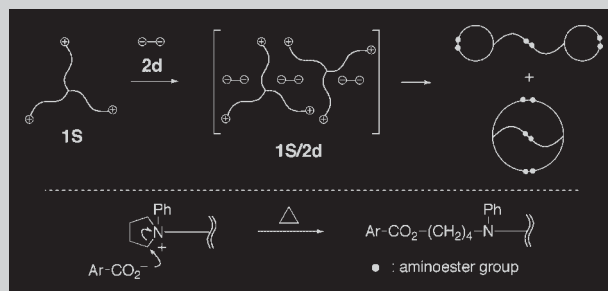


**Summary:** A pair of macromolecular constitutional isomers having topologically distinctive, dicyclic constructions, that is,  $\theta$ -shaped and manacle-shaped polymers, has been synthesized from a polymer self-assembly, comprised of three-armed star poly(tetrahydrofuran) [poly(THF)] having *N*-phenylpyrrolidinium salt end groups carrying dicarboxylate counteranions (**1S/2d**). The presence of the two constitutional polymeric isomers was confirmed by means of a reversed-phase liquid chromatography (RPC) technique. Moreover, size exclusion chromatography (SEC) showed that a major component possesses notably larger hydrodynamic volume than the others, and is assignable as a manacle-shaped isomer while a minor component is assigned as a  $\theta$ -shaped isomer. The statistics of the covalent-linking process of **1S/2d** were consistent with the other experimental results.



An “electrostatic self-assembly and covalent fixation” process of a trifunctional star-shaped precursor gives rise to  $\theta$ -shaped and manacle-shaped polymers.

# Synthesis of Polymeric Topological Isomers through Electrostatic Self-Assembly and Covalent Fixation with Star Telechelic Precursors<sup>a</sup>

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## Introduction

Novel macromolecular architectures comprised of monocyclic and polycyclic polymer units with optional free branches are of an increasing interest.<sup>[1–14]</sup> Besides a simple ring construction,<sup>[15]</sup> there exist three dicyclic polymer topologies,<sup>[16]</sup> that is, eight-shaped,<sup>[17]</sup>  $\theta$ -shaped,<sup>[18,19]</sup> and manacle-shaped<sup>[18,20]</sup> constructions. Attempts to realize such unusual polymer topologies are an ongoing challenge in synthetic polymer chemistry.<sup>[13,14]</sup> We have recently reported an “electrostatic self-assembly and covalent fixation” process by making use of specifically designed *linear* telechelic polymer precursors having moderately strained

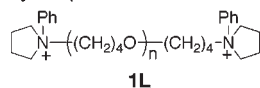
cyclic ammonium salt end groups carrying appropriately nucleophilic counteranions like carboxylates.<sup>[13,14,18–21]</sup> A variety of single cyclic and multicyclic, that is, such double-cyclics as eight-shaped,  $\theta$ -shaped, and a triple-cyclic trefoil-shaped, polymer constructions have been effectively produced by this methodology. In particular, two of the three dicyclic topologies, namely a pair of constitutional isomers of  $\theta$ -shaped and manacle-shaped polymers, are formed from an assembly comprised of *linear* bifunctional precursors (**1L**) and trifunctional carboxylates (**2t**), in which cations and anions balance the charges (see structures below and Scheme 1a).<sup>[18,20]</sup> They are identical in their molecular weights and in their chemical compositions, but distinctive in their topological connectivity, that is, topological isomers.<sup>[12,22,23]</sup> It is notable that such multicyclic, polymeric topological isomers are common products in the equimolar reaction of not only *linear* but also *branched* polymer precursors with polyfunctional end-linking reagents.<sup>[12]</sup> Moreover, the selective synthesis of  $\theta$ -shaped polymers has been achieved by a trifunctional star-shaped poly(THF) precursor (**1S**)<sup>[24]</sup>

<sup>a</sup> Supporting information (<sup>1</sup>H NMR spectra (S-Figure 1) of isolated  $\theta$ - and manacle-shaped polymers, obtained from **1S/2d**) for this article is available on the journal's homepage at <http://www.mrc-journal.de> or from the author.

