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Macromolecular Chirality Induction on Optically Inactive Poly(4-carboxyphenyl isocyanide) with Chiral Amines: A Dynamic Conformational Transition of Poly(phenyl isocyanide) Derivatives

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Abstract: Optically active polyisocyanides (poly(iminomethylenes)) have been prepared with much interest in developing new functional materials. Polyisocyanides have been considered to have a stable 4_1 helical conformation even in solution when they have a bulky side group. However, the conformational characteristics of poly(phenyl isocyanide) (PPI) derivatives are still under debate. We now report that an optically inactive PPI derivative, poly(4-carboxyphenyl isocyanide) (poly-**1**), shows optical activity in the polymer backbone induced by external, chiral stimuli through acid−base interactions under thermodynamic control and exhibits induced circular dichroism (ICD) in the UV−visible region in DMSO. The ICD intensities of the poly-**1**-chiral amine complexes in DMSO gradually increased with time, and, in one case, the value reached 3 times that of the original value after 2 months at 30 °C. The conformational changes also occurred very slowly for poly-**1** alone and its ethyl ester with time on the basis of ^{1}H NMR spectroscopic analysis. These results indicate that PPIs bearing a less bulky substituent may not have a 4_1 helical conformation but have a different type of *prochiral* conformation, for instance, an *s-trans* (zigzag) structure which may transform to a dynamic, one-handed helical conformation when the PPIs have a functional group capable of interacting with chiral compounds. The mechanism of helicity induction on poly-**1** through a dynamic conformational transition is discussed on the basis of the above results together with molecular dynamic simulation results for PPI.

Introduction

Polyisocyanides (poly(iminomethylenes)) are interesting and unique polymers which can adopt a stable 4_1 helical conformation even in solution when they have a bulky side group.[1] This was evidently confirmed by direct resolution of poly(*t*-butyl isocyanide) into optical antipodes[2] and the helix-sense selective polymerization of achiral, bulky *t*-butyl isocyanide and diphenylmethyl isocyanide with optically active transition-metal catalysts or initiators, which yielded one-handed helical, optically active polyisocyanides under predominantly kinetic control.[3]

However, the question of the preferred conformation of polyisocyanides derived from less bulky aliphatic, aralkyl, and aromatic isocyanides, in particular, phenyl isocyanides, has been addressed in earlier studies.[4] Green et al.,[4a] and later, Salvadori et al.,[4b] reported that a polyisocyanide with a chiral 1-phenylethyl or a 1-cyclohexylethyl group might not have a complete single sense of helix because of their stereoirregular structures due to *syn*−*anti* configurational isomerism around the C═N double bond and *s-cis* and *s-trans* conformational isomerism around the C−C bond of the main chain on the basis of the NMR and circular dichroism (CD) analyses of the polyisocyanides. Green et al. claimed that the CD of optically active polyisocyanides appearing in the long wavelength region might arise from local asymmetric perturbations rather than from an

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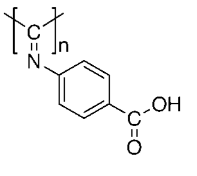
extended helical conformation.[4a] Clericuzio and co-workers theoretically proposed a preference for nonhelical *s-cis-s-trans* alternating conformation with syndio geometry for aliphatic polyisocyanides.[5a] Recently, Euler and Rosen et al. experimentally showed a linear *s-trans* or zigzag conformation for phenyl isocyanide oligomers in solution,[6] whereas Takahashi et al.[7] and Veciana et al.[8] independently reported that the helical conformations of PPIs having bulky chiral substituents were stable in solution even at high temperatures.

We now report that an optically inactive PPI, poly(4-carboxyphenyl isocyanide) (poly-**1**), shows optical activity in the polymer backbone induced by external, chiral stimuli through acid−base interactions under thermodynamic control, thus showing induced circular dichroism (ICD) in the UV−visible region in DMSO. We also found unique, very slow conformational changes in poly-**1** in the presence and absence of chiral amines and its ethyl ester on the basis of NMR and CD spectroscopic analyses. These observations are the first clear experimental results showing the conformational mobility of PPIs. On the basis of these results together with molecular dynamics (MD) simulation results for a model polymer, poly(phenyl isocyanide) (PPI), the significant nature of the structure of polyisocyanides under debate will be discussed.



poly-**1**

Results and Discussion

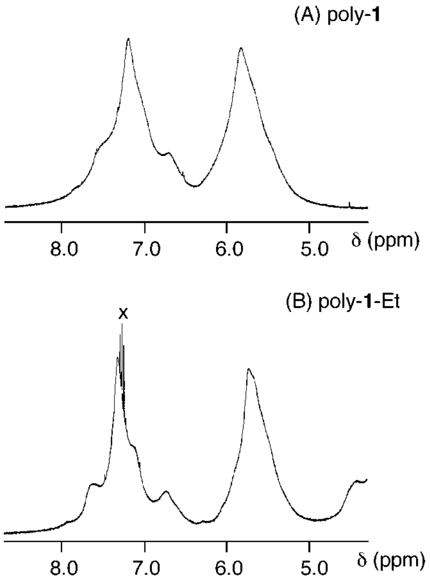


Figure 1. ^{1}H NMR spectra of poly-**1** (A) and poly-**1**-Et (B) at 30 °C in DMSO-d_6 and $CDCl_3$, respectively. X designates protons from solvents or impurities.

Scheme 1

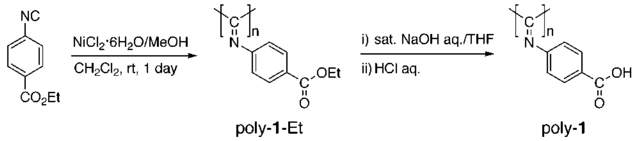
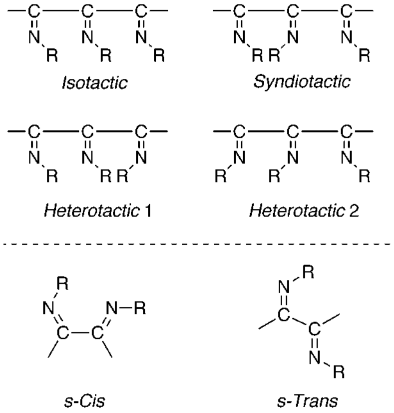


Chart 1. Possible Triad Structures of Polyisocyanides and *s-Cis* and *s-Trans* Conformations



Synthesis and Structural Characteristics of Poly(4-carboxyphenyl isocyanide). Poly-**1** was prepared by polymerization of 4-(ethoxycarbonyl)phenyl isocyanide with $NiCl_2 \cdot 6H_2O$[4,9] as the catalyst in dry dichloromethane, followed by alkaline hydrolysis of the ester group (93% yield, Scheme 1). The molecular weight (M_n) of poly(4-(ethoxycarbonyl)phenyl isocyanide) (poly-**1**-Et) was estimated to be 3.0 × 10^4 (M_w/M_n = 2.0; degree of polymerization (DP) = ca. 171) as determined by size exclusion chromatography (SEC) with polystyrene standards using chloroform as the eluent. Figure 1 shows the selected regions of the ^{1}H NMR spectra of poly-**1** and poly-**1**-Et before hydrolysis in DMSO-d_6 and $CDCl_3$, respectively. The chemical shift and line shape of the aromatic protons are considered to be sensitive to the polymer conformation and configuration.[4a] Rather broad, complicated peaks were observed at 30 °C for both polymers, which may imply some stereoirregularity of the main chains for triad tacticity due to the *syn*−*anti* isomerism and/or conformationally different segments (*s-cis* and *s-trans*) (Chart 1) as previously assigned for other polyisocyanides.[4] The ^{1}H NMR spectrum of the aromatic regions of poly-**1** measured at 80 °C more clearly indicates the existence of some resonances. However, the ^{1}H NMR spectral patterns

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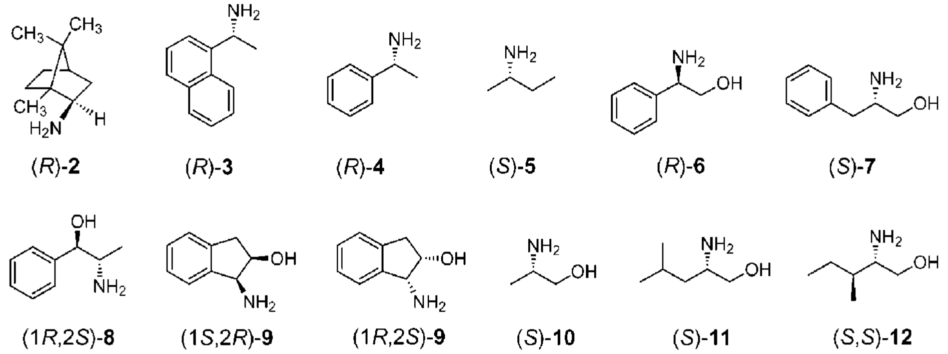
Chart 2. Structures of Chiral Amines and Amino Alcohols (**2**−**12**)



