One-Pot Synthesis of Polyrotaxane by Clipping and Cyclopolymerization of α,ω-Diethynyl Isophthalamide with Pyridiniumdicarboxamide Chloride

TAKUYA ISONO,[1] TOSHIFUMI SATOH,[2] TOYOJI KAKUCHI[2]

[1]Graduate School of Chemical Sciences and Engineering, Hokkaido University, Sapporo 060-8628, Japan

[2]Division of Biotechnology and Macromolecular Chemistry, Faculty of Engineering, Hokkaido University, Sapporo 060-8628, Japan

Received 18 March 2011; accepted 27 April 2011
DOI: 10.1002/pola.24755
Published online 16 May 2011 in Wiley Online Library (wileyonlinelibrary.com).

ABSTRACT: The one-pot synthesis of a main chain-type polyrotaxane composed of axle molecules threaded through the macrocyclic units on the polymer main chain was achieved via the combination of cyclopolymerization and clipping procedures. The cyclopolymerization of an α,ω-diethynyl monomer bearing an isophthalamide moiety (**1**), which clips onto an axle component bearing a pyridiniumdicarboxamide moiety (**2**·**Cl**) through a chloride anion was carried out in chloroform with the monomer concentration of 0.06 mol L^{-1} at 40 °C using $[Rh(nbd)Cl]_2$/Et_3N as a catalyst to afford a gel-free polymer. The resulting polymer was assigned to the main chain-type polyrotaxane with a poly(phenylacetylene) backbone (poly-**3**·**Cl**) based on size exclusion chromatography and ^1H NMR measurements. The diffusion-order two-dimensional NMR and circular dichroism spectra provided definitive proof of the rotaxaned architecture in the polymer. The mole fraction of the rotaxane unit in the total cyclic repeating unit was determined to be 26.3%. © 2011 Wiley Periodicals, Inc. J Polym Sci Part A: Polym Chem 49: 3184–3192, 2011

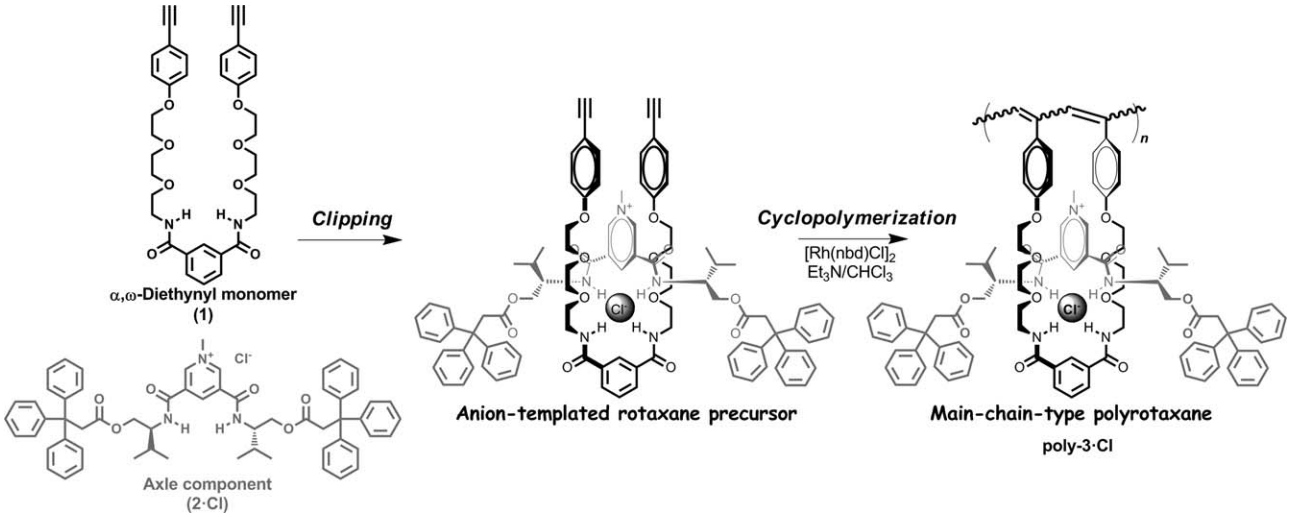
KEYWORDS: cyclopolymerization; polyrotaxanes; supramolecular structure

INTRODUCTION The polymeric rotaxane system, that is, polyrotaxane, features a mechanically interlocked macromolecular architecture.[1–6] The incorporation of dynamic mechanical bonds into polymers has allowed the development of high performance materials, such as a topological gel,[7] recyclable gel,[8] and molecular actuator.[9] Therefore, there have been many efforts dedicated to the molecular design and synthesis of polyrotaxanes. The most remarkable example is the cyclodextrin-based polyrotaxanes[10,11] with polymers as axle molecules. Harada et al.[12] have established a highly efficient protocol for the preparation of cyclodextrin-based polyrotaxanes, which allowed a variety of practical applications. In addition, Takata et al.[13] have accomplished the synthesis of various types of polyrotaxanes bearing crown ether moieties as the wheel components.[14–17] Recently, Stoddart et al.[9] synthesized an acid-base switchable polyrotaxane bearing a crown ether-based daisy chain structure. In these polyrotaxane syntheses, the synthetic strategy is composed of multistep reactions involving rotaxanation and polymer formation, in which functionalized macrocyclic compounds were required as the starting materials. Therefore, it is interesting to develop easy and simple methods for producing polyrotaxanes; for example, a method without using macrocycles.

To design the macrocycle-free synthetic strategy, we adopted the cyclopolymerization of α,ω-bifunctional monomers because of the formation of polymer chains and cyclic units at the same time. We previously succeeded in the synthesis of polymers bearing macrocyclic units on the main chain, polymeric macrocycles, by the cyclopolymerization of well-designed bifunctional monomers of α,ω-divinyl ether,[18,19] α,ω-diepoxide,[20,21] α,ω-diepisulfide,[22] α,ω-diisocyanate,[23] and α,ω-diynes.[24–29] Although these polymeric macrocycles are applicable as the wheel components of main chain-type polyrotaxanes, the rotaxanation process is still a remaining task. Thus, a one-pot synthetic methodology should be achieved by the rotaxanation during the formation of the polymeric macrocycle, that is, the combination of cyclopolymerization and rotaxanation. Finally, we designed an α,ω-bifunctional monomer as a wheel-precursor capable of clipping with an axle component before the cyclopolymerization.

Herein, we first report the one-pot synthesis using the cyclopolymerization and clipping techniques to produce polyrotaxanes composed of axle molecules threaded through the macrocyclic units on the polymer main chain, that is, main chain-type polyrotaxane. In this study, we used the chloride anion templation methodology[30–32] for the clipping of an axle component and a bifunctional monomer. A main chain-type polyrotaxane with a poly(phenylacetylene) backbone (poly-**3**·**Cl**) has been synthesized by *in situ* generation of the rotaxane precursor through the clipping of an α,ω-diethynyl

Additional Supporting Information may be found in the online version of this article. Correspondence to: T. Kakuchi (E-mail: kakuchi@poly-bm.eng.hokudai.ac.jp)
Journal of Polymer Science Part A: Polymer Chemistry, Vol. 49, 3184–3192 (2011) © 2011 Wiley Periodicals, Inc.



SCHEME 1 Combination of clipping and cyclopolymerization procedure.

monomer (**1**) and an axle component (**2·Cl**), followed by the Rh-catalyzed cyclopolymerization, as illustrated in Scheme 1. We investigated the cyclopolymerization of **1** using the $[Rh(nbd)Cl]_2/Et_3N$ catalyst system under a highly diluted condition in the presence of **2·Cl**. The obtained polymer was assigned to poly-**3·Cl** based on size exclusion chromatography (SEC) and NMR measurements. The rotaxaned structure of poly-**3·Cl** was confirmed by two-dimensional (2D) diffusion-order NMR spectroscopy (DOSY) and circular dichroism (CD) measurements.