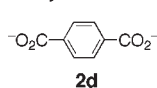
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carrying a trifunctional trimesate counteranion (See structures below and Scheme 1c).<sup>[19]</sup>

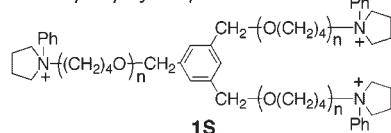
#### Linear polymer precursor



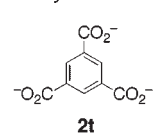
#### Dicarboxylate



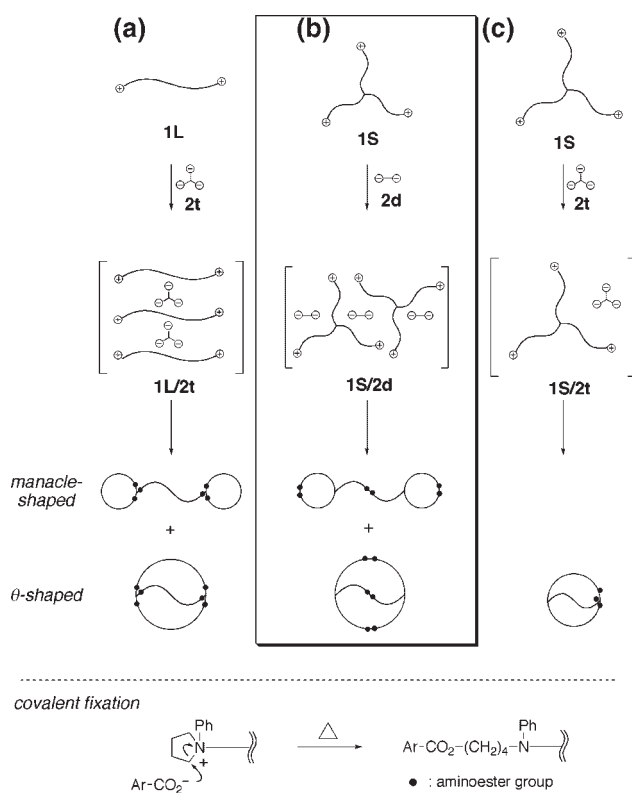
#### Star-shaped polymer precursor



#### Tricarboxylate



As the extension of these studies, we report here an alternative approach for a pair of polymeric constitutional isomers, that is,  $\theta$ -shaped and manacle-shaped polymers, from an assembly composed of a *trifunctional star-shaped* precursor through the “electrostatic self-assembly and covalent fixation” process (Scheme 1b). It is remarkable that the  $\theta$ - and manacle-shaped structures obtainable from linear and from three-armed star precursors are distinctive from each other with respect to the position of linking groups (aminoester groups) within their identical polymer framework (Scheme 1). New synthetic polymer materials having functional groups at the precise position within a topologically unique polymer framework could be considered as a prototype of relevant biological macromolecules having diverse and specific functions.



Scheme 1.

## Experimental Part

### Synthesis of Star Telechelic Precursors

A solution (1.0 mL) of a trifunctional star-shaped poly(THF) precursor carrying triflate counteranions<sup>[24]</sup> (0.400 g, 0.039 mmol) in tetrahydrofuran (THF) was added dropwise to an ice-cooled ( $<5^{\circ}\text{C}$ ) aqueous solution (120 mL) containing an excess amount of a sodium terephthalate (0.123 g, 10 equiv.) under vigorous stirring. After 1 h, the precipitated ion-exchange product **1S/2d** was collected by filtration and dried under vacuum for 1.5 h. This precipitation treatment was repeated three times to give **1S/2d**, with a yield of 0.370 g (containing a trace amount of residual water to avoid uncontrolled ring-opening reaction, with 92% ion-exchange yield).

<sup>1</sup>H NMR:  $\delta$  = 1.53–1.69 (m,  $\text{CH}_2\text{CH}_2\text{O}$ ), 1.92–2.05 (m, 6H, *endo*- $\text{NCH}_2\text{CH}_2$ ), 2.21–2.34 (m, 6H, *endo*- $\text{NCH}_2\text{CH}_2$ ), 3.31–3.55 (m,  $\text{CH}_2\text{CH}_2\text{O}$ ), 3.83–4.00 (m, 12H, *endo*-, *exo*- $\text{NCH}_2$ ), 4.48 (s, 6H,  $\text{ArCH}_2\text{O}$ ), 4.33–4.51 (m, 6H, *endo*- $\text{NCH}_2$ ), 7.20 (s, 3H,  $\text{Ar-H}$  *ortho* to  $\text{CH}_2\text{O}$ ), 7.45–7.61 (m, 15H,  $\text{NPh}$ ), 8.05 (s, 6H,  $\text{Ar-H}$  *ortho* to  $\text{CO}_2^-$ ).