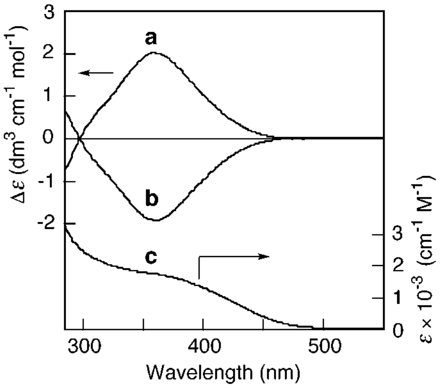


Figure 2. CD spectra of poly-**1** with (1*R*,2*S*)- (a) and (1*S*,2*R*)-**9** (b) and absorption spectrum (c) with (1*R*,2*S*)-**9** in DMSO; molar ratio of **9** to monomeric unit of poly-**1** is 50. The CD spectra were measured in DMSO solutions in a 0.1 cm quartz cell at ambient temperature (ca. 20−25 °C) with a poly-**1** concentration of 1.0 mg (6.8 μmol monomer units)/mL.

of poly-**1** and poly-**1**-Et very slowly changed with time at 30 °C, which indicates that their conformations are not rigid, but mobile or flexible, and that the splitting resonances in Figure 1 may be ascribed not only to tacticity but also to conformational isomerism. The results will be discussed later in detail.

CD Studies on the Complexation of Poly-1 with Chiral Amines and Amino Alcohols. A number of optically active polyisocyanides bearing an optically active substituent have been prepared so far, and their chiroptical properties have been studied using CD.[1b,4,7,8] However, the assignments of the CD bands with respect to the polymer conformations are still not completely understood.[4a,b,5a] We show that the optically inactive poly-**1** forms a complex with various chiral amines (**2**−**5**) and amino alcohols (**6**−**12**) (Chart 2) through an acid−base interaction in DMSO and the complexes exhibit an ICD in the UV−visible region of the polymer backbone. Figure 2 shows typical CD and absorption spectra of poly-**1** in the presence of (1*S*,2*R*)- and (1*R*,2*S*)-**9** in DMSO. The poly-**1**−**9** complexes exhibited ICDs in the n−π^* transition region of the imino chromophores, and the ICDs are mirror images of each other. The appearance of the ICDs accompanied negligible changes in the UV−visible spectra just after the preparation of the sample solution. The ICD pattern and $\lambda_{\max}$ (362 nm) of the Cotton effects are very similar to those of the reported optically active PPIs bearing bulky chiral substituents on the phenyl moieties.[7,8,10]

The intensity of the ICD increased with an increase in the concentration of the chiral amine and reached an almost constant value at [(1*S*,2*R*)-**9**]/[poly-**1**] = 20 ($\Delta\epsilon$ = ca. -1.9 dm^3 cm^{-1} mol^{-1} at 362 nm; see Supporting Information). This indicates that a chiral conformation, for instance, a helical conformation with a predominant screw sense, may be induced at least in part on the poly-**1** backbone in the presence of the chiral amines and that the helix sense can be controlled by the chirality of the chiral amines, even though the complexation involves fluxional ion-pairing; in accordance with Rosen et al., PPI may not have a long-accepted, stable 4_1 helical conformation in solution.[4d,6] A possible structure for the induced helical conformation of poly-**1** will be discussed later. As expected, the optical activity of the poly-**1**−**9** complexes almost completely disappeared when the complexes were exposed to a stronger acid such as trifluoroacetic acid, which frees the poly-**1** so that it reverts to the original, optically inactive polymer.

Similar helicity induction on an optically inactive polymer through intermolecular chiral interactions has been reported for polyacetylenes,[11] polyguanidines,[12] polyanilines,[13] polyisocyanates,[14] and poly(organophosphazene)s.[15]

Poly-**1** responded to other chiral amines and amino alcohols, and the complexes exhibited similar ICDs in their patterns (Table 1). Primary amines (**2**−**4**) and structurally similar amino alcohols (**6**−**8**) of the same configuration gave the same sign for the induced Cotton effect. However, other amino alcohols (**9**, **10**, and **12**) used in the present study exhibited the opposite Cotton effect signs depending on the configuration.

Conformational Dynamics of Poly(phenyl isocyanides) with and without Chiral Amines. Interestingly, the CD intensities of the poly-**1**−amine complexes increased very slowly with time at room temperature or at 30 °C (Figure 3A); for instance, the ICD intensity ($\Delta\epsilon$ at 362 nm) of the poly-**1**−

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Table 1. Signs of Cotton Effects and Differential Molar Absorptivities ($\Delta\epsilon$) for Poly-**1**−Amine Complexes[a]

amine	sign	$\Delta\epsilon$ (λ)[b]	time (days)	$\Delta\epsilon$[c]
(*R*)-**2**	+	0.17 (368)	2	0.15
(*R*)-**3**	+	0.65 (362)	145	0.73
(*R*)-**4**[d]	+	0.81 (365)	62	0.70
(*S*)-**5**		ca. 0	6	ca. 0
(*R*)-**6**[d,e]	−	0.58 (358)	63	1.83
(*S*)-**7**	+	0.34 (368)	143	0.64
(*S*)-**7**[d]	+	0.10 (372)	88	1.46
(1*R*,2S)-**8**	+	0.67 (357)	143	1.00
(1*S*,2*R*)-**9**	−	1.93 (362)	140	4.72
(1*R*,2S)-**9**[d]	+	1.92 (362)	61	6.75
(*S*)-**10**	−	0.12 (366)	140	0.10
(*S*)-**11**	+	0.47 (361)	143	0.98
(*S*,*S*)-**12**	−	0.52 (364)	143	0.51

[a] CD spectra were measured in DMSO at ambient temperature (ca. 20−25 °C) with poly-**1** (1.0 mg/mL); molar ratio of a chiral amine to monomer units of poly-**1** is 50; $\Delta\epsilon$ (dm^3 cm^{-1} mol^{-1}) and λ (nm). [b] Measured immediately after the preparation of samples. [c] Measured after the samples had been allowed to stand at ambient temperature or 30 °C for days. [d] Measured at 30 °C. [e] Molar ratio of a chiral amine to poly-**1** is 20.

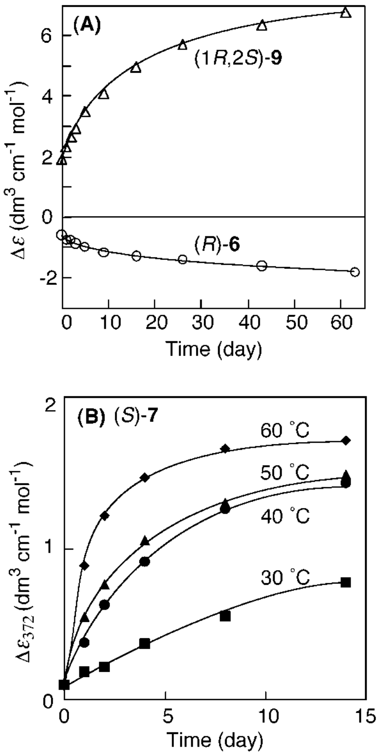

Figure 3. Changes in the CD intensity of the complexes of poly-**1** with (1*R*,2*S*)-**9** (362 nm) and (*R*)-**6** (358 nm) at 30 °C (A) and (*S*)-**7** (372 nm) at 30, 40, 50, and 60 °C (B) in DMSO with a poly-**1** concentration of 1.0 mg/mL; molar ratio of amines to monomeric unit of poly-**1** is 50 (**7** and **9**) and 20 (**6**).

