ORIGINAL ARTICLE

Modulation of reversible self-assembling of dumbbell-shaped poly(ethylene glycol)s and β -cyclodextrins: precipitation and heat-induced supramolecular crosslinking

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A series of dumbbell-shaped poly(ethylene glycol) (PEG) chains **1** attached to bulky end groups were prepared, and some of the chains formed supramolecular assemblies with β -cyclodextrin (β -CD) and its multiple, ditopic and tetra-topic, derivatives. The chains with proper end groups successfully allowed β -CD to be trapped onto PEG through formation of hydrogen bonds at room temperature and higher. Mixing of the PEG chain and the ditopic supramolecular crosslinker in water at 40 °C led to a change in solution property from viscous to elastic, accompanied by a significant increase in viscosity, whereas this change was not induced at room temperature. A supramolecular network formed only when the PEG chain was mixed with the tetra-topic supramolecular crosslinker at 40 °C. Once formed, the supramolecular crosslinking was maintained even after the system cooled down. Instead, dilution and shaking at room temperature resulted in a return to a solution with low viscosity. These assemblies and dissociations were affected by the end groups of **1**.

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INTRODUCTION

One of the greatest findings in the 1990s was the self-assembly of cyclic molecules onto a linear polymeric chain, represented by α -cyclodextrin (α -CD) onto poly(ethylene glycol) (PEG)^{1,2} and β -cyclodextrin (β -CD) onto poly(propylene glycol),^{3,4} leading to the development of supramolecular materials based on cyclodextrins^{5–8} and others.^{9,10} In the assembly, CD molecules formed intermolecular hydrogen bonds^{2,4,6,7} with each other to stay on the chain while threading and dethreading were competing, and finally a supramolecular assembly called pseudopolyrotaxane was obtained as a kinetic product. As a matter of course, some thermodynamic advantages accompanied this process, such as enthalpic gain on forming hydrogen bonds,⁶ and total entropic changes on assembly of the components, as well as desolvation. It seems that PEG and poly(propylene glycol) chains provided a suitable guide for α -CD and β -CD to fill the size-matched cavity and align cooperatively through formation of hydrogen bonds. In recent years, Takata *et al.* reported an excellent synthetic approach for yielding pseudopolyrotaxanes based on self-assembly of modified CD molecules onto a linear polymeric chain without relying on forming hydrogen bonds, but using heterogeneous systems in which permethylated α -CD and poly(tetrahydrofuran) or PEG were used in hydrocarbon solvents¹¹ as well as in water.¹² Even though the initial

Scheme 1 (a) Pseudopolyrotaxane formation between size-matched cyclic and linear components, (b) pseudopolyrotaxane formation between size-mismatched cyclic and dumbbell-shaped linear components and (c) supramolecular crosslinking based on pseudopolyrotaxane formation between size-mismatched crosslinked cyclic and dumbbell-shaped linear components.

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Figure 1 Chemical structures of dumbbell-shaped poly(ethylene glycol) chains **1a-e**, β -cyclodextrin **2**, permethylated β -cyclodextrin **3**, ditopic crosslinker **4** and tetra-tert-butyl crosslinker **5**.

Scheme 2 Preparation of dumbbell-shaped poly(ethylene glycol) chains **1**. PEGBA, poly(ethylene glycol) bis(2-aminoethyl) ether

Scheme 3 Preparation of tetra-topic crosslinker **5**.

Scheme 4 Mixing of **1** with **2** in water leading to precipitation (**1a**, **1b**) at room temperature (r.t.) or elevated temperature, or no precipitation (**1c**, **1d** and **1e**), and dissociation by dilution.

