Articles

Synthesis and Properties of Glutamic Acid-Derived Optically Active Phenyleneethynylene-Based Helical Polymers

Ruiyuan Liu, Fumio Sanda,* and Toshio Masuda*,†

Department of Polymer Chemistry, Graduate School of Engineering, Kyoto University,
Katsura Campus, Kyoto 615-8510, Japan

Received March 27, 2008; Revised Manuscript Received May 19, 2008

ABSTRACT: Di(iodophenyl)-substituted L-glutamic acid-derived benzenetetracarboxylic diimide (**1**) was synthesized, and the polycondensation of **1** with *p*-/*m*-diethynylbenzenes (**2p/2m**) was carried out to obtain optically active phenyleneethynylene-based polymers carrying ester-protected carboxy groups [poly(**1-2p**) and poly(**1-2m**)] with M_n's in the range from 6500 to 37 600 in 84−96% yields. The polymers were satisfactorily converted into the corresponding polymers [poly(**1-2p**)′ and poly(**1-2m**)′] with free carboxy groups by alkaline hydrolysis. The polymer structures were characterized by IR, NMR, UV, and CD spectroscopies. All the polymers exhibited intense CD signals, indicating that they formed helices with predominantly one-handed screw sense. The helical structures of the polymers were stable against heat. *Para*-linked poly(**1-2p**) carrying ester-protected carboxy groups and poly(**1-2p**)′ carrying free carboxy groups formed helices with opposite predominant helical senses each other, while their *meta*-linked counterparts [poly(**1-2m**) and poly(**1-2m**)′] formed helices with the same screw sense. Poly(**1-2p**)′ lost the one-handed helicity by the addition of KOH, and the resultant polymer recovered the original conformation upon HCl addition. On the other hand, poly(**1-2m**)′ kept stable by KOH addition.

Introduction

Poly(phenyleneethynylene)s have attracted much attention owing to photo- and electroluminescence properties, nonlinear optical properties, and supramolecular organization.[1] *Meta*-linked poly(phenyleneethynylene)s are likely to form a helix due to the bended backbone. For example, oligo(*m*-phenyleneethynylene)s with short ethylene glycol chains fold into a helical conformation, which is thermodynamically driven by solvophobic effects.[2] Amphiphilic poly(*m*-phenyleneethynylene)s undergo conformational transition that is consistent with folding of the main chains into a helix.[3] *m*-Phenyleneethynylene-based polyelectrolytes take a helical structure in aqueous solution.[4] Poly(*m*-ethynylpyridine)s bind saccharides to form helical complexes.[5] The helical structures of most *meta*-linked poly(phenyleneethynylene)s are susceptible to external stimuli such as heating and solvent.[6] Thus, several helical poly(phenyleneethynylene)s carrying chiral side chains have been synthesized, while phenyleneethynylene-based helical polymers with stereogenic centers in the main chain have been scarcely reported so far.[7] The latter type of polymers may be preferable from the viewpoint of helicity induction because the polymer backbone itself has chirality, which makes the direct control of the helical structure possible.

Meanwhile, amino acids are not only biologically important but also useful substances for chiral auxiliaries and building blocks in organic synthesis. Amino acid-based synthetic polymers are expected to show biocompatibility and biodegradability similarly to those of polypeptides and form secondary structures such as helices.[8] Helical poly(phenylacetylene) derivatives carrying amino acid moieties exhibit self-assembling properties, formation of superhelical fibers, and chirality transcription, liquid crystalline properties based on the regulated secondary structure.[9] We have synthesized a series of helical amino acid-based poly(*N*-propargylamide)s that transform the structure from a helix to a random coil and/or invert the helical sense according to external stimuli such as photoirradiation,[10] heat, solvent,[11] acid,[12] and base.[13] In the course of our study on a series of substituted helical polyacetylenes, we have been convinced that amino acid is an effective chiral source, and carboxy groups endow the polymers pH responsiveness.

Herein, we wish to construct a benzenetetracarboxylic diimide moiety from an amino acid to obtain optically active one and use it as a component of the main chain of phenyleneethynylene-based polymers. It is expected that the optically active benzenetetracarboxylic diimide moiety makes the polymer backbone rigid and twisted regularly, leading to a helix even though the main chain conjugation is lost. Benzenetetracarboxylic diimide is a rigid electron-withdrawing group and gathers interest in electrooptical and supramolecular chemistry fields. Because of the extended π-surface, benzenetetracarboxylic diimide causes charge transfer interaction with aromatics to form π-associated molecular assemblies exhibiting photophysical and redox functions.[14] Benzenetetracarboxylic diimide plays an important role in the design of supramolecular architectures, such as catenanes,[15] rotaxanes,[16] and macrocycles.[17]

The present study deals with the synthesis and examination of the secondary structures of novel phenyleneethynylene-based polymers consisting of glutamic acid-derived benzenetetracarboxylic diimide moieties in the main chain (Scheme 1). It discloses the responsiveness of chain helicity to heating and pH change.

---

* To whom all correspondence should be addressed. E-mail: sanda@adv.polym.kyoto-u.ac.jp, masuda@fukui-ut.ac.jp.

† Present address: Department of Environmental and Biotechnological Frontier Engineering, Faculty of Engineering, Fukui University of Technology, 3-6-1 Gakuen, Fukui 910-8505, Japan.

10.1021/ma800674f CCC: $40.75

Scheme 1. Polycondensation of 1 with 2p and 2m and Alkaline Hydrolysis of Ester Moieties of the Obtained Polymers