(1*R*,2*S*)-**9** complex gradually increased from 1.92 to 6.75 after the sample had been allowed to stand at 30 °C for ca. 2 months, but the ICD magnitude had not reached a constant value after this time period. A similar slow increase in the ICD intensity was also observed for other complexes with several chiral amines (Table 1). The ICD intensities and their changes with time depended on the structures of the chiral amines used. It seems that bulky aromatic amines tended to induce more intense ICDs, while aliphatic amines exhibited a rather weak ICD and showed a small change or no change with time except for (*S*)-**11**. Novak et al. recently reported an irreversible transition for an optically inactive polyguanidine during complexation with (*S*)-camphorsulfonic acid at higher temperatures.[12] They observed a dramatic increase in optical rotation after annealing the mixture. Recently, we also found a similar increase in optical rotation for achiral poly(bis(4-carboxyphenoxy)phosphazene) in the presence of optically active amines in DMSO; the polymer exhibited a large optical rotational change after annealing the complex solution at 65 °C for ca. 2 h.[15]

We then investigated such a temperature effect on the macromolecular chirality induction for the poly-**1**−chiral amine complexes and found a similar trend; ICD intensities tended to increase rapidly at higher temperatures, but this is highly dependent on the chiral amines used. The poly-**1**−(*S*)-**7** complex showed a gradual increase in the ICD intensity at higher temperatures (Figure 3B), while the poly-**1**−(1*R*,2*S*)-**9** complex exhibited a different temperature effect; the ICD intensity increased at 40 and 50 °C in the initial stage, but their values reached almost constant values after 5 days and were rather weak as compared with that observed at 30 °C. In the case of the complex with (*R*)-**6**, the ICD intensity increased at higher temperatures in the range of 30−50 °C, but at 60 °C, it significantly decreased (see Supporting Information). At higher temperatures, the induced helical conformation of poly-**1** assisted by (1*R*,2*S*)-**9** and (*R*)-**6** may not be stable enough, and an equilibrium may lie between the folding and unfolding process (acid−base ion-pairing equilibrium also shifts). This speculation is supported by the temperature jump experiments of the poly-**1**−(1*R*,2*S*)-**9** complex (see below).

We first attempted to follow this conformational change in poly-**1** in the presence of the chiral amine using ^{1}H NMR spectroscopy. However, it was difficult because the aromatic proton resonances of poly-**1** were substantially broadened with (1*R*,2*S*)-**9**, and almost no peak was detected in the 5−8 ppm range even at 70 °C; the segmental motion of poly-**1** was unequivocally restricted due to binding with the amine. Similar broadening of the proton resonances was also observed for the induced helical poly((4-carboxyphenyl)acetylene) with chiral amines in DMSO.[11d]

In the course of our studies, we have incidentally found that the conformation of the original ("as-prepared") poly-**1** in the absence of chiral amines also changed very slowly with time at 30 °C. Figure 4A shows the changes in the ^{1}H NMR spectra of the aromatic proton resonances of poly-**1** in DMSO-d_6 at 30 °C with time. The most significant change was observed for the main peak centered at 7.23 ppm; the initial peak was broad with a shoulder, but it became sharp after ca. 10 days at 30 °C (d in Figure 4A). It seems likely that the shoulder peak almost disappeared accompanied by a decrease in the peak intensities at 6.71 and 7.54 ppm after the time period. The Lorentzian resolution (Figure 4B) roughly reveals the changes in the peak areas for the four resonances; the peak area ratios of the resonances at 7.54, 7.23, 7.06, and 6.71 ppm change from 19:36:32:13 (0 day) to 15:47:28:10 (1 day), 14:57:22:7 (6 days), 11:55:25:9 (10 days), and 14:58:21:7 (25 days). Notably, upon heating the poly-**1** (sample e in Figure 4A, "as-treated" sample) at 80 °C for 17 h, it showed almost the same ^{1}H NMR spectrum at 30 °C (f in Figure 4A) as that just after the preparation of the sample solution (sample a in Figure 4A). These results suggest that an equilibrium exists in the poly-**1** conformation which slowly shifts at 30 °C via a two-state process, for instance,

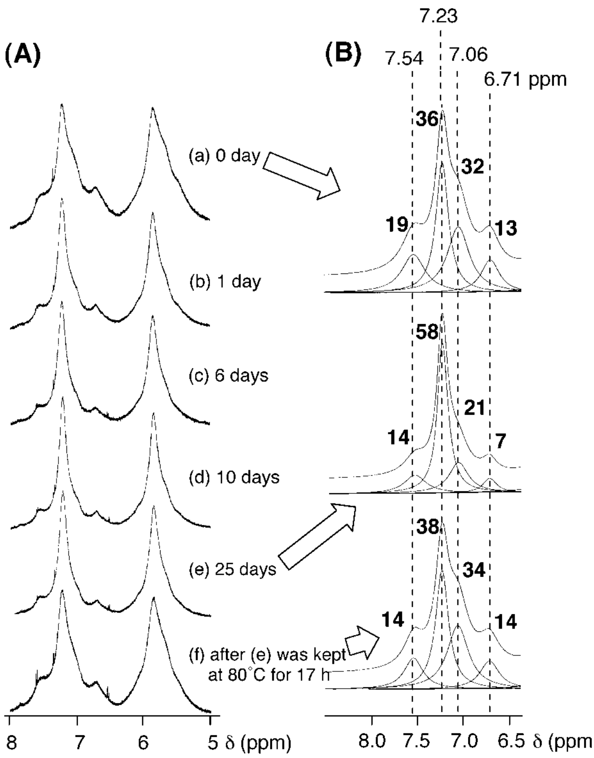

Figure 4. Time-dependent ^{1}H NMR spectral changes of poly-**1** (10 mg/mL) in DMSO-d_6 at 30 °C after standing the sample at 30 °C for 0 (a), 1 (b), 6 (c), 10 (d), and 25 days (e) and the NMR spectrum (f) after heating the sample (e) at 80 °C for 17 h (left). Curve fitting results of the samples a, e, and f are also shown (right).

a coil-to-helix transition as seen in proteins[16] and Moore's phenylene ethynylene oligomers.[17] The line shape analyses indicate that these four resonances in Figure 4B might be not only from stereoirregularity (tacticity) but also from conformational segments.[18] We tried to follow the change in the ^{13}C NMR resonances of poly-**1** with time at 30 °C, but it was difficult because of the broadening of the peaks in DMSO. Similar changes in the peak shape could also be observed in the ^{1}H and ^{13}C NMR spectra of poly-**1**-Et in CDCl$_3$ at 30 °C with time; the peak area ratios of the ^{1}H resonances at 7.66, 7.32, 7.11, and 6.72 ppm changed from 10:42:32:16 (0 day) to 9:69:16:6 (after 15 days). Broad ^{13}C resonances of the poly-**1**-Et also became sharp after 28 days at 30 °C (see Supporting Information). However, unexpectedly, the "as-treated" poly-**1**-Et (at 30 °C for 15 days) retained its conformation even after 1 day at 60 or 80 °C. The reason is not clear at present, but the poly-**1**-Et may have a rather stable conformation as compared with that of poly-**1**.

The conformational changes in poly-**1** took place more rapidly at higher temperatures, and the peak area ratios of the ^{1}H resonances reached constant values within 2 days, but the changes in the area ratios were rather small as compared with that at 30 °C; the peak area ratios of the four resonances after 2 days were 33:50:11:6 (40 °C), 28:47:18:7 (50 °C), and 23:44:24:9 (60 °C). A number of chiral and achiral polyisocyanides have been prepared, and their structures have been studied using NMR spectroscopies. Rather broad complicated signals were usually observed for most of the polyisocyanides, but changes in their NMR resonances with time have not yet been investigated.[1b,4,7,8,10]

Poly-**1** was prepared by hydrolysis of poly-**1**-Et so that it is interesting to see if the conformation of the "as-treated" poly-**1**-Et could be preserved after hydrolysis of the ester groups. Poly-**1**-Et which had been allowed to stand for ca. 1 month in chloroform was hydrolyzed in the same way, and the resulting poly-**1** was recovered as soon as possible to measure the ^{1}H NMR spectrum. The peak area ratios of the four resonances changed from 9:69:16:6 to 21:47:26:6, indicating that the preserved poly-**1**-Et conformation was partially lost during the hydrolysis reaction.[19,20]

The changes in the poly-**1** conformation were also monitored in DMSO at 30 °C by UV−visible spectroscopy. We observed a slight decrease in the absorbance intensity with time (with almost no red and blue shift); the UV−visible intensity of poly-**1** at 350 nm was reduced by 6% after 3−10 days. However, the UV−visible intensity recovered to the original value after annealing the sample at 80 °C for 2 h. This process is reversible. The hypochromism indicates that some extent of conjugation of the imino group of the polymer backbone may be slightly prevented during the conformational transition. A similar time-dependent, small hypochromism was also observed for the complexes of poly-**1** with chiral amines in DMSO at 30 °C.

If the conformational changes observed for the poly-**1** in the absence and presence of chiral amines were substantially the same, the initial CD intensity of the "as-treated" poly-**1**−chiral amine complexes would be expected to be larger than that of the "as-prepared" poly-**1**−chiral amine complexes just after the sample preparation. To check this possibility, we carried out the following experiments. A stock solution of the "as-prepared"

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[16] Schulz, G. E.; Schirmer, R. H. *Principles of Protein Structure*; Springer-Verlag: New York, 1979.

