxanes have been synthesized using linear cationic polymers except for CD-based ones. However, it is difficult to synthesize linear cationic polymers with high molecular weight and their solubility in nonpolar solvents is poor, making their corresponding polyrotaxanes unsuitable for use as materials such as topological gels.¹¹ Methods to synthesize nonionic polymer-based polyrotaxanes are therefore required. In this study, we synthesized pillar[5]arene-based nonionic polyrotaxanes consisting of pillar[5]arene wheels and nonionic polymer chain PTHF using cyclic host liquids (CHLs), which are cyclic compounds in liquid state at room temperature.^{12,13} Modification of a pillar[5]arene core with tri(ethylene oxide) chains (**Fig. 1**, CHL **2**) changed the state of the material from solid to liquid at room temperature¹³ because the introduction of the soft tri(ethylene oxide) chains reduced the crystallinity of the pillar[5]arene core. CHLs can efficiently synthesize mechanically interlocked molecules because they can act as both host and solvent for the guest molecules, maximizing the concentration of host and guest species. The maximized concentration results in facile, high-yield synthesis of [2]rotaxanes even in the case of the weak host-guest complexes formed between alkane axles and pillar[5]arene wheels (association constants $K = 10\text{-}20\text{ M}^{-1}$).¹³ In the present study, we expand this concept to the synthesis of polyrotaxanes. We synthesized pillar[5]arene-based nonionic polyrotaxanes from PTHF (degree of polymerization: DP = 102) containing azido groups at both ends (**Fig. 2**). Furthermore, we prepared a topological gel using cross-linkable CHL **3** (**Fig. 1**).

Host-guest complexation between liquid pillar[5]arene **2** and PTHF was investigated in the presence and absence of CDCl_3 by ^1H NMR spectroscopy. When PTHF was mixed with one equivalent of **2** in CDCl_3 , the methylene protons of PTHF did not shift (**Fig. S4**), indicating that the host-guest complex was

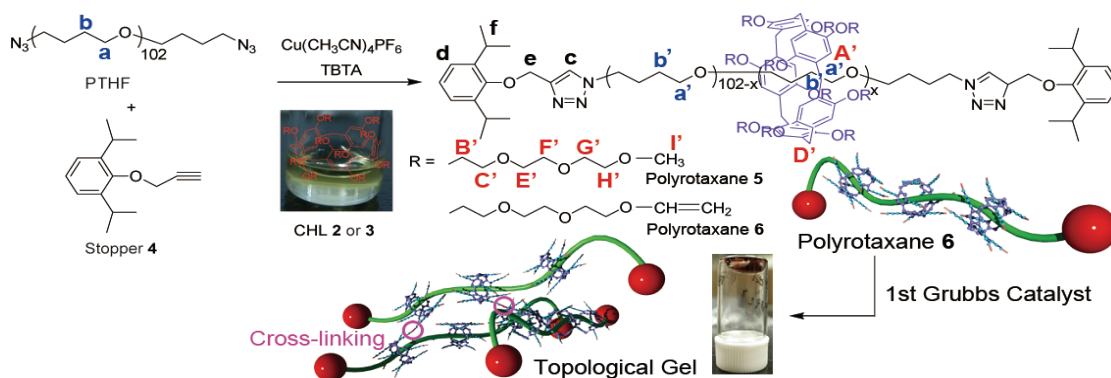


Fig. 2 Synthesis of nonionic polyrotaxanes and topological gel prepared from CHLs.

very weak in CDCl_3 . This is because host-guest complexes of pillar[5]arene derivatives with linear neutral guest molecules are weak in CDCl_3 ($K = 10\text{--}100 \text{ M}^{-1}$).¹³ Host-guest complexation in the absence of CDCl_3 was investigated using a double NMR tube. PTHF and **2** were placed in the inner tube, and CDCl_3 in the external. When PTHF was mixed with CHL **2** (**Fig. 3b**) in the absence of CDCl_3 , a substantial upfield shift of 0.65 ppm, was observed for the methylene proton (peak b) of PTHF. Thus, like the formation of *pseudo*[2]rotaxane in the CHL system,¹³ it also promotes formation of *polypseudorotaxanes* compared with typical complexation systems because no solvent is added.