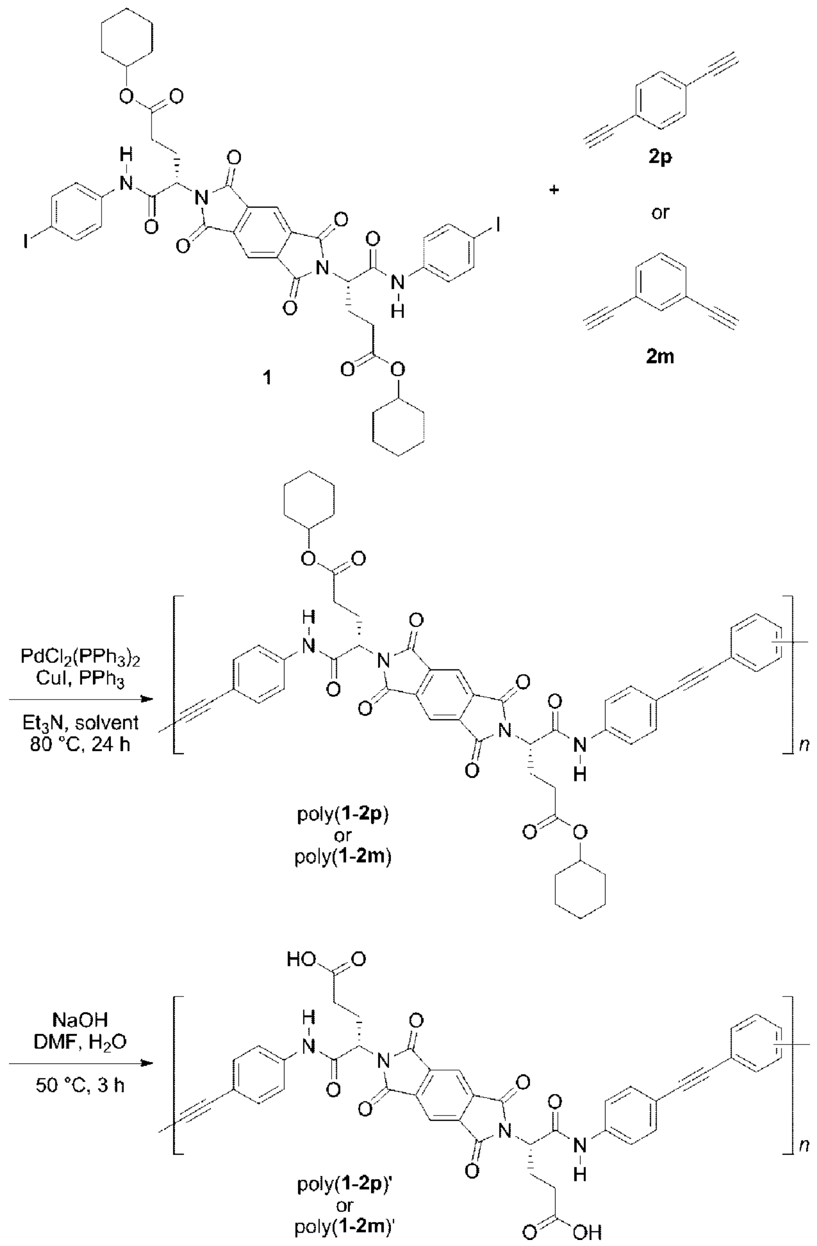


Table 1. Polycondensation of 1 with 2p and 2m[a]

run	monomer	solvent	yield[b] (%)	M_n[c]	M_w/M_n[c]
1	**1 + 2p**	DMF	86	32 500	2.47
2	**1 + 2p**	DMSO	91	37 600	1.51
3	**1 + 2p**	toluene	95	6 500	2.56
4	**1 + 2m**	DMF	84	24 500	1.37
5	**1 + 2m**	DMSO	89	26 500	1.31
6	**1 + 2m**	toluene	96	7 700	2.84

[a] Conditions: [**1**] = [**2**] = 0.2 M, [$PdCl_2(PPh_3)_2$] = 0.01 M, [CuI] = 0.005 M, [PPh_3] = 0.02 M, solvent/Et_3N = 3/2 (v/v), 80 °C, 24 h. [b] MeOH-insoluble part. [c] Determined by GPC eluted with LiBr solution in DMF (10 mM) calibrated by polystyrene standards.

Table 2. Alkaline Hydrolysis of Poly(1-2p) and Poly(1-2m)[a]

polymer[b]	yield[c] (%)	M_n[d]	M_w/M_n[d]
poly(**1-2p**)	82	3500	1.51
poly(**1-2m**)	86	3000	1.48

[a] Conditions: NaOH 3.6 equiv in DMF/H_2O =1/1 (v/v), 50 °C, 3 h. [b] Samples obtained by the polycondensation in DMF. [c] H_2O-insoluble part. [d] Determined by GPC eluted with LiBr solution in DMF (10 mM) calibrated by polystyrene standards.

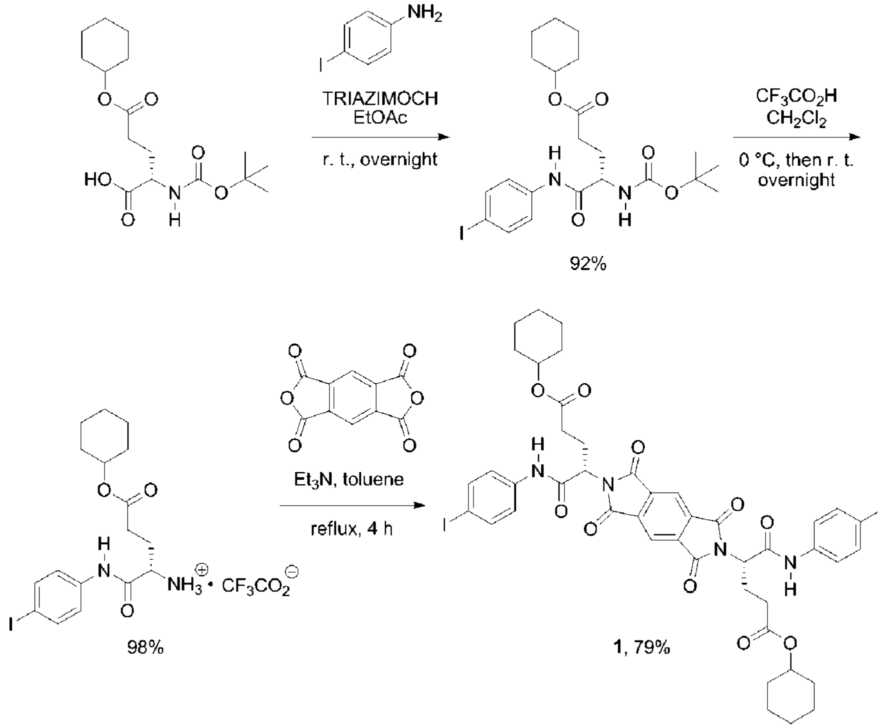
Experimental Section

Measurements. ^1H (400 MHz) and ^{13}C (100 MHz) NMR spectra were recorded on a JEOL EX-400 spectrometer. IR spectra were measured on a JASCO FTIR-4100 spectrophotometer. The number- and weigh-average molecular weights (M_n and M_w) of polymers were determined by gel permeation chromatography (GPC) on a Jasco Gulliver system (PU-980, CO-965, RI-930, and UV-1570) equipped with polystyrene gel columns (Shodex columns K804, K805, and J806), using DMF as an eluent calibrated by polystyrene standards at 40 °C. Melting points (mp) were measured on a Yanaco micro-melting point apparatus. Elemental analysis was performed at the Microanalytical Center of Kyoto University. Specific rotations ($[\alpha]_D$) were measured on a JASCO DIP-1000 digital polarimeter. CD and UV−vis spectra were recorded on a JASCO J-820 spectropolarimeter. Dynamic light scattering (DLS) measurements were performed on a Viscotek 802DLS equipped with a 50 mW fiber coupled diode laser (830 nm), using omniSIZE 3.0 software.

Materials. DMF, DMSO, toluene, and Et_3N used for polymerization were distilled over CaH_2 prior to use. All other reagents were commercially obtained and used as received without purification.

Synthesis of Di(iodophenyl)-Substituted L-Glutamic Acid-Derived Benzenetetracarboxylic Diimide (1). *N*-α-*tert*-Butoxy-

Scheme 2. Synthesis of 1



carbonyl-*O*-cyclohexyl-L-glutamic acid (6.59 g, 20 mmol) and 4-iodoaniline (4.38 g, 20 mmol) were dissolved in AcOEt (200 mL), and the resulting solution was stirred at room temperature for 10 min. 4-[4,6-Dimethoxy-1,3,5-triazine-2-yl]-4-methylmorpholinium chloride [TRIAZIMOCH (Tokuyama) 5.6 g, 20 mmol] was added to the solution, and the resulting mixture was stirred at room temperature overnight. The mixture was subsequently washed with 0.5 M HCl, saturated aqueous $NaHCO_3$, and saturated aqueous NaCl, dried over anhydrous $MgSO_4$, and concentrated on a rotary evaporator. The residue was purified by silica gel column chromatography eluted with *n*-hexane/AcOEt (1/1, v/v) to obtain *N*-α-*tert*-butoxycarbonyl-*O*-cyclohexyl-L-glutamic acid *N*′-4-iodophenylamide as white powder in 92% yield (9.75 g, 18 mmol).