EXPERIMENTAL

Materials

4-(4,6-Dimethoxy-1,3,5-triazin-2-yl)-4-methylmorpholinium chloride (DMT-MM),[33] 4-trimethylsilylethynylphenol,[34] and 3,3,3-triphenylpropanoyl chloride[35] were prepared by reported methods. 1,1,1,3,3,3-Hexafluoroisopropanol (HFIP) was supplied by the Central Glass Co. All other chemicals were purchased from commercial sources and used without further purification unless otherwise noted. Chloroform used for the polymerization was dried over $CaCl_2$ and distilled under an argon atmosphere. Triethylamine used for the polymerization was dried over CaH_2 and distilled under an argon atmosphere.

Instruments

The ^1H (400 MHz) and ^{13}C NMR (100 MHz) spectra were recorded using a JEOL JNM-A400II or JEOL JNM-ECS400 instrument. The 2D DOSY spectrum of poly-**3·Cl** was obtained in $CDCl_3$ (polymer concentration was 12.5 g L^{-1}) at 25 °C using a Bruker AMX500 (500 MHz). The DOSY experiment used the bipolar pulse pair and longitudinal eddy current delay sequence. The gradient was applied for 2 ms (δ/2), and the diffusion time (Δ) was 100 ms. The gradient settling time was 500 μs, and the eddy current elimination duration was 5 ms. Homospoil gradient was applied for 1 ms during the diffusion and eddy current settling durations. The gradient (g) was incremented 64 times from 1.14 to 54.15 G cm^{-1}, resulting in attenuation of the polymer resonance to approximately 47% of its original intensity. A total of 16 free induction decays containing 16 K points were collected at each gradient amplitude. The delay between each scan was 2 s, and 32 dummy scans were applied before the first data were collected. The SEC was performed at 40 °C using a Jasco high-performance liquid chromatography system (PU-980 Intelligent HPLC pump, CO-965 Column oven, RI-930 Intelligent RI detector, and Shodex DEGAS KT-16) equipped with a Shodex Asahipak GF-310 HQ column (linear, 7.6 × 300 mm^2; exclusion limit, 4×10^4) and a Shodex Asahipak GF-7 M HQ column (linear, 7.6 × 300 mm^2; exclusion limit, 4×10^7) in *N*,*N*-dimethylformamide (DMF) containing lithium chloride (0.01 mol L^{-1}) at the flow rate of 0.4 mL min^{-1}. The number-average molecular weight (M_n) and polydispersity (M_w/M_n) of the polymer were calculated based on a polystyrene calibration. The preparative SEC was performed in $CHCl_3$ (flow late, 3.5 mL min^{-1}) at ambient temperature using a JAI LC-9201 equipped with a JAI JAIGEL-3H column (20 × 600 mm^2; exclusion limit, 7×10^4) and a JAI RI-50s refractive index detector. The CD spectra were measured in a 1-mm path length cell using a Jasco J-720 spectropolarimeter. The optical rotations were measured in a 50-mm path length cell by a Jasco DIP-1000 digital polarimeter.

2-[2-(2-Aminoethoxy)ethoxy]ethanol

2-[2-(Chloroethoxy)ethoxy]ethanol (46.40 g, 275.2 mmol) and phthalimide potassium salt (51.00 g, 275.2 mmol) were dissolved in dry DMF (300 mL) and stirred for 19 h at 100 °C. After cooling to room temperature, the reaction mixture was filtered, and the filtrate was evaporated. The residue was dissolved in AcOEt (200 mL) and washed with water (200 mL), and the aqueous layer was extracted into AcOEt (100 mL × 3). The combined organic layer was dried over anhydrous Na_2SO_4, and evaporated to dryness to give a corresponding phthalimide derivative with satisfactory purity (60.86 g, 217.9 mmol) as pale yellow syrup. To a solution of the obtained material in EtOH (1.2 L), $NH_2NH_2{\cdot}H_2O$ (13.62 g, 272.1 mmol) and water (3.4 mL) were added, and the

solution was stirred for 3 h at reflux temperature. After cooling to room temperature, the reaction mixture was filtered, and the filtrate was evaporated to dryness. The residue was purified by vacuum distillation to give 2-[2-(2-aminoethoxy)ethoxy]ethanol as a colorless liquid.

Yield: 16.84 g (40.1% overall). b.p.: 112 °C/0.9 mmHg. Characterization of this compound has been reported.[36]

N^1,N^3-*Bis(2-(2-(2-hydroxyethoxy)ethoxy)ethyl)isophthalamide (4)*

DMT-MM (14.00g, 50.59 mmol) was added to a stirred solution of 2-[2-(2-aminoethoxy)ethoxy]ethanol (7.54 g, 50.54 mmol) and isophthalic acid (4.00 g, 24.08 mmol) in MeOH/tetrahydrofuran (THF) (100 mL/100 mL). After stirring for 5 h at room temperature, the solvent was removed. The resulting residue was dissolved in acetone, and the insoluble material was filtered off. The soluble part was evaporated to dryness. The crude product was purified by column chromatography on silica gel with AcOEt/MeOH (3/1, v/v) to give **4** as pale yellow syrup.

Yield: 7.53 g (73.0%). R_f = 0.19 (SiO_2, AcOEt/MeOH = 3/1). ^{1}H NMR (400 MHz, $CDCl_3$): δ 3.57 (m, 4H, CONH—CH_2—), 3.76–3.62 (m, 20H, —CH_2—), 7.53 (t, J = 11.3 Hz, 1H, isophthal), 7.66 (s, 2H, CON*H*), 8.08 (dd, J = 2.7, 11.7 Hz, 2H, isophthal), 8.26 ppm (s, 1H, isophthal). ^{13}C NMR (100 MHz, $CDCl_3$): δ 40.30 (CONH—*C*H_2—), 50.84 (HO—*C*H_2—), 61.61, 70.29, 70.34, 72.78 (—*C*H_2—), 125.04, 129.13, 131.18, 134.34 (isophthal), 167.37 ppm (*C*O). Anal. Calcd. for $(C_{20}H_{32}N_2O_8)_3{\cdot}(H_2O)$: C, 55.29; H, 7.58; N, 6.45; O, 30.69. Found: C, 55.35; H, 7.54; N, 6.65.

N^1,N^3-*Bis(2-(2-(2-(4-ethynylphenoxy)ethoxy)ethoxy)ethyl)-isophthalamide (1)*

An aqueous solution of NaOH (0.93 g, 22.6 mmol in 4.8 mL of water) was added to a stirred solution of **4** (3.39 g, 7.91 mmol) in THF (8 mL). The stirred solution was slowly added a solution of *p*-toluenesulfonyl chloride (3.06 g, 16.1 mmol) in THF (10 mL) at 0–5 °C over 1 h, and stirred for 2 h at this temperature. The reaction mixture was poured into water (120 mL), and partitioned with CH_2Cl_2 (250 mL). The organic layer was washed with water (150 mL × 3), dried over anhydrous Na_2SO_4, and evaporated to dryness to give the corresponding ditosylate as pale yellow syrup with satisfactory purity (4.87 g, 83.6%). The ditosylate (4.87 g, 6.61 mmol), 4-trimethylsilylethynylphenol (3.22 g, 19.6 mmol), K_2CO_3 (4.58 g, 33.1 mmol), and tetra-*n*-butylammonium bromide (0.11 g, 0.34 mmol) were suspended in dry THF (25 mL), and the mixture was stirred for 6 h at reflux temperature. After cooling to room temperature, methanol (10 mL) was added to the stirred reaction mixture to deprotect the trimethylsilyl group. After stirring for 1 h at room temperature, the reaction mixture was filtered, and the filtrate was evaporated. The residue was dissolved in CH_2Cl_2 (100 mL), then washed with water (100 mL × 3). The organic layer was dried over anhydrous Na_2SO_4 and then evaporated to dryness. The residue was purified by column chromatography on silica gel with AcOEt/MeOH (96/4, v/v) to yield **1** as pale yellow solid.

