DOI: 10.1002/asia.200700284

Induction of Optical Activity in an Oligothiophene Synchronized with pH-Sensitive Folding of Amylose

Takanobu Sanji,* Nobu Kato, and Masato Tanaka*[a]

Abstract: Control of the helical sense in α-sexithiophene (6T) through pH-responsive wrapping with left-handed-helical amylose is demonstrated. A change in pH of the medium caused a significant conformational change in amylose as the host polymer, which resulted in either supramolecular complexation with 6T as the guest molecule to induce optical activity or decomplexation leading to loss of optical activity. Furthermore, we observed that chirality reversal in 6T does not require hosts of opposite helical chirality, but can be made possible simply by taking advantage of the pH sensitivity of the amylose folding, which is dependent on the pH history of the aqueous medium. In helical amylose, 6T assumes a clockwise-twisted conformation when the pH is changed from acidic to neutral, but assumes an anticlockwise-twisted conformation when the aqueous solution is acidified from very basic conditions.

Keywords: chirality · helical structures · host–guest systems · molecular recognition · supramolecular chemistry

Introduction

The helical structure is one of the most significant motifs in macromolecules. It can exist in either a right- or a left-handed twist sense and displays optical activity. In nature, helical structures are often found in biomacromolecules, and appear to play a critical role in biological phenomena such as molecular recognition and information storage, as exemplified by the double helix of DNA and the α-helices of proteins.[1] Recent progress in the design and synthesis of optically active macro- and supramolecules has enabled the discussion of their roles in biological phenomena and the proposal of potential applications in materials science, including their use as chiral selectors in separation technology, as catalysts and adsorbents, and especially as chiroptical materials.[2]

Among optically active polymeric materials,[3] π-conjugated polymers and oligomers are of particular interest, in view of their pronounced semiconducting and optoelectronic properties, as exemplified by the widely studied poly- and oligothiophenes.[4] For instance, α-sexithiophene (6T) and its derivatives have been employed as the active layer in organic electronic devices.[5] Some optically active polythiophenes and oligothiophenes with chiral substituents were reported to display optical activity in the π–π*-transition region derived from main-chain chirality in circular-dichroism (CD) measurements.[6,7]

In the design of new advanced materials, the control of chirality in response to an external stimulus, such as temperature, pH, or solvent, is particularly interesting.[8–10] Such systems would mimic biological phenomena and provide chiroptical materials for switching and memory devices.

Herein, we show the control of the helical sense in oligothiophenes through pH-responsive wrapping with left-handed-helical amylose. In a broader sense, this is based on the molecular communication between a helical host polymer and a guest molecule through supramolecular complexation. A change in pH of the medium causes a significant conformational change in amylose as the host polymer, thus resulting in either supramolecular complexation with the guest molecule to induce optical activity or decomplexation leading to the loss of optical activity. Furthermore, we discuss the observation that reversal of chirality in oligothiophenes does not require hosts of opposite helical chirality, but can be made possible simply by taking advantage of the pH sensitivity of the amylose folding, which is dependent on the history of the pH of the medium.

[a] Dr. T. Sanji, N. Kato, Prof. Dr. M. Tanaka
Chemical Resources Laboratory
Tokyo Institute of Technology
4259-R1-13 Nagatsuta, Midori-ku, Yokohama 226-8503 (Japan)
Fax: (+81) 45-924-5279
E-mail: sanji@res.titech.ac.jp
m.tanaka@res.titech.ac.jp

Supporting information for this article is available on the WWW under http://www.chemasianj.org or from the author.

Results and Discussion

Among a number of polymers that can adopt ordered helical conformations, we chose amylose as the host polymer. Amylose is composed of α-1,4-linkages between D-glucopyranose residues[11] (Scheme 1). Amylose assumes a random-coil conformation in acidic media, but has a loose left-handed-helical conformation in neutral or basic media.[12] With an appropriate guest molecule, amylose can form inclusion complexes as a result of hydrophobic interactions, with the guest molecule confined within the helical cavities.[13,14] Amylose, however, serves as a polyelectrolyte above pH 11 and unfolds again to a random-coil conformation.[12] In our experiments, we used plain amylose ($M_n = 5.8\times10^4$, $M_w/M_n = 1.7$) or, occasionally, partially carboxymethylated amylose (CMA; degree of substitution = 36%) to increase the solubility of the resulting inclusion complex in aqueous solution. Recently, we found the induction of a preferential helical conformation to the main chain of oligosilanes and oligothiophenes within the helical channel of amylose and schizophyllan (SPG), in which the helical sense of the guest molecules is controlled by wrapping with either the left- or the right-handed helical-sense conformation of the host polymer.[15] Shinkai and co-workers also reported the supramolecular chiral complex between SPG and water-soluble polythiophenes.[16]