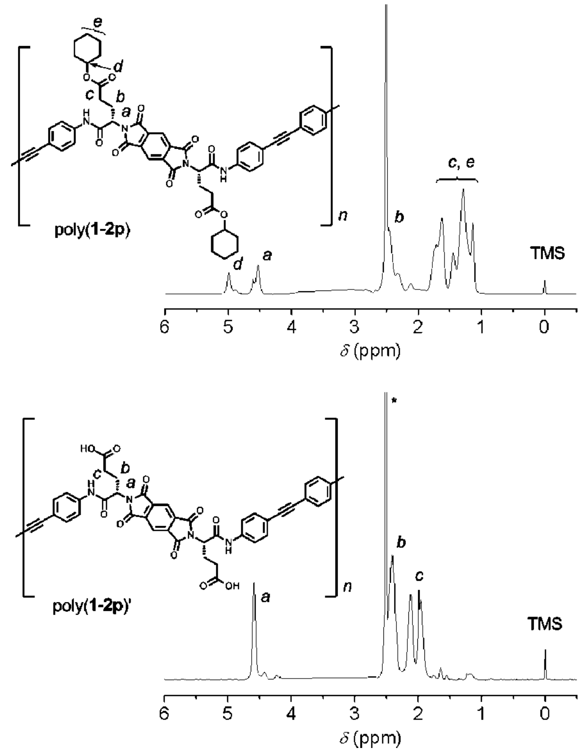


Figure 1. Partial ^{1}H NMR spectra of poly(**1**-**2p**) and poly(**1**-**2p**)′ measured in DMSO-d_6. The solvent is marked with an asterisk (∗).

Trifluoroacetic acid (TFA, 20 mL, 270 mmol) was added to a solution of *N*-α-*tert*-butoxycarbonyl-*O*-cyclohexyl-L-glutamic acid *N*′-4-iodophenylamide (9.75 g, 18 mmol) in CH_2Cl_2 (20 mL) at 0 °C. The resulting mixture was stirred at room temperature overnight. The solvent was removed under vacuum to obtain *O*-cyclohexyl-L-glutamic acid *N*-4-iodophenylamide·TFA in 98% yield (11.3 g, 17.6 mmol).

A solution of *O*-cyclohexyl-L-glutamic acid *N*-4-iodophenylamide (11.3 g 17.6 mmol), 1,2,4,5-benzenetetracarboxylic dianhydride (1.92 g, 8.8 mmol), and Et_3N (10 mL) in toluene (100 mL) was refluxed in a glass flask equipped with a Dean−Stark trap for 6 h. The organic solvent was removed in vacuo. To the residue, 2 M HCl(aq) (200 mL) was added, and the resulting mixture was stirred for 1 h. H_2O-insoluble solid was filtered off and dried. The solid was purified by silica gel column chromatography eluted with hexane/AcOEt (1/1, v/v) to obtain **1** as yellow powder in 79% yield (7.24 g, 6.95 mmol); mp 124−125 °C, $[\alpha]_D = +5.3°$ (c = 0.1 g/dL, $CHCl_3$, room temperature). ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.26−1.37 [m, 12H, $(CH_2)_3$], 1.71−1.85 [m, 8H, $COOCH(CH_2)_2$], 2.48 (s, 4H, $NHCHCH_2CH_2$), 2.63 (s, 4H, $CHCH_2CH_2$), 4.76 (s, 2H, NHC*H*COO), 4.97 (s, 2H, COOCH), 7.27 (s, 4H, Ar), 7.55 (s, 4H, Ar), 8.18 (s, 2H, Ar), 8.88 (s, 2H, NHCO). ^{13}C NMR (100 MHz, $CDCl_3$): δ 23.7, 24.5, 25.2, 31.5, 55.0, 73.9, 88.0, 118.8, 121.8, 136.9, 137.2, 137.8, 165.9, 166.1, 172.8. IR (cm^{-1}, KBr): 3375, 3106, 2936, 2857, 2106, 1775, 1731, 1589, 1526, 1487, 1450, 1356, 1113, 1006, 916, 820, 726, 638. Anal. Calcd for $C_{44}H_{44}I_2N_4O_{10}$: C, 50.69; H, 4.25; N, 5.37. Found: C, 50.77; H, 4.20; N, 5.17.

Polycondensation [Synthesis of Poly(1-2p) and Poly(1-2m)]. The polycondensation was carried out in a glass tube equipped with a three-way stopcock under nitrogen. A solution of **1** (1.04 g, 1.00 mmol) and *p*- or *m*-diethynylbenzene (**2p** or **2m**, 126 mg, 1.00 mmol), $PdCl_2(PPh_3)_2$ (50 μmol), CuI (50 μmol), and PPh_3(50 μmol) in a solvent (3 mL) and Et_3N (2 mL) was stirred at 80 °C for 24 h. After that, the resulting mixture was poured into MeOH (300 mL)

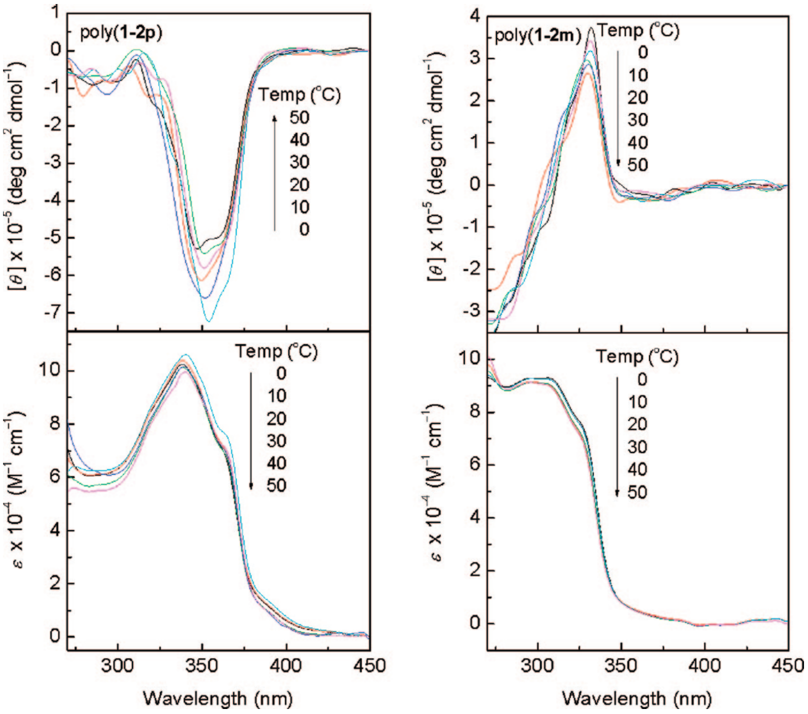


Figure 2. Temperature-variable CD and UV−vis spectra of poly(**1-2p**) and poly(**1-2m**) measured in DMF ($c = 2.0 \times 10^{-5}$ mol/L).

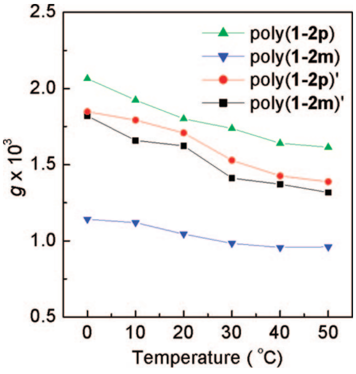


Figure 3. Plots of Kuhn's dissymmetry factor (g) of poly(**1-2p**), poly(**1-2m**), poly(**1-2p**)′, and poly(**1-2m**)′ vs temperature calculated from the data in Figures 2 and 5.