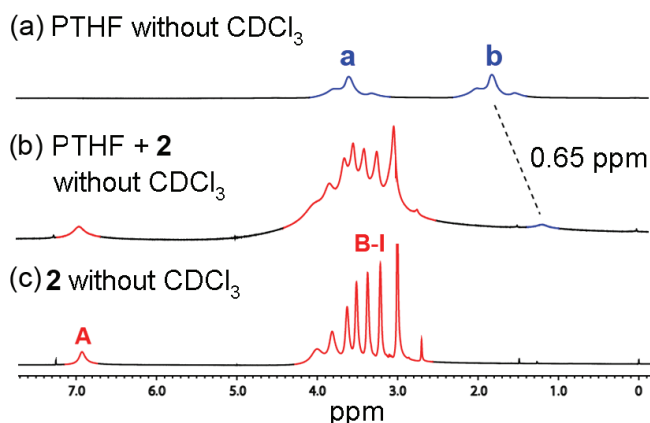


Fig. 3 ^1H NMR spectra of (a) PTHF, (b) 1:1 mixture of PTHF and **2**, and (c) **2** without CDCl_3 at 42°C . Resonances are labeled as shown in **Figs. 1** and **2**.

Based on the efficient formation of *polypseudorotaxane* in the CHL, we synthesized polyrotaxanes using CHL **2**. Polyrotaxanes were synthesized by Sharpless click reaction between a terminal alkyne and azido moiety (**Fig. 2**). PTHF and alkyne stopper **4** (3 equiv. to PTHF) were dissolved in CHL **2** (10 equiv. to PTHF unit) with $[\text{Cu}(\text{CH}_3\text{CN})_4\text{PF}_6]$ and tris[(1-benzyl-1H-1,2,3-triazol-4-yl)methyl]amine (TBTA). The mixture was stirred for 12 h at 25°C . To remove excess CHL **2**, the resulting mixture was simply washed with water, because CHL **2** is soluble in water and polyrotaxane **5** is not. ^1H NMR

spectra of the resulting mixture (**Fig. S5**) contained new peaks at 1.1 and 3.0 ppm. These peaks are assigned as the methylene moiety of PTHF in polyrotaxane **5**. The proton peaks of the methylene moiety of PTHF without wheel pillar[5]arene **2** were also observed at 1.6 and 3.4 ppm. Conversion to polyrotaxane **5** (the percentage of PTHF converted to polyrotaxane **5**) determined from the integration ratio between these sets of peaks was 71%. Because stopper **4** and PTHF are soluble in hexane but polyrotaxane **5** is not, the residue was washed with hexane to give polyrotaxane **5** in moderate yield (44%).

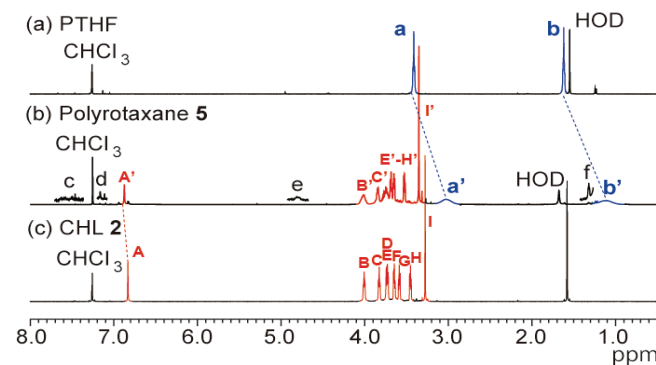


Fig. 4 ^1H NMR spectra (25°C , CDCl_3) of (a) PTHF, (b) polyrotaxane **5**, and (c) CHL **2**. Resonances are labeled as shown in **Figs. 1** and **2**.

Fig. 4 shows ^1H NMR spectra of polyrotaxane **5**, PTHF and pillar[5]arene wheel **2**. Proton signals from the methylene chains of **5** (blue peaks, a' and b') were upfield compared with those of PTHF (blue peaks, a and b) because the methylene moiety was shielded by wheel **2**. No observation of proton signals from PTHF, CHL **2** and stopper **4** indicated isolation of polyrotaxane **5**. The signal from the phenyl protons of the wheel in polyrotaxane **5** (red peak, A') was situated at downfield compared with those of the wheel (red peak, A) because of deshielding caused by the PTHF chain. A two-dimensional NOESY study of polyrotaxane **5** (**Fig. S6**) showed correlations between the signals from the phenyl protons (red peak, A') of the wheel and methylene protons (blue peaks, a' and b') of the polymeric chain, and between the methylene moiety adjacent to the O atom of the wheel (red peaks, B' and C') and methylene protons (blue peaks, a' and b') of the polymeric chain. These results indicate that the wheels are located on the methylene moieties of PTHF in polyrotaxane **5**.