Amylose: R = H
Carboxymethylated amylose (CMA):
R = CH_2CO_2H (DS = 0.36)

α-Sexithiophene (6T)

Scheme 1. Chemical structures of the host (amylose and carboxymethylated amylose) and guest (α-sexithiophene). DS = degree of substitution.

pH-Dependent Complexation of Amylose and Oligothiophene 6T

To begin with, the pH-dependent complexation of amylose and oligothiophene 6T was examined. In a typical experiment, 6T (0.15 mg, 3.0×10^{-4} mmol) and CMA (1.54 mg, 8.40×10^{-3} mmol glucose unit) were dispersed in dimethyl sulfoxide (DMSO; 0.3 mL) ultrasonically for 2 min. The resulting mixture was added to water (2.7 mL) adjusted to an appropriate pH value and was further sonicated for 5 min. The cloudy orange mixture gradually became a clear pale-yellow solution (Figure 1). The resulting solution was stirred at room temperature for 2 h and was subjected to spectroscopic measurement.[17]

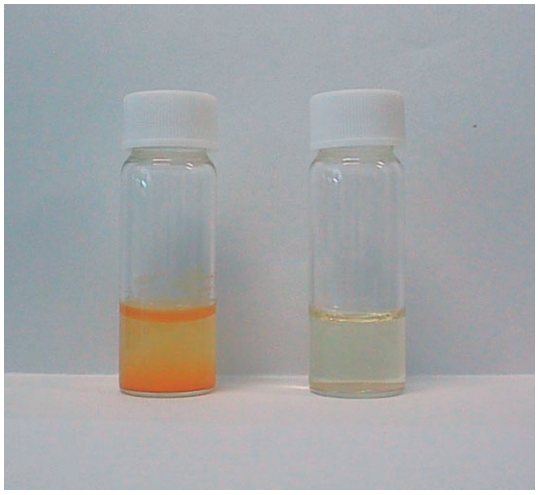


Figure 1. Photograph of 6T (left) and a mixture of 6T and CMA (right) in 10% aqueous DMSO at pH 10.5.

Figure 2 shows the UV/Vis and CD spectra of the resulting aqueous DMSO solutions at different pH values, as well as a plot of the intensity of the induced circular dichroism (ICD) signal at 360 nm as a function of pH. At a low pH, the UV/Vis absorption and Cotton signal of the aqueous solution are very weak, which indicates that most of the 6T remained in the uncomplexed state in the acidic aqueous medium. Under these conditions, the uncomplexed 6T did not show any optical effect. However, at neutral and alkaline pH values up to pH 10, the aqueous DMSO solution exhibited a broad absorption at around 380 nm and a bisignate Cotton signal with a positive sign for the first Cotton effect, along with the $\theta = 0$ crossing wavelength that basically coincides with the absorption maximum, which is characteristic of the π–π* transition of the 6T main chain. The Cotton effect increased gradually with increasing pH ($\Delta\varepsilon_{1(360\,nm)} = 0.89\,M^{-1}cm^{-1}$ at pH 10.5). Oligothiphene 6T itself does not show any CD signals. Accordingly, these spectral features demonstrate the formation of a supramolecular complex, in which a preferential twisted conformation is induced in the oligothiophene chain residing in the helical channel of the CMA as a result of complexation with the chiral helical host under the experimental conditions used (Scheme 2). The dissymmetry ratio of the complex, g_1 ($=\Delta\varepsilon_1/\varepsilon_1$), at 360 nm, which is usually used to characterize the properties of helical structures, such as the right- and left-handed helix populations, is 1.2×10^{-4}. The complexes of induced chirality were stable even at 80 °C.[15b] However, when the pH of the aque-