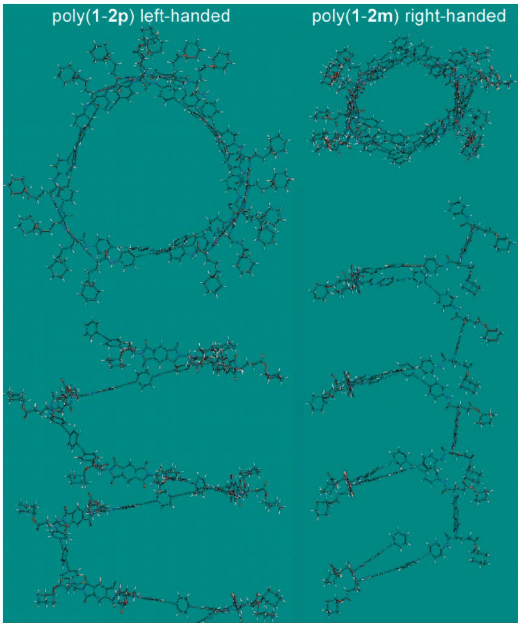


Figure 4. Top and side views of possible conformers of poly(**1-2p**) and poly(**1-2m**) (octamer).

to precipitate a polymer. It was separated by filtration using a membrane filter (ADVANTEC H100A047A) and dried under reduced pressure.

Alkaline Hydrolysis of Poly(1-2p) and Poly(1-2m) [Synthesis of Poly(1-2p)′ and Poly(1-2m)′]. To a solution of a polymer (250 mg, 0.27 mmol) in DMF (20 mL) and H_2O (10 mL), 0.1 M NaOH aqueous solution (10 mL, 1 mmol) was added dropwise at 0 °C, and then the resulting mixture was stirred at 50 °C for 3 h. The reaction mixture was poured into 2 M HCl (300 mL) to precipitate a polymer. It was separated by filtration using a membrane filter (ADVANTEC H100A047A) and dried under reduced pressure.

Spectroscopic Data of the Polymers. Poly(**1-2p**): ^1H NMR (400 MHz, $CDCl_3$): δ 1.28 [br, 16H, $2(CH_2)_3$, $COOCH(CH_2)_2$], 1.62 [br, 8H, $COOCH(CH_2)_2$, $2CH_2COO$], 2.46 (br, 4H, $2NHCHCH_2CH_2$), 4.53 (s, 2H, 2NHC*H*CO), 4.99 (s, 2H, 2COOCH), 7.46 (br, 14H, Ar), 8.97 (s, 2H, 2NHCO). IR (cm^{-1}, KBr): 3338, 2934, 2857, 2213, 1775, 1727, 1521, 1434, 1357, 1113, 1014, 839, 742, 693. Poly(**1-2m**): ^1H NMR (400 MHz, $CDCl_3$): δ 1.31 [br, 16H, $2(CH_2)_3$, $COOCH(CH_2)_2$], 1.64 [br, 8H, $COOCH(CH_2)_2$, $2CH_2COO$], 2.41 (br, 4H, $2NHCHCH_2CH_2$), 4.48 (s, 2H, 2NHC*H*CO), 4.66 (s, 2H, 2COOCH), 7.79 (br, 14H, Ar), 8.83 (s, 2H, 2NHCO). IR (cm^{-1}, KBr): 3330, 2941, 2853, 2208, 1774, 1726, 1508, 1396, 1355, 1112, 1016, 835, 722, 700. Poly(**1-2p**)′: ^1H NMR (400 MHz, $CDCl_3$): δ 1.99 (br, 4H, $2CH_2COO$), 2.42 (br, 4H, $2NHCHCH_2CH_2$), 4.58 (s, 2H, 2NHC*H*CO), 7.46 (br, 14H, Ar), 8.97 (s, 2H, 2NHCO), 10.22 (s, 2H, COOH). IR (cm^{-1}, KBr): 3323, 3055, 2933, 2858, 2208, 1710, 1590, 1517, 1439, 1407, 1249, 1112, 1037, 930, 839, 754, 688. Poly(**1-2m**)′: ^1H NMR (400 MHz, $CDCl_3$): δ 1.63 (br, 4H, $2CH_2COO$), 2.51 (br, 4H, $2NHCHCH_2CH_2$), 4.64 (s, 2H, 2NHC*H*CO), 7.78 (br, 14H, Ar), 8.96 (s, 2H, 2NHCO), 10.2 (s, 2H, COOH). IR (cm^{-1}, KBr): 3313, 3054, 2936, 2860, 2214, 1715, 1595, 1520, 1436, 1405, 1246, 1120, 1017, 934, 835, 750, 698.

Results and Discussion

Monomer Synthesis and Polycondensation. Di(iodophenyl)-substituted L-glutamic acid-derived benzenetetracarboxylic diimide (**1**) was synthesized by the route illustrated in Scheme 2.

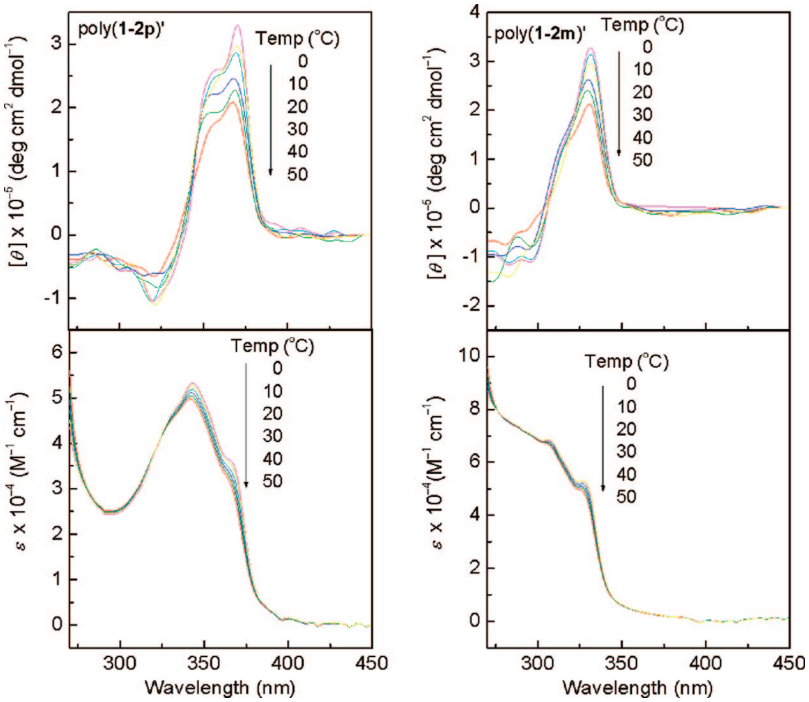


Figure 5. Temperature-variable CD and UV−vis spectra of poly(**1**-**2p**)′ and poly(**1**-**2m**)′ measured in DMF ($c = 2.7 \times 10^{-5}$ mol/L).

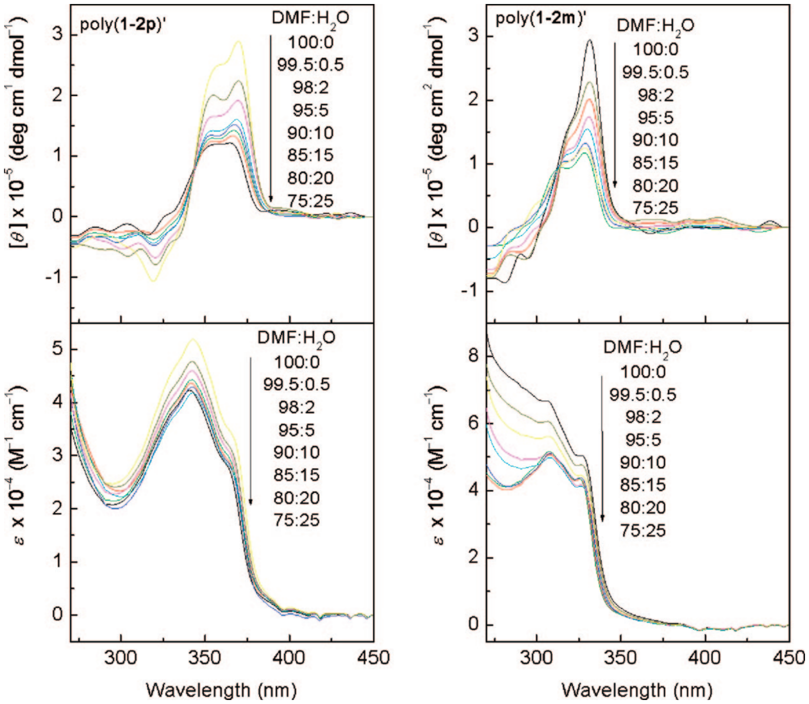


Figure 6. CD and UV−vis spectra of poly(**1**-**2p**)′ and poly(**1**-**2m**)′ measured in DMF/H_2O ($c = 2.7 \times 10^{-5}$ mol/L) at room temperature.