Yield: 2.13 g (51.3%). R_f = 0.23 (SiO_2, AcOEt/MeOH = 96/4). ^{1}H NMR (400 MHz, $CDCl_3$): δ 3.00 (s, 2H, Ph-C≡C*H*), 3.60-3.76 (m, 16H, −CH_2-), 3.85 (dd, J = 3.5, 5.9 Hz, 4H, Ph-O—CH_2CH_2—O—), 4.08 (dd, J = 3.3, 5.7 Hz, 4H, Ph-O—C$H_2$$CH_2$—O—), 6.78 (d, J = 8.8 Hz, 4H, phenyl), 6.90 (s, 2H, CON*H*), 7.34 (d, J = 8.8 Hz, 4H, phenyl), 7.42 (d, J = 7.3 Hz, 1H, isophthal), 7.88 (dd, J = 2.0, 7.8 Hz, 2H, isophthal), 8.18 ppm (s, 1H, isophthal). ^{13}C NMR (100 MHz, $CDCl_3$): δ 39.44 (CONH—*C*H_2—), 66.85 (Ph-O—*C*H_2—), 69.10, 69.25, 69.80, 70.28 (—*C*H_2—), 75.48 (Ph-C≡*C*H), 83.07 (Ph*C*≡CH), 113.89, 113.98 (phenyl), 124.95, 128.3, 129.48 (isophthal), 133.06 (phenyl), 134.27 (isopthal), 158.46 (phenyl), 166.12 (*C*O). Anal. Calcd. for $C_{36}H_{40}N_2O_8$: C, 68.77; H, 6.41; N, 4.46; O, 20.36. Found: C, 68.74; H, 6.35; N, 4.32.

N^3,N^5-*Bis((S)-1-hydroxy-3-methylbutan-2-yl)pyridine-3,5-dicarboxamide (5)*

DMT-MM (8.05 g, 29.1 mmol) was added to a stirred solution of L-valinol (3.00 g, 29.1 mmol) and 3,5-pyridinedicarboxylic acid (2.43 g, 14.5 mmol) in THF/MeOH (50 mL/50 mL). After stirring for 8 h at room temperature, the insoluble material in the reaction mixture was removed by filtration. The filtrate was evaporated, and the resulting residue was added acetone (50 mL). The insoluble material was removed again, and the soluble part was evaporated to dryness. The residue was purified by column chromatography on silica gel with AcOEt/MeOH (95/5, v/v → 85/15, v/v → 75/25, v/v) to give **5** as a white solid.

Yield: 3.29 g (67.1%). R_f = 0.19 (SiO_2, AcOEt/MeOH = 95/5). $[\alpha]_D$ = −33.9° (*c* 1.0, MeOH). ^{1}H NMR (400 MHz, DMSO-d_6): δ 0.88 [d, J = 6.8 Hz, 6 H, −CH (CH_3)$_2$], 0.89 [d, J = 6.8 Hz, 6 H, —CH (CH_3)$_2$], 1.93 [sex, J = 6.6 Hz, 2H, —C*H*(CH_3)$_2$], 3.53 (m, 4H, —CH_2—O*H*), 3.84 (m, 2H, HO—CH_2—C*H*—), 4.64 (t, 2H, OH), 8.36 (d, 2H, CON*H*), 8.59 (t, J = 1.9 Hz, 1H, py.), 9.10 ppm (d, J = 2.5 Hz, 2H, py.). ^{13}C NMR (100 MHz, DMSO-d_6): δ 19.73, 19.99 [—CH(*C*H_3)$_2$], 28.56 [—*C*H(CH_3)$_2$], 65.96 (HO—CH_2—*C*H—), 61.20 (HO—*C*H_2—CH—), 130.16, 134.19, 150.31 (py.), 164.68 ppm (*C*O). Anal. Calcd. for $(C_{17}H_{27}N_3O_4)_3{\cdot}(H_2O)$: C, 59.46; H, 8.12; N, 12.24; O, 20.19. Found: C, 59.51; H, 8.06; N, 12.30.

(2S,2′S)-((Pyridine-3,5-dicarbonyl)bis(azanediyl))bis(3-methylbutane-2,1-diyl)bis(3,3,3-triphenylpropanoate) (6)

5 (2.00 g, 5.93 mmol), 3,3,3-triphenylpropanoyl chloride (4.18 g, 13.0 mmol), and *N*,*N*-dimethyl-4-aminopyridine (0.036 g, 0.30 mmol) were dissolved in dry THF/triethylamine (20 mL/5 mL), then the solution was refluxed for 14 h. After cooling to room temperature, the reaction mixture was evaporated. The resulting residue was dissolved in CH_2Cl_2 (50 mL), and washed with 2 mol L^{-1} citric acid aq. (150 mL × 2), saturated $NaHCO_3$ aq. (150 mL), and water (150 mL). The organic layer was dried over anhydrous $MgSO_4$ and then evaporated to dryness. The residue was immersed in *n*-hexane, washed with *n*-hexane, and dried *in vacuo* to give **6** as a pale orange solid.

Yield: 4.63 g (86.2%). $[\alpha]_D$ = −22.9° (*c* 1.0, $CHCl_3$). ^{1}H NMR (400MHz, $CDCl_3$): δ 0.88 (d, J = 3.5 Hz, 6H, —CH(CH_3)$_2$), 0.89 (d, J = 3.5 Hz, 6H, −CH(CH_3)$_2$), 1.57 (sex, J = 6.8 Hz,

2H, —C*H*(CH_3)$_2$), 3.74 (q, 4H, —O(CO)CH_2C-Ph_3), 3.92 (m, 2H, —NH—CH—CH_2—O—), 3.97 (m, 2, —NH—C*H*—CH_2—O—), 4.13 (m, 2H, —NH—CH—CH_2—O—), 5.90 (d, 2H, N*H*), 7.09–7.28 (m, 30H, phenyl), 8.31 (t, 1H, py.), 8.94 (d, 2H, py.). ^{13}C NMR (100 MHz, $CDCl_3$): δ 19.11, 19.29 (—CH(*C*H_3)$_2$), 28.97 (—*C*H(CH_3)$_2$), 46.40 (—O(CO)*C*H_2C-Ph_3), 55.59 (—NH—*C*H—CH_2—O—), 64.38 (—NH—CH—*C*H_2—O—), 77.00 (—*C*—Ph_3), 126.35, 127.80, 129.00 (phenyl), 129.85, 133.73 (isophthal), 146.20 (phenyl), 150.37 (isophthal), 164.42 (NH*C*=O), 171.19 (O*C*=O). Anal. Calcd. for $C_{59}H_{59}N_3O_6$: C, 78.21; H, 6.56; N, 4.64; O, 10.59. Found: C, 77.95; H, 6.60; N, 4.17. FD-HRMS (m/z): calcd for $C_{59}H_{59}N_3O_6$ $[M]^+$, 905.4404; found, 905.4430.