Abstract in Japanese:
アミロースとオリゴチオフェンとの超分子錯体形成の pH 依存性について検討した。錯形成は pH に大きく依存し、中性および塩基性条件下ではオリゴチオフェンはアミロースのらせん空孔に取り込まれ一方向にねじれることで光学活性となり、一方、酸性あるいは強塩基性条件では、錯形成は起きない。またオリゴチオフェン誘起される主鎖のねじれ方向は、錯形成時の pH によって逆転することを明らかにした。

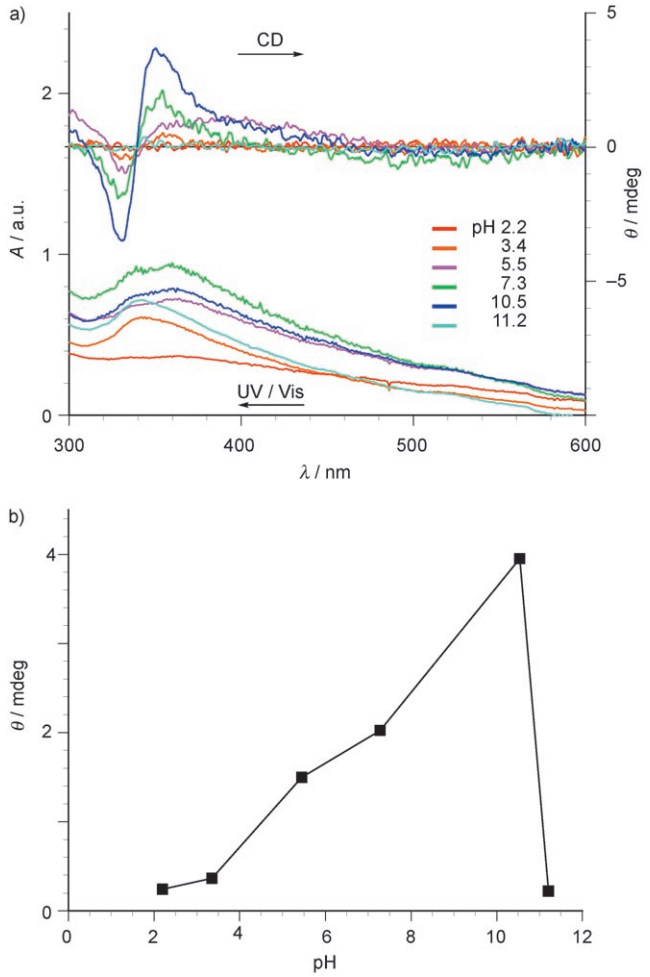
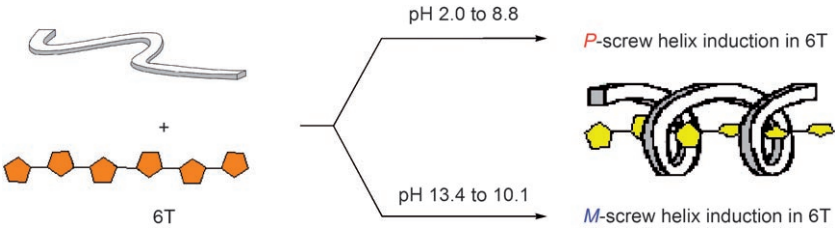


Figure 2. a) pH-dependent UV/Vis and CD spectra of a mixture of 6T and CMA in 10% aqueous DMSO. b) Plot of ICD intensity at 360 nm as a function of pH.



Scheme 2. Schematic illustration of the pH-sensitive supramolecular complexation of α-sexithiophene (6T) and amylose.

ous solution was adjusted to pH 11.2, the CD signal faded, in agreement with unfolding of the CMA in the more basic medium (see above). Thus, the abrupt change in optical activity of the oligothiophene at a critical pH value is associated with supramolecular complexation with the CMA, whose conformation is pH-dependent.