Table 1 Conditions (concentration and temperature) for complexation of **1a**, **1b** or PEGBA with **2**, **3** or α -CD,^a and results (time for precipitation, ratio^b of PEG to CD in an isolated solid and yield^c)

PEG	CD	Concentration (mM)		Temperature (°C)	Time (day)	Ratio ^b (PEG:CD)	Yield ^c (%)
		PEG	CD				
1a	2	1.3	15	rt	10	1:10	29
		4.8	57	60	4	1:10	28 ^d
	3	64	7.1×10^2	rt	–	–	0
		64	7.1×10^2	60	–	–	0
1b	2	1.3	15	rt	5	1:10	23
		4.8	55	60	2	1:10	20 ^d
		1.3	15	rt	–	–	0
PEGBA	2	1.3	15	rt	–	–	0
	α -CD	13	1.4×10^2	rt	<1	–(1:10)	0 (92)

Abbreviations: α -CD, α -cyclodextrin; PEG, poly(ethylene glycol); PEGBA, poly(ethylene glycol) bis(2-aminoethyl) ether; rt, room temperature.

^aPEG was added to a solution of CD in water, and the mixture was stirred. A solid was obtained by filtration, followed by washing with 10 times the amount of water.

^bThe ratio was determined by the ¹H nuclear magnetic resonance spectrum of an isolated solid measured in DMSO-*d*₆, based on an assumption that the average number of repeating units (*n*) was maintained in the solid.

^cThe yield was calculated based on PEG with the same assumption as above. The number in parenthesis is the ratio or yield obtained when the solid was washed with a small amount of water, as reported in references 1 and 2, where PEG (*M*_w=1000) was used instead of PEGBA.

^dThese solids were used to measure powder X-ray diffraction.

Table 2 Conditions (concentration,^a temperature and time) for mixing of **1a–e** or PEGBA with **4** or **5**, and zero-shear viscosity

PEG	Crosslinker	Concentration ^a (mM)		Temperature (°C)	Time (day)	Zero-shear viscosity (Pa·s)
		PEG	Crosslinker			
1a	4	46	2.5×10^2	rt	10	– ^b
				40	6/8	1.7×10^5 – ^c
		31	1.6×10^2	40	8	2.1×10^3
		20	1.0×10^2	40	8	– ^b
		19	52	40	3	– ^c
1b	4	46	2.5×10^2	rt	10	– ^b
				40	3/6	2.4×10^2 – ^c
		31	1.6×10^2	40	8	1.9×10^2
		20	1.0×10^2	40	8	– ^b
		46	2.4×10^2	rt	10	– ^b
1c	4	46	2.4×10^2	rt	10	– ^b
				40	8	9.7×10^3
		31	1.6×10^2	40	8	– ^b
		20	1.0×10^2	40	8	– ^b
		19	52	40	3	8.8×10
1d	4	46	2.5×10^2	40	6	– ^b
1e	4	46	2.5×10^2	40	6	– ^b
PEGBA	4	46	2.5×10^2	40	8	– ^b

Abbreviations: PEG, poly(ethylene glycol); PEGBA, poly(ethylene glycol) bis(2-aminoethyl) ether; rt, room temperature.

^aThe ratio of PEG to methylated β -CD component in **4/5** is 1:11 in all solutions.

^bNot determined or insignificant at most on the order of $\sim 10^0$ Pa·s.

^cNot determined because of the disappearance of the terminal region.

1:1 complex is not necessarily preferred to form, threading occurs sequentially and the complexation reaction proceeds because dethreading is retarded through kinetic and/or thermodynamic stabilization of intermediary complexes in a cooperative manner, which seems unfavorable for a size-mismatched combination (Scheme 1a).² Each cyclic molecule enters on threading and leaves at the end of a chain. Setting up a barrier at each end of a chain affects both entering and leaving,^{6,7} and brings about changes in the ratio of k_n/k_{-n} . A precise barrier ideally allows a cyclic molecule to remain on any chain, instead of relying on specific combinations of cyclic and linear components with size adequacy (Scheme 1b). In addition, cyclic molecules would stay on chains cooperatively when they were cross-linked by a spacer, leading to a supramolecular network through the pseudopolyrotaxane formation (Scheme 1c).^{13–17}

Here we report the roles of barriers at the ends of a chain, and crosslinking of cyclic molecules in self-assembly of size-mismatched components, PEG and β -CD.^{17–19} We investigated systematically the pseudopolyrotaxane formation of a series of dumbbell-shaped PEG chains **1a–e** with native β -CD **2** and its permethylated derivative **3**²⁰ (Scheme 1b and Figure 1). Two crosslinked β -CD derivatives, ditopic **4**¹⁷ and tetratopic **5**, were used to form a supramolecular network on mixing with **1** in water (Scheme 1c and Figure 1).