[17] Prince, R. B.; Saven, J. G.; Wolynes, P. G.; Moore, J. S. *J. Am. Chem. Soc.* **1999**, *121*, 3114−3121.

[18] Time-dependent viscosity measurements of the "as-prepared" poly-**1** and poly-**1**−(1*R*,2*S*)-**9** were conducted in DMSO at 30 °C to correlate the changes observed in the NMR and CD spectra. In these experiments, we used a poly-**1** with $M_n = 3.7 \times 10^4$ and $M_w/M_n = 2.2$. The "as-prepared" poly-**1** showed a linear relationship in the Huggins plot with the intrinsic viscosity of 0.56 and showed no significant change in the viscosity with time ([poly-**1**] = 1.0 g/dL), suggesting that the changes observed in the NMR are probably due to a change in the local mobility of the polymer backbone and could not reflect a global conformational change. Although the molecular weight of the polymer used in this viscosity study may not be high enough to detect such a global conformational change, these results indicate that the "as-prepared" poly-**1** is not a rigid rod but rather a flexible polymer. However, in the presence of (1*R*,2*S*)-**9**, the solution viscosity gradually decreased with time ([poly-**1**] = 1.0 g/dL and [**9**]/[poly-**1**] = 2); the reduced viscosity value ($[\eta_{sp}]/c$) decreased from 0.994 to an almost constant value (0.916) after 35 days. During this viscosity change, the $\Delta\epsilon$ value (362 nm) of the same solution gradually increased from 3.53 to 9.18, indicating that the formation of aggregates or gelation could be excluded. AFM analyses of the polymer in solution in the presence and absence of (1*R*,2*S*)-**9** also support this conclusion (see the text). The reduced viscosity ($[\eta_{sp}]/c$) value of the poly-**1**−(1*R*,2*S*)-**9** solution decreased monotonically with the decrease in the polymer concentration (1−0.3 g/dL), but it increased with further decrease in the polymer concentration (0.3−0.06 g/dL). This is a typical viscosity change in polyelectrolytes, suggesting that the polymer is a weak polyelectrolyte in DMSO in the presence of the chiral amine.

[19] The "as-treated" poly-**1** (e in Figure 4A) maintained the preserved conformation after precipitation of the polymer into methanol. The ^{1}H NMR spectrum of the recovered poly-**1** in DMSO-d_6 showed the same spectral pattern as that before the precipitation.

[20] Nolte et al. studied *syn*−*anti* isomerism (see Chart 1) in PPI derivatives using NMR and observed a dramatic change in the spectral pattern of the two methoxy protons of poly(4-methoxyphenyl isocyanide) in the presence of trifluoroacetic acid; addition of the acid resulted in *syn*-to-*anti* (or vice versa) isomerization, and, therefore, the two methoxy signals changed to almost a single signal.[1b,21] We prepared poly(4-methoxyphenyl isocyanide) and confirmed the reproducibility of the data. The ^{1}H NMR spectra of the "as-prepared" poly-**1** and poly-**1**-Et in the presence of trifluoroacetic acid were then measured. However, the spectral pattern scarcely changed even after the samples had been allowed to stand for two weeks at 30 or 60 °C. In the former case, main chain-isomerization, that is, polyisocyanide-to-polycyanide isomerization, may be taken into consideration. See ref 1a and Nolte, R. J. M.; Stephany, R. W.; Drenth, W. *Recl. Trav. Chim. Pays-Bas* **1973**, *92*, 83−91.

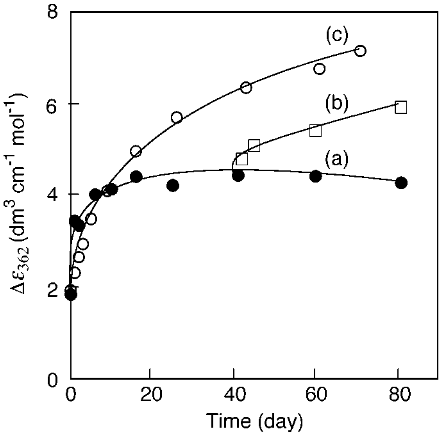

Figure 5. Changes in the CD intensity (362 nm) of the "as-treated" poly-**1**−(1*R*,2*S*)-**9** complex at 30 °C in DMSO (a). The CD spectra were measured by adding (1*R*,2*S*)-**9** after the "as-prepared" poly-**1** alone had been standing in DMSO for days. The changes in the CD intensity of the complex of the "as-treated" poly-**1** (after 41 days at 30 °C) with (1*R*,2*S*)-**9** are shown in (b). The time-dependent ICD changes of the "as-prepared" poly-**1**−(1*R*,2*S*)-**9** complex are also shown in (c) for comparison (see Figure 3A). Poly-**1** concentration = 1.0 mg/mL; molar ratio of amines to monomeric unit of poly-**1** = 50.

poly-**1** alone (2 mg/mL) in DMSO was prepared in a 20 mL flask equipped with a stopcock, and the flask was thermostated at 30 °C under shielded light. A 1 mL aliquot of the poly-**1** solution was transferred to a 2 mL flask using a transfer pipet after the sample had been allowed to stand for 1, 2, 6, 10, 16, 25, 41, 60, and 81 days. To the flask was added 50 equiv of (1*R*,2*S*)-**9** to poly-**1** directly into the poly-**1** solution, and the solution was diluted with DMSO to maintain the poly-**1** concentration at 1 mg/mL. The CD spectrum was then taken at 30 °C for each flask immediately after the addition of the amine (Figure 5a). The initial CD intensities of the "as-treated" poly-**1**−(1*R*,2*S*)-**9** complex increased with time and reached a constant value ($\Delta\epsilon$ = ca. 4.2) when the "as-prepared" poly-**1** had been standing for over 16 days (Figure 5a). This value is larger than the initial value of the "as-prepared" poly-**1**−(1*R*,2*S*)-**9** complex ($\Delta\epsilon$ = 1.8, see Figure 5c) by a factor of 2.3. These changes are closely correlated with those in the ^{1}H NMR spectral pattern of the "as-prepared" poly-**1** with time. The CD intensity of the "as-treated" poly-**1**−(1*R*,2*S*)-**9** complex further increased with time in a manner similar to that seen in Figure 5b. The results support a two-step conformational transition of poly-**1**; the first conformational transition of poly-**1** gradually occurs with time despite the absence of chiral amines, and the second transition takes place further in the presence of chiral amines to form probably a helical conformation with a predominant screw sense.

Atomic Force Microscopy Studies. Atomic force microscopy (AFM) analyses of poly-**1** ($M_n = 3.7 \times 10^4$ (DP = ca. 211) and $M_w/M_n = 2.2$) with or without (1*R*,2*S*)-**9** on a freshly cleaved mica surface were then conducted to observe changes in morphology and conformation of the polymer main chains. Figure 6 shows typical AFM images of the "as-prepared" poly-**1** (Figure 6A and B) and the "as-prepared" poly-**1**−(1*R*,2*S*)-**9** complex (Figure 6C). Under a relatively high poly-**1** concentration (0.5 mg/mL), the mica substrates were covered with a nanostructured network and wormlike poly-**1** chains (Figure 6A), while individual poly-**1** and poly-**1** chains complexed with (1*R*,2*S*)-**9** can be directly visualized on mica prepared from a dilute solution of poly-**1** (0.05 mg/mL) (Figure 6B and C). The average height (*h*) of the "as-prepared" poly-**1** was determined to be 1.4 ± 0.3 and 1.1 ± 0.2 nm from ca. 100 cross-section profiles in Figure 6A and B, respectively, which was shorter than the molecular diameter of a helical poly-**1** model; the computer-generated molecular diameters (widths) of helical poly-**1**s having all *s-cis* (4_1 helix) and all *s-trans* conformations were 1.9 and 1.7 nm, respectively (see Supporting Information). This reduced height of the poly-**1** molecules indicates that the "as-prepared" poly-**1** may not have a rigid-rod helical conformation but a rather planar one, particularly on the mica surface.[22] Under a dilute condition, single molecules of poly-**1** could be observed, and such molecular resolution allowed direct measurements of the average molecular length of poly-**1**.[23] On the basis of the evaluation of more than 200 molecules in the AFM images including the image in Figure 6B, the number average length (L_n), the weight average length (L_w), and the average diameter (*d*) of the "as-prepared" poly-**1** were estimated to be 28.1, 45.8, and 18 ± 2.0 nm, respectively. These values were measured without compensation for the tip radius of curvature (ca. 10 nm), and, therefore, the measured values were overestimated due to the broadening effect of the tip.[23,24] However, the vertical resolution of the AFM images is much better, and the height value can be used as an alternate value of diameter.[25] The L_n of 28 nm corresponds to all *s-cis* and all *s-trans* extended poly-**1**s with DP = 233 and 175, respectively, which roughly agrees with the number-average molecular weight of the "as-prepared" poly-**1**-Et estimated by SEC (DP = 211). The computer models of all *s-cis* and *s-trans* poly-**1** also indicate that the all *s-trans* poly-**1** has an extended conformation, and its length is longer than that of the all *s-cis* helical poly-**1** by a factor of 1.3 if the DP is the same. This means that we may be able to observe a conformational change directly by AFM if a poly-**1** sample with a narrow molecular weight distribution is available.[7]