First, 4-iodoaniline was condensed with *N*-α-*tert*-butoxycarbonyl-*O*-cyclohexyl-L-glutamic acid using TRIAZIMOCH as a condensation agent to obtain *N*-α-*tert*-butoxycarbonyl-*O*-cyclohexyl-L-glutamic acid *N*′-4-iodophenylamide, whose *tert*-butoxycarbonyl group was removed with TFA. Then, *O*-cyclohexyl-L-glutamic acid *N*′-4-iodophenylamide·TFA obtained was reacted with 1,2,4,5-benzenetetracarboxylic dianhydride to afford **1**. It was identified by ^{1}H, ^{13}C NMR, and IR spectroscopies besides elemental analysis.

The polymers were synthesized by the Sonogashira−Hagihara polycondensation of **1** with *p*-/*m*-diethynylbenzenes (**2p**, **2m**) in DMF, DMSO, and toluene at 80 °C for 24 h. The polycondensation satisfactorily proceeded to afford the corresponding polymers [poly(**1-2p**) and poly(**1-2m**)] as listed in Table 1. The polycondensation in toluene afforded the polymers almost quantitatively, but the molecular weights were low (M_n 6500−7700) compared with those obtained by the polycondensation in DMF and DMSO (M_n 24 500−37 600). The structures of the polymers were characterized spectroscopically. The ^{1}H NMR, ^{13}C NMR, and IR spectra of the polymers exhibited signals reasonably assignable to the structures illustrated in Scheme 1. The polymers were soluble in DMF and DMSO and partly soluble in CH_2Cl_2, $CHCl_3$, THF, and 1,4-dioxane, while insoluble in hexane, toluene, and MeOH.

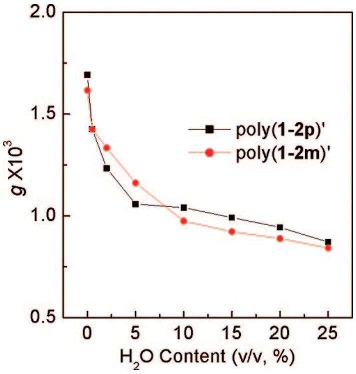


Figure 7. Plots of Kuhn's dissymmetry factor (g) of poly(**1**-**2p**)′ and poly(**1**-**2m**)′ vs H_2O content in DMF/H_2O calculated from the data in Figure 6.

Hydrolysis of the Ester Groups of the Polymers. We next examined the hydrolysis of cyclohexyl ester moieties of poly(**1-2p**) and poly(**1-2m**) using NaOH. The polymers satisfactorily underwent alkaline hydrolysis to give the corresponding polymers [poly(**1-2p**)′ and poly(**1-2m**)′] carrying free carboxy groups in good yields as listed in Table 2. The GPC-determined M_n's of the hydrolyzed polymers were lower than those of the polymers before hydrolysis. This is partly because of removal of cyclohexyl groups from the side chains, and probably the large interaction between the pendent free carboxy groups and polystyrene gels as well, resulting in the long elution times. In fact, when the carboxy groups of the polymers were converted into methyl esters with $(CH_3)_3SiCHN_2$,[18] the M_n's of the methyl-esterified polymers were estimated to be 27 300 and 10 200 by GPC, which were much higher than those of the polymers carrying carboxy groups. Figure 1 compares the partial ^{1}H NMR spectra of poly(**1-2p**) and poly(**1-2p**)′. The cleavage of the cyclohexyl moiety was confirmed by the disappearance of signals *d* and *e*. In a similar manner, the hydrolysis of the ester part of poly(**1-2m**) was also confirmed.

Chiroptical Properties of the Polymers. We examined the secondary structures of the polymers by CD and UV−vis spectroscopies. As depicted in Figure 2, poly(**1-2p**) and poly(**1-2m**) exhibited clear CD signals based on the phenyleneethynylene linkage around 330−350 nm in DMF at 0−50 °C, indicating the formation of a helical conformation with an excess of one-handedness in the solvent. Poly(**1-2p**) showed the ϵ_{max} at a wavelength 30 nm longer than poly(**1-2m**) did. This indicates that the *p*-phenyleneethynylene moieties are more largely conjugated than the *meta*-counterpart. Poly(**1-2p**) monotonically decreased the [θ], while it kept the UV−vis intensity almost constant in the temperature range. The temperature-variable CD change was completely reversible. It did not change the preference of helical sense upon heating but tuned the magnitude of molar ellipticity. Reduction of CD intensity generally indicates either the decrease of one-handedness of helicity or transformation of helix into random coil structure. Chain helicity is commonly decreased by an increase in temperature because the thermal perturbation activates the randomization of chain conformations. The CD and UV−vis spectra of poly(**1-2m**) also exhibited similar responsiveness to temperature change with that of poly(**1-2p**), but the degree was small compared to the case of poly(**1-2p**).

Kuhn's dissymmetry factor ($g = \Delta\epsilon/\epsilon$)[19] enables us to evaluate the degree of predominantly screw sense of helical polymers quantitatively.[20] Figure 3 depicts the g values of poly(**1-2p**) and poly(**1-2m**) at various temperatures to determine the influence of temperature on the helical sense, along with those of poly(**1-2p**)′ and poly(**1-2m**)′ that will be discussed later. It is concluded that poly(**1-2p**) and poly(**1-2m**) slightly increased the helix reversal at higher temperature judging from the small decrease of g values upon raising temperature. The conformation of helical polymers is commonly stabilized by noncovalent interactions such as van der Waals interaction, electrostatic interaction, hydrogen bonding, and metal coordination, which are disturbed by heating, change of solvent polarity, and folding-disrupting agents. Compared to common poly(phenyleneethynylene)s reported so far,[6a,c] the helical structure of poly(**1-2p**) and poly(**1-2m**) is thermally stable.