EXPERIMENTAL PROCEDURE

Materials

Poly(ethylene glycol)s (average M_n : 380–420 and 950–1050) were purchased from Aldrich Co. Ltd. (St Louis, MO, USA), and used as a starting material to prepare PEG bis(prop-2-ynyl) ether **7** (matrix-assisted laser desorption/ionization time-of-flight mass spectrometry m/z 513 ($[M(m=9)+Na]^+$, BP),²¹ and PEG bis(2-aminoethyl) ether (matrix-assisted laser desorption/ionization time-of-flight MS m/z 1096 ($[M(n=22)+Na]^+$, BP).²² Pentaerythritol ethoxylate **16** (average M_n : ~797) was purchased from Aldrich Co. Ltd., and derived to quadruply-azidated **10**. Heptakis(2,3-di-O-methyl)-hexakis(6-O-methyl)-6-monodeoxy-6-monoazido- β -CD **8** and heptakis(2,3-di-O-methyl)-hexakis(6-O-methyl)-6-monodeoxy-6-monoamino- β -CD **3** were prepared according to literature.²⁰ Synthetic procedures and spectral data of new compounds (**1**, **5**, **9**, **10**, **12**, **13** and **17**), and experimental details of complexation study are described in Supporting Information.

Measurements

The frequency dependence of the oscillatory shear moduli, such as shear storage modulus G' and loss modulus G'' in aqueous solutions, was measured by a cone-and-plate rheometer (MR500, UBM, Kyoto, Japan) at 25 ± 1 °C. The cone angle was 5° and the diameter was 25 mm.

X-ray diffraction measurement was performed with a powder diffractometer (RINT2000, Rigaku, Tokyo, Japan) using graphite-monochromatized CuK α radiation ($\lambda=1.542$ Å).

Matrix-assisted laser desorption/ionization time-of-flight mass spectra were recorded in the reflector mode on a mass spectrometer (Voyager DE RP, PerSeptive Biosystems, Framingham, MA, USA) using a nitrogen laser (337 nm) and an accelerating potential of 25 kV. α -Cyano-4-hydroxycinnamic acid was used as a matrix.

RESULTS AND DISCUSSION

Preparation of dumbbell-shaped PEG chains **1** and supramolecular crosslinkers, ditopic **4** and tetratopic **5**

The dumbbell-shaped PEG chains **1a–e** were prepared by a reaction of PEG (average $n=22$) bis(2-aminoethyl) ether with corresponding benzoyl chlorides **6** that have one or two alkoxy group(s) at 2-, 4- or 6-position (Scheme 2). The ditopic crosslinker **4** was prepared by attachment of monoaminated permethylated β -CD to each end of PEG (average $l=7$) bis(carboxymethyl) ether through a condensation

Figure 2 Zero-shear viscosities (η_0) of aqueous solution of (a) dumbbell-shaped PEG **1a**, (b) **1b** and (c) **1c** (46 mm) in the presence of ditopic crosslinker **4** (0.25 M), determined by measurement of complex viscosities (η^*) at 25 ± 1 °C, followed by calculation according to the equation $\eta_0 \equiv \lim_{\omega \rightarrow 0} G'(\omega)/\omega$. For a solution of **1b** stirred at 40 °C for 6 days (Figure 2b), the viscosity was not determined due to disappearance of the terminal region.

reaction.¹⁷ The tetratopic crosslinker **5** was prepared by repeated 1,3-dipolar cycloaddition reactions^{23,24} of monoazidated permethylated β -CD **8**²⁰ and quadruply-azidated pentaerythritol ethoxylate **10** (average $a+b+c+d=15$) at the respective ends of PEG (average $m=9$) bis(prop-2-ynyl) ether **7** (Scheme 3).