1-methyl-3,5-bis(((S)-3-methyl-1-((3,3,3-triphenylpropanoyl)oxy)butan-2-yl)carbamoyl)pyridin-1-ium Iodide (2·I)

6 (4.10 g, 4.52 mmol) and methyl iodide (5.5 mL, 88 mmol) was dissolved in acetone (100 mL). After refluxing of the solution for 12.5 h, the solvent was removed by evaporation. The resulting residue was dried *in vacuo* to give **2·I** as a bright yellow solid.

Yield: 4.43 g (93.4%). $[\alpha]_D = -6.5°$ (c 1.0, $CHCl_3$). ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.87 (d, J = 6.6 Hz, 6H, —CH(C*H*$_3$)$_2$), 0.96 (d, J = 6.6 Hz, 6H, —CH(C*H*$_3$)$_2$), 2.02 (sex, J = 7.2 Hz, 2H, —C*H*(CH_3)$_2$), 3.82 (q, 4H, —O(CO)CH_2C-Ph_3), 3.94 (m, 2H, —NH—CH—CH_2—O—), 3.97 (m, 2, —NH—C*H*—CH_2—O—), 4.19 (m, 2H, —NH—CH—CH_2—O—), 4.22 (s, 3H, N^+-C*H*$_3$), 7.05-7.34 (m, 30H, phenyl), 8.41 (d, 2H, N*H*), 9.18 (s, 2H, py.), 9.51 (s, 1H, py.). ^{13}C NMR (100 MHz, $CDCl_3$): δ 19.44, 19.60 (—CH(*C*H_3)$_2$), 28.69 (—*C*H(CH_3)$_2$), 46.52 (—O(CO)*C*H_2C-Ph_3), 49.17 (N^+-*C*H_3), 55.58 (—NH—*C*H—CH_2—O—), 63.60 (—NH—CH—*C*H_2—O—), 77.00 (—*C*—Ph_3), 126.13, 127.79, 129.14 (phenyl), 134.40, 142.46 (isophthal), 146.07 (phenyl), 146.44 (isophthal), 160.88 (NH*C*=O), 171.32 (O*C*=O). Anal. Calcd. for $C_{60}H_{62}IN_3O_6$: C, 68.76; H, 5.96; I, 12.11; N, 4.01; O, 9.16. Found: C, 69.03; H, 5.98; N, 3.70.

1-methyl-3,5-bis(((S)-3-methyl-1-((3,3,3-triphenylpropanoyl)oxy)butan-2-yl)carbamoyl)pyridin-1-ium Chloride (2·Cl)

A solution of **2·I** (2.10 g, 2 mmol) in $CHCl_3$ (100 mL) was vigorously stirred with saturated NH_4Cl aq. (100 mL) for 30 min. The organic layer was separated and the procedure was further repeated five times. The organic layer was dried over anhydrous $MgSO_4$ and evaporated to dryness to give **2·Cl** as a pale brown solid.

Yield: 1.85 g (96.4%). $[\alpha]_D = +6.0°$ (c 1.0, $CHCl_3$). ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.86 (d, J = 6.6 Hz, 6H, —CH(C*H*$_3$)$_2$), 0.94 (d, J = 6.6 Hz, 6H, —CH(C*H*$_3$)$_2$), 1.97 (sex, 6.4 Hz, 2H, —C*H*(CH_3)$_2$), 3.76 (q, 4H, —O(CO)CH_2C-Ph_3), 3.89 (m, 2H, —NH—CH—CH_2—O—), 3.94 (m, 2, —NH—C*H*—CH_2—O—), 4.17 (s, 3H, N^+—C*H*$_3$), 4.17 (m, 2H, —NH—CH—CH_2—O—), 7.08-7.25 (m, 30H, phenyl), 9.20 (s, 2H, py.), 9.47 (d, 2H, N*H*), 10.41 (s, 1H, py.). ^{13}C NMR (100 MHz, $CDCl_3$): δ 19.06, 19.38 (—CH(*C*H_3)$_2$), 28.89 (—*C*H(CH_3)$_2$), 46.17 (—O(CO)*C*H_2C-Ph_3), 48.76 (N^+—*C*H_3), 55.58 (—NH—*C*H—CH_2—O—), 63.66 (—NH—CH—*C*H_2—O—), 77.20 (—*C*-Ph_3), 126.12, 127.76, 129.13 (phenyl), 135.58, 142.46 (isophthal), 146.12 (phenyl), 146.47 (isophthal), 160.79 (NH*C*=O), 171.63 (O*C*=O). Anal. Calcd. for ($C_{60}H_{62}ClN_3O_6$)$_3$·($CHCl_3$)$_2$: C, 70.32; H, 6.10; Cl, 10.26; N, 4.06; O, 9.26. Found: C, 70.58; H, 6.06; N, 3.75. FD-HRMS (m/z): calcd for $C_{60}H_{62}N_3O_6$ $[M - Cl]^+$, 920.4633; found, 920.4661.

Poly-1

The polymerization was carried out in a dry Schlenk flask, and the monomer and catalyst were dried overnight under high vacuum before the polymerization. A solution of $[Rh(nbd)Cl]_2$ (1.5 mg, 3.2 μmol) and dry Et_3N (44 μL, 3.3 mmol) in dry $CHCl_3$ (1.0 mL) was added to a stirred solution of **1** (100 mg, 0.159 mmol) in dry $CHCl_3$ (4.3 mL) under an argon atmosphere. This mixture was stirred for 24 h at room temperature, and the polymerization was terminated by adding an excess of triphenylphosphine. The solution was poured into a large amount of diethyl ether to precipitate the polymer. The precipitate was collected by filtration and dried *in vacuo* to give poly-**1** as a brown solid.

Yield: 88.1 mg (87.6%). $M_n = 22.0 \times 10^4$, $M_w/M_n = 4.8$. ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.7-4.2 (br, —CH_2—), 5.3–6.0 (br, =C*H*—), 6.0–7.0 (br, phenyl), 7.2–7.6 (br, isophthal), 7.7–8.0 (br, isophthal), 8.0–8.3 (br, isophthal).