The average height value of the "as-prepared" poly-**1** significantly increased to 1.8 ± 0.3 nm after complexation with (1*R*,2*S*)-**9** ($\Delta\epsilon$ = 1.67 (362 nm), Figure 6C), and the polymer chains appeared to grow thicker. However, this value is still shorter than those of the computer-generated molecular diameters of helical poly-**1**s complexed with the amine; the calculated diameters of the all *s-cis* and all *s-trans* poly-**1**−(1*R*,2*S*)-**9** complexes are 3.2 and 2.7 nm, respectively.[22] Almost similar AFM images were observed after the "as-prepared" poly-**1** with

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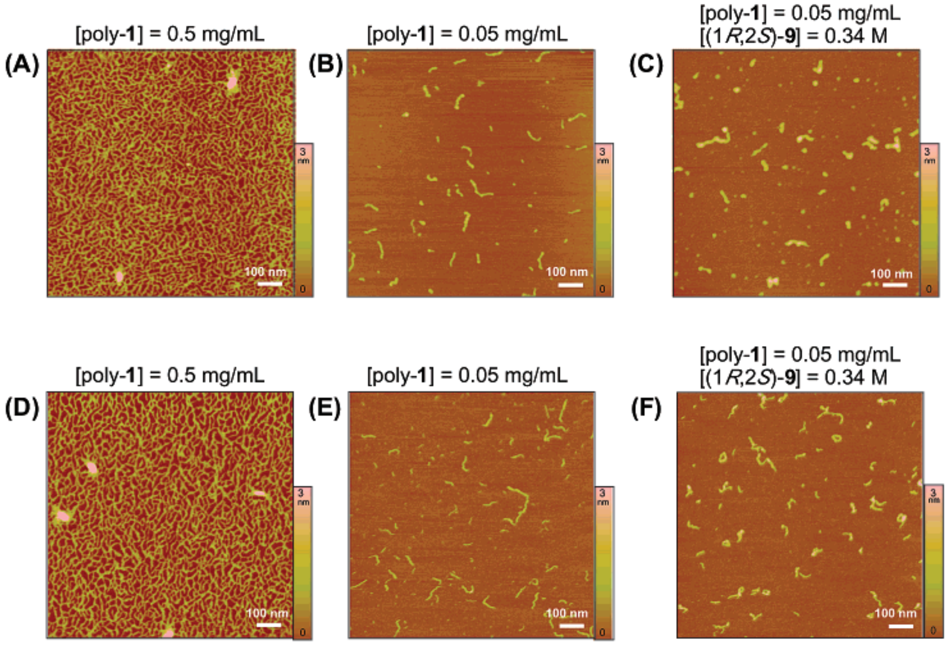

Figure 6. AFM tapping mode images (1 × 1 μm^2) of the "as-prepared" poly-**1** (A and B), the "as-prepared" poly-**1**−(1*R*,2*S*)-**9** complex (C), the "as-treated" poly-**1** (D and E), and the "as-treated" poly-**1**−(1*R*,2*S*)-**9** complex (F) on mica. The concentrations of poly-**1** are 0.5 (A and D) and 0.05 mg/mL (B, C, E, F) in DMSO (A, B, D, E) and in 0.34 M DMSO solution of (1*R*,2*S*)-**9** (C and F).

(Figure 6F) or without (Figure 6D and E) the chiral amine had been allowed to stand over 1 week ($\Delta\epsilon$ value (362 nm) of the poly-**1**−(1*R*,2*S*)-**9** complex = 3.76), indicating that the morphology of the poly-**1** chains was retained after conformational changes either in the presence or in the absence of the chiral amine. Apparently, a further study using scanning tunneling microscopy (STM) may be necessary to detect an atomic level conformational change in this system.[24c,26]

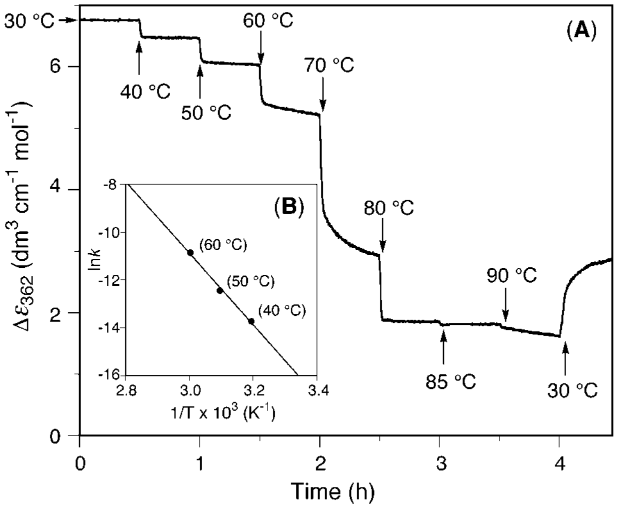

Figure 7. Kinetics of the CD intensity changes process for the poly-**1**−(1*R*,2*S*)-**9** complex in DMSO following temperature jumps (A); molar ratio of **9** to poly-**1** is 50. Changes in CD intensity at 362 nm were followed in a 0.10 cm quartz cell with a poly-**1** concentration of 1.0 mg/mL. Arrhenius plot of the temperature dependence of the first-order rate constants obtained at 40, 50, and 60 °C is also shown in B (see the text).

Kinetic Study. To study the kinetics of the chiral (helical) conformation of the poly-**1** induced by (1*R*,2*S*)-**9**, we monitored the CD intensity changes in a solution of the complex showing $\Delta\epsilon = 6.8$ at 362 nm which had been prepared on allowing the sample solution to stand at 30 °C for ca. 2 months, following temperature jumps of 10° with final temperatures in the range 40−90 °C (Figure 7A). The complex exhibited unusual decays of optical activity consisting of, first, a kinetically unresolved, very fast process (probably due to temperature-dependent ion-pairing) and, second, a slower decrease to shift to new conformational equilibria after the temperature jumps.[27] In cases where the final temperatures were in the range of 40−60 °C, first-order kinetics in semilogarithmic plots of the CD intensity changes against time could describe the observed second changes; the apparent rate constants at 40, 50, and 60 °C were 0.109×10^{-5}, 0.394×10^{-5}, and 1.94×10^{-5} s^{-1}, respectively. The activation energy was then calculated to be 29.7 kcal/mol (124.4 kJ/mol) from the Arrhenius plot of the temperature dependence of the rate constants (Figure 7B). If the "as-treated" poly-**1**−(1*R*,2*S*)-**9** complex ($\Delta\epsilon = 6.8$ at 362 nm) had a predominantly one-handed helical conformation, this process could be regarded as either a helix-to-coil transition or a helix-to-helix transition (helix inversion). The latter seems the case, because this value is comparable to those of the activation energies for the helix inversion of synthetic helical polymers estimated by means of dynamic NMR spectroscopy or from kinetics of racemization: *cis-transoidal* poly(hexyl propiolate) (18.5 kcal/mol), isotactic chloral hexamer and poly(2-butylhexyl isocyanate) (19.6 kcal/mol), isotactic, optically active poly(diphenyl-2-pyridylmethyl methacrylate) (23 kcal/mol), and threodiisotactic poly(triphenylmethyl crotonate) (28.4 kcal/mol).[1g,28] The rather large energy barrier for the "as-treated" poly-**1**−(1*R*,2*S*)-**9** complex may be due to electrostatic repulsion