Inclusion complexation of dumbbell-shaped **1** with β -CD **2**

Complexation of the dumbbell-shaped PEG chains **1** with native β -CD **2** was first investigated by mixing in water at room temperature

Scheme 5 Mixing of **1** with **4** in water leading to increase in viscosity only at elevated temperature (**1a**, **1b** and **1c**) or no increase (**1d**, **1e**), and dissociation by dilution.

Figure 3 Photographs of aqueous solution of dumbbell-shaped poly(ethylene glycol) **1a** (46 mM) and ditopic crosslinker **4** (0.25 M), stirred at 40 °C for 8 days, followed by inverting and standing for (a) 0 and (b) 24 h.

and at 60 °C (Scheme 4 and Table 1). Mixing of **1a** with **2** in water at room temperature for 10 days successfully gave a white solid. The ^1H nuclear magnetic resonance spectrum of the isolated solid measured in DMSO- d_6 indicated a simple integration of **1a** and **2** at a ratio of 1 to 10. An indistinguishable solid was given on mixing at 60 °C from the solid formed at room temperature. The powder X-ray diffraction pattern for the solid of **1a** and **2** is quite similar to that of β -CD itself.^{4,25} Mixing of **1a** with permethylated **3** failed to produce any solid, and just gave a transparent solution at both room temperature and 60 °C. If we consider the hydrophobic inherence in **1a**, whose solution is turbid in water at any temperature, the solubilization would be accounted for by assuming inclusion complexation with **3** at least at the end of **1a**.¹⁷ It would be difficult to judge whether the methylated β -CD was trapped onto **1a** or not from only the appearance due to high water solubility of **3**.¹⁸ Similar results were obtained from mixing of **1b** with **2** or **3** qualitatively, in terms of precipitation or solubilization (Table 1). Note that mixing at 60 °C accelerated precipitation,⁷ and gave an indistinguishable solid in a similar yield to that given at room temperature. A longer time was required for precipitation that resulted in a higher yield for **1a** [$R^2=\text{OPr}$, $R^4=\text{OBn}$] than for **1b** [$R^2=\text{OEt}$, $R^4=\text{OBn}$] (Table 1). All solids obtained here dissolved in DMSO or in an excessive amount of water, indicating formation of hydrogen bonds as commonly seen in an inclusion

complex of native cyclodextrins.^{1–4,26,27} As previously reported, the results of mixing PEG bis(2-aminoethyl) ether, which has no bulkiness at the ends, with α -CD^{1,2} and β -CD^{3,4} are also listed in Table 1 for reference. As in the case of the mixing of **1a** with **3**, no precipitates were formed from a transparent solution of **1c** [$R^2=\text{OPr}$, $R^4=\text{OPr}$], **1d** [$R^2=\text{OPr}$] or **1e** [$R^2=\text{OPr}$, $R^6=\text{OPr}$] in the presence of **2** at any temperature (Scheme 4).

Supramolecular crosslinking of dumbbell-shaped **1** with ditopic **4** and tetratopic **5**