Chirality Inversion of 6T with Amylose During pH Change

We examined the CD spectral features of 6T during a change in pH (Figure 3). We found that the complexation of 6T with amylose is sensitive to the folding of the latter

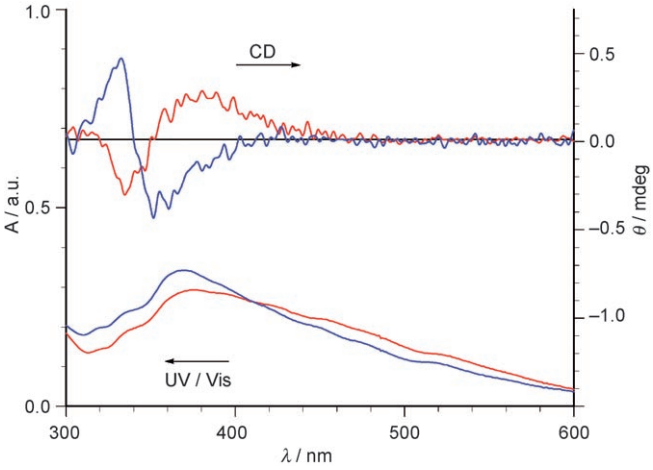


Figure 3. UV/Vis and CD spectra of 6T/amylose in 10% aqueous DMSO upon pH change from pH 2.0 to 8.8 (red) and from pH 13.4 to 10.1 (blue). $[6T]=1.0\times10^{-4}$ M, $[amylose]=2.8\times10^{-3}$ M.

during pH change in the induction of the selective twist-sense bias of conformation to produce optical activity. In a similar manner to the foregoing observations made with CMA, a mixture of plain amylose and 6T did not display any CD signal in very acidic (pH 2.0) or basic (pH 13.4) aqueous DMSO, owing to the lack of complexation as the amylose took on the random-coil conformation. Amylose was found to form a supramolecular complex with 6T (Figure 3) only within an intermediate pH range, over which the ability for complexation with 6T is almost the same for CMA and amylose, on the basis of a comparison of the CD spectra of 6T/amylose and 6T/CMA (see Supporting Information). The absorption and CD intensities were much lower than those observed in Figure 2, because part of the 6T (or amylose) precipitated readily, and the precipitated 6T was not complexed with amylose under the experimental conditions.

Interestingly, the ICD spectral feature has proved to be dependent on the pH history of the aqueous medium in which 6T and amylose are present. Thus, when a solution in aqueous DMSO was basified from pH 2 to pH 8.8, the resulting mixture displayed a bisignate CD spectrum with a positive sign for the first Cotton effect at around 370 nm (Figure 3). On the other hand, when the aqueous solution

was acidified from pH 13.4 to pH 10.1, the ICD signal also appeared at around 370 nm, but with a negative sign for the first Cotton effect. Furthermore, the spectral features remained almost same after the solution was stood for 24 h (see Supporting Information). This clearly indicates that 6T adopts an opposite twisted conformation. The positive and negative first Cotton effects are related to a clockwise and anticlockwise twisted conformation, respectively.[6]

The key development in the present work is that the induced chirality in 6T can be controlled and switched by the pH sensitivity of the amylose folding, in which the pH of the medium is adjusted from acidic or very basic medium. The reversal of chirality in 6T can be achieved by changing the single-molecule screw sense. It can be related to the structural change in amylose; that is, when the pH changes, the complexation causes kinetic trapping of 6T as the guest molecule in the helical channel of amylose to induce the opposite chirality. Alternatively, the chirality inversion may be attributed to the formation of two types of π-stacked chiral superstructures: a cholesteric liquid-crystalline-type assembly of coplanar chains and a stack of twisted backbone chains based on a cholesteric hard-core model.[18] Detailed understanding of the origin of the chirality inversion requires further study.

Conclusions

We have demonstrated the induction of chirality in 6T synchronized with complexation with left-handed-helical amylose, in which the twisted conformation of 6T is controlled and reversed through pH change of the aqueous media. In our previous study, reversal of induced chirality occurred when the guest is wrapped with the host polymer of either the left- or the right-handed helical conformation. The present paper offers an alternative strategy for chirality control in insulated molecular wires[19] and provides a simple approach to the design of new chiral materials.