We analyzed the conformation of poly(**1-2p**) and poly(**1-2m**) consisting of eight repeating units by the molecular mechanics

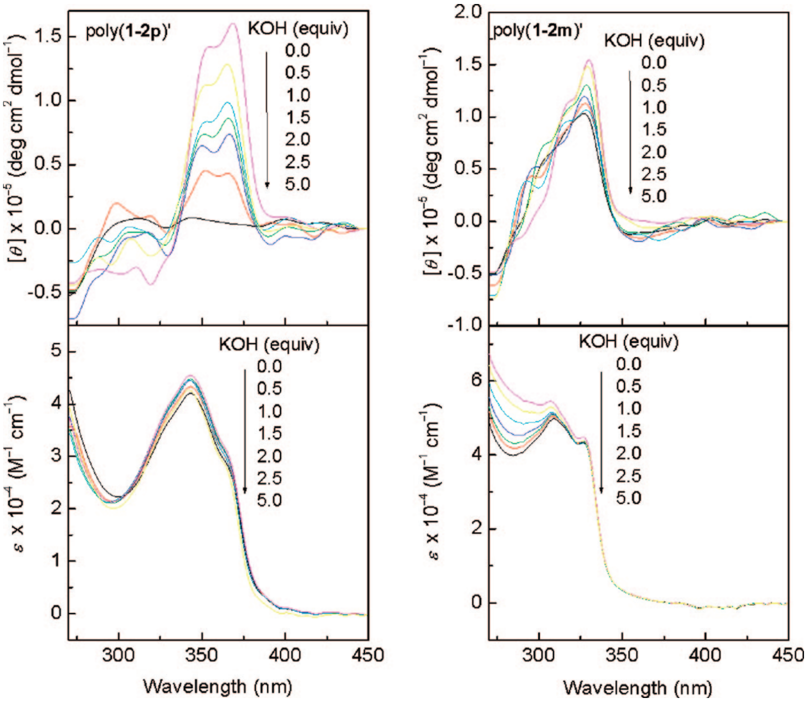


Figure 8. CD and UV−vis spectra of poly(**1**−**2p**)′ and poly(**1**−**2m**)′ upon addition of KOH measured in DMF/H_2O = 9/1 (v/v, $c = 2.7 \times 10^{-5}$ mol/L) at room temperature.

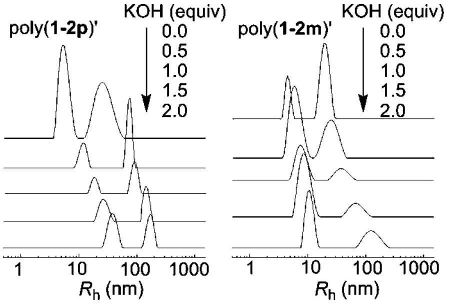


Figure 9. Distribution of particle size (R_h: hydrodynamic radius) of poly(**1-2p**)′ and poly(**1-2m**)′ upon addition of KOH measured in DMF/H_2O = 9/1 (v/v, $c = 2.7 \times 10^{-5}$ mol/L) at room temperature.

calculation. Figure 4 illustrates the top and side views of their possible right- and left-handed helical conformers, respectively, whose geometries were fully optimized by MMFF94. Herein, we adopted *syn* geometry regarding the amino acid side chains with respect to the benzenetetracarboxylic diimide. This geometry allows the main chains of the polymers to bend at the benzenetetracarboxylic diimide moieties, forming helices as depicted in Figure 4. *p*-Phenylene-linked poly(**1-2p**) forms a triangular form with a longer diameter, while *m*-phenylene-linked poly(**1-2m**) forms a hexagonal one with a shorter diameter due to the geometrical restriction. Poly(**1-2p**) seems to predominantly possess a left-handed helical structure because the left-handed helical conformer of poly(**1-2p**) was more stable than the right-handed one by 6.63 kJ/mol per repeating unit. On the other hand, the right-handed helical conformer of poly(**1-2m**) was more stable than the left-handed one by 2.49 kJ/mol per repeating unit. The opposite preferable helical sense predicted by the molecular mechanics calculation agrees with the opposite sign of the CD signals of *para*- and *meta*-linked ones as depicted in Figure 2.

Figure 5 shows the CD and UV−vis spectra of poly(**1-2p**)′ and poly(**1-2m**)′ carrying carboxy groups measured in DMF at 0−50 °C. In a manner similar to the ester counterparts [poly(**1-2p**) and poly(**1-2m**)], they exhibited intense phenyleneethynylene-based CD signals around 330−370 nm and slightly decreased the intensity upon raising temperature. Consequently, it is concluded that they also take a helical conformation with an excess of predominantly one-handed screw sense in the solvent. It should be noted that poly(**1-2p**) showed a minus-signed CD signal (Figure 2, left), while poly(**1-2p**)′ showed a plus-signed one (Figure 5, left). This indicates that the polymer kept a helical form after hydrolysis but changed the predominant screw sense. On the contrary, poly(**1-2m**)′, obtained by the hydrolysis of poly(**1-2m**), exhibited a CD signal with the same sign and similar pattern as those of the prepolymer [poly(**1-2m**)] (Figure 2, right, and Figure 5, right), indicating that these polymers form the same helical conformation as each other irrespective of the substituents (carboxy and ester groups). The difference of the helical tightness may be the reason for the dramatically different results regarding helical conformation between *para*- and *meta*-linked polymers before and after hydrolysis as suggested by the molecular mechanics calculation. Namely, loosely twisted *para*-linked poly(**1-2p**) is feasible to undergo conformational transition according to the transformation of the ester groups into carboxy groups, while tightly twisted poly(**1-2m**) is not so. As shown in Figure 3, poly(**1-2m**)′ exhibited *g* values larger than poly(**1-2m**) did, indicating that poly(**1-2m**)′ formed a helix with higher degree of preferential screw sense. Both poly(**1-2p**)′ and poly(**1-2m**)′ decreased the *g* values according to temperature raising in a manner similar to the prepolymers.

Solvent-Induced Conformational Change. We next examined the solvent effect on the helicity of the polymers. Figure 6 depicts the CD and UV−vis spectra of poly(**1-2p**)′ and poly(**1-2m**)′ measured in DMF/H_2O with various compositions. Both the polymers decreased the Cotton effect upon raising H_2O content. In DMF/H_2O = 75/25, the [θ] of poly(**1-2p**)′ and poly(**1-2m**)′ became 47% and 43% of those in DMF, while ϵ_{max} became 78% and 79%, respectively. It is considered that the polymers mostly kept a helical form in the mixed solvent but decreased the degree of predominance of screw sense.

Figure 7 depicts the effect of H_2O addition on the *g* values

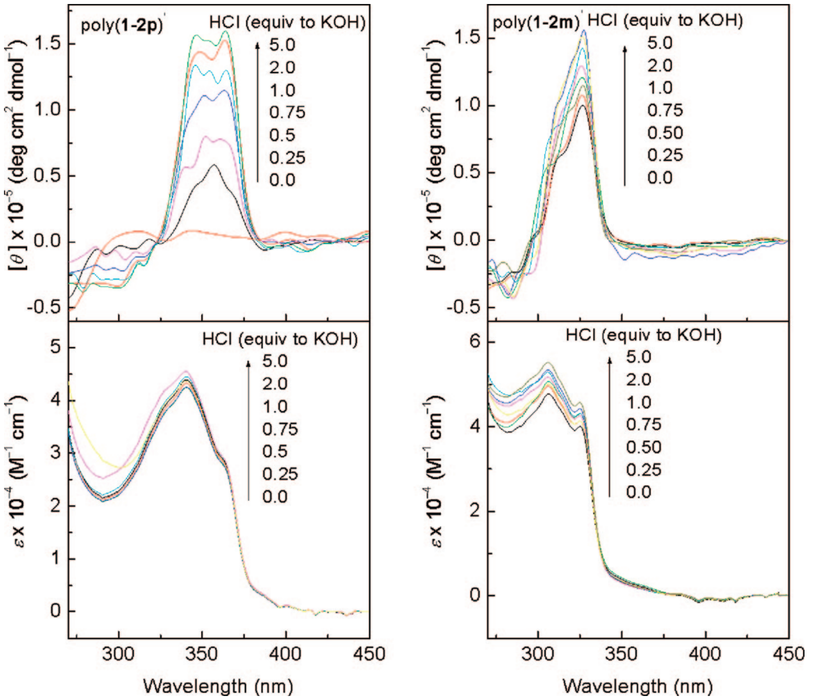


Figure 10. CD and UV−vis spectra of poly(**1-2p**)′ and poly(**1-2m**)′ upon addition of HCl measured in KOH, DMF, and H_2O mixture (DMF/H_2O = 9/1 v/v, $c = 2.7 \times 10^{-5}$ mol/L, $c_{KOH} = 2.0 \times 10^{-4}$ mol/L) at room temperature.

of poly(**1-2p**)′ and poly(**1-2m**)′ solutions in DMF. The addition of 10% of H_2O immediately decreased the *g* values to 61% and 60% of the original ones, while further addition of H_2O slightly decreased them. It seems that H_2O decreases the degree of predominance of one-handedness. It is assumed that the large change in the first stage is brought about by aggregation due to the decrease of solubility of the polymers to some extent. In fact, the addition of H_2O more than 25% made the solutions turbid and partial precipitation of the polymers.