Complexation of dumbbell-shaped **1** with the ditopic crosslinker **4** was then investigated in terms of the zero-shear viscosity (η_0) of a transparent solution in water under several conditions (Table 2). If each of the two permethylated β -CD molecules in **4** is discretely assembled onto a chain, and the supramolecularly crosslinked complexes are stable, this will lead to an increase in viscosity.²⁸ Mixing of **1a/b** (46 mM) with **4** (0.25 M) at room temperature for 10/5 days led to no change in viscosity (Figures 2a and b), but the solution appeared to be similar to a solution of **1a** and permethylated **3**. Alternatively, heating these systems induced increases in viscosity over time, which attained an order of 10^5 Pa·s after periods of 6 days for **1a** [$R^2=\text{OPr}$, $R^4=\text{OBn}$], and 3 days for **1b** [$R^2=\text{OEt}$, $R^4=\text{OBn}$] (Scheme 5 and Figures 2a and b). If the increase in viscosity was achieved through inclusion complexation with **4** only at the ends of **1a/b**, the solution viscosity would decrease with heating.^{29–32} It is noteworthy that a gradual increase in viscosity was also found in a solution of **1c** (46 mM) [$R^2=\text{OPr}$, $R^4=\text{OPr}$] in the presence of **4** (0.24 M) at 40 °C (Scheme 5 and Figure 2c), if we consider the failure of precipitation to occur on mixing of **1c** with native β -CD **2** at any temperature (Scheme 4). The viscosity did not increase at room temperature as in the case of mixing of **1a** or **1b** with **4** (Figure 2). Also note that these increased viscosities still remained for weeks after the system cooled down, and returned to solutions with low viscosity ($\sim 10^{-2}$ Pa·s) by triple dilution with water followed by shaking at room temperature for 5 days for **1a**, for 2 days for **1b** and within 1 day for **1c** (Scheme 5). These results indicate that the pseudopolyrotaxanes were formed on heating,¹⁸ and were kinetically stable during the supramolecular crosslinking. It is important for the system to be heated to form an assembly through the supramolecular crosslinking, although slipping on/off is allowed even at room temperature (see above). The values of η_0 measured at low concentrations ($[\mathbf{1a-c}] < 20$ mM, $[\mathbf{4}] < 0.10$ M) were

Figure 4 Frequency dependency of storage modulus (G' , red circle) and loss modulus (G'' , blue square) of aqueous solution of (a) dumbbell-shaped poly(ethylene glycol) **1a** in the presence of ditopic crosslinker **4** stirred at 40 °C for 8 days, (b) **1b** in the presence of **4** stirred at 40 °C for 6 days and (c) **1c** in the presence of **4** stirred at 40 °C for 8 days ([**1**]=46 mM, [**4**]=0.25 M), measured at 25 $\pm$ 1 °C.

on the order of $\sim 10^0$ Pa·s. The values increased with concentration as follows: $\eta_0=2.1 \times 10^3$ Pa·s for **1a** and **4**, and 1.9×10^2 Pa·s for **1b** and **4** ([**1a**], [**1b**]=31 mM, [**4**]=0.16 M) and so on, measured after maintaining a solution at 40 °C for 8 days. Solutions with so high concentrations are no longer allowed to measure nuclear magnetic resonance

Figure 5 Frequency dependency of storage modulus (G' , red circle) and loss modulus (G'' , blue square) of aqueous solution of (a) dumbbell-shaped poly(ethylene glycol) **1a** in the presence of tetratopic crosslinker **5**, and (b) **1c** in the presence of **5** stirred at 40 °C for 3 days ([**1**]=19 mM, [**5**]=52 mM), measured at 25 $\pm$ 1 °C. In a solution of **1a/c** (19 mM) itself or **5** (52 mM) itself, the values of G' and G'' were on the order of $\sim 10^{-2}$ Pa, measured under the same conditions.

with suitable quality. In a transparent solution of **1d**, **1e** or PEG bis(2-aminoethyl) ether in the presence of **4**, the viscosity remained on an order of 10^{-2} Pa·s under any conditions (Scheme 5). These results are also summarized in Table 2.