Experimental Section

General

^{1}H and ^{13}C NMR spectra were recorded on a Bruker DPX 300 FT-NMR spectrometer at 300 and 75.4 MHz, respectively. ^{1}H and ^{13}C NMR chemical shifts are referenced to residual solvent ($CDCl_3$; ^{1}H: $\delta = 7.24$ ppm; ^{13}C: $\delta = 77.0$ ppm). Gas–liquid chromatography data were recorded on a Shimadzu GC-8A chromatograph. Cross-polarization magic-angle-spinning (CP-MAS) ^{13}C NMR spectra were recorded at 67 MHz on a JEOL Excalibur 270 spectrometer. Gel-permeation chromatography was performed with a Shimadzu LC 10 HPLC equipped with PL-gel mixed-C columns calibrated with a polystyrene standard and a solution of *N,N*-dimethylacetamide (DMAc)/5% LiCl as the eluent. X-ray diffraction patterns were recorded on a Rigaku RAXIS-IIc X-ray diffractometer. UV/Vis spectra were recorded on an HP Agilent 8453 spectrometer. CD spectra were obtained on a JASCO J-820 spectrometer by using 1-cm quartz cells, with the following scanning conditions: scan rate = 50 nm min^{-1}, bandwidth = 2.0 nm, response time = 1 s, number of accumulations = 2.

Materials

All solvents and reagents used were of reagent grade, purchased from commercial sources, and used without further purification unless otherwise specified. Amylose was obtained from Nacalai Tesque, Inc. The number-average molecular weight (M_n) and the polydispersity index (M_w/M_n) were 5.8×10^4 and 1.7, respectively. CMA was prepared as described in the literature.[20] α-Sexithiophene (6T) was obtained from Aldrich Chemicals. Water was purified with a Millipore Milli-Q system.

Sample Preparation

CMA/6T inclusion complex: A typical example is as follows. A mixture of 6T (0.15 mg, 3.0×10^{-4} mmol) and CMA (1.54 mg, 8.40×10^{-3} mmol glucose unit) in DMSO (0.3 mL) was dispersed ultrasonically for 2 min, added to water (2.7 mL), adjusted to an appropriate pH value, and subsequently sonicated for 5 min. The resulting solution was stirred at room temperature for 2 h and subjected to spectroscopic measurement.

pH-adjustment experiments: Change in pH from pH 2.0 to 8.8: A mixture of 6T (0.155 mg, 3.13×10^{-4} mmol) and amylose (1.37 mg, 8.43×10^{-3} mmol glucose unit) in DMSO (0.3 mL) was dispersed ultrasonically for 2 min. Aqueous HCl (0.01 N, 0.2 mL) was added, and the mixture was again dispersed ultrasonically for 2 min. After the mixture was stirred for 1 h, aqueous NaOH (1.0×10^{-3} N, 2.5 mL) was added and dispersed ultrasonically for 5 min. The mixture was then subjected to spectroscopic measurement.

Change in pH from pH 13.4 to 10.1: A mixture of 6T (0.145 mg, 2.93×10^{-4} mmol) and amylose (1.36 mg, 8.39×10^{-2} mmol glucose unit) in DMSO (0.3 mL) was dispersed ultrasonically for 2 min. Aqueous NaOH (0.25 N, 0.1 mL) was then added, and the mixture was again dispersed ultrasonically for 2 min. After the mixture was stirred for 1 h, aqueous HCl (0.01 N, 2.5 mL) was added, and the mixture was then subjected to spectroscopic measurement.

Acknowledgements

This work was supported by the Ministry of Education, Culture, Sports, Science, and Technology of Japan (No. 16685004).

[1] a) W. Saenger, *Principles of Nucleic Acid Structure*, Springer, New York, **1984**; b) P. H. Pain, *Mechanism of Protein Folding*, *2nd ed.*, Oxford University Press, Oxford, **2000**.

[2] a) T. Nakano, Y. Okamoto, *Chem. Rev.* **2001**, *101*, 4013–4038; b) D. J. Hill, M. J. Mio, R. B. Prince, T. S. Hughes, J. S. Moore, *Chem. Rev.* **2001**, *101*, 3893–4011.

[3] a) E. Yashima, K. Maeda, Y. Okamoto, *Nature* **1999**, *399*, 449–451; b) V. Berl, I. Huc, R. G. Khoury, M. J. Krische, J.-M. Lehn, *Nature* **2000**, *407*, 720–723; c) A. Tanatani, M. J. Mio, J. S. Moore, *J. Am. Chem. Soc.* **2001**, *123*, 1792–1793; d) M. Fujiki, *J. Am. Chem. Soc.* **1994**, *116*, 11 976–11 977.

[4] *Handbook of Oligo- and Polythiophenes* (Ed.: D. Fichou), Wiley-VCH, Weinheim, **1999**.