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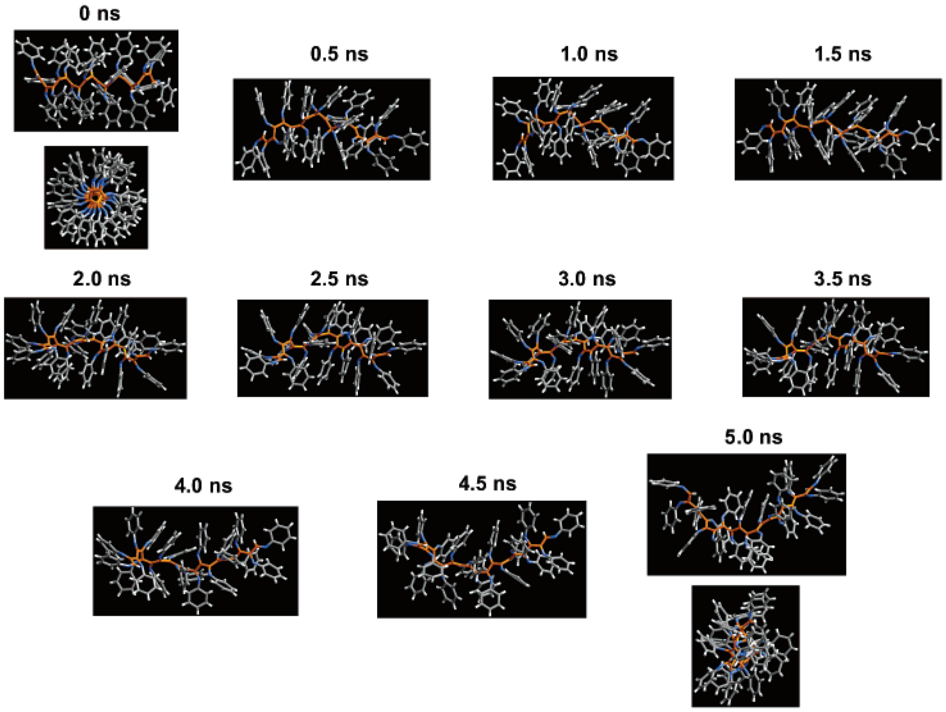

Figure 8. Snapshots of the conformations of poly(phenyl isocyanide) (PPI) at the beginning (0 ns) of the MD simulations over 5 ns at 0.5 ns intervals. The chains are placed so that the chain axes are on the figure plane. View perpendicular to the chain axis is also shown in the snapshots at 0 and 5 ns. The main chain carbon atoms of PPI and nitrogen atoms are shown in orange and blue, respectively.

between neighboring ion pairs at the side groups, although in the case of a helical polyguanidine induced by the complexation with (*S*)-camphorsulfonic acid, its activation energy for the helix inversion was reported to be rather small (6.4 kcal/mol).[12]

In cases where the final temperature was 70 °C (Figure 7A), strong deviations from first-order kinetics were observed for the changes. In DMSO, the acid−base complexation equilibrium lies between the ion pairs and the free ions, and ion pairing seems to be necessary for the ICD.[11d,29,30] However, at higher temperatures, the dissociation of ion pairs to free ions may be accelerated, which may cause a steep decrease in the ICD intensity.[29a] The poly-**1** did not lose its optical activity even at 90 °C.[31] After a temperature jump from 90 to 30 °C, the reversed slow recovery of the optical activity was observed again, indicating that this process was reversible.

Molecular Dynamics Simulations. To gain information regarding the conformation of PPI derivatives, we performed molecular mechanics and molecular dynamics (MD) calculations for a polymer model of 20 mer using the Dreiding force field.[32] The starting main chain conformation of PPI was set to retain a 4_1 helical conformation with a stereoregular isotactic structure,[1b,5a] and MD calculations were then run for the model polymer for 5 ns at constant volume and temperature (400 K) (NVT MD using the Hoover temperature thermostat) with a step size of 1 fs.[33] Figure 8 shows representative snapshots of the PPI chain over 0−5 ns at 0.5 ns intervals. The PPI chain gradually transformed from a 4_1 helical conformation to an extended all *s-trans*-like conformation over 5 ns. During the MD simulations, transitional conformations consisting of *s-cis*, *s-trans*, and *s-cis-s-trans* domains were observed, and the total potential energy gradually decreased. This indicates that the 4_1 helical conformation[1a−c] is not a preferable conformation, but the all *s-trans* conformation[6] may certainly be a favorable conformation for PPIs. Such an extended conformation of PPIs can be related to the absorptions at longer wavelengths. These results appear to be very useful in explaining the changes in the NMR spectra of poly-**1** and poly-**1**-Et and the changes in the ICDs of poly-**1** in the presence of chiral amines.

Conformational Transitions and Mechanism of Macromolecular Chirality Induction on PPIs. The question may be raised regarding what the conformations of the “as-prepared” poly-**1** and poly-**1**-Et, the “as-treated” poly-**1** and poly-**1**-Et, and the poly-**1** complexed with chiral amines are. Figure 9A schematically illustrates a possible conformational change in PPIs on the basis of the results of NMR and CD measurements and the MD simulations. As described earlier, the 4_1 helical conformation (I) has long been accepted for polyisocyanides and may be true for bulky polyisocyanides.[1a−c,2,3] Euler and

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(30) IR spectra of free poly-**1** and the poly-**1**−(1*R*,2*S*)-**9** complex in DMSO also support this ion-pair formation. Poly-**1** showed absorption at 1700 cm^{-1} corresponding to the carboxylic acid carbonyl band, which almost completely disappeared in the presence of (1*R*,2*S*)−**9**, and the band shifted to 1534 cm^{-1} assigned to the ion-paired and/or dissociated acid carbonyl band.

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(33) At 300 K, however, the structure of PPI did not change significantly even after 5 ns MD calculations.

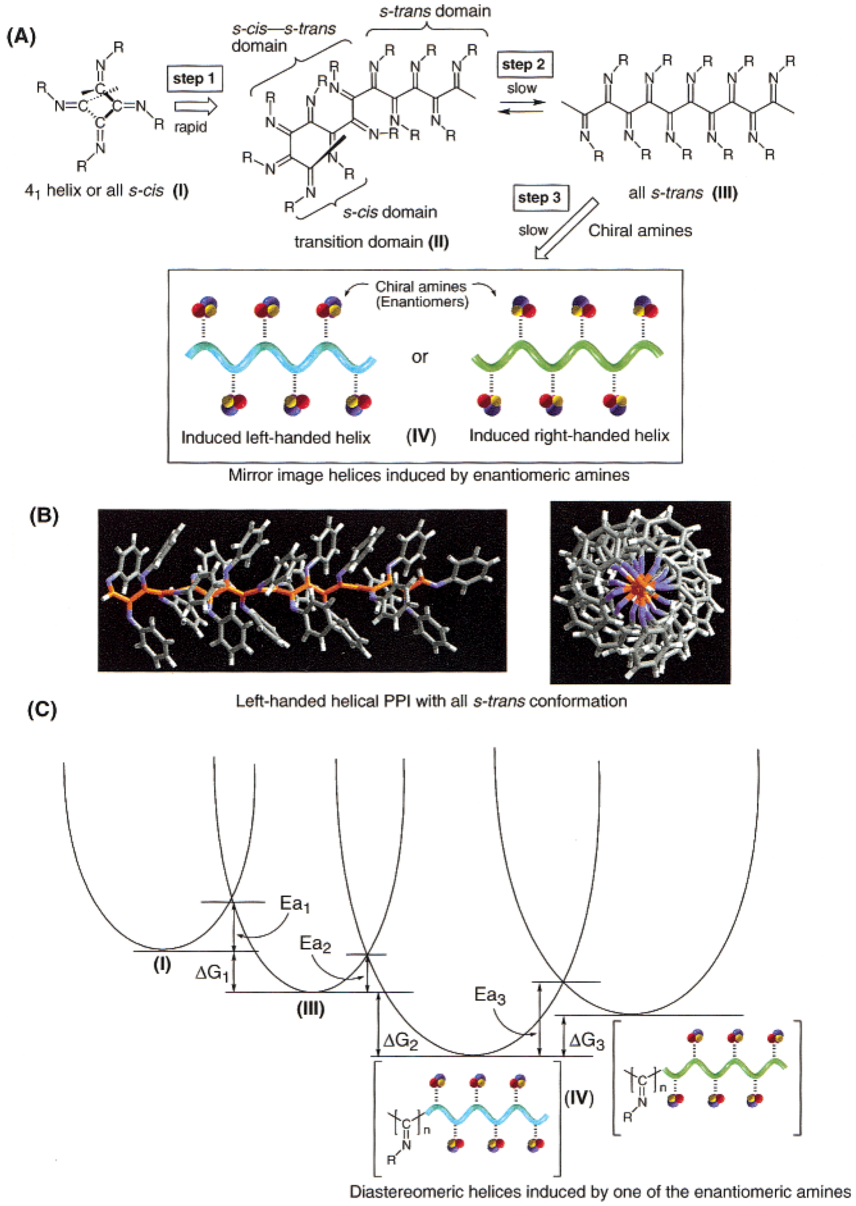

Figure 9. Possible conformational changes and helicity induction of poly(phenyl isocyanides) (A) and an optimized all *s-trans* structure with a predominant one-handed helix (B). The main chain carbon atoms of PPI and nitrogen atoms are shown in orange and blue, respectively. View along the chain axis (left) and perpendicular to the chain axis (right) in B. Energy diagrams for the conformational transition of PPIs are also shown in C.