A solution with increased viscosity becomes harder to stir. In fact, a stirring bar stopped on the 8th/6th day from the time a solution of **1a/b** and **4** was heated to 40 °C, whereas it had been continuing in a solution of **1c** and **4** for 8 days at that temperature. As shown in Figure 3, the solution of **1a** and **4** appears deceptively something similar to a gel in the photograph (Figure 3a), and is fluent in the long term (~ 2 days; Figure 3b). We describe these macroscopic observations through dynamic viscoelastic measurement.³³ For the solution of **1a/b** and **4** stirred at 40 °C for 8/6 days, we can find the rubbery region in high frequency, indicating that the solution property changed from viscous to elastic (Figures 4a and b). Alternatively, for the solution of **1c** and **4**, the terminal region was clearly detected (Figure 4c). Changes over time in the oscillatory shear moduli are summarized in Supplementary Figures S1–S3.

We found a remarkable change in the dynamic viscoelastic property when the tetratopic crosslinker **5** was used in complexation with **1a**. In a solution of **1a** (19 mM) and **5** (52 mM) stirred at 40 °C, a stirring bar stopped on the 3rd day. The frequency dependence of the oscillatory shear moduli showed plateaus at low frequency, and indicated that a network structure had formed in the transparent solution (Figure 5a).³³ Once formed, returning to a low viscosity solution required a 7-day shaking after triple dilution. Replacing the tetratopic **5** with the ditopic **4** (0.10 M) in the above solution resulted in the value of η_0 lying on the order of 10^0 Pa·s, although almost the same amount of permethylated β -CD was present in the solution (Table 2). In a solution of **1c** (19 mM) and **5** (52 mM) stirred at 40 °C for 3 days, the terminal region was found (Figure 5b), which was not detected when the ditopic **4** (0.10 M) was used in place of **5** (Table 2).

CONCLUSIONS

A series of dumbbell-shaped PEG chains **1** were designed and prepared to investigate systematically the role of barriers at the ends of **1** through the self-assembling of size-mismatched cyclic and linear components (pseudopolyrotaxane formation). Differences in chemical structure at the ends of a chain were projected on macroscopic behaviors: substituents on 2,4-positions (**a**, **b** or **c**) affected the rate and yield of precipitation in the complexation with native β -CD that forms hydrogen bonds, and the rates of assembly as well

as dissociation in complexation with a ditopic/tetratopic supramolecular crosslinker **4/5** that kinetically stabilizes the assembly without relying on hydrogen bonds. In addition, the self-assembling of **1a-c** with **4/5** was induced only at 40 °C or higher, although a number of supramolecular assemblies dissociate on heating.^{1,29–32,34–38} Substituent(s) on 2- or 2,6-positions (**d** or **e**) were too small or bulky to work well. The system was also well modulated by crosslinking of a cyclic component, as demonstrated by combinations of **1a-c** and monotopic **3/ditopic 4**, or **1a/c** and ditopic **4/tetratopic 5**. A precise design of end groups according to a cyclic component would broaden the range of possibilities in selecting a chain without relying on a specific interaction between the components.