[5] a) A. Dodabalapur, L. Torsi, H. E. Katz, *Science* **1995**, *268*, 270–271; b) A. Yassar, G. Horowitz, P. Valat, V. Wintgens, M. Hmyene, F. Delofre, P. Srivastava, P. Lang, F. Garnier, *J. Phys. Chem.* **1995**, *99*, 9155–9159; c) F. Garnier, *Acc. Chem. Res.* **1999**, *32*, 209–215.

[6] a) M. M. Bouman, E. W. Meijer, *Adv. Mater.* **1995**, *7*, 385–387; b) B. M. W. Langeveld-Voss, R. A. J. Janssen, M. P. T. Christiaans, S. C. J. Meskers, H. P. J. M. Dekkers, E. W. Meijer, *J. Am. Chem. Soc.* 1996, ***118***, 4908–4909; c) B. M. W. Langeveld-Voss, M. P. T. Christiaans, R. A. J. Janssen, E. W. Meijer, *Macromolecules* **1998**, *31*, 6702–6704; d) B. M. W. Langeveld-Voss, R. A. J. Jassen, E. W. Meijer, *J. Mol. Struct.* **2000**, *521*, 285–301; e) A. F. M. Kilbinger, A. P. H. J. Schenning, F. Goldoni, W. J. Feast, E. W. Meijer, *J. Am. Chem. Soc.* **2000**, *122*, 1820–1821; f) A. P. H. J. Schenning, A. F. M. Kilbinger, F. Biscarini, M. Cavallini, H. J. Cooper, P. J. Derrick, W. J.

Feast, R. Lazzaroni, P. Leclère, L. A. McDonell, E. W. Meijer, S. C. J. Meskers, *J. Am. Chem. Soc.* **2002**, *124*, 1269–1276; g) J. R. Matthews, F. Goldoni, A. P. H. J. Schenning, E. W. Meijer, *Chem. Commun.* **2005**, 5503–5505.

[7] a) E. Yashima, H. Goto, Y. Okamoto, *Macromolecules* **1999**, *32*, 7942–7945; b) Z.-B. Zhang, M. Fujiki, M. Motonaga, H. Nakashima, K. Torimitsu, H.-Z. Tang, *Macromolecules* **2002**, *35*, 941–944.

[8] a) C. Dolain, V. Maurizot, I. Huc, *Angew. Chem.* **2003**, *115*, 2844–2846; *Angew. Chem. Int. Ed.* **2003**, *42*, 2738–2740; b) E. Kolomiets, V. Berl, I. Odriozola, A.-M. Stadler, N. Kyritsakas, J.-M. Lehn, *Chem. Commun.* **2003**, 2868–2869; c) A.-M. Stadler, N. Kyritsakas, J.-M. Lehn, *Chem. Commun.* **2004**, 2024–2025; d) S. Y. Yang, M. M. Green, G. Schultz, S. K. Jha, A. H. E. Müller, *J. Am. Chem. Soc.* **1997**, *119*, 12404–12405.

[9] a) R. Prince, T. Okada, J. S. Moore, *Angew. Chem.* **1999**, *111*, 245–249; *Angew. Chem. Int. Ed.* **1999**, *38*, 233–236; b) J. J. D. Jong, L. N. Lucas, R. M. Kellogg, J. H. Esch, B. L. Feringa, *Science* **2004**, *304*, 278–281; c) A.-M. Stadler, N. Kyritsakas, R. Graff, J.-M. Lehn, *Chem. Eur. J.* **2006**, *12*, 4503–4522.

[10] a) P. R. Ashton, R. Ballardini, V. Balzani, I. Baxter, A. Credi, T. Fyfe, M. T. Gandolfi, M. M. Gomez-Lopez, M.-V. Martinez-Diaz, A. Piersanti, N. Spencer, J. F. Stoddart, M. Venturi, A. J. P. White, D. J. Williams, *J. Am. Chem. Soc.* **1998**, *120*, 11932–11942; b) J. W. Lee, K. Kim, K. Kim, *Chem. Commun.* **2001**, 1042–1043; c) N. Hida, F. Takei, K. Onitsuka, K. Shiga, S. Asaoka, T. Iyoda, S. Takahashi, *Angew. Chem.* **2003**, *115*, 4485–4488; *Angew. Chem. Int. Ed.* **2003**, *42*, 4349–4352; d) F. Huang, K. A. Switek, H. W. Gibson, *Chem. Commun.* **2005**, 3655–3657; e) H.-Z. Tang, P. D. Boyle, B. M. Novak, *J. Am. Chem. Soc.* **2005**, *127*, 2136–2142; f) A. Khan, C. Kaiser, S. Hecht, *Angew. Chem.* **2006**, *118*, 1912–1915; *Angew. Chem. Int. Ed.* **2006**, *45*, 1878–1881.