Responsiveness to pH. Some helical polymers carrying carboxy groups in the side chains change the conformation according to pH.[13,21] In a similar fashion, the helical structure of poly(**1-2p**)′ and poly(**1-2m**)′ is possibly susceptible to base. Figure 8 depicts the effect of KOH addition on the CD and UV−vis spectra of poly(**1-2p**)′ and poly(**1-2m**)′ in DMF/H_2O = 9/1 (v/v). The addition of 0.5 equiv of KOH immediately weakened the CD signals of poly(**1−2p**)′ around 370 nm to 81% of the original. The further addition of KOH led to the continuous decrease of the CD intensity. The Cotton effect almost vanished, when 5.0 equiv of KOH was added. It means that the transition of helical sense and/or transformation of helix into random coil were brought about and completed. Compared to the degree of decrease in the CD spectra, that of the UV−vis spectra was negligibly small. It is concluded that the change of the secondary structure does not affect the electronic states of the phenyleneethynylene chromophore. KOH ionizes the carboxy groups of the polymer chains to increase the repulsion between the side chains, leading to the collapse of the predominantly one-handed helical structure. On the other hand, poly(**1-2m**)′ only slightly decreased the CD intensity upon KOH addition. It kept 66% of the CD intensity even after the addition of 5.0 equiv of KOH. The helical structure of poly(**1-2m**)′ was much more stable to KOH than that of poly(**1-2p**)′, presumably due to the tightness as described above.

We performed DLS to obtain information on the change of polymer conformation upon KOH addition. As depicted in Figure 9, both poly(**1-2p**)′ and poly(**1-2m**)′ exhibited a bimodal distribution of hydrodynamic radius (R_h) in DMF/H_2O = 9/1 (v/v). The peak tops of R_h of poly(**1-2p**)′ appeared around 5 and 25 nm. It seems that the particles around 5 nm correspond to unimeric polymer molecules and 25 nm correspond to aggregated molecules. The addition of KOH gradually shifted the R_h tops to a larger particle size region according to an increase in the molar equivalent of KOH, presumably reflecting the collapse of predominantly one-handed helical structure as well as increase of electrostatic repulsion between negatively charged carboxylate groups in a manner similar to vesicles of poly(glutamic acid)-based diblock copolymers.[22]

Poly(**1-2m**)′ also shifted the peak tops of R_h to a larger particle size region upon addition of KOH. It should be noted that the degree of shift of R_h assignable to unimers is smaller than that of poly(**1-2p**)′. This can be explained by the difference of responsiveness of conformation to KOH as shown in Figure 8. Namely, since poly(**1-2m**)′ almost keeps the original tight helical structure irrespective of KOH addition, the R_h does not become so large compared to that of poly(**1-2p**)′ that undergoes transition of secondary structure. Judging from the ratio of the population between the small and large particles, KOH addition leads to segregation of polymer molecules presumably due to intermolecular electrostatic repulsion.

We next added HCl to the resulting solutions of poly(**1-2p**)′ and poly(**1-2m**)′ in DMF/H_2O = 9/1 (v/v) after the addition of 5.0 equiv of KOH. As shown in Figure 10, they almost completely recovered the original CD intensities by the addition of 5.0 equiv of HCl to KOH. Thus, we could reversibly modulate the chain helicity of poly(**1-2p**)′ and poly(**1-2m**)′ by pH.

Conclusions

In this article, we have demonstrated the synthesis of L-glutamic acid-derived novel *para*- and *meta*-linked phenyleneethynylene-based polymers carrying ester-protected carboxy groups [poly(**1-2p**) and poly(**1-2m**)] and free carboxy groups [poly(**1-2p**)′ and poly(**1-2m**)′] with moderate molecular weights in good yields. All the polymers formed helical structures with predominantly one-handed screw sense, which were unusually stable against heat compared to those of poly(phenyleneethylene)s reported so far. *Para*-linked poly(**1-2p**) carrying ester-protected carboxy groups and poly(**1-2p**)′ carrying free carboxy groups formed helices with opposite predominant helical senses each other, while their *meta*-linked counterparts [poly(**1-2m**) and poly(**1-2m**)′] formed helices with the same screw sense. Poly(**1-2p**)′ largely decreased one-handed helicity upon KOH addition, while poly(**1-2m**)′ did only slightly. Both the polymers recovered the original helicity upon HCl addition almost completely. Poly(**1-2p**)′ increased the particle size more largely than poly(**1-2m**)′ in solution. The conformation study by the molecular mechanics calculation suggested that poly(**1-2p**) took a loose helix, while poly(**1-2m**) took a tight one. The difference of helix tightness reasonably explained the different behavior of helix formation and responsiveness to KOH between the *para*- and *meta*-linked polymers.

Acknowledgment. The authors are grateful to the financial support from the Global COE Program, "International Center for Integrated Research and Advanced Education in Materials Science", and Kyowa Hakko Kogyo Co., Ltd., and Mr. Kenji Saeki at Asahi Techneion for measurement of DLS. R.L. acknowledges financial support from the Ministry of Education, Culture, Sports, Science, and Technology, Japan.

References and Notes

(1) (a) Tour, J. M. *Chem. Rev.* **1996**, *96*, 537. (b) Moore, J. S. *Chem. Rev.* **1997**, *30*, 402. (c) Bunz, U. H. F. *Chem. Rev.* **2000**, *100*, 1605.

(2) (a) Nelson, J. C.; Saven, J. G.; Moore, J. S.; Wolynes, P. G. *Science* **1997**, *277*, 1793. (b) Gin, M. S.; Yokozawa, T.; Prince, R. B.; Moore, J. S. *J. Am. Chem. Soc.* **1999**, *121*, 2643. (c) Prince, R. B.; Barnes, S. A.; Moore, J. S. *J. Am. Chem. Soc.* **2000**, *122*, 2758. (d) Tanatani, A.; Mio, M. J.; Moore, J. S. *J. Am. Chem. Soc.* **2001**, *123*, 1792. (e) Heemstra, J. M.; Moore, J. S. *J. Am. Chem. Soc.* **2004**, *126*, 1648.

(3) Arnt, L.; Tew, G. N. *Macromolecules* **2004**, *37*, 1283.

(4) (a) Tan, C.; Pinto, M. R.; Kose, M. E.; Ghiviriga, I.; Schanze, K. S. *Adv. Mater.* **2004**, *16*, 1208. (b) Zhao, X. Y.; Schanze, K. S. *Langmuir* **2006**, *22*, 4856.

(5) (a) Inouye, M.; Waki, M.; Abe, H. *J. Am. Chem. Soc.* **2004**, *126*, 2022. (b) Abe, H.; Masuda, N.; Waki, M.; Inouye, M. *J. Am. Chem. Soc.* **2005**, *127*, 16189. (c) Waki, M.; Abe, H.; Inouye, M. *Chem.—Eur. J.* **2006**, *12*, 7839.

