Polymerization of an optically active phenylacetylene derivative bearing an azide residue by click reaction and reaction with a rhodium catalyst†

Shinzo Kobayashi, Ken Itomi, Kazuhide Morino, Hiroki Iida and Eiji Yashima*

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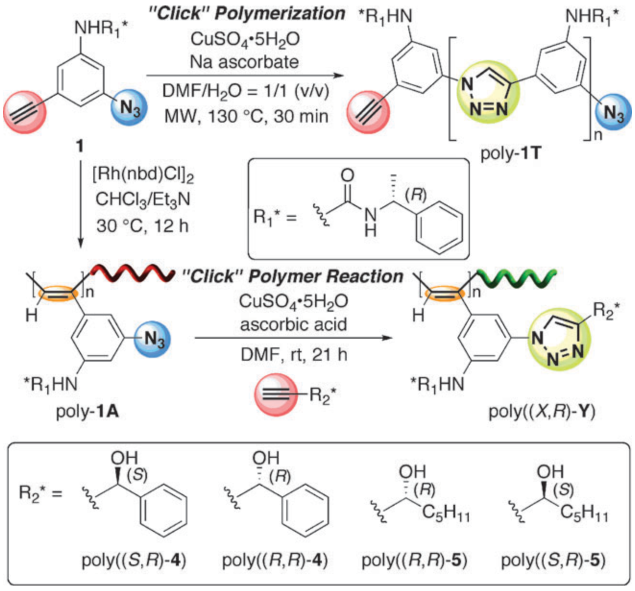
A facile method for synthesizing diverse optically active polymers with different backbone structures was developed by the polymerization of an optically active aromatic azide bearing an acetylene unit with a rhodium catalyst followed by the click reaction of the pendant azides or by the click polymerization of the monomer.

The Cu(I)-catalyzed Huisgen-type 1,3-dipolar cycloaddition of azides and alkynes, known as ''click chemistry'', has recently attracted significant attention in widespread fields including the materials and life sciences, because of its versatility, high selectivity, and tolerance for various functional groups.[1] In polymer chemistry, the click reaction has already been successfully used to develop a variety of functional polymers with unique architectures, such as cyclic, block, graft, dendritic, star-shaped, and network polymers.[2] However, there are relatively few examples where the click reaction has been employed to prepare optically active polymers[3] in spite of their attractive applications to chiral materials as enantioselective catalysts, adsorbents, and biocompatible materials.[4] We now report a novel approach to generate diverse optically active polymers through the click reaction as well as a normal chain-polymerization followed by side-chain modification using the click reaction.

Our strategy to make diverse optically active polymers from a single monomer is illustrated in Scheme 1. A novel optically active monomer **1** bearing both azide and acetylene groups within the molecule was designed and synthesized. This monomer can produce two types of optically active polymers with different main-chain structures by the choice of the polymerization catalysis, *i.e.*, copper or rhodium. The Cu(I)-catalyst promotes the polyaddition reaction of **1** to give an optically active ''click'' polymer (poly-**1T**) bridged by the *anti*-1,2,3-triazole-ring, whereas a rhodium complex catalyzes a normal chain polymerization of the acetylene moiety to afford an optically active helical poly(phenylacetylene) (poly-**1A**) with a preferred-handed helical conformation biased by the optically active side group (R_1*).[4f,g,5] In addition, the polyacetylene has azide pendant groups after the polymerization, and further modification of the azide pendant groups through the ''click'' polymer reaction with optically active acetylenes is possible, thus producing modified diverse poly(phenylacetylene)s with optical activity. Due to their dynamic helical scaffold,[4f,g,5] we anticipated that the ''click'' modification of poly-**1A** could bring about inversion of the macromolecular helicity,[4f,g,5c,6] which would be used to sense the chirality of the chiral acetylenes used as the modifier.