[11] a) W. Hinrichs, G. Büttner, M. Steifa, C. Betzel, V. Zabel, B. Pfannemüller, W. Saenger, *Science* **1987**, *238*, 205–208; b) G. Wulff, S. Kubik, *Makromol. Chem.* **1992**, *193*, 1071–1080; c) O. Nimz, K. Gessler, I. Usón, G. M. Sheldrick, W. Saenger, *Carbohydr. Res.* **2004**, *339*, 1427–1437.

[12] a) H. L. Doppert, A. J. Staverman, *J. Polym. Sci.Polym. Chem. Ed.* **1966**, *4*, 2353–2366; b) J. R. Patel, R. D. Patel, *Biopolymers* **1971**, *10*, 839–848; c) M. B. Senior, E. Hamori, *Biopolymers* **1973**, *12*, 65–78; d) P. L. Dubin, D. A. Brant, *Macromolecules* **1975**, *8*, 831–842; e) N. W. H. Cheetham, L. Tao, *Carbohydr. Polym.* **1998**, *35*, 287–295.

[13] a) A. Star, D. W. Steuerman, J. R. Heath, J. F. Stoddart, *Angew. Chem.* **2002**, *114*, 2618–2622; *Angew. Chem. Int. Ed.* **2002**, *41*, 2508–2512; b) O.-K. Kim, J. Je, J. W. Baldwin, S. Kooi, P. E. Pehrsson, L. J. Buckley, *J. Am. Chem. Soc.* **2003**, *125*, 4426–4427.

[14] a) O.-K. Kim, L.-S. Choi, *Langmuir* **1994**, *10*, 2842–2846; b) J. Kadokawa, Y. Kaneko, H. Tagaya, K. Chiba, *Chem. Commun.* **2001**, 449–450; c) M. Ikeda, Y. Furusho, K. Okoshi, S. Tanahara, K. Maeda, S. Nishino, T. Mori, E. Yashima, *Angew. Chem.* **2006**, *118*, 6641–6645; *Angew. Chem. Int. Ed.* **2006**, *45*, 6491–6495–6495; d) O.-K. Kim, J. Je, J. S. Melinger, *J. Am. Chem. Soc.* **2006**, *128*, 4532–4533; e) T. Kida, T. Minabe, S. Okabe, M. Akashi, *Chem. Commun.* **2007**, 1559–1561.

[15] a) T. Sanji, N. Kato, M. Kato, M. Tanaka, *Angew. Chem.* **2005**, *117*, 7467–7470; *Angew. Chem. Int. Ed.* **2005**, *44*, 7301–7304; b) T. Sanji, N. Kato, M. Tanaka, *Org. Lett.* **2006**, *8*, 235–238; c) T. Sanji, N. Kato, M. Tanaka, *Macromolecules* **2006**, *39*, 7508–7512.

[16] C. Li, M. Numata, A.-H. Bae, K. Sakurai, S. Shinkai, *J. Am. Chem. Soc.* **2005**, *127*, 4548–4549.

[17] NMR spectroscopic measurements in solution were not possible because of the low solubility in H_2O and 10% aqueous DMSO solution (concentrations below $\approx 10^{-4}$ M).

[18] K. Nakanishi, N. Berova, *Circular Dichroism: Principles and Applications*, VCH, Weinheim, **1994**, chap. 19.

[19] M. J. Frampton, H. L. Anderson, *Angew. Chem.* **2007**, *119*, 1046–1083; *Angew. Chem. Int. Ed.* **2007**, *46*, 1028–1064.

[20] G. Wulff, A. Steinert, O. Höller, *Carbohydr. Res.* **1998**, *307*, 19.

Received: September 6, 2007
Published online: December 3, 2007