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- Harada, A. & Kamachi, M. Complex formation between poly(ethylene glycol) and α -cyclodextrin. *Macromolecules* **23**, 2821–2823 (1990).
- Harada, A., Li, J. & Kamachi, M. Preparation and properties of inclusion complexes of poly(ethylene glycol) with α -cyclodextrin. *Macromolecules* **26**, 5698–5703 (1993).
- Harada, A. & Kamachi, M. Complex formation between cyclodextrin and poly(propylene glycol). *J. Chem. Soc. Chem. Commun* **19**, 1322–1323 (1990).
- Harada, A., Okada, M., Li, L. & Kamachi, M. Preparation and characterization of inclusion complexes of poly(propylene glycol) with cyclodextrins. *Macromolecules* **28**, 8406–8411 (1995).
- Nepogodiev, S. A. & Stoddart, J. F. Cyclodextrin-based catenanes and rotaxanes. *Chem. Rev.* **98**, 1959–1976 (1998).
- Wenz, G., Han, B. H. & Müller, A. Cyclodextrin rotaxanes and polyrotaxanes. *Chem. Rev.* **106**, 782–817 (2006).
- Wenz, G. Recognition of monomers and polymers. *Adv. Polym. Sci.* **222**, 1–54 (2009), and references therein.
- Harada, A., Hashidzume, A., Yamaguchi, H. & Takashima, Y. Polymeric rotaxanes. *Chem. Rev.* **109**, 5974–6023 (2009).
- Huang, F. & Gibson, H. W. Polypseudorotaxanes and polyrotaxanes. *Prog. Polym. Sci.* **30**, 982–1018 (2005).
- Takata, T., Kihara, N. & Furusho, Y. Polyrotaxanes and polycatenanes: recent advances in syntheses and applications of polymers comprising of interlocked structures. *Adv. Polym. Sci.* **171**, 1–76 (2004).
- Nakazono, K., Takashima, T., Arai, T., Koyama, Y. & Takata, T. High-yield one-pot synthesis of permethylated α -cyclodextrin-based polyrotaxane in hydrocarbon solvent through an efficient heterogeneous reaction. *Macromolecules* **43**, 691–696 (2010).
- Arai, T., Hayashi, M., Takagi, N. & Takata, T. One-pot synthesis of native and permethylated α -cyclodextrin-containing polyrotaxanes in water. *Macromolecules* **42**, 1881–1887 (2009).
- Li, J., Harada, A. & Kamachi, M. Sol–gel transition during inclusion complex formation between α -cyclodextrin and high molecular weight poly(ethylene glycol)s in aqueous solution. *Polym. J.* **26**, 1019–1026 (1994).
- Gong, C. & Gibson, H. W. Supramolecular chemistry with macromolecules: macromolecular knitting, reversible formation of branched polyrotaxanes by self-assembly. *Macromol. Chem. Phys.* **199**, 1801–1806 (1998).
- Sohgawa, Y. H., Fujimori, H., Shoji, J., Furusho, Y., Kihara, N. & Takata, T. Polyslipping: a new approach to polyrotaxane-like assemblies. *Chem. Lett.* **30**, 774–775 (2001).
- Gibson, H. W., Yamaguchi, N. & Jones, J. W. Supramolecular pseudorotaxane polymers from complementary pairs of homoditopic molecules. *J. Am. Chem. Soc.* **125**, 3522–3533 (2003).
- Katoono, R., Kobayashi, Y., Yamaguchi, M. & Yui, N. Heat-induced supramolecular crosslinking of dumbbell-shaped PEG with β -CD dimer based on reversible loose-fit rotaxation. *Macromol. Chem. Phys.* **212**, 211–215 (2011).
- Katoono, R., Kobayashi, Y. & Yui, N. Preparation of loose-fit polyrotaxane composed of β -cyclodextrin and poly(ethylene glycol) derivatives through the slipping–expanding protocol. *Chem. Lett.* **39**, 892–893 (2010).
- Udachin, K. A., Wilson, L. D. & Ripmeester, J. A. Solid polyrotaxanes of poly(ethylene glycol) and cyclodextrins: the single crystal X-ray structure of PEG β -cyclodextrin. *J. Am. Chem. Soc.* **122**, 12375–12376 (2000).
- Muderawan, I. W., Ong, T. T., Lee, T. C., Young, D. J., Ching, C. B. & Ng, S. C. A reliable synthesis of 2- and 6-amino- β -cyclodextrin and permethylated- β -cyclodextrin. *Tetrahedron Lett.* **46**, 7905–7907 (2005).