The ''click'' polymerization of **1** was carried out with a catalytic amount of $CuSO_4{\cdot}5H_2O$ in a mixture of dimethylformamide (DMF)–H_2O (1 : 1, v/v) in the presence of sodium ascorbate at 130 °C under microwave irradiation.[7] After 30 min, the ''click'' polymer (poly-**1T**), soluble in dimethyl sulfoxide (DMSO) and DMF, was obtained in 25% yield. The number-average molecular weight (M_n) and its distribution (M_w/M_n) were 4.3×10^4 and 3.8, respectively, as determined by size exclusion chromatography (SEC) (see ESI†). The IR and ^1H NMR spectra of poly-**1T** revealed that the addition polymerization took place stereospecifically *via* the *anti*-1,2,3-triazole-ring formation (Fig. S1 and S2†).

The circular dichroism (CD) and absorption spectra of poly-**1T** were then measured in order to explore the chiroptical property of poly-**1T** in solution in the presence and absence of poor solvents (Fig. 1). Poly-**1T** showed a broad absorption peak up to 450 nm and exhibited an apparent CD at around 270–340 nm in DMF and DMSO (Fig. 1A(b) and B), whereas the corresponding monomer **1** showed a negligibly weak CD (Fig. 1A(a)), suggesting that the poly-**1T** may have a chiral main-chain structure.[8] Interestingly, the Cotton effect pattern of the poly-**1T** drastically changed in DMF and DMSO upon the addition of a poor solvent such as $CHCl_3$ (Fig. 1A(c) and B



Scheme 1

Department of Molecular Design and Engineering, Graduate School of Engineering, Nagoya University, Chikusa-ku, Nagoya 464-8603, Japan. E-mail: yashima@apchem.nagoya-u.ac.jp;
Fax: +81-52-789-3185; Tel: +81-52-789-4495

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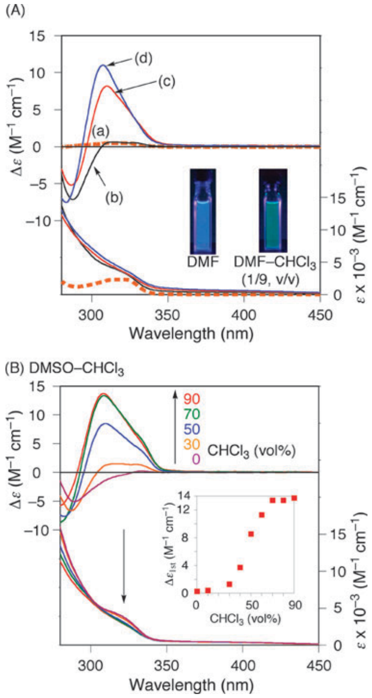

Fig. 1 (A) CD and absorption spectra of **1** in DMF (a), poly-**1T** in DMF (b), DMF–$CHCl_3$ (1 : 9, v/v) (c), and DMF–methanol (5 : 5, v/v) (d). Insets show the visible difference of poly-**1T** in DMF (left) and DMF–$CHCl_3$ (1 : 9, v/v) (right) under UV light at 365 nm. (B) CD and absorption spectral changes of poly-**1T** in DMSO–$CHCl_3$ mixtures. Inset shows plots of the CD intensity of the 1st Cotton effect ($\Delta\varepsilon_{1st}$) of poly-**1T** (at 308–333 nm) *versus* $CHCl_3$ content (vol%) in DMSO–$CHCl_3$ mixtures. CD and absorption spectra were measured at ambient temperature (26–28 °C) with a concentration of 0.2 mg mL^{-1} of poly-**1T**.

and Fig. S3A†) or methanol (Fig. 1A(d) and Fig. S3B†), and their CD intensities of the first Cotton effect ($\Delta\varepsilon_{1st}$) tended to gradually increase with the increasing volume of the poor solvents (Fig. 1B and Fig. S3†). Furthermore, the "click" polymerization of **1** led to a considerable increase in the fluorescence intensity with a large red shift, and a further red-shift was observed in the presence of a poor solvent accompanied by a fluorescence color change from blue to light green (Fig. 1A, insets and Fig. S4†).