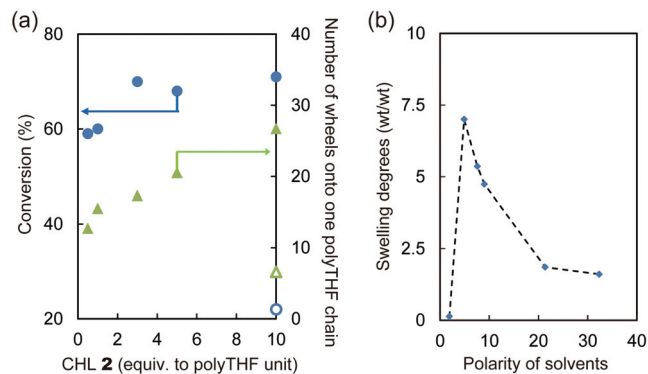


Fig. 5 (a) Percentage conversion to polyrotaxane **5** (blue filled circles) and the number of wheels on one PTHF chain (green filled triangles) versus molar equivalents of CHL **2** to PTHF units in the CHL systems and in a typical solvent system (open green triangle and blue circle). (b) Plot of the swelling degree of the topological gel versus polarity of the solvent.

The effects of the amount of CHL **2** used on the formation of polyrotaxane **5**, and the average number of wheels on one PTHF chain (DP = 102) were studied (Fig. 5a). The average cover number was calculated from the integration ratio between the peaks from the phenyl protons of the stopper (Fig. 4b, blue peak d) and those of the wheel (red peak A'). The conversion and average coverage number were 59% and 13 (/102 units), respectively, using 0.5 eq. of CHL **2**. The conversion and coverage number increased to 71% and 27 when 10 equiv. of CHL **2** was used. The feed of CHL **1** was 10 times, the number of wheel **2** in the obtained polyrotaxane **5** became 1.8 times. For comparison with a typical preparation system using solvents, we also investigated the synthesis of polyrotaxane **5** in CHCl₃ (20 mL) using the same feed ratios as for the preparation of polyrotaxane **5** in CHL **2**. In CHCl₃, the conversion and coverage number were 22 % and 7, respectively, which are low compared with those of CHL system. The low conversion and coverage number resulted from the weak complexation between **2** and PTHF in CDCl₃. Therefore, polyrotaxane formation in CHL **2** is promoted compared with that in typical solvent systems.

To construct topological gels using the CHL system, we synthesized a new CHL containing 10 reactive alkene ends, **3**. Like **2**, **3** was a liquid at 25 °C. Differential scanning calorimetry measurement showed that CHL **3** was liquid even at -50 °C (Fig. S8). Using CHL **3**, we also synthesized polyrotaxane **6** containing **3** as wheels using the same reaction conditions as for the synthesis of polyrotaxane **5** (Fig. 2, yield 35%). The number of wheels threaded onto one PTHF chain in polyrotaxane **6** determined by the same method as for polyrotaxane **5** was 12.

To obtain a topological gel from polyrotaxane **6**, intermolecular crosslinking between polyrotaxanes **6** was performed using olefin metathesis. A solution of polyrotaxane **6** in chloroform changed to a gel state after 10 h of addition of first generation Grubbs catalyst. The gel was not soluble in methanol, but polyrotaxane **6** is soluble, indicating the gel is not a physical gel but a chemical gel. The gel did not swell in non-polar solvent hexane or highly polar solvents such as acetone

and methanol, but swelled and absorbed solvents with intermediate dielectric constants ($4 < \epsilon < 10$) including chloroform, dichloromethane and THF (Fig. 5b).

In conclusion, we synthesized nonionic polyrotaxanes consisting of PTHF chains and pillar[5]arene wheels in moderate yields (35-44%) using CHL systems, while the yield is very low (22%) in normal solvent system. Thus, CHL systems are a useful way to improve the yield of pillar[5]arene-based nonionic polyrotaxanes. Another advantage of this system is that functional groups can be installed in the polyrotaxane because of the high functionality of pillar[5]arenes.^{7,8}

Introducing alkene moieties into CHL enabled synthesis of the first pillar[5]arene-based topological gel. The topological gel swelled in organic solvents with intermediate dielectric constants ($4 < \epsilon < 10$). The number of wheels is changed depending on the feed ratio between PTHF and CHL. Therefore, we will synthesize super-absorbent lipophilic topological gels for nonpolar organic solvents by changing the number of wheels on the polyrotaxane.

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† Electronic Supplementary Information (ESI) available: Experimental section, characterization data and ¹H and 2D NOESY NMR spectra and DSC trace. See DOI: 10.1039/c000000x/

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