General Procedure for the Synthesis of Poly-3·Cl

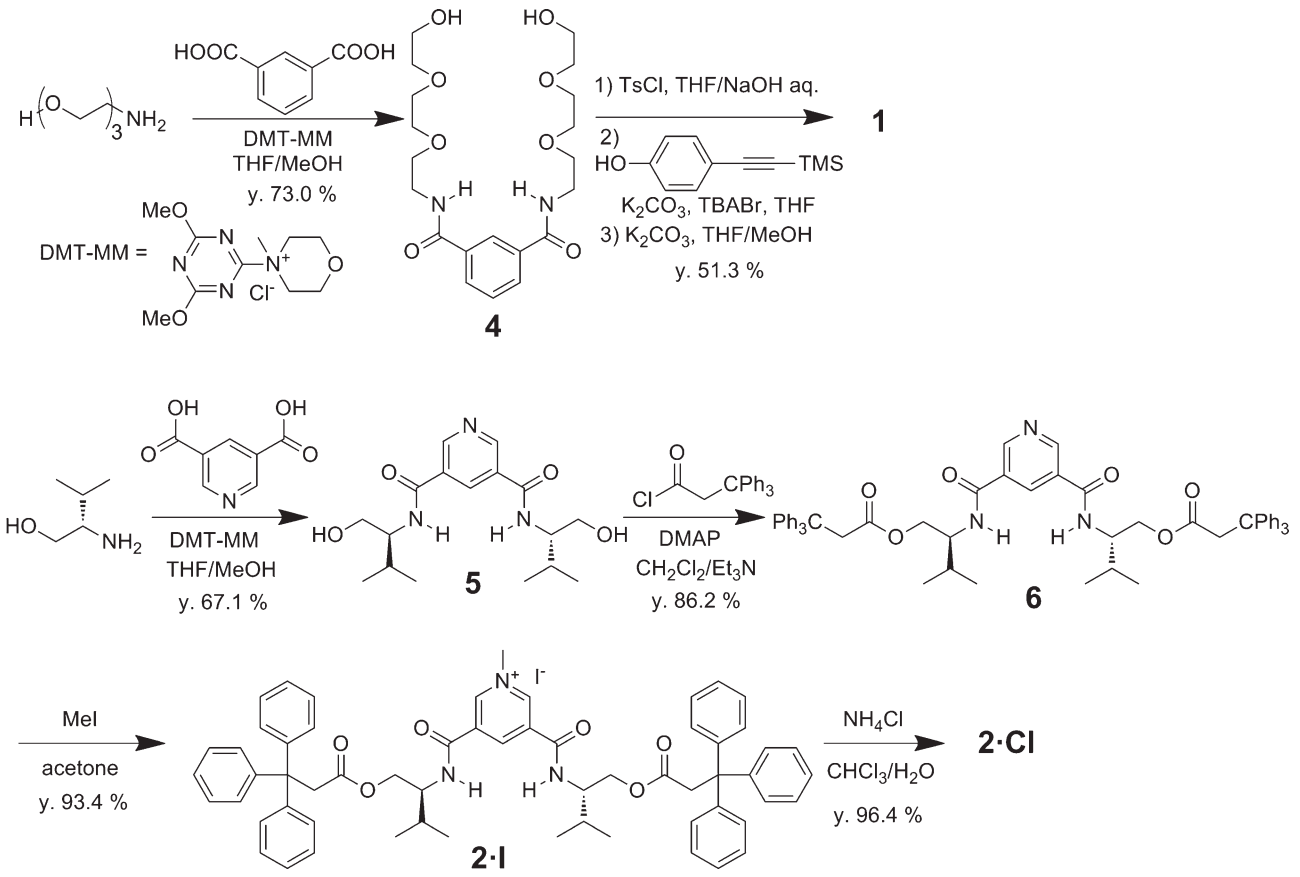
The polymerizations were carried out in a dry Schlenk flask, and the monomer, axle, and catalyst were dried overnight under high vacuum before the polymerization. A mixture of **1** (100 mg, 0.159 mmol) and **2·Cl** (152 mg, 0.159 mmol) in dry $CHCl_3$ (4.3 mL) was stirred, and then a solution of $[Rh(nbd)Cl)]_2$ (1.5 mg, 3.2 μmol) and dry Et_3N (44 μL, 32 mmol) in dry chloroform (1.0 mL) was added to this monomer solution under an argon atmosphere. After stirring for 24 h at room temperature, the polymerization was terminated by adding an excess of triphenylphosphine and then poured into a large amount of diethyl ether. The precipitate was filtered and dried *in vacuo* to give the crude poly-**3·Cl**. The crude material was purified by preparative SEC (eluent: chloroform) to give the pure poly-**3·Cl** as a brown solid. The absence of free **2·Cl** in the polymer was confirmed by an SEC measurement after the purification.

Yield: 45.2 mg (35.2%). $M_n = 9.7 \times 10^4$, $M_w/M_n = 1.5$. $[\alpha]_D = +129.5°$ (c 0.36, $CHCl_3$). ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.7–0.9 (br, —CH(C*H*$_3$)$_2$ derived from the axle component), 2.7–4.2 (br, —CH_2—, and methylene, methyne, N^+-C*H*$_3$ derived from the axle component), 5.3–6.0 (br, =C*H*—), 6.0–7.0 (br, phenyl), 7.0–7.3 (phenyl derived from the axle component), 7.7–8.0 (br, isophthal), 8.0–8.3 (br, isophthal).

RESULTS AND DISCUSSION

Monomer Design for Clipping

Several types of rotaxanes have been synthesized via a variety of template-directed clipping procedures. Among them, we selected the chloride anion templation,[30–32] which relies on the 1:1 association of an isophthalamide and a pyridiniumdicarboxamide chloride. On the basis of this concept, we designed and synthesized N^1,N^3-bis(2-(2-(2-(4-



SCHEME 2 Syntheses of **1** and **2·Cl**.

ethynylphenoxy)ethoxy)ethoxy)ethyl)isophthalamide (**1**) as the wheel-precursor and 1-methyl-3,5-bis(((*S*)-3-methyl-1-((3,3,3-triphenylpropanoyl)oxy)butan-2-yl)carbamoyl)pyridin-1-ium chloride (**2·Cl**) as the axle component, as shown in Scheme 1. The ethynyl group was chosen for **1** because the polymerization of ethynylphenyl derivatives, even though bearing a variety of polar groups, sufficiently occurred using the Rh catalyst. The triphenylmethyl group was used as a bulky blocking group for **2·Cl**. Scheme 2 describes the synthetic routes for **1** and **2·Cl**.

Before the polymerization, we confirmed the clipping between **1** and **2·Cl**. The ^{1}H NMR spectra of **1**, a 1:1 mixture of **1** and **2·Cl**, and **2·Cl** are shown in Figure 1. The downfield shift of the protons *c* and *d* for **1** and the slight upfield shift of the protons *h* and *i* for **2·Cl** are observed in Figure 1(b), indicating the hydrogen bonding of the amide protons with the chloride anion. These results are similar to that for the formation of the anion-templated *pseudo*rotaxane reported by Beer and coworkers.[37] These observations assured the formation of the anion-templated rotaxane precursor, that is, **1** clipped onto **2·Cl**.

Cyclopolymerization of 1 with 2·Cl

To clarify the polymerization property of **1**, the polymerization of **1** in the absence of **2·Cl** was conducted before the polyrotaxane synthesis. The polymerization of **1** using $[Rh(nbd)Cl]_2/Et_3N$ was carried out in chloroform at room temperature for 24 h ($[\mathbf{1}]_0 = 0.03$ mol L^{-1}, $[\mathbf{1}]_0/[\text{Rh cat.}]_0 = 50$, $[Et_3N]/[\text{Rh cat.}]_0 = 100$). The polymerization homogeneously proceeded to afford a gel-free polymer in 87.6% yield (run 1, Table 1). The obtained polymer showed a good solubility in organic solvents, such as chloroform, dichloromethane, and DMF. The M_n and M_w/M_n values were 22.0×10^4 and 4.8, respectively. In the ^{1}H NMR spectrum of the polymer [Fig. 2(b)], the signal at 3.0 ppm due to the ethynyl protons of **1** had completely disappeared, and the signal in the region from 5.4 to 5.9 ppm due to the proton of the cis-transoidal main chain appeared, indicating the extent of cyclization (f_c) of > 99%. These results strongly suggested that the polymerization of **1** proceeded through a cyclopolymerization mechanism leading to the poly(phenylacetylene) containing macrocycles as a constitutional repeating unit, poly-**1**, as shown in Scheme 3.