- Zhang, G., Fang, L., Zhu, L., Sun, D. & Wang, P. G. Syntheses and biological activity of bisdaunorubicins. *Bioorg. Med. Chem.* **14**, 426–434 (2006).
- Harada, A., Li, J. & Kamachi, M. Preparation and characterization of a polyrotaxane consisting of monodisperse poly(ethylene glycol) and α -cyclodextrins. *J. Am. Chem. Soc.* **116**, 3192–3196 (1994).
- Rostovtsev, V. V., Green, L. G., Fokin, V. V. & Sharpless, K. B. A Stepwise huisgen cycloaddition process: copper(I)-catalyzed regioselective “ligation” of azides and terminal alkynes. *Angew. Chem. Int. Ed.* **41**, 2596–2599 (2002).
- Rodionov, V. O., Fokin, V. V. & Finn, M. G. Mechanism of the ligand-free copper(I)-catalyzed azide–alkyne cycloaddition reaction. *Angew. Chem. Int. Ed.* **44**, 2210–2215 (2005).
- Saenger, W. Cyclodextrin inclusion compounds in research and industry. *Angew. Chem. Int. Ed.* **19**, 344–362 (1980).
- Harada, A., Li, J., Suzuki, S. & Kamachi, M. Complex formation between polyisobutylene and cyclodextrins: inversion of chain-length selectivity between β -cyclodextrin and γ -cyclodextrin. *Macromolecules* **26**, 5267–5268 (1993).
- Harada, A., Li, J. & Kamachi, M. The molecular necklace: a rotaxane containing many threaded α -cyclodextrins. *Nature* **356**, 325–327 (1992).
- Ferry, J. D. *Viscoelastic Properties of Polymers* Ch. 11, 264–320 (John Wiley & Sons Inc., New York, 1980).
- Sandier, A., Brown, W. & Mays, H. Interaction between an adamantane end-capped poly(ethylene oxide) and a β -cyclodextrin polymer. *Langmuir* **16**, 1634–1642 (2000).
- van de Manakker, F., van der Pot, M., Vermonden, T., van Nostrum, C. F. & Hennink, W. E. Self-assembling hydrogels based on β -cyclodextrin/cholesterol inclusion complexes. *Macromolecules* **41**, 1766–1773 (2008).
- Herbst, F., Schröter, K., Gunkel, I., Gröger, S., Albrecht, T. T., Balbach, J. H. & Binder, W. Aggregation and chain dynamics in supramolecular polymers by dynamic rheology: cluster formation and self-aggregation. *Macromolecules* **43**, 10006–10016 (2010).
- Dingenouts, N., Klyatskaya, S., Rosenfeldt, S., Ballauff, M. & Höger, S. Temperature-induced switching between aggregated and nonaggregated states in coilringcoil block copolymers. *Macromolecules* **42**, 5900–5902 (2009).
- Larson, R. G. *The Structure and Rheology of Complex Fluids* (ed. Gubbins, K.E.) Ch. 5, 232–260 (Oxford University Press, New York, 1999).
- Brunsveld, L., Folmer, B. J. B., Meijer, E. W. & Sijbesma, R. P. Supramolecular polymers. *Chem. Rev.* **101**, 4071–4097 (2001).
- Borzsonyi, G., Beingsner, R. L., Yamazaki, T., Cho, J. Y., Myles, A. J., Malac, M., Egerton, R., Kawasaki, M., Ishizuka, K., Kovalenko, A. & Fenniri, H. Water-soluble J-type rosette nanotubes with giant molar ellipticity. *J. Am. Chem. Soc.* **132**, 15136–15139 (2010).
- Nieuwenhuizen, M. M. L., de Greef, T. F. A., van der Bruggen, R. L. J., Paulusse, J. M. J., Appel, W. P. J., Smulders, M. M. J., Sijbesma, R. P. & Meijer, E. W. Self-assembly of ureido-pyrimidinone dimers into one-dimensional stacks by lateral hydrogen bonding. *Chem. Eur. J.* **16**, 1601–1612 (2010).
- George, S. J. & Ajayaghosh, A. Self-assembled nanotapes of oligo(p-phenylene vinylene)s: sol–gel-controlled optical properties in fluorescent π -electronic gels. *Chem. Eur. J.* **11**, 3217–3227 (2005).
- Ikeda, M., Nobori, T., Schmutz, M. & Lehn, J. M. Hierarchical self-assembly of a bowl-shaped molecule bearing self-complementary hydrogen bonding sites into extended supramolecular assemblies. *Chem. Eur. J.* **11**, 662–668 (2005).

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