The observed increase in the CD intensity and fluorescence color change of poly-**1T** upon the addition of poor solvents may be due to the formation of chiral aggregates. Dynamic light scattering (DLS) measurements support this speculation; the estimated hydrodynamic diameter (d_H) of poly-**1T** in DMSO increased from 8.5 ± 1.8 nm to 76 ± 19 nm in the presence of 70 vol% $CHCl_3$ (Fig. S5†). These results indicate that poly-**1T** self-assembled to form a π-stacked, supramolecular aggregate upon the addition of poor solvents, thus showing an intense induced CD (ICD) in the π-conjugated main-chain region due to the induced supramolecular chirality, as often seen in π-conjugated optically active polymers such as polythiophenes.[9,10]

Next, the monomer **1** was polymerized with $[Rh(nbd)Cl]_2$ (nbd: norbornadiene) in $CHCl_3$ in the presence of triethylamine at 30 °C for 12 h. The polymerization homogeneously proceeded to give an optically active poly(phenylacetylene) (poly-**1A**) in 87% yield, bearing azide residues as reactive pendant groups for the click reaction (Scheme 1) as indicated by its IR spectrum (Fig. S8A†). The obtained poly-**1A** (M_n and M_w/M_n values were 1.6 × 10^5 and 3.9, respectively) showed a sharp singlet centered at 5.7 ppm, due to the main chain protons, in its ^{1}H NMR spectrum, indicating that the polymer possesses a highly *cis*-transoidal, stereoregular structure (Fig. S7†).[4f,g,5] This assignment was also supported by its laser Raman spectrum (Fig. S9A†). As expected from previous studies on dynamic helical poly(phenylacetylene)s,[4f,g] poly-**1A** exhibited an ICD in the long absorption region of the polymer backbone due to a preferred-handed helical conformation (Fig. 2A), although the CD intensity was relatively weak compared with those of analogous poly(phenylacetylene)s with optically active bulky substituents at the *para* position.[4f,g,11] The CD intensity increased with decreasing temperature (Fig. S11A†), indicating that the single-handedness excess in the polymer increased with decreasing temperature.

The reactive azide groups of poly-**1A** were then further modified with a series of optically active acetylenes, such as (*R*)- and (*S*)-1-phenyl-2-propyn-1-ol (**2**) and (*R*)- and (*S*)-1-octyn-3-ol (**3**) by the "click" polymer reaction to yield diastereomeric helical poly-**1A**s, namely, poly((*S*,*R*)-**4**), poly((*R*,*R*)-**4**), poly((*R*,*R*)-**5**), and poly((*S*,*R*)-**5**), respectively (Scheme 1), while maintaining the helical conformation of the poly-**1A**. The conversion of the azide groups into the triazoles was