Based on this result, the polymerization of **1** in the presence of **2·Cl** was then carried out using $[Rh(nbd)Cl]_2/Et_3N$ (runs 2–5, Table 1). All the polymerizations homogeneously proceeded to give gel-free products. The crude products were separated into polymers, oligomeric products, and unused **2·Cl** using preparative SEC. The polymers were obtained as brown solids in 4.1–46.7% isolated yields with high molecular weights with M_ns of 4.1×10^4–12.0×10^4. These relatively low polymer yields should be caused by steric

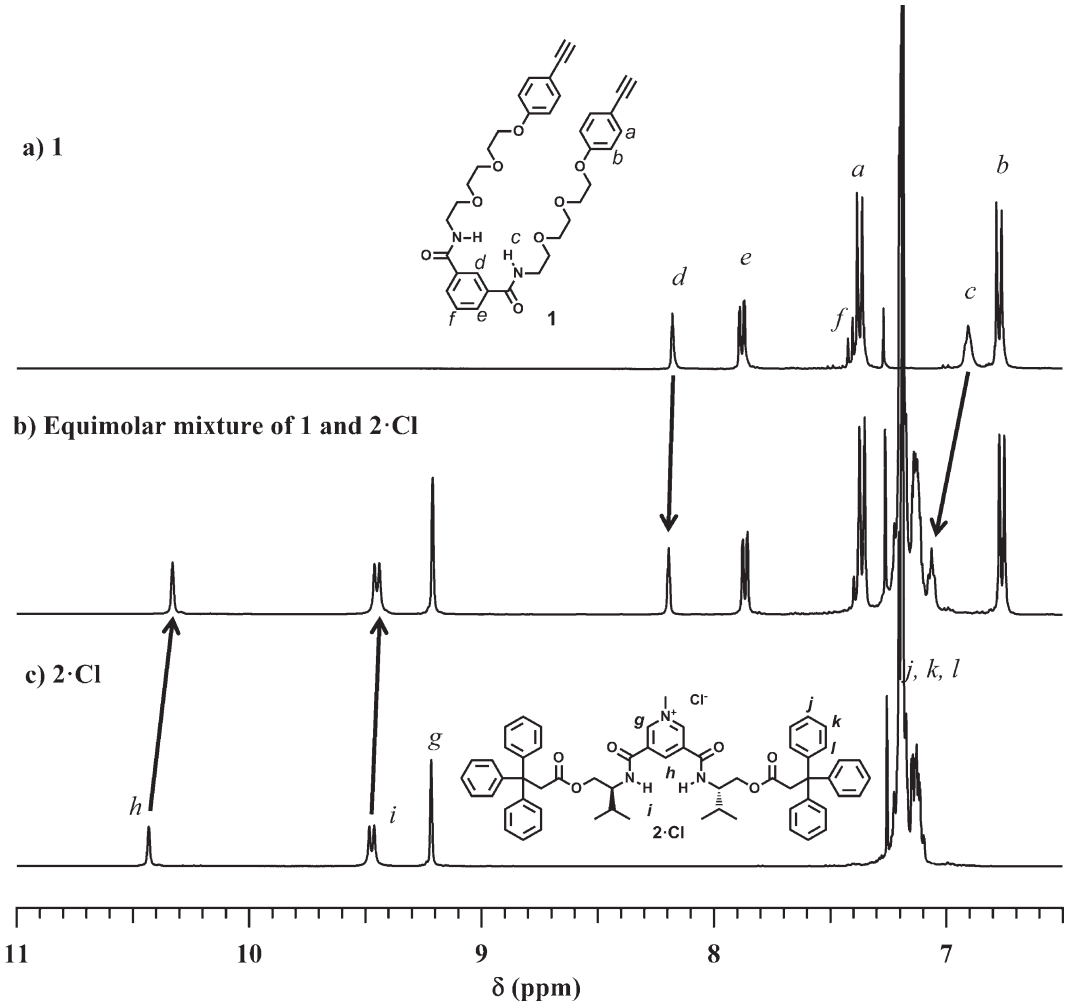


FIGURE 1 Partial ^{1}H NMR spectra of **1** (a), a 1:1 mixture of **2·Cl** and **1** (b), and **2·Cl** (c) in $CDCl_3$ (0.06 mol L^{-1}, r.t.).

hindrance of the rotaxane precursor. The solubility of the isolated polymers toward organic solvents was similar to that of poly-**1**.

The ^{1}H NMR spectrum of the isolated polymer [run 5, Fig. 2(c)] showed the absence of the ethynyl proton, indicating that the polymerization of **1** in the presence of **2·Cl** proceeded through a cyclopolymerization mechanism, that is, the f_c value was >99%. The ^{1}H NMR spectrum of the polymer closely resembled that of poly-**1** though new signals due to the isopropyl and triphenylmethyl groups for the axle component clearly appeared at 0.8 and 7.1–7.3 ppm, respectively. The mole fraction of the rotaxane unit toward the total cyclic repeating unit, R, could be estimated from the ^{1}H NMR spectrum, and the R value was 18.6∼26.3%. These

TABLE 1 Cyclopolymerizations of **1** in the Presence of **2·Cl** Using $[Rh(nbd)Cl]_2/Et_3N$[a]

Run	$[\mathbf{1}]_0$ (mol L^{-1})	$[\mathbf{2{\cdot}Cl}]_0/[\mathbf{1}]_0$	Temp. (°C)	Yield[b] (%)	$M_n \times 10^{-4}$ (M_w/M_n)[c]	R[d] (%)
1	0.03	None	r.t.	87.6	22.0 (4.8)	–
2	0.03	1	r.t.	35.2	9.7 (1.5)	18.6
3	0.06	1	r.t.	46.7[e]	12.0 (8.8)	19.7
4	0.06	3	r.t.	4.1	7.1 (1.8)	23.2
5	0.06	1	40	10.6	4.1 (1.4)	26.3

[a] Ar atmosphere; solvent, $CHCl_3$; $[\mathbf{1}]_0/[Rh\ cat.]_0 = 50$; $[Et_3N]/[Rh\ cat.]_0 = 100$; time = 24 h.
[b] Isolated yield using preparative SEC ($CHCl_3$).
[c] Determined by SEC in DMF containing 0.01 mol L^{-1} LiCl based on a PSt calibration.
[d] Determined by ^{1}H NMR measurement.
[e] Isolated yield using reprecipitation with ether/MeCN = 2/1.

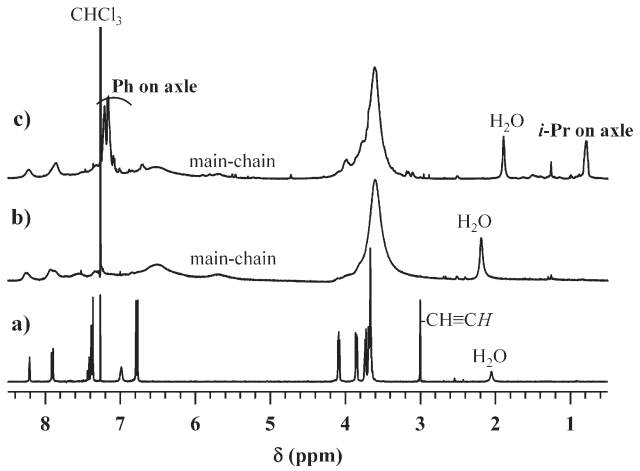
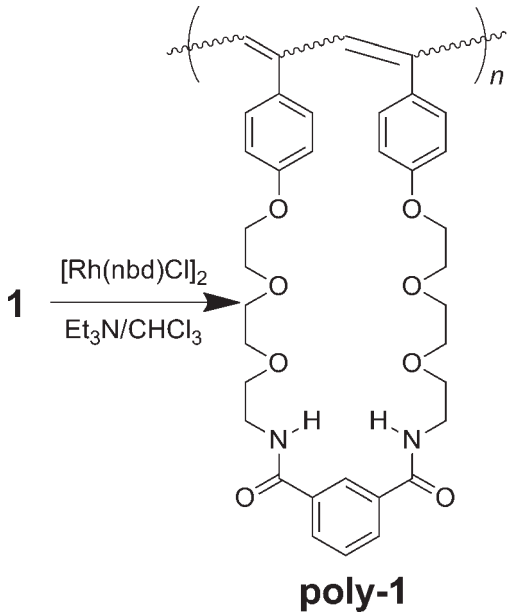


FIGURE 2 ^{1}H NMR spectra of **1** (a), poly-**1** (b), and poly-**3**·**Cl** (run 5) (c) in $CDCl_3$.

results strongly suggested that the desired main chain-type polyrotaxane, poly-**3**·**Cl**, was obtained.