### Synthesis of Topological Isomers

The polymeric topological isomers, comprised of  $\theta$ -shaped and manacle-shaped poly(THF)s, were prepared from **1S/2d** as in the following example. The ionic polymer precursor **1S/2d** (0.110 g) was dissolved in THF (550 mL,  $0.2\text{ g} \cdot \text{L}^{-1}$ ) and was heated to reflux (bath temp of  $90^{\circ}\text{C}$ ) for 3 h. The reaction solvent was removed by evaporation, and the recovered product (0.110 g) was further purified by preparative thin-layer chromatography ( $\text{SiO}_2$ , hexane/acetone = 2:1) to yield 0.106 g (97%) of a mixture of  $\theta$ -shaped and manacle-shaped poly(THF).

<sup>1</sup>H NMR:  $\delta$  = 1.46–1.71 (m,  $\text{CH}_2\text{CH}_2\text{O}$ ), 3.24–3.54 (m,  $\text{CH}_2\text{CH}_2\text{O}$ ), 4.37 (t,  $J$  = 6.0 Hz, 6H,  $\text{CO}_2\text{CH}_2$ ), 4.48 (s, 6H,  $\text{ArCH}_2\text{O}$ ), 6.61–6.68 (m, 9H,  $\text{Ar-H}$  *ortho* and *para* to  $\text{N}$ ), 7.13–7.26 (m, 9H,  $\text{Ar-H}$  *meta* to  $\text{N}$ , and  $\text{Ar-H}$  *ortho* to  $\text{CH}_2\text{O}$ ), 8.04 (s, 6H,  $\text{Ar-H}$  *ortho* to  $\text{CO}_2\text{CH}_2$ ).

### Measurements

Size exclusion chromatography (SEC) measurements were performed using a Tosoh Model CCPS equipped with a refractive index detector Model RI 8020, a UV detector Model UV 8020 at 254 nm, and a conductivity detector Model CM 8010. A column of either TSK G3000HXL or TSK G4000HXL was employed with THF as an eluent at a flow rate of  $1.0\text{ mL} \cdot \text{min}^{-1}$  at  $40^{\circ}\text{C}$ . SEC fractionation of the reaction product from **1S/2d** was performed by means of JAI Model LC-908W apparatus with a refractive index detector Model RI-5, and with a column set of JAIGEL-2H-F and JAIGEL-3H-F. The sample solution (3.0 mL containing 40 mg of the product) was injected and recycled before fractionation. The eluent was THF at a flow rate of  $3.5\text{ mL} \cdot \text{min}^{-1}$ . A stabilizer for the SEC eluent, that is, 2,6-di-*tert*-butyl-4-methylphenol, was removed by precipitation of the product into petroleum ether cooled at  $-78^{\circ}\text{C}$ . The recovered yield was 13 mg for the larger hydrodynamic volume fraction and 7 mg for the smaller hydrodynamic volume fraction, respectively. Reversed-phase

chromatography (RPC) measurements were conducted by an isocratic mode using a Tosoh Model CCPS equipped with a UV detector Model UV 8020 at 254 nm. A C18-bonded silica column of TSK ODS-80TS was employed with a mixture of THF/CH<sub>3</sub>CN (50:50, v/v) at 25 °C. <sup>1</sup>H NMR spectra were recorded with a JEOL JNM-AL300 apparatus in CDCl<sub>3</sub> at 40 °C. The proton chemical shifts (ppm) were referenced from a signal of tetramethylsilane.