Rosen et al. experimentally showed a preference for linear *s-trans* or zigzag conformation (III) for phenyl isocyanide oligomers in solution.[6] They also reported that PPI maintains a 4_1 helical conformation kinetically during the polymerization, while it becomes a random coil polymer with a transition domain (II-like conformation) once it is dissolved in solution on the basis of the structure of a unique heterocyclic ring molecule isolated from the nickel-ion catalyzed polymerization of phenyl isocyanide[34] and the time-dependent, conformational changes in PPI by means of X-ray diffraction and light-scattering measurements.[4d] Unfortunately, they could not follow the conformational change in solution by NMR because the "as-prepared" PPI isolated from the polymerization system precipitated rather quickly. Clericuzio and co-workers theoretically proposed a preference for an *s-cis*-*s-trans* alternating conformation with syndio geometry for aliphatic polyisocyanides.[5a] Other structures including an *s-cis*-*s-trans* alternating conformation with isotactic geometry may also be possible.

Although we do not have unambiguous spectroscopic data including tacticity to propose the exact structure in such a transition, our speculative models can be shown in Figure 9A. The changes in the ^{1}H and ^{13}C NMR spectra of the "as-prepared" poly-**1**-Et in $CDCl_3$ with time indicate a change in the conformation during the time period as proposed by Euler and Rosen et al. for PPI.[4d] Poly-**1**-Et may have a 4_1 helical conformation during the polymerization (I), but the helical conformation might be substantially lost at least after isolation and hydrolysis of the polymer to form a random conformation consisting of *s-cis* and *s-trans* sequences about the C−C bond of the main chain (II, step 1 in Figure 9A). However, the "as-prepared" poly-**1** and poly-**1**-Et also exhibited a very slow conformational change at 30 °C in solution either in the presence

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(34) Euler, W. B.; Huang, J.-T.; Kim, M.; Spencer, L.; Rosen, W. *Chem. Commun.* **1997**, 257−258.

or in the absence of chiral amines, which indicates that the conformation changes to a thermodynamically stable, rather regular conformation (for energy diagrams for the conformational transitions, see also Figure 9C), probably an all *s-trans* conformation (III) as proposed by Euler and Rosen[4d,6] and as demonstrated in this study (step 2 in Figure 9A). Such an extended conformation of PPIs can explain why optically active PPIs have longer wavelength absorptions.[35] This conformation III seems to be achiral, but can become chiral if the random twist around the C−C bonds of the main chain is transformed into one direction to form a dynamic, one-handed helical conformation (see IV in Figure 9A and C and Supporting Information) when the polymer can interact with chiral amines. The induced helix sense can be controlled by the chirality of the chiral amines, because the induced right- and left-handed helices of PPIs by one of the enantiomeric amines are not enantiomers, but diastereomers, so that one of the helices should be predominant (see Figure 9C). A computer modeling suggests that such an all *s-trans* PPI can form a one-handed helical conformation (five turns with 12 monomer units) as the lowest energy conformation (Figure 9B). This also implies that all *s-trans* PPI may exist in dynamic helices (a mixture of right- and left-handed helices). Similar helicity induction can be possible on optically inactive, *cis-transoidal* poly((4-carboxyphenyl)acetylene) with chiral amines.[11d] The transition from II to III may be the rate-determining step, and it will occur more rapidly in the absence of chiral amines.

This speculation is supported by the previous fact that PPI and its derivatives bearing a less bulky substituent on the phenyl moieties, for instance, a methoxy group at the para position, could not yield optically active, helical polymers by the screw-sense selective polymerization using chiral catalysts.[3a] These results suggest that the PPI is a nonhelical or a dynamic helical polymer in solution. If PPI is a dynamic helical polymer with a persistence length, a prevailing one-handed helical PPI can possibly be prepared when phenyl isocyanide is copolymerized with a small amount of chiral isocyanide. Actually, a copolymer of phenyl isocyanide with an optically active aliphatic isocyanide (23 mol %) showed a relatively larger $\Delta\epsilon$ value (ca. -2 at 350 nm) than that of the corresponding optically active homopolymer ($\Delta\epsilon$ is less than -1).[36] This suggests the dynamic nature of PPI, although the results may be explained on the basis of the difference in polymerization rates of achiral and chiral isocyanides on the assumption that both homopolymers and copolymers could form a stable helical conformation.[36] Takahashi et al.[7] prepared a one-handed helical, living polyisocyanide derived from an optically active phenyl isocyanide bearing L-menthyl residues using the dinuclear transition metal complex and used it as an initiator for the block polymerization of achiral phenyl isocyanides. A block copolymer with bulky phenyl isocyanides such as 3,5-dipropoxycarbonylphenyl isocyanide preserved the one-handed helical conformation of the prepolymer used as the initiator, whereas those with less hindered phenyl isocyanides bearing a 4-butyl or 4-cyclohexyloxycarbonyl group on the phenyl moieties showed a significant loss of optical activity.[7c,d] These results strongly suggest that long sequences of phenyl isocyanide having a less bulky side group cannot maintain a one-handed helical conformation, although the possibility of the dynamic helical nature of PPI having helix-reversal points[1p,4a] may not be ruled out.

Conclusions

The present results for the first time demonstrate that PPIs bearing a less bulky substituent cannot maintain a 4_1 helical conformation but can adopt a dynamic, one-handed helical conformation upon complexation with chiral molecules as observed for polyacetylenes.[11] Conformational dynamics of PPIs are clearly observed using NMR and CD spectroscopies and MD simulations. These findings may be useful to design and construct novel functional chiral materials consisting of dynamic helical polyisocyanides. We hope that the induced helical conformation of poly-**1** may be able to be "memorized" when the chiral amine is replaced with achiral amines.[37] This work is now in progress.

Experimental Section

Materials. DMSO was dried over calcium hydride, distilled under reduced pressure, and stored under nitrogen over molecular sieves 4 Å (Nacalai Tesque, Tokyo, Japan). Dichloromethane and chloroform were dried over calcium hydride and distilled. The dichloromethane was distilled again under high vacuum just before use. $CDCl_3$ (99.8 atom %D, Nacalai Tesque) and DMSO-d_6 (99 atom %D, Aldrich) were dried over molecular sieves 4 Å and stored under nitrogen. All solvents used for measurements of CD and NMR spectra were purged with nitrogen prior to use. (*R*)-**3** and (*R*)-**4** were kindly supplied from Yamakawa Chemical (Tokyo, Japan). Other optically active amines and amino alcohols were available from Aldrich or Tokyo Kasei (Tokyo, Japan).

4-(Ethoxycarbonyl)phenyl isocyanide was prepared from ethyl 4-aminobenzoate according to the previously reported method.[38] The crude product was purified by silica gel chromatography with hexanes−ethyl acetate (3/1, v/v) as the eluent (66.3% yield). Mp (35.4−36.4 °C). IR (Nujol, cm^{-1}): 2219 ($\nu_{C\equiv N}$), 1730 ($\nu_{C=O}$). ^1H NMR ($CDCl_3$): δ 1.41 (t, $J = 7.2$ Hz, CH_3, 3H), 4.40 (q, $J = 7.2$ Hz, CH_2, 2H), 7.45 and 8.09 (d, $J = 6.6$ Hz, aromatic, 4H).

Polymerization. Polymerization was carried out in a dry glass ampule using $NiCl_2 \cdot 6H_2O$ as a catalyst in a similar way previously reported[4,9] (Scheme 1). 4-(Ethoxycarbonyl)phenyl isocyanide (4.80 g, 27.4 mmol) was placed in a dry ampule, which was then evacuated on a vacuum line and flushed with dry nitrogen. After this evacuation-flush procedure was repeated three times, a three-way stopcock was attached to the ampule, and dry dichloromethane (137 mL) was added with a syringe. To this was added a solution of $NiCl_2 \cdot 6H_2O$ in dry methanol (0.3 M, 0.91 mL) at room temperature with stirring in the presence of air. The concentrations of the monomer and the Ni catalyst were 0.2 and 0.002 M, respectively. After 1 day, the resulting polymer was precipitated into a large amount of methanol, collected by centrifugation, washed with methanol, and then dried in vacuo at 50 °C for 2 h (4.46 g, 93% yield).

Spectroscopic data of poly(4-(ethoxycarbonyl)phenyl isocyanide). IR (Nujol, cm^{-1}): 1721 ($\nu_{C=O}$), 1654 ($\nu_{C=N}$). ^1H NMR ($CDCl_3$, 30 °C): δ 0.8−1.6 (br, CH_3, 3H), 3.5−4.7 (br, CH_2, 2H), 5.2−6.2 and 6.4−8.1 (br, aromatic, 4H). ^{13}C NMR ($CDCl_3$, 30 °C): δ 14.1 (br, CH_3), 60.8 (br, CH_2), 117.2, 127.3, 129.9, 150.5 (br, aromatic), 162.7 (br, C═N), 165.1 (br, C═O). Anal. Calcd for $(C_{10}H_9NO_2)_n$: C, 68.56; H, 5.18; N, 8.00. Found: C, 68.51; H, 5.36; N, 8.00.