We confirmed the rotaxane structure in poly-**3**·**Cl** by CD spectroscopy and DOSY. The CD spectral measurements were carried out for poly-**3**·**Cl** and a physical mixture of poly-**1** and **2**·**Cl** in HFIP (Fig. 3). The CD spectrum of a physical mixture of poly-**1** and **2**·**Cl** shows a Cotton effect in the absorption region of <300 nm, whereas poly-**3**·**Cl** shows a Cotton effect in the absorption region from 320 to 420 nm due to the polymer main chain. The result clearly indicated that the chirality in the polymer main chain was induced by the optically active axle component through the rotaxaned structure. For further evidence of the rotaxaned structure, a DOSY experiment was performed for poly-**3**·**Cl**. Zhao and Beckham applied the DOSY experiments to provide definitive proof of



SCHEME 3 Cyclopolymerization of **1**.

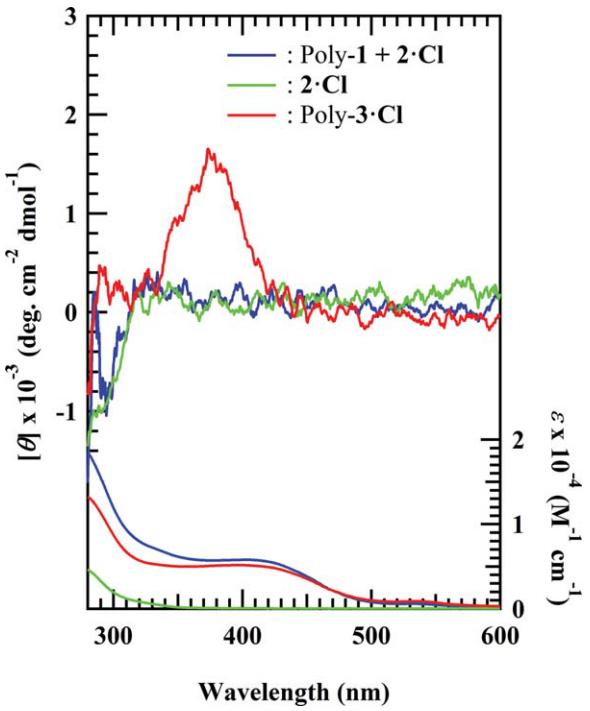


FIGURE 3 CD (upper) and absorption (lower) spectra of poly-**3**·**Cl** (run 3, 1.5 g L^{-1}), **2**·**Cl** (1 g L^{-1}), and a mixture of poly-**1** (1 g L^{-1}) and 1 equiv of **2**·**Cl** in HFIP at 25 °C.

the threading architecture in poly[(stylene)-*rotaxa*-(30-crown-10)][38] and poly[(ethylene glycol)-*rotaxa*-(α-cyclodextrin)].[39] Figure 4 depicts the DOSY spectrum of poly-**3**·**Cl** in $CDCl_3$. All the signals due to the polymer backbone as well as the axle component are correlated with a diffusion coefficient (D) of 1×10^{-10} m^2 s^{-1}. The agreement in the diffusion coefficients between the polymer backbone and the axle component definitely indicated that these two components moved together in solution, as required by a rotaxaned structure. In addition, we also checked the interlocked structure by breaking the chloride anion template. Poly-**3**·**Cl** was converted into poly-**3**·$\mathbf{PF_6}$ by adding $AgPF_6$, and a peak due to the free axle component was not found in its SEC trace (Supporting Information). The result demonstrated that the rotaxaned structure was maintained by the mechanically interlocked bond in the absence of the chloride anion template. Thus, we concluded that the main chain-type polyrotaxane could be synthesized by the clipping and cyclopolymerization of the bifunctional monomer and the axle component in a one-pot manner.

Generally, the monomer concentration affects the cyclopolymerization tendency. Thus, we carried out the polymerization of **1** by varying the monomer concentration of 0.03, 0.06, and 0.1 mol L^{-1} ($[\mathbf{2}\cdot\mathbf{Cl}]_0/[\mathbf{1}]_0 = 1$). Although the polymerization at the 0.1 mol L^{-1} monomer concentration gave a gel product, the R value was almost same as $R = 18.6\%$ for 0.03 mol L^{-1} (run 2) and $R = 19.7\%$ for 0.06 mol L^{-1} (run 3).

Furthermore, we carried out the polymerization by changing the $[\mathbf{2}\cdot\mathbf{Cl}]_0/[\mathbf{1}]_0$ and temperature. The R value slightly

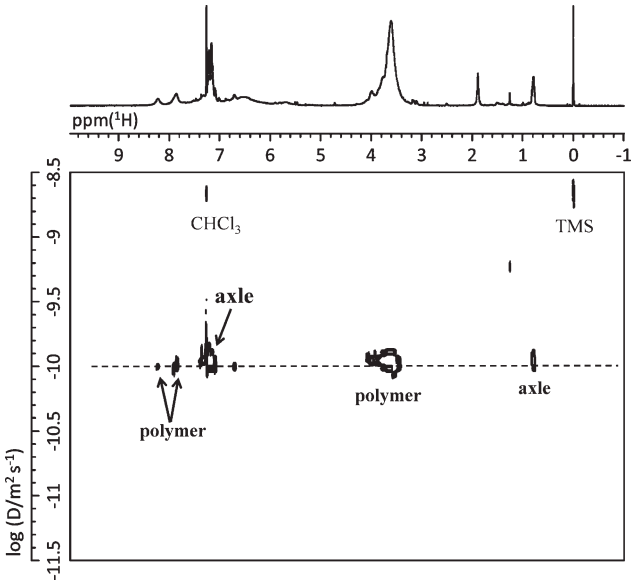


FIGURE 4 2D DOSY spectrum of poly-**3**·**Cl** (run 5) in $CDCl_3$ at 25 °C.

increased from 19.7 to 23.2% (runs 3 and 4, respectively) for the $[\mathbf{2}\cdot\mathbf{Cl}]_0/[\mathbf{1}]_0$ of 1 and 3 ($[\mathbf{1}]_0 = 0.06$ mol L^{-1}), and the polymer yield decreased from 46.7 to 4.1% with the increasing $[\mathbf{2}\cdot\mathbf{Cl}]_0/[\mathbf{1}]_0$. When the polymerization of **1** ($[\mathbf{1}]_0 = 0.06$ mol L^{-1}) was carried out at 40 °C ($[\mathbf{2}\cdot\mathbf{Cl}]_0/[\mathbf{1}]_0 = 1$, run 5), the *R* value reached 26.3%, which is the maximum value for this system. The *R* value was 6.5% higher than that obtained at r.t. The *R* value should mainly depend on the equilibrium of the complex formation between **1** and **2**·**Cl** in the solution and the rate of intramolecular cyclization. The increase in the polymerization temperature should cause the acceleration of the intramolecular cyclization rather than the prevention of the complex formation, resulting in the increase in the *R* value. However, triethylamine as the indispensable cocatalyst acted as an alternative hydrogen bond acceptor leaded to the decrease in the stability of the rotaxane precursor, resulting in the relatively low *R* value of about 20%.