## Results and Discussion

A polymer precursor/counteranion assembly, composed of *two* star-shaped, trifunctional polymer precursor having

*N*-phenylpyrrolidinium salt end groups carrying *three* bi-functional carboxylate as counteranions (**1S/2d**), was prepared by the precipitation of the poly(THF) precursor, carrying trifluoromethanesulfonate (triflate) counteranions, into an aqueous solution containing a terephthalate anion as a sodium salt form. The subsequent covalent conversion of **1S/2d** was conducted by heating under dilution at 0.2 g · L<sup>-1</sup> in THF. The recovered products were then purified by the preparative thin-layer chromatography (TLC) of silica gel to remove any residual ionic species. <sup>1</sup>H NMR of the isolated product (Figure 1) showed signals arising from ester methylene protons at 4.37 ppm as a triplet, indicating

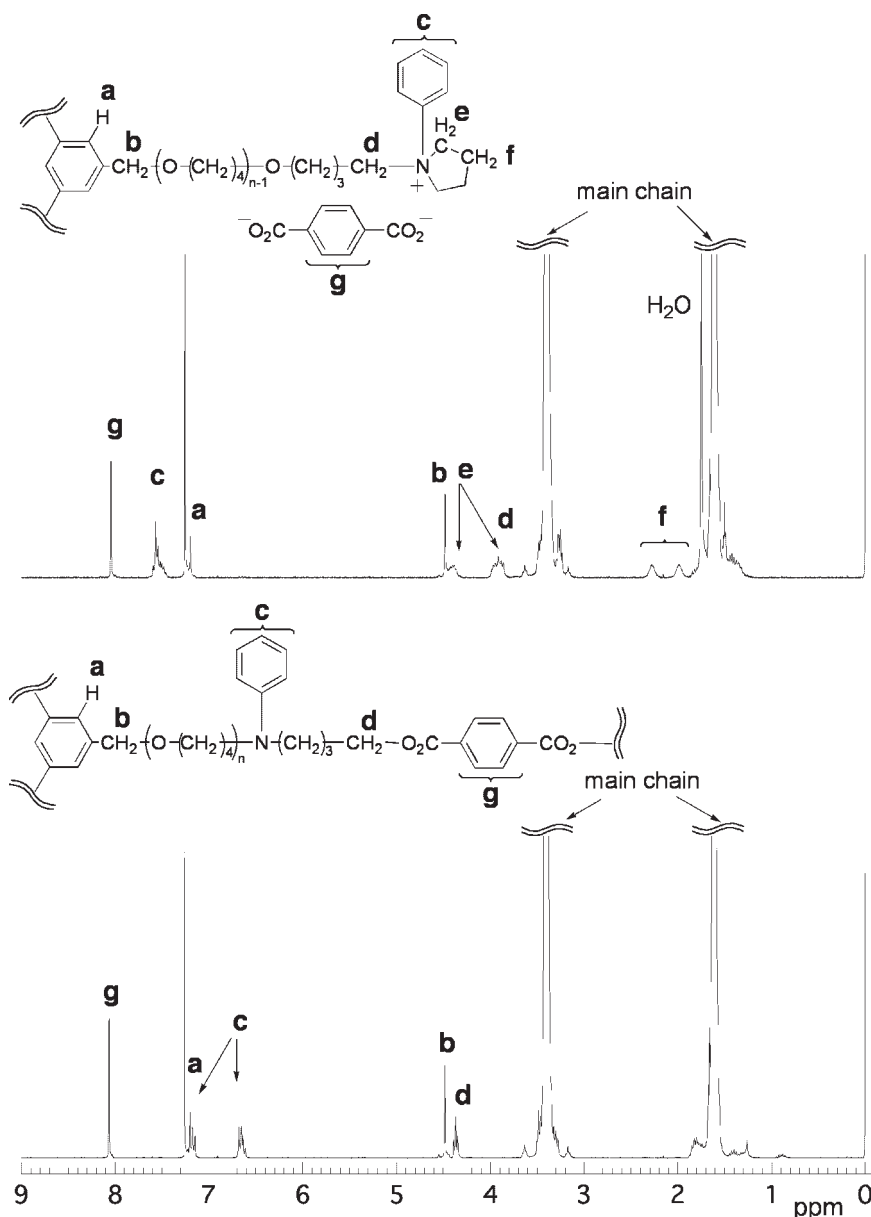


Figure 1. 300 MHz <sup>1</sup>H NMR spectra of the ion-exchange product of trifunctional poly(THF) with a terephthalate counteranion, **1S/2d**, before (top) and after (bottom) the heat treatment (sample; run 1 in Table 1, CDCl<sub>3</sub>, 40 °C).

a quantitative and selective ring-opening reaction of *N*-phenylpyrrolidinium salt groups<sup>[25]</sup> at the polymer precursor chain ends by terephthalate counteranions.