Poly(4-(ethoxycarbonyl)phenyl isocyanide) (4.25 g) was converted to poly-**1** by hydrolysis of the ester groups in 100 mL of THF and aqueous 10 N NaOH (14 mL) at room temperature. After 3 days, the aqueous layer was separated and acidified with 1 N aqueous HCl. The

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(35) A similar extended conformation was recently reported for aliphatic polyisocyanides, see: Yamada, Y.; Kawai, T.; Abe, J.; Iyoda, T. *J. Polym. Sci., Part A: Polym. Chem.* **2002**, *40*, 399−408.

(36) Kamer, P. C. J.; Cleij, M. C.; Nolte, R. J. M.; Harada, T.; Hezemans, A. M. F.; Drenth, W. *J. Am. Chem. Soc.* **1988**, *110*, 1581−1587.

(37) Yashima, E.; Maeda, K.; Okamoto, Y. *Nature* **1999**, *399*, 449−451.

(38) Skorna, G.; Ugi, I. *Angew. Chem., Int. Ed. Engl.* **1977**, *16*, 259−260.

precipitated polymer was then collected by centrifugation, washed with methanol, and dried in vacuo at 50 °C for 2 h (100% yield).

Spectroscopic data of poly-**1**. IR (Nujol, cm^{-1}): 1700 ($\nu_{C=O}$), 1655 ($\nu_{C=N}$). ^{1}H NMR (DMSO-d_6, 30 °C): δ 5.2−6.3 and 6.5−8.0 (br, aromatic, 4H), 12.2 (br, COOH, 1H). ^{13}C NMR (DMSO-d_6, 60 °C): δ 117.1, 127.4, 129.4, 150.0 (br, aromatic), 161.2 (br, C═N), 166.0 (br, C═O). Anal. Calcd for $(C_8H_5NO_2{\cdot}{}^1/_2H_2O)_n$: C, 61.54; H, 3.87; N, 8.97. Found: C, 61.24; H, 3.82; N, 8.87.

Instruments. Melting points were measured on a Büchi melting point apparatus and are uncorrected. NMR spectra were measured on a Varian VXR-500S spectrometer operating at 500 MHz for ^{1}H and 125 MHz for ^{13}C, respectively, using TMS as the internal standard. Line shape analysis was performed using standard Varian software. A Lorentzian function was applied to the line shape analysis for PPI derivatives, and the curves gave good agreements with the observed spectra. IR spectra were recorded using a Jasco Fourier Transform IR-620 spectrophotometer. Absorption spectra were taken on a Jasco V-570 spectrophotometer. CD spectra were measured in a 0.05 cm quartz cell unless otherwise noted using a Jasco J-725-L spectropolarimeter. Temperature was controlled with Jasco PTC-348WI and ETC-505T apparatuses for CD and absorption measurements, respectively. SEC was performed using a Jasco PU-980 liquid chromatograph equipped with a UV−visible (254 nm; Jasco UV-970) detector. A Tosoh TSKgel Multipore H_{XL}-M GPC column (30 cm) was connected, and chloroform was used as the eluent at a flow rate of 1.0 mL/min. The molecular weight calibration curve was obtained with standard polystyrenes (Tosoh). Dilute solution viscosity was measured using an Ubbelohde viscometer at 30 °C in DMSO. AFM measurements were performed on a Nanoscope IIIa microscope (Digital Instruments, Santa Barbara, CA) in air using standard silicon tips (NCH-10V) in the tapping mode. Height and phase images were simultaneously measured at the resonance frequency of the tips with 125 μm long cantilevers (235−240 kHz). All of the images were collected with the maximum available number of pixels (512) in each direction (1 μm). Scanning speed was at a line frequency of 1.0 Hz.

CD Measurements. The concentration of poly-**1** was calculated on the basis of monomer units. A typical experimental procedure is described below. A stock solution of poly-**1** (2 mg/mL) in DMSO was prepared in a 10 mL flask equipped with a stopcock. A 1 mL aliquot of the stock solution of poly-**1** was transferred using a transfer pipet to a 2 mL flask equipped with a stopcock, and an appropriate amount of a chiral amine was added to the flask using a Hamilton microsyringe. The solution was immediately mixed with a vibrator (Iuchi, Japan) and finally diluted with DMSO to keep the poly-**1** concentration of 1.0 mg/mL to measure UV−visible and CD spectra. The temperature jump experiments were performed in a 0.1 cm quartz cell using the same CD system. The temperature was thermostated with a Jasco PTC-348WI thermostat. The change of temperature was achieved within ca. 5 s.

AFM Measurements. Stock solutions of poly-**1** ($M_n = 3.7 \times 10^4$ and $M_w/M_n = 2.2$; 0.5 and 0.05 mg/mL) in DMSO and poly-**1** (0.05 mg/mL) in 0.34 M DMSO solution of (1*R*,2*S*)-**9** were prepared. Fifty microliter aliquots of the stock solutions were dropped on freshly cleaved mica substrates, the solutions were blown off simultaneously with a stream of nitrogen, and the mica substrates were dried in vacuo overnight to measure the AFM images in the tapping mode.[39] All of the experiments were performed in air at ambient temperature. Polymer lengths were measured using the NIH Image program, developed at the National Institutes of Health (available on the Internet at http://rsb.info.nih.gov/nih-image/).

Molecular Modeling and Calculations. Molecular modeling, molecular mechanics calculations, and molecular dynamics simulations were performed with the Dreiding force field (version 2.11)[32] as implemented in Cerius^2 software (version 1.5, Molecular Simulations, Inc., Burlington, MA) running on an Indigo^2-Impact graphics workstation (Silicon Graphics). Charges on the atoms of PPI were calculated using charge equilibration (QEq) in Cerius^2; the total charge of the molecule was zero. The polymer model of 20 mer (20 repeating monomer units of phenyl isocyanide, PPI) was built by Polymer Builder in Cerius^2. The starting main chain conformation of a polymer model was defined as a conformation of a rotational single C−C bond (*s-cis* or *s-trans*). The C═N double bond geometry was fixed to isotactic, and the initial dihedral angle of a single bond (ϕ) from planarity was allowed to rotate from 180° (*s-trans*) to 10° (*s-cis*) at 10° intervals. The energy minimization was accomplished by conjugate gradient (CG) until the root-mean-square (rms) value became less than 0.1 kcal mol^{-1} Å^{-1}. The optimized *s-cis* and *s-trans* PPIs had a helical conformation with $\phi = 59.9 \pm 1.8°$ and $146.4 \pm 3.9°$, respectively (see Supporting Information). MD calculations were then run for the all *s-cis* polymer for 5 ns at constant volume and temperature (400 K) (NVT MD using the Hoover temperature thermostat) with a step size of 1 fs, and the trajectory structures were obtained at 0.5 ps intervals.

All *s-cis* and *s-trans* poly-**1** models (20-mer) were constructed on the basis of the average dihedral angles of the optimized PPIs; the initial ϕ was set to 60° (*s-cis*) and 140° (*s-trans*), and the energy minimization was accomplished by CG. The optimized *s-cis* and *s-trans* poly-**1**s had a helical conformation with $\phi = 57.2 \pm 1.1°$ and $144.4 \pm 1.6°$, respectively (see Supporting Information). In a similar way, *s-cis* and *s-trans* poly-**1** models complexed with (1*R*,2*S*)-**9** were constructed. First, (1*R*,2S)-**9** was manually placed on the carboxy group of a repeating unit of poly-**1**, and the *s-cis* and *s-trans* polymer models of 20 mer were built by Polymer Builder. The complexes were further minimized by CG to relieve unfavorable van der Waals contacts, while the geometry of the poly-**1** was fixed. The energy minimization of the complexes was further accomplished by CG. The diameters and lengths of these helical poly-**1**s and poly-**1**−(1*R*,2*S*)-**9** complexes were then measured (see Supporting Information).

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Supporting Information Available: Changes in the CD intensity of the complexes of poly-**1** with (*R*)-**6** and (1*R*,2*S*)-**9** with time at various temperatures in DMSO, time-dependent ^{1}H and ^{13}C NMR changes of poly-**1**-Et, and optimized structures of all *s-cis* and *s-trans* PPI, poly-**1**, and the poly-**1**−(1*R*,2*S*)-**9** complexes (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

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