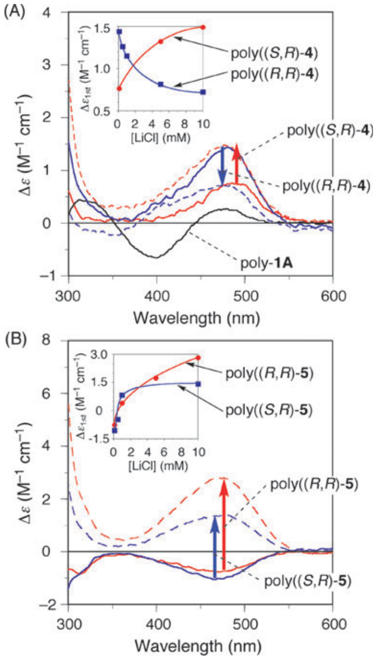

Fig. 2 (A) CD spectra of poly-**1A** (black line), poly((*S*,*R*)-**4**) (0.1 mM LiCl: red solid line, 10 mM LiCl: red dashed line), and poly((*R*,*R*)-**4**) (0.1 mM LiCl: blue solid line, 10 mM LiCl: blue dashed line) in DMF at −10 °C. (B) CD spectra of poly((*R*,*R*)-**5**) (0.1 mM LiCl: red solid line, 10 mM LiCl: red dashed line) and poly((*S*,*R*)-**5**) (0.1 mM LiCl: blue solid line, 10 mM LiCl: blue dashed line) in DMF at −10 °C. Insets show plots of the CD intensity of the 1st Cotton effect ($\Delta\varepsilon_{1st}$) *versus* LiCl concentration. Concentrations of polymers were 0.1 mg mL^{-1}.

confirmed by IR, ^{1}H NMR, and elemental analyses (see ESI†, Fig. S8 and S10).

Due to the solubility problem of the modified poly(phenylacetylene)s, the CD and absorption spectra were measured in DMF containing a small amount of LiCl. After the click reaction, the CD intensities of the modified polymers significantly increased compared to that of poly-**1A**, accompanied with changes in their CD spectral patterns. Although the CD spectral patterns of each pair of diastereomeric helical poly(phenylacetylene)s were not different from each other, an obvious difference was observed in their CD intensities depending on the absolute configuration of the pendant groups (R_2*) derived from the chiral acetylenes (Fig. 2). The modified poly(phenylacetylene)s are also sensitive to environmental factors such as temperature and salt (LiCl) concentration, and their CD intensities increased with decreasing temperature or increasing LiCl concentration except for poly((*R*,*R*)-**4**) (Fig. S11 and S12, respectively†). We noted that the CD intensity of poly((*R*,*R*)-**4**) gradually decreased with an increase in the LiCl concentration, whereas that of poly((*S*,*R*)-**4**) monotonically increased (Fig. 2A). These results suggest that the click reaction of poly-**1A** with chiral acetylenes may be applicable to sense the chirality of chiral acetylenes.

Contrary to the positive first Cotton effects observed for poly((*R*,*R*)-**4**) and poly((*S*,*R*)-**4**) in 0.1 mM LiCl-containing DMF, poly((*R*,*R*)-**5**) and poly((*S*,*R*)-**5**) showed the opposite, negative Cotton effect, which further inverted to the positive effect in the presence of an increasing amount of LiCl (Fig. 2B).[12] These inversions of the Cotton effects may be ascribed to the inversion of the helix-sense of the polymers.[4f,g,5,6] The difference in the CD intensities of poly((*R*,*R*)-**5**) and poly((*S*,*R*)-**5**) in DMF containing 10 mM LiCl also suggests a possible application of this system for chirality-sensing of chiral acetylenes.

In summary, we have developed a novel method to synthesize two types of optically active polymers from a single monomer having both azide and acetylene units by Rh-catalyzed chain-polymerization and Cu-catalyzed click polymerization. The helical poly(phenylacetylene) obtained by the former polymerization could be further modified with chiral acetylenes through the click polymer reaction. Although the resulting diastereomeric helical polymers did not show significantly different CDs for the chirality recognition of chiral acetylenes, we believe that the rational design of bifunctional chiral monomers will also produce more effective chirality-responsive helical poly(phenylacetylene)s and optically active click polymers with a helical conformation.

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10. We first anticipated that poly-**1T** formed intra- or intermolecular hydrogen bonds between the urea pendant groups resulting in the formation of a unique helical conformation or a supramolecular chiral aggregate, respectively. However, the IR spectroscopic analysis of poly-**1T** in DMSO, DMSO–$CHCl_3$ (1 : 1, v/v), and in the solid state revealed that such hydrogen bonds could not be formed in solution in the presence and absence of poor solvents (Fig. S6†). It seems likely that an intermolecular π-stacked interaction assisted by the planar triazole-ring formation may be the major driving force for such a chiral aggregate formation.
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12. LiCl probably coordinates to the triazole residues of the polymers, which may assist in their conformational changes such as an inversion of the macromolecular helicity.