(6) (a) Prince, R. B.; Saven, J. G.; Wolynes, P. G.; Moore, J. S. *J. Am. Chem. Soc.* **1999**, *121*, 3114. (b) Prince, R. B.; Brunsveld, L.; Meijer, E. W.; Moore, J. S. *Angew. Chem., Int. Ed.* **2000**, *39*, 228. (c) Brunsveld, L.; Meijer, E. W.; Prince, R. B.; Moore, J. S. *J. Am. Chem. Soc.* **2001**, *123*, 7978.

(7) Dautel, O. J.; Wantz, G.; Flot, D.; Lere-Porte, J.; Moreau, J. J. E.; Parneix, J.; Serein-Spiraua, F.; Vignau, L. *J. Mater. Chem.* **2005**, *15*, 4446.

(8) (a) Sanda, F.; Endo, T. *Macromol. Chem. Phys.* **1999**, *200*, 2651. (b) Hill D, J.; Mio, M. J.; Prince, R. B.; Hughes, T. S.; Moore, J. S. *Chem. Rev.* **2001**, *101*, 3893.

(9) (a) Cheuk, K. K. L.; Lam, J. W. Y.; Chen, J.; Lai, L. M.; Tang, B. Z. *Macromolecules* **2003**, *36*, 5947. (b) Li, B. S.; Kang, S. Z.; Cheuk, K. K. L.; Wan, L. J.; Ling, L. S.; Bai, C. L.; Tang, B. Z. *Langmuir* **2004**, *20*, 7598. (c) Okoshi, K.; Sakajiri, K.; Kumaki, J.; Yashima, E. *Macromolecules* **2005**, *38*, 4061. (d) Okoshi, K.; Sakurai, S.; Ohsawa, S.; Yashima, E. *Angew. Chem., Int. Ed.* **2006**, *45*, 8173.

(10) Sanda, F.; Teraura, T.; Masuda, T. *J. Polym. Sci., Part A: Polym. Chem.* **2004**, *42*, 4641.

(11) (a) Gao, G.; Sanda, F.; Masuda, T. *Macromolecules* **2003**, *36*, 3932. (b) Sanda, F.; Araki, H.; Masuda, T. *Macromolecules* **2004**, *37*, 8510. (c) Zhao, H.; Sanda, F.; Masuda, T. *Macromolecules* **2004**, *37*, 8888.

(12) Liu, R.; Sanda, F.; Masuda, T. *Polymer* **2007**, *48*, 6510.

(13) (a) Sanda, F.; Terada, K.; Masuda, T. *Macromolecules* **2005**, *38*, 8149.

(b) Cheuk, K. K. L.; Lam, J. W. Y.; Lai, L. M.; Dong, Y. P.; Tang, B. Z. *Macromolecules* **2003**, *36*, 9752.

(14) (a) Staab, H. A.; Nikolic, S. *Eur. J. Org. Chem.* **1999**, 1459. (b) Hamilton, D. G.; Prodi, L.; Feeder, N.; Sanders, J. K. M. *J. Chem. Soc., Perkin Trans.* **1999**, *1*, 1057. (c) Hamilton, D. G.; Montalti, M.; Prodi, L.; Fontani, M.; Zanello, P.; Sanders, J. K. M. *Chem.—Eur. J.* **2000**, *6*, 608. (d) Hansen, J. G.; Feeder, N.; Hamilton, D. G.; Gunter, M. J.; Becher, J.; Sanders, J. K. M. *Org. Lett.* **2000**, *2*, 449. (e) Hansen, J. G.; Bang, K. S.; Thorup, N.; Becker, J. *Eur. J. Org. Chem.* **2000**, *65*, 2135. (f) Chen, C.; Lean, J. T.; Alcak, M.; Mallouk, T. E. *J. Org. Chem.* **2001**, *66*, 3021. (g) Colquhoun, H. M.; Williams, D. J.; Zhu, Z. *J. Am. Chem. Soc.* **2002**, *124*, 13346.

(15) (a) Hamilton, D. G.; Davies, J. E.; Prodi, L.; Sanders, J. K. M. *Chem.—Eur. J.* **1998**, *4*, 608. (b) Hamilton, D. G.; Feeder, N.; Prodi, L.; Teat, S. J.; Clegg, W.; Sanders, J. K. M. *J. Am. Chem. Soc.* **1998**, *120*, 1096.

(16) (a) Wang, X.-Z.; Li, X.-Q.; Shao, X.-B.; Zhao, X.; Deng, P.; Jiang, X.-K.; Li, Z.-T.; Chen, Y.-Q. *Chem.—Eur. J.* **2003**, *9*, 2904. (b) Vignon, S. A.; Jarrosson, T.; Iijima, T.; Tseng, H.-R.; Sanders, J. K. M.; Stoddart, J. F. *J. Am. Chem. Soc.* **2004**, *126*, 9884. (c) Iijima, T.; Vignon, S. A.; Tseng, H.-R.; Jarrosson, T.; Sanders, J. K. M.; Marchioni, F.; Venturi, M.; Apostoli, E.; Balzani, V.; Stoddart, J. F. *Chem.—Eur. J.* **2004**, *10*, 6375.

(17) (a) Iwanaga, T.; Yasutake, M.; Takemura, H.; Sako, K.; Shinmyozu, T. *Angew. Chem., Int. Ed.* **2006**, *45*, 3643. (b) Kato, S.; Matsumoto, T.; Ideta, K.; Shimasaki, T.; Goto, K.; Shinmyozu, T. *J. Org. Chem.* **2006**, *71*, 4723. (c) Chen, Z.; Stepanenko, V.; Dehm, V.; Prins, P.; Siebbeles, L. D. A.; Seibt, J.; Marquetand, P.; Engel, V.; Wurthner, F. *Chem.—Eur. J.* **2007**, *13*, 436. (d) Chen, Z.; Baumeister, U.; Tschierske, C.; Wurthner, F. *Chem.—Eur. J.* **2007**, *13*, 450.

(18) A 0.60 M solution of $(CH_3)_3SiCHN_2$ in hexane (2.17 mL, 1.3 mmol) was added to a solution of poly(**1-2p**)′ or poly(**1-2m**)′ (722 mg, 1 mmol) in DMF (5.0 mL) and MeOH (2.0 mL) at room temperature. The resulting mixture was stirred at room temperature for 30 min and then concentrated to a volume of 5.0 mL. The resulting solution was poured into a large amount of MeOH to precipitate a polymer. It was separated by filtration using a membrane filter (ADVANTEC H100A047A) and dried under reduced pressure.

(19) Kuhn, W. *Trans. Faraday Soc.* **1930**, *26*, 293.

(20) (a) Fujiki, M. *Appl. Phys. Lett.* **1994**, *65*, 3251. (b) Fujiki, M. *J. Am. Chem. Soc.* **1994**, *116*, 6017. (c) Fujiki, M. *Macromol. Rapid Commun.* **2001**, *22*, 539. (d) Kim, S. Y.; Fujiki, M.; Ohira, A.; Kwak, G.; Kawakami, Y. *Macromolecules* **2004**, *37*, 4321.

(21) Li, B. S.; Cheuk, K. K. L.; Ling, L.; Chen, J.; Xiao, X.; Bai, C.; Tang, B. Z. *Macromolecules* **2003**, *36*, 77.

(22) (a) Kukula, H.; Schlaad, H.; Antonietti, M.; Förster, S. *J. Am. Chem. Soc.* **2002**, *124*, 1658. (b) Chécot, F.; Brûlet, A.; Oberdisse, J.; Gnanou, Y.; Mondain-Monval, O.; Lecommandoux, S. *Langmuir* **2005**, *21*, 4308.

MA800674F