CONCLUSIONS

We designed a novel one-pot strategy using the combination of cyclopolymerization and clipping procedures to afford the main chain-type polyrotaxane. The one-pot strategy was realized via the Rh-catalyzed cyclopolymerization of the α,ω-diethynyl monomer, N^1,N^3-bis(2-(2-(2-(4-ethynylphenoxy)ethoxy)ethoxy)ethyl)isophthalamide (**1**), which clipped onto the axle component, 1-methyl-3,5-bis(((*S*)-3-methyl-1-((3,3,3-triphenylpropanoyl)oxy)butan-2-yl)carbamoyl)pyridin-1-ium chloride (**2**·**Cl**), through the chloride anion templation. The cyclopolymerization of **1** using $[Rh(nbd)Cl]_2$ in the presence of **2**·**Cl** homogeneously proceeded to give gel-free polymers, which were assigned to the desired main chain-type polyrotaxane, poly-**3**·**Cl**, by the SEC and NMR measurements. The definitive proofs of the rotaxaned structure in poly-**3**·**Cl** was obtained from CD and DOSY measurements. The *R* value was insufficient as 26.3%, and we are now trying to achieve a higher *R* value by optimizing the monomer design using the other templation methodology, such as Stoddart's π stacking template[40] and Leigh's amide template.[41]

The authors thank Eri Fukushi (GC-MS and NMR Laboratory, Graduate School of Agriculture, Hokkaido University) for the measurements of the 2D DOSY spectrum.

REFERENCES AND NOTES

1 Harada, A.; Hashidzume, A.; Yamaguchi, H.; Takashima, Y. Chem Rev 2009, 109, 5971–6023.

2 Huang, F.; Gibson, H. W. Prog Polym Sci 2005, 30, 982–1018.

3 Gibson, H. W.; Bheda, M. C.; Engen, P. T. Prog Polym Sci 1994, 19, 843–945.

4 Harada, A. Acta Polym 1998, 49, 3–17.

5 Takata, T.; Kihara, N.; Furusho, Y. Adv Polym Sci 2004, 171, 1–75.

6 Harada, A. Acc Chem Res 2001, 34, 456–464.

7 Okumura, Y.; Ito, K. Adv Mater 2001, 13, 485–487.

8 Oku, T.; Furusho, Y.; Takata, T. Angew Chem Int Ed 2004, 43, 966–969.

9 Fang, L.; Hmadeh, M.; Wu, J.; Olson, M. A.; Spruell, J. M.; Trabolsi, A.; Yang, Y.-W.; Elhabiri, M.; Albrecht-Gray, A.-M.; Stoddart, J. F. J Am Chem Soc 2009, 131, 7126–7134.

10 Harada, A.; Takashima, Y.; Yamaguchi, H. Chem Soc Rev 2009, 38, 875–882.

11 Wenz, G.; Han, B.-H.; Müller, A. Chem Rev 2006, 106, 782–817.

12 Harada, A. Li, J.; Kamachi, M. Nature 1992, 356, 325–327.

13 Takata, T.; Kawasaki, H.; Kihara, N.; Furusho, Y. Macromolecules 2001, 34, 5449–5456.

14 Sato, T.; Takata, T. Macromolecules 2008, 41, 2739–2742.

15 Sasabe, H.; Inomoto, N.; Kihara, N.; Suzuki, Y.; Ogawa, A.; Takata, T. J Polym Chem Part A: Polym Chem 2007, 45, 4154–4160.

16 Lee, Y.-G.; Koyama, Y.; Yonekawa, M.; Takata, T. Macromolecules 2010, 43, 4070–4080.

17 Oku, T.; Furusho, Y.; Takata, T. J Polym Sci Part A: Polym Chem 2003, 41, 119–123.

18 Kakuchi, T.; Haba, O.; Yokota, K. Macromolecules 1992, 25, 4854–4858.

19 Kakuchi, T.; Aoki, K.; Haba, O.; Yokota, K. Polym J 1993, 25, 839–845.

20 Hashimoto, H.; Kakuchi, T.; Haba, O.; Yokota, K. Macromolecules 1992, 25, 1828–1831.

21 Kakuchi, T.; Hashimoto, H.; Harada, Y.; Satoh, T.; Yokota, K. J. Macromol Sci Pure Appl Chem 1994, A31, 751–759.

22 Yokota, K.; Hashimoto, H.; Kakuchi, T.; Takada, Y. Makromol Chem Rapid Commun 1984, 5, 767–770.

23 Sakai, R.; Satoh, T.; Kakuchi, R.; Kaga, H.; Kakuchi, T. Macromolecules 2004, 37, 3996–4003.

24 Kakuchi, T.; Kamimura, H.; Matsunami, S.; Yokota, K. Macromolecules 1995, 28, 658–660.

25 Kakuchi, T.; Watanabe, T.; Kamimura, H.; Matsunami, S.; Yokota, K. Polymer 1996, 37, 3767–3769.

26 Kakuchi, T.; Watanabe, T.; Matsunami, S.; Kamimura, H.; Haba, O.; Yokota, K. Polymer 1997, 38, 1233–1238.

27 Kakuchi, R.; Sakai, R.; Otsuka, I.; Satoh, T.; Kakuchi, T. Macromolecules 2005, 38, 9441–9447.

28 Sakai, R.; Yonekawa, T.; Otsuka, I.; Kakuchi, R.; Satoh, T.; Kakuchi, T. J Polym Sci Part A: Polym Chem 2010, 48, 1197–1206.

29 Prata et al. independently reported the cyclopolymerizations of calix[4]arene compounds bearing two ethynylphenyl moieties to afford calixarene-based poly(phenylacetylene)s: Costa, A. I.; Prata, J. J Polym Sci Part A: Polym Chem 2006, 44, 7054–7070.

30 Wisner, J. A.; Beer, P. D.; Drew, M. G. B.; Sambrook, M. R. J Am Chem Soc 2002, 124, 12469–12476.

31 Sambrook, M. R.; Beer, P. D.; Lankshear, M. D.; Ludlow, R. F.; Wisner, J. A. Org Biomol Chem 2006, 4, 1529–1538.

32 Vickers, M. S.; Beer, P. D. Chem Soc Rev 2007, 36, 211–225.

33 Kunishima, M.; Kawachi, C.; Morita, J.; Terao, K.; Iwasaki, F.; Tani, S. Tetrahedron 1999, 55, 13159–13170.

34 Mohamed, M. S.; Mori, A. Tetrahedron 2004, 60, 9977–9982.

35 Gibson, H. W.; Liu, S.; Lecavalier, P.; Wu, C.; Shen, Y. X. J Am Chem Soc 1995, 117, 852–874.

36 Sato, H.; Hayashi, E.; Yamada, N.; Yatagai, M.; Takahara, Y. Bioconjugate Chem 2001, 12, 701–710.

37 Wisner, J. A.; Beer, P. D.; Drew, M. G. B. Angew Chem Int Ed 2001, 40, 3606–3609.

38 Zhao, T.; Beckham, H. W.; Gibson, H. W. Macromolecules 2003, 36, 4833–4837.

39 Zhao, T.; Beckham, H. W. Macromolecules 2003, 36, 9859–9865.

40 Anelli, P. L.; Ashton, P. R.; Ballardini, R.; Balzani, V.; Delgado, M.; Gandolfi, M. T.; Goodnow, T. T.; Kaifer, A. E.; Philp, D.; Pietraszkiewicz, M.; Prodi, L.; Reddington, M. V.; Slawin, A. M. Z.; Spencer, N.; Stoddart, J. F.; Vicent, C.; William, D. J. J Am Chem Soc 1992, 114, 193–218.

41 Gatti, F. G.; Leigh, D. A.; Nepogodiev, S. A.; Slawin, A. M. Z.; Teat, S. J.; Wong, J. K. Y. J Am Chem Soc 2001, 123, 5983–5989.