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Hetero-Double-Helix Formation by an Ethynylhelicene Oligomer Possessing Perfluorooctyl Side Chains

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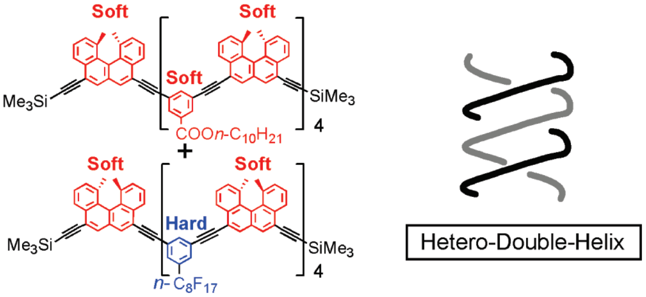

Monomeric to pentameric (*P*)-ethynylhelicene oligomers possessing perfluorooctyl side chains were synthesized. The circular dichroism (CD) and vapor pressure osomometry (VPO) studies indicated the formation of a helix-dimer for the (*P*)-pentamer, for example, in trifluoromethylbenzene at 5 °C at concentrations above 2×10^{-6} M. Compared with a (*P*)-pentamer possessing decyloxycarbonyl side chains, the perfluorooctyl (*P*)-pentamer exhibited lower solubilities in organic solvents, formed a thermodynamically more stable helix-dimer, and exhibited a mirror image CD spectrum. The perfluorooctyl (*P*)-pentamer formed a hetero-helix dimer with a decyloxycarbonyl (*M*)-pentamer but not with a (*P*)-pentamer. It indicated higher stability of the hetero-helix dimer over the homo-helix dimers.

Introduction

As exemplified by DNA, the double-helix is an essential molecular structure in biological systems, and structural changes in response to changes in the environment play important roles in its functions. A double-helix is constructed by noncovalent interactions between two acyclic compounds, and homo- and hetero-double-helices can be formed depending on the affinity of the two compounds. A homo-double-helix is formed from two identical compounds, while the formation of a hetero-double-helix requires two distinct compounds which recognize each other.

Recently, synthetic oligomeric compounds that can form double-helices have attracted much interest,[1] since they exhibit novel functions that utilize their structural changes and can be used to promote understanding of the function of double-helical biomolecules. While several homo-double-helices have been reported,[2] hetero-double-helices are rare because of the difficulty in designing two different acyclic compounds that recognize each other. Lehn used five-coordinate Cu^{2+} ions to bind bipyridine oligomers and terpyridine oligomers to form a hetero-double-helix.[3] Huc reported the formation of a hetero-double-helix between aromatic oligoamides and their *N*-oxides via hydrogen bonds and $\pi-\pi$ interactions.[4] Yashima developed a double-helical assembly composed of two crescent-shaped

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(1) Reviews: (a) Hill, D. J.; Mio, M. J.; Prince, R. B.; Hughes, T. S.; Moore, J. S. *Chem. Rev.* **2001**, *101*, 3893–4011. (b) Albecht, M. *Angew. Chem., Int. Ed.* **2005**, *44*, 6448–6451. (c) Furusho, Y.; Yashima, E. *Chem. Rec.* **2007**, *1*, 11.

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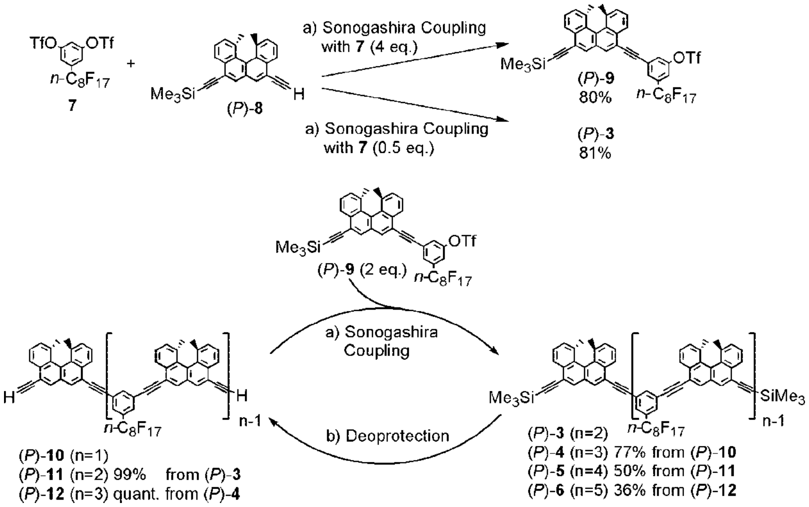
10.1021/jo8010057 CCC: $40.75

SCHEME 1[a]



[a] Key: (a) $Pd_2(dba)_3 \cdot CHCl_3$, CuI, Ph_3P, Mes_3P, n-Bu_4NI, Et_3N, DMF/THF; (b) Bu_4NF, THF, 0 °C.

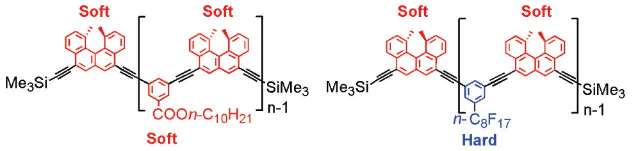
m-terphenyl derivatives[5a] and their analogues[5b,e] using aminidium-carboxylate salt bridges. The formation of a hetero-double-helix between oligoresolcinols and oligosaccharides has also been reported.[6] Further studies to synthesize hetero-double-helices are required to develop substances that can exhibit novel functions.

Previously, we reported the synthesis of optically active ethynylhelicene oligomers possessing two to nine helicenes connected by *m*-phenylene spacers (Scheme 1).[7,8] The CD ($CHCl_3$, 5×10^{-6} M, 25 °C) spectrum of the heptamer (*P*)-**2** was quite different from those of oligomers from dimer to hexamer and exhibited an extremely strong Cotton effect (the large absolute values of $\Delta\epsilon$ up to several thousands) over the hexamer with an inverted sign between 300 and 400 nm. Vapor pressure osmometry (VPO) analysis of (*P*)-**2** ($CHCl_3$, 40 °C) showed the dimeric structure. These observations indicated that (*P*)-**2** formed a helix dimer, most probably a double-helix.

Further investigations of (*P*)-**2** revealed that the rate constant k for the unfolding of the double-helix to random coil was largely dependent on the aromatic solvents used.[8a] The k values differed by 7 orders of magnitude between iodobenzene and trifluoromethylbenzene, and the log k values exhibited a good correlation with the absolute hardness η of aromatic molecules, which were obtained by Pearson employing the ionization potential and electron affinity.[9] Higher unfolding rates were observed in soft arenes and lower rates in hard arenes. Hard arenes such as trifluoromethylbenzene and *m*-difluorobenzene are strong helix-forming solvents. The results suggest a strong relationship between the $\pi-\pi$ interaction and the HSAB principle: the $\pi-\pi$ interaction is a soft interaction.

Thus, we investigated the effect of the hardness of the arenes contained in the oligomers. The *m*-phenylene spacers of (*P*)-**2** were changed from the relatively soft decyloxycarbonylphenylene spacers to hard perfluorooctylphenylene spacers. The former can be regarded as oligomers containing soft aromatic moieties, and the manipulation would provide compounds with an alternating arrangement of soft and hard arenes. We compared the decyloxycarbonyl compounds and the perfluorooctyl compounds on the basis of homo-double-helix formation. In addition, the hetero-double-helix formation was examined between the decyloxycarbonyl compounds and perfluorooctyl compounds.

In this study, perfluorooctyl dimer (*P*)-**3** to pentamer (*P*)-**6** were synthesized, and the CD and VPO studies demonstrated that the pentamer (*P*)-**6** and the decyloxycarbonyl pentamer (*P*)-**1** formed stable homo-double-helix in trifluoromethylbenzene. A notable feature of (*P*)-**6** compared to (*P*)-**1** is that the screw sense of the homo-double-helix was inverted, despite both helicenes having the same configuration. (*P*)-**6** formed a hetero-double-helix with (*M*)-**1** but not with (*P*)-**1**. This is a novel methodology to construct hetero-double-helix using enantiomeric compounds with different side chains.



(*P*)-**1** (n=5)
(*P*)-**2** (n=7)

(*P*)-**3** (n=2)
(*P*)-**4** (n=3)
(*P*)-**5** (n=4)
(*P*)-**6** (n=5)

Results and Discussion

A series of (*P*)-perfluorooctyl oligomers (*P*)-**3** to (*P*)-**6** were synthesized by repeating the Sonogashira coupling and deprotection by a two-directional method using a building block (*P*)-**9** according to the synthesis of (*P*)-decyloxycarbonyl oligomers (Scheme 1).[8a] The building block (*P*)-**9** was synthesized by coupling monosilylated helicene (*P*)-**8**[11] and 4 equiv of spacer

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(10) See the Supporting Information.

(11) Nakamura, K.; Okubo, H.; Yamaguchi, M. *Org. Lett.* **2001**, *3*, 1097–1099.

7, which in turn was synthesized from 3,5-dihydroxyiodobenzene.[10] The reaction of (*P*)-diethynylhelicene (*P*)-**10**[11] and 2 equiv of (*P*)-**9** under the rapid Sonogashira coupling conditions[12] yielded the trimer (*P*)-**4** in 77% yield. (*P*)-**4** was treated with Bu_4NF in THF giving the deprotected trimer (*P*)-**12**, and the subsequent coupling gave the pentamer (*P*)-**6** in 36% yield. The dimer (*P*)-**3** and the tetramer (*P*)-**5** were synthesized in 81% and 50% yield, respectively, by the sequence of the reactions starting from **7**. The solubility of the oligomers in organic solvents significantly decreased with the increase in the number of helicenes, and the yield of the coupling reaction decreased. Because of the solubility problem, the hexamer could not be obtained in an acceptable yield.

The solubilities of the pentamers (*P*)-**1** and (*P*)-**6** in organic solvents were compared. Whereas (*P*)-**1** readily dissolved in various aromatic solvents, chloroform, and tetrahydrofuran (THF) at 1×10^{-3} M, (*P*)-**6** was soluble at 1×10^{-3} M in chloroform, THF, and *m*-difluorobenzene at 40 °C but only partially soluble at 5 °C. Under identical conditions, (*P*)-**6** was partially soluble in toluene, chlorobenzene, fluorobenzene, and trifluoromethylbenzene. The solubility of (*P*)-**6** was not improved in fluorophilic solvents, such as hexafluorobenzene, *n*-perfluorooctane, and perfluoro(2-butyltetrahydrofuran). At 1×10^{-4} M, (*P*)-**6** was soluble only in chloroform, THF, *m*-difluorobenzene, toluene, chlorobenzene, and fluorobenzene at 5 °C. The solubility in trifluoromethylbenzene, a strong helix-forming solvent, was examined in more detail. At 5 and 60 °C, (*P*)-**6** dissolved only at concentrations below 2.5×10^{-5} M, and slow precipitation was observed after 30 min at 5 °C. The spectroscopic studies of (*P*)-**6** in trifluoromethylbenzene, therefore, were conducted within 30 min after cooling the solution to 5 °C. In addition, reproducibility was checked for all the CD experiments shown below, and the homogeneity of the solutions was confirmed. Formation of precipitate resulted in ill reproducibility of such experiments. The poor solubility of (*P*)-**6** compared to (*P*)-**1** may be related to double-helix formation with the perfluorootyl group directed to the outside of the helix. Presumably, the regular arrangement of the side chain strengthened the intermolecular aggregation between double-helices resulting in poor solubility.

The CD studies were conducted on dimer (*P*)-**3** to pentamer (*P*)-**6** in chloroform and trifluoromethylbenzene, which are weak and strong helix-forming solvents, respectively. In chloroform, $|\Delta\epsilon|$ (the absolute value of $\Delta\epsilon$) of the CD spectra (5×10^{-6} M, 25 °C) of (*P*)-**3** to (*P*)-**6** showed a monotonic increase in accordance with the number of helicenes on the basis of (*P*)-**3** (Figure 1a). In trifluoromethylbenzene (5×10^{-6} M, 25 °C), (*P*)-**3**, (*P*)-**4**, and (*P*)-**5** showed similar spectra to those in chloroform, whereas (*P*)-**6** showed an obviously different shape: An increased $|\Delta\epsilon|$ compared to that in chloroform with the maxima at 330 and 360 nm (Figure 1b). The CD spectra of (*P*)-**6** in trifluoromethylbenzene changed depending on temperature. A spectrum similar to that in chloroform was obtained at 60 °C, while it showed an increased $|\Delta\epsilon|$ at 5 °C over that at 25 °C (Figure 1c). The CD studies suggest the formation of a helical structure of (*P*)-**6** at 5 °C in trifluoromethylbenzene, most likely a double-helix, and a random coil at 60 °C.

For the following discussions, it was necessary to know the CD spectra of (*P*)-**6** in the pure double-helix state. The study was conducted in trifluoromehylbenzene, which is a strong helix-forming solvent. Because of the solubility at 5 °C, the CD spectra of (*P*)-**6** were obtained at concentrations below 2×10^{-6} M, and the CD spectra were obtained within 30 min of cooling to 5 °C. In order to know the CD spectra in the pure double-helix state, temperature, time course, and concentration were examined. The CD (2×10^{-6} M) spectra of (*P*)-**6** were obtained at various temperatures between −10 and 60 °C. Above 25 °C, the random coil state was formed. An increase of $|\Delta\epsilon|$ compared to that at the random coil state were observed as the temperature decreased, and a steady state was reached at −10 °C with $\Delta\epsilon$ at 330 nm at approximately $+800\ \mathrm{cm^{-1}M^{-1}}$ (Figure 2a). Next, the $\Delta\epsilon$ value at 330 nm was monitored after heating the solution to 60 °C and then cooling it to −10 °C (Figure 2b). The $\Delta\epsilon$ value reached steady state after 30 min, at a value of approximately $+800\ \mathrm{cm^{-1}M^{-1}}$. The effect of concentration on the CD spectra was also examined. Very similar CD spectra were obtained at 5 °C at the concentrations between 5×10^{-6} M and 2.5×10^{-5} M, reaching a $\Delta\epsilon$ value of approximately $+800\ \mathrm{cm^{-1}\ M^{-1}}$ at 330 nm and an decreased $|\Delta\epsilon|$ from those was obtained at 2×10^{-6} M (Figure 2c). The studies indicated a steady state below a certain temperature and above a certain concentration providing very similar CD spectra with a $\Delta\epsilon$ value of $+800\ \mathrm{cm^{-1}\ M^{-1}}$ at 330 nm. It was concluded that the CD spectra at these steady states in trifluoromethylbenzene represent the pure helix state.

The degree of aggregation was investigated by VPO for the helix state. *m*-Difluorobenzene was used as a solvent, since (*P*)-**6**

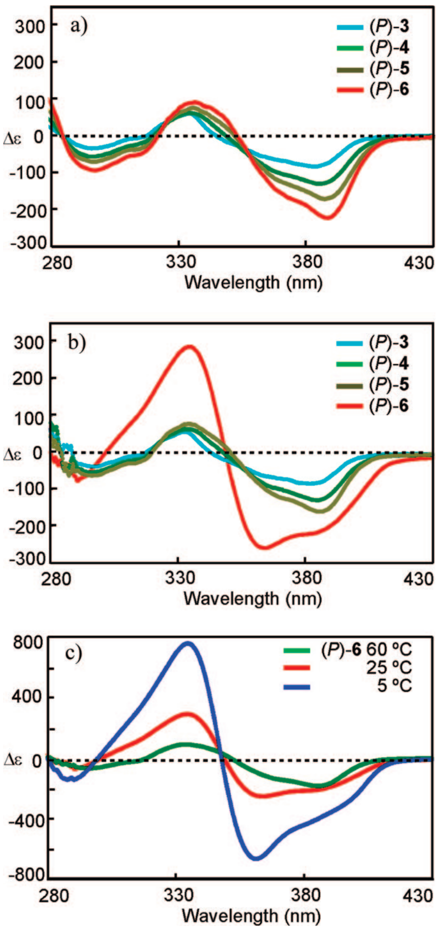

FIGURE 1. (a) CD spectra (chloroform, 5×10^{-6} M, 25 °C) of (*P*)-**3**, **4**, **5**, and **6**. (b) CD spectra (trifluoromethylbenzene, 5×10^{-6} M, 25 °C) of (*P*)-**3**, **4**, **5**, and **6**. (c) CD spectra (trifluoromethylbenzene, 5×10^{-6} M) of (*P*)-**6** at 60, 25, and 5 °C. The spectra were obtained within 30 min of cooling or heating.

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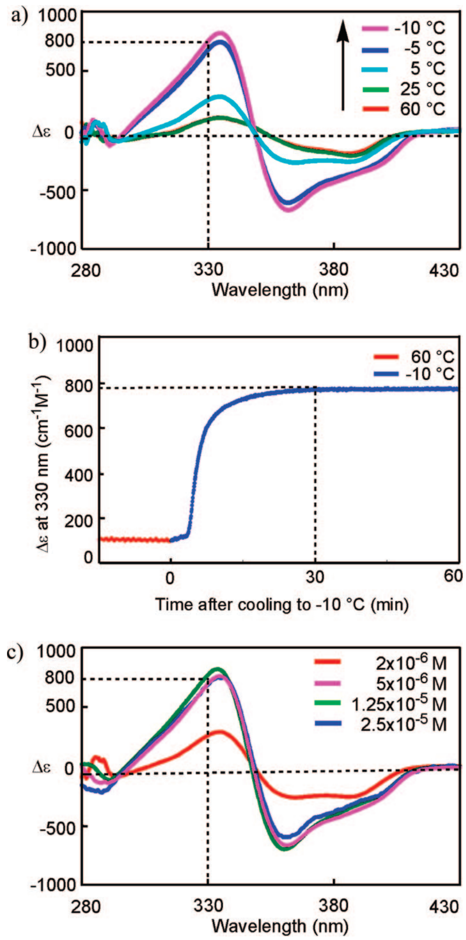

FIGURE 2. (a) CD spectra (trifluoromethylbenzene, 2×10^{-6} M) of (*P*)-**6** at various temperatures. The spectra were obtained within 30 min of heating or cooling. (b) Profiles of $\Delta\epsilon$ at 330 nm (trifluoromethylbenzene, 2×10^{-6} M) of (*P*)-6 heated at 60 °C and then cooled to −10 °C. (c) CD spectra (trifluoromethylbenzene, 5 °C) of (*P*)-**6** at various concentrations. The spectra were obtained within 30 min of cooling.

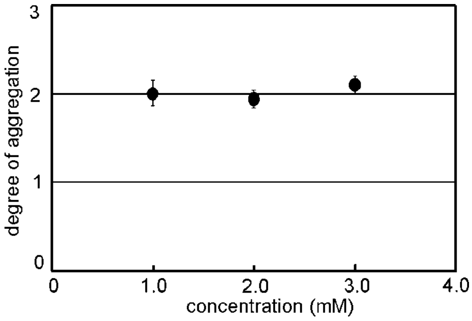

FIGURE 3. Degree of aggregation (*m*-difluorobenzene, 40 °C) of (*P*)-**6** by VPO at various concentrarions.

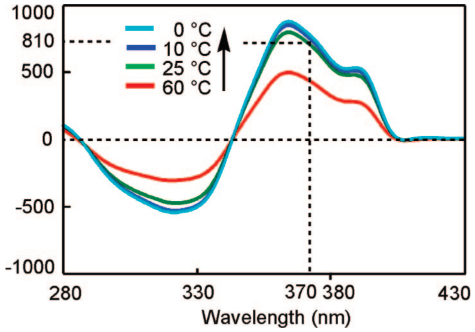

FIGURE 4. CD Spectra (trifluoromethylbenzene, 1×10^{-3} M) of (*P*)-**1** at various temperatures.

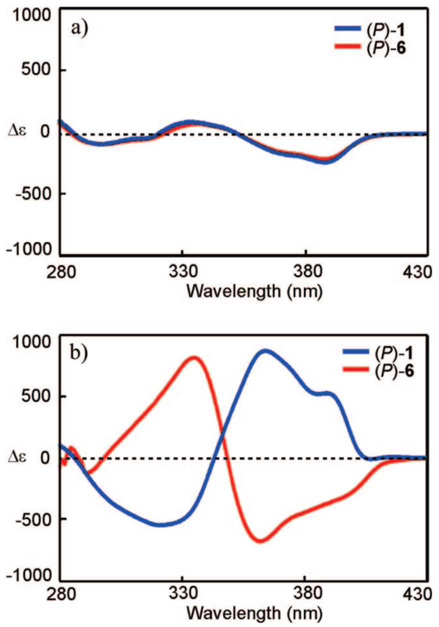

FIGURE 5. (a) CD spectra (chloroform, 5×10^{-6} M, 25 °C) of (*P*)-**1** and (*P*)-**6**. (b) CD spectra (trifluoromethylbenzene) of (*P*)-**1** (1×10^{-3} M, 0 °C) and (*P*)-**6** (2×10^{-6} M, −10 °C).

was soluble at 1×10^{-3} M at 40 °C in this solvent. At 40 °C, VPO indicated the dimeric structure at concentrations between $1-3 \times 10^{-3}$ M (Figure 3), and indicated helix-dimer formation by (*P*)-**6** in the solution, most probably as the double-helix.

On the basis of the experiments on the pentamer (*P*)-**6** with perfluorooctyl side chains, comparative studies were conducted with the original pentamer (*P*)-**1** with decyloxycarbonyl side chains. It was confirmed that (*P*)-**1** also formed a double helix, although the use of a strong helix-forming solvent, trifluoromethylbenzene, was required compared to the solvents for the heptamer (*P*)-**2** previously reported.[8] The CDs of (*P*)-**1** at 1×10^{-3} M were measured at different temperatures. Below 25 °C, typical double-helix spectra were obtained with a $\Delta\epsilon$ value at 370 nm at +810 $cm^{-1}M^{-1}$ (Figure 4), and unfolding was observed at 60 °C. Thus, both pentamers (*P*)-**6** and (*P*)-**1** possessing perfluorooctyl and decyloxycarbonyl side chains formed helix-dimers in trifluoromethylbenzene.

The CD spectra of (*P*)-**1** and (*P*)-**6** were compared in the random coil state and the double-helix state. Although they showed very similar CD spectra for the random coil state in chloroform (Figure 5a), nearly mirror-image spectra were obtained for the double-helix (Figure 5b). This means that (*P*)-**6** also formed double-helix structure similar to (*P*)-**1**, but had an inverted screw sense. This result was quite unexpected, since (*P*)-**6** and (*P*)-**1** had the same helicene configuration, and differ only in the structure of the side chains. The result was attributed to a significant difference in the absolute hardness of the *m*-phenylene moieties. It was supposed that the strong hard/hard interactions between the *m*-phenylene moieties of (*P*)-**6** compared to (*P*)-**1** changed the mode of interaction at the backbone, which resulted in a change in the stable helical conformation (Figure 6). Several single-stranded polymers and oligomer possessing chiral side chains are known to exhibit inversion of the helical screw sense[13] by the ratio of the *R*-side

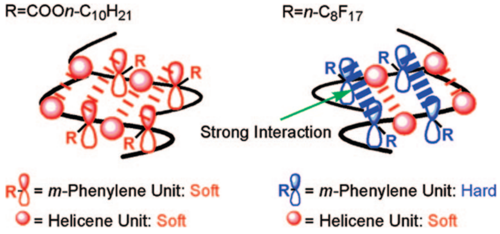

FIGURE 6. Proposed effect of hard arenes arranged among soft arenes in (*P*)-**6**.

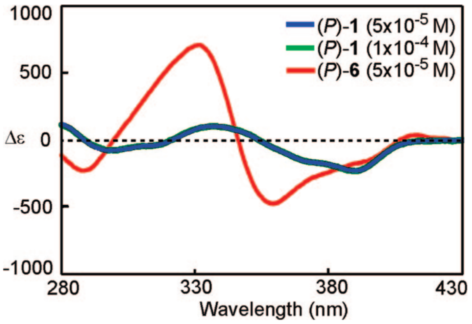

FIGURE 7. CD spectra (toluene, 5 °C) of (*P*)-**1** (5×10^{-5} M and 1×10^{-4} M) and (*P*)-**6** (5×10^{-5} M).

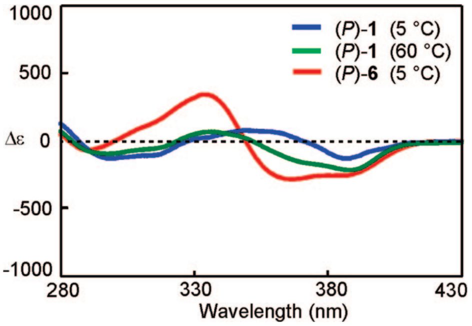

FIGURE 8. CD spectra (*m*-difluorobenzene, 1×10^{-4} M) of (*P*)-**1** (5 and 60 °C) and (*P*)-**6** (5 °C).

chain to the *S*-side chain[14] or by external stimuli such as changes in pH, solvent, and temperature.[15] The inversion of a double-helix depending on solvent has been also reported.[5d] These observations of (*P*)-**6** and (*P*)-**1** are another notable example of such inversions caused by the effect of achiral side chains.

The stability of the double-helix structure was compared between (*P*)-**6** and (*P*)-**1**. In toluene, (*P*)-**6** showed an increase in $|\Delta\epsilon|$ compared to the random coil state at 5×10^{-5} M, while (*P*)-**1** was in the random coil state even at 1×10^{-4} M (Figure 7). In *m*-difluorobenzene at 1×10^{-4} M, (*P*)-**6** showed a spectrum with relatively increased $|\Delta\epsilon|$ over the random coil state due to a partial double-helix structure, and (*P*)-**1** was random coil (Figure 8). In general, (*P*)-**6** formed a double-helix at lower concentrations than (*P*)-**1**, indicating that the double-helix of (*P*)-**6** is more stable than that of (*P*)-**1**. It was presumed that the hard/hard $\pi-\pi$ interactions strengthened the binding and stabilized the double-helix structure of (*P*)-**6**, which possessed alternating soft and hard arene moieties (Figure 6).

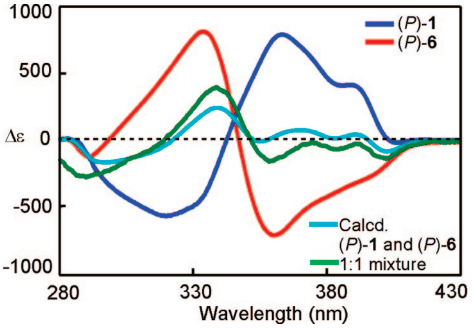

FIGURE 9. CD spectra of a 1:1 mixture of (*P*)-**1** and (P)-6 (trifluoromethylbenzene, total concentration 2.5×10^{-5} M, 5 °C), (*P*)-**1**, and (*P*)-**6** (trifluoromethylbenzene, 1.25×10^{-5} M, 5 °C) obtained within 30 min of cooling. The spectrum calculated by adding those of (*P*)-**1** and (*P*)-**6** is also shown.

Since a new double-helix-forming (*P*)-**6** possessing perfluorooctyl side chains was obtained in this study, the interactions between (*P*)-**6** and the conventional oligomer (*P*)-**1** were examined. Experiments were conducted to determine whether (*P*)-**1** and (*P*)-**6** form heterodimers or a mixture of individual homodimers. It was also of interest to compare the interactions of (*M*)-**1** and (*P*)-**6** to examine the chiral recognition phenomena. Our previous studies revealed that the same configurations were favored as for the enantiomeric helicenes in noncovalent interactions.[16]

The complexation of (*P*)-**1** and (*P*)-**6** was examined in trifluoromethylbenzene, in which the total concentration of (*P*)-**1** and (*P*)-**6** was adjusted to 2.5×10^{-5} M, because both formed a double-helix at 1.25×10^{-5} M at 5 °C (Figure 9). Solutions of (*P*)-**1** and (*P*)-**6** in trifluoromethylbenzene were prepared and were mixed in a 1:1 ratio at room temperature. The solution was then cooled to 5 °C, and the CD spectra were obtained within 30 min. The 1:1 mixture showed a spectrum similar to the sum of the spectra[10] of each double-helix in trifluoromethylbenzene (1.25×10^{-5} M, 5 °C), which suggested the formation of homo-double-helices (Figure 9). In order to further confirm this interpretation, the ratio of (*P*)-**1** to (*P*)-**6** was changed, keeping the total concentration at 2.5×10^{-5}M (Figure 10a), and $\Delta\epsilon$ value at 330 and 370 nm were plotted against the ratio of (*P*)-**1** to (*P*)-**6** (Figure 10b). Both plots were on approximate straight lines giving the maxima of the $\Delta\epsilon$ value for pure (*P*)-**1** and pure (*P*)-**6**. It was therefore concluded that the structural changes of (*P*)-**1** and (*P*)-**6** were independent and resulted in the formation of individual homo-double-helices.

CDs were measured in a solvent of less helix-forming tendency. In toluene (1×10^{-4} M, 5 °C), (*P*)-**6** formed a partial double-helix, and (*P*)-**1** was random coil. The 1:1 mixture of (*P*)-**1** and (*P*)-**6** showed a spectrum similar to the sum of both

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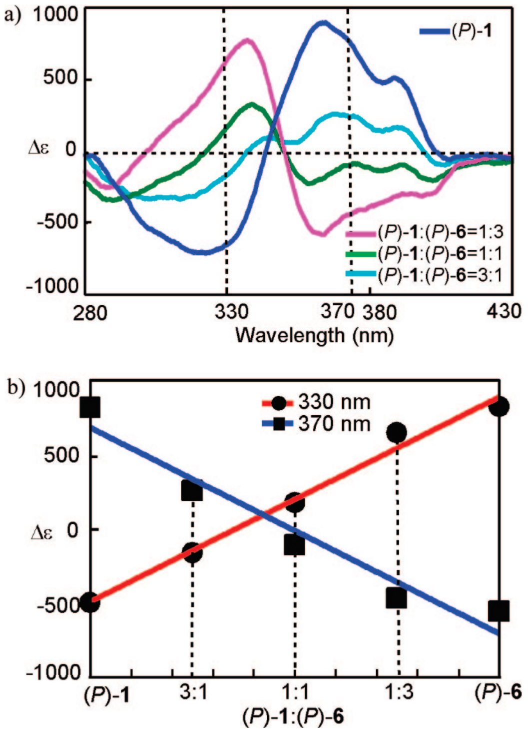

FIGURE 10. (a) CD spectra (trifluoromethylbenzene, total concentration 2.5 × 10^{-5} M, 5 °C) of a mixture of (*P*)-**1** and (*P*)-**6** at various ratio obtained within 30 min of cooling. (b) Plots of Δϵ (trifluoromethylbenzene, total concentration 2.5 × 10^{-5} M, 5 °C) at 330 and 370 nm against the ratio of (*P*)-**1** to (*P*)-**6**. Lines were approximated to the points.

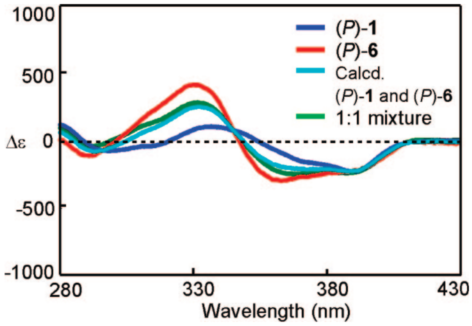

FIGURE 11. CD spectra of a 1:1 mixture of (*P*)-**1** and (*P*)-**6** (toluene, total concentration 1 × 10^{-4} M, 5 °C), (*P*)-**1**, and (*P*)-**6** (toluene, 5 × 10^{-5} M, 5 °C) obtained within 30 min of cooling. The spectrum calculated by adding those of (*P*)-**1** and (*P*)-**6** is also shown.

spectra (Figure 11), which indicated that only (*P*)-**6** formed a homo-double-helix. In chloroform (1 × 10^{-5} M, 5 °C), the 1:1 mixture showed a spectrum corresponding to the random coil.[10]

Next, we turned our attention to the interactions between (*M*)-**1** and (*P*)-**6**, and experiments were conducted in trifluoromethylbenzene at a total concentration of 5 × 10^{-6} M. Experiments at low concentrations were conducted compared to those for the (*P*)-**1**/(*P*)-**6** system, because both (*M*)-**1** and (*P*)-**6** were random coil at 2.5 × 10^{-6} M at 25 °C in this solvent. Solutions of (*M*)-**1** and (*P*)-**6** in trifluoromethylbenzene (5 x10^{-6} M) were prepared and mixed in a 1:1 ratio at 25 °C. The mixture showed much increased |Δϵ| compared to the calculated spectrum within 5 min suggesting the formation of a helical structure in solution (Figure 12a). The CD spectrum was similar to those of (*M*)-**1** and (*P*)-**6** in the double-helix-structures (Figure 5b), and suggested a similar structure of the (*M*)-**1**/(*P*)-**6** complex. Although the solution was initially clear, precipitation occurred and was complete after 2 h. The precipitate was isolated by centrifugation, and elemental analysis showed a fairly good agreement with the analysis calculated for a 1:1 complex, Anal. Calcd: C, 71.29; H, 4.52. Found: C, 68.80; H, 4.71. The values are intermediate between the calculated analytical data for (*M*)-**1**, C, 86.36; H, 6.96, and for (*P*)-**6**, C, 60.14; H, 2.77. MALDI-TOF MS analysis, *m/z* 2699.6 and 3634.7, was also consistent with the complex formation of (*M*)-**1**, *m/z* 2699.0, and (*P*)-**6**, *m/z* 3635.6. The precipitated solid showed a CD spectrum similar to that in solution (Figure 12b), and the complex seemed to possess a similar structure in solution and in the solid state. The observations suggest the formation of a chiral 1:1 complex of (*M*)-**1** and (*P*)-**6**, probably the hetero-double-helix. However, once a precipitate was formed, it was insoluble even at higher temperature in solvents such as trifluoromethylbenzene, toluene, and chloroform. Therefore, the solution experiments were conducted within 30 min of mixing (*M*)-**1** and (*P*)-**6**, before the precipitate appeared.

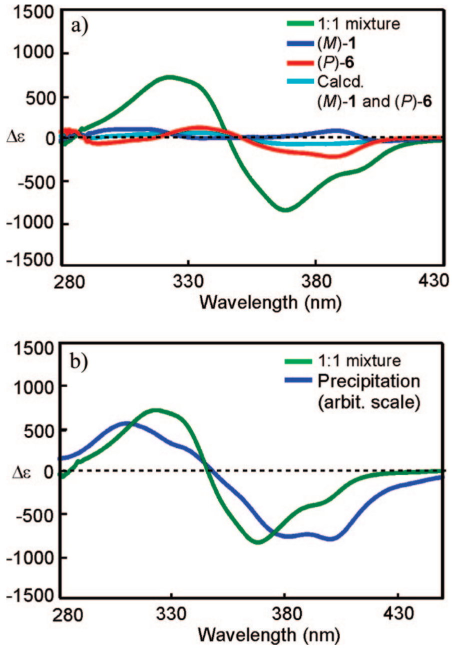

FIGURE 12. (a) CD spectra (trifluoromethylbenzene, 25 °C) of a 1:1 mixture of (*M*)-**1** and (*P*)-**6** (total concentration 5 × 10^{-6} M, obtained within 5 min of mixing), (*M*)-**1**, and (*P*)-**6** (2.5 × 10^{-6} M). The spectrum calculated by adding those of (*M*)-**1** and (*P*)-**6** is also shown. (b) CD spectrum (trifluoromethylbenzene, 5 × 10^{-6} M, 25 °C, obtained within 5 min of mixing) of a 1:1 mixture of (*M*)-**1** and (*P*)-**6**. CD spectrum of the precipitate is also shown with an arbitrary scale.

The same experiment was conducted in chloroform (total concentration 5 × 10^{-6} M, 25 °C), in which both (*M*)-**1** and (*P*)-**6** are random coil. The 1:1 mixture again showed an increased |Δϵ| over the calculated spectrum similar to that in trifluoromethylbenzene after 5 min (Figure 13a), and the precipitate was complete after 2 h. When the solution stood at 25 °C for 30 min and was then heated at 60 °C for 30 min, only a small change in the CD spectrum was observed. The chiral structure was thermally stable than homo-double-helices of (*M*)-**1** and (*P*)-**6** that were unfolded under the same condition. The precipitation showed a Cotton effect similar to that in solution (Figure 13b), and similar to that obtained in a solution of trifluoromethylbenzene and in the solid state. The results indicated that (*M*)-**1** and (*P*)-**6** formed a stable hetero-double-

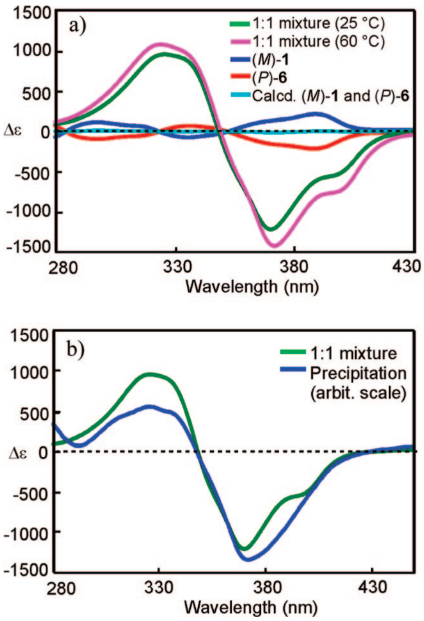

FIGURE 13. (a) CD spectra (chloroform, 25 °C) of a 1:1 mixture of (*M*)-**1** and (*P*)-**6** (total concentration 5 × 10^{-6} M, obtained within 30 min of mixing), (*M*)-**1**, and (*P*)-**6** (2.5 × 10^{-6} M). The spectrum calculated by adding those of (*M*)-**1** and (*P*)-**6** is also shown. The 1:1 mixture was heated at 60 °C for 30 min after standing at 25 °C for 30 min, and the CD spectrum was obtained. (b) CD spectrum (chloroform, 5 × 10^{-6} M, 25 °C, obtained within 30 min of mixing) of a 1:1 mixture of (*M*)-**1** and (*P*)-**6**. CD spectrum of the precipitate is also shown with an arbitrary scale.

helix in both solvents, and the formation of hetero-double-helix was favored over homo-double-helices.

In order to confirm the formation of a hetero-double-helix, the ratio of (*M*)-**1** to (*P*)-**6** was changed, keeping the total concentration at 5 × 10^{-6} M (Figure 14a). The $\Delta\epsilon$ values at 330 nm were plotted against the (*M*)-**1**/(*P*)-**6** ratio (Figure 14b). A maximum was obtained at a 1:1 ratio, which indicates the 1:1 stoichiometry of (*M*)-**1** and (*P*)-**6** in the hetero complex.

(*M*)-**1** and (*P*)-**6** formed a hetero-double-helix, while (*P*)-**1** and (*P*)-**6** formed a homo-double-helix (Figure 15). This result indicates that (*P*)-**6** preferres to complex with (*M*)-**1** rather than (*P*)-**1** or (*P*)-**6**, (*M*)-**1**/(*P*)-**6** is a matched pair. The complexation of the hetero-double-helix (*M*)-**1**/(*P*)-**6** was more stable than the homo-double-helices (*P*)-**6**/(*P*)-**6** and (*M*)-**1**/(*M*)-**1**. These phenomena were in contrast with our previous observations that helicene derivatives favor interaction with helicenes of the same configuration rather than the opposite.[16] It was also shown in this study that the (*P*)-**6**/(*P*)-**6** complex, (*M*)-**1**/(*M*)-**1** complex, and (*M*)-**1**/(*P*)-**6** showed similar CD spectra, which indicates a similar double-helix structure. (*P*)-**6** may recognize the screw sense of the double-helix state rather than configuration of helicene moieties.

In summary, we synthesized dimeric to pentameric ethynylhelicene oligomers possessing perfluorooctyl side chains. CD and VPO studies revealed the formation of double-helix for the pentamer (*P*)-**6**. Compared to the conventional pentamer (*P*)-**1** possessing decyloxycarbonyl side chains, (*P*)-**6** formed a more stable double-helix with inverted screw sense. It was also found that (*M*)-**1** and (*P*)-**6** formed a stable hetero-double-helix rather than homo-double-helices, whereas (*P*)-**1** and (*P*)-**6** formed homo-double-helices. The investigation of homo- and hetero-double-helix compounds will lead to the discovery of interesting supramolecular functions.