The SEC analysis of the product showed a main unimodal peak with a minor shoulder at smaller hydrodynamic volume region. (Figure 2[A] top). The hydrodynamic volume of the main peak, estimated from the apparent molecular weight by SEC, was notably smaller than that of the relevant linear polymer having the same molecular weight (Table 1). The formation of the contracted hydrodynamic-volume product, compared with the linear analogue, is consistent with the formation of the doubly cyclized  $\theta$ - and manacle-shaped polymers. The latter polymer is thought to be larger than the former in its three-dimensional size, since the manacle topology is apparently more linear in character compared with the  $\theta$ -topology.

The two components were subsequently separated by means of preparative recycling SEC technique (Figure 2[A] middle and bottom). <sup>1</sup>H NMR spectra of both components (see S-Figure 1 in Supporting Information) were coincident with each other, despite the noticeable difference in their hydrodynamic volumes. Thus, the observed  $\overline{DP}_n$  values for the larger and the smaller hydrodynamic volume components were 123 and 130, respectively, and are consistent with the  $\overline{DP}_n$  (125) for the product before fractionation (see Figure 1, bottom). Matrix-assisted laser desorption/ionization time-of-flight mass spectrometry (MALDI-TOF MS) measurements, on the other hand, have so far been unsuccessful, presumably because of ineffective ionization of the present products having the molecular weights of higher than  $10^4$ .

Moreover, RPC (Figure 2[B], top) analysis evidently showed that the reaction product is comprised of two components, as in the reaction of the relevant linear bifunctional precursor carrying trifunctional counteranions (**1L/2t**).<sup>[18,20]</sup> The larger and the smaller hydrodynamic volume fractions recovered by SEC fractionation do indeed correspond to the

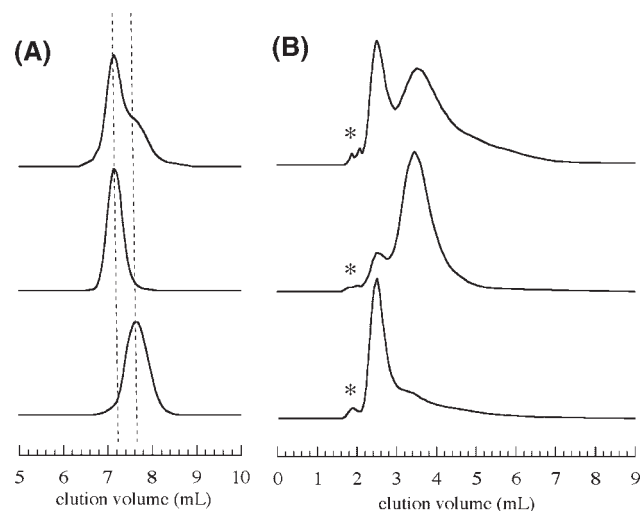


Figure 2. SEC (RI) and RPC (UV) traces ([A] and [B], respectively) of the product from trifunctional poly(THF) with a terephthalate counteranion, **1S/2d**, before (top) and after (middle and bottom) SEC fractionation (samples; run 2 in Table 1, SEC; TSK G4000HXL, eluent: THF,  $1.0 \text{ mL} \cdot \text{min}^{-1}$ , RPC; TSK ODS-80TS, eluent: THF/CH<sub>3</sub>CN (50:50, v/v), isocratic;  $1.0 \text{ mL} \cdot \text{min}^{-1}$ ). The peaks marked by an asterisk (\*) are those of unassigned fractions.

two components observed in the RPC chromatograms (Figure 2[B], middle and bottom).

As shown in Scheme 2, the manacle- and  $\theta$ -isomers will be produced in the ratio of 3:2 by the random and stepwise linking through the covalent conversion of the cationic precursor chain ends by terephthalate counteranions in **1S/2d**. In fact, the larger hydrodynamic volume component was predominant (>70%, even higher than the statistical 60%) regardless of the molecular weight of the polymer precursor (Table 1). Hence, we assigned the larger hydrodynamic volume component as a manacle-shaped isomer and the other, having a smaller hydrodynamic volume, as a

Table 1. Synthesis of manacle- and  $\theta$ -shaped poly(THF)s through electrostatic self-assembly and covalent fixation with three-armed star telechelic precursors (**1S**).

Run <sup>a)</sup>	$\overline{M}_n$ of <b>1S</b> <sup>b)</sup> $\times 10^{-3}$ c)	Isolated yield <sup>d)</sup> %	$\overline{M}_{p,SEC} \times 10^{-3}$ e)	$\overline{M}_{p,SEC}/\overline{M}_{n,NMR}$ <sup>f)</sup>	$\theta$ /manacle isomer ratio <sup>g)</sup>
1	7.7	72	10.8	0.70	23:77
2	10.2	97	14.1	0.69	30:70
3	11.7	92	16.4	0.70	21:79

<sup>a)</sup> Pyrrolidinium ring opening was performed in THF ( $0.2 \text{ g} \cdot \text{L}^{-1}$ ) at  $66^\circ\text{C}$  for 3 h.

<sup>b)</sup> See formulae above.

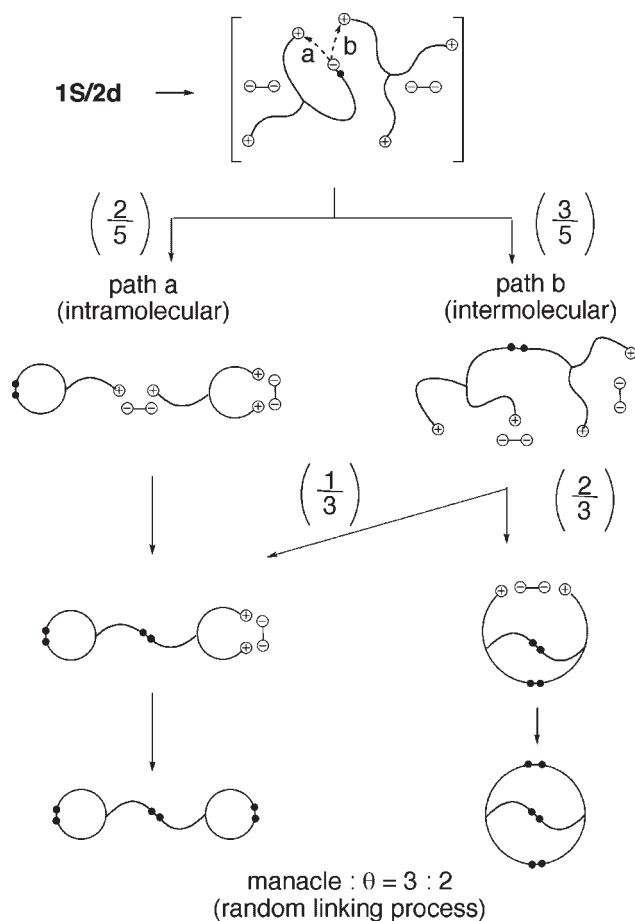
<sup>c)</sup> Determined by <sup>1</sup>H NMR spectroscopy based on the signal ratio between the end groups and the poly(THF) main chain.

<sup>d)</sup> Isolated yields after purification by preparative TLC.

<sup>e)</sup>  $\overline{M}_{p,SEC}$ : Apparent main peak molecular weight determined by SEC relative to linear polystyrene standards by a conversion factor of 0.556.<sup>[26]</sup>

<sup>f)</sup> A measure of the hydrodynamic volume ratio between manacle-shaped poly(THF), including a minor portion of  $\theta$ -shaped poly(THF), and their corresponding linear polymers. The  $\overline{M}_{p,NMR}$  is twice that of  $\overline{M}_n$  of **1S**.

<sup>g)</sup> Determined from reversed-phase chromatography.



Scheme 2.

$\theta$ -shaped isomer, respectively. It is also reasonable that the manacle-shaped product obtainable through an intramolecular polymer cyclization (**path a** in Scheme 2), could be further favored under dilution in the present covalent conversion of **1S/2d**, as was the previous case of **1L/2t**,<sup>[20]</sup> over the  $\theta$ -shaped product formed through an intermolecular polymer combination (**path b** in Scheme 2).

## Conclusion

We have constructed a pair of unusual macrocyclic polymer topologies through the “electrostatic self-assembly and covalent fixation” process with a novel three-armed star telechelic precursor. This strategy may offer novel polymer materials designed through topological control of the flexible polymer framework with the precise positioning of functional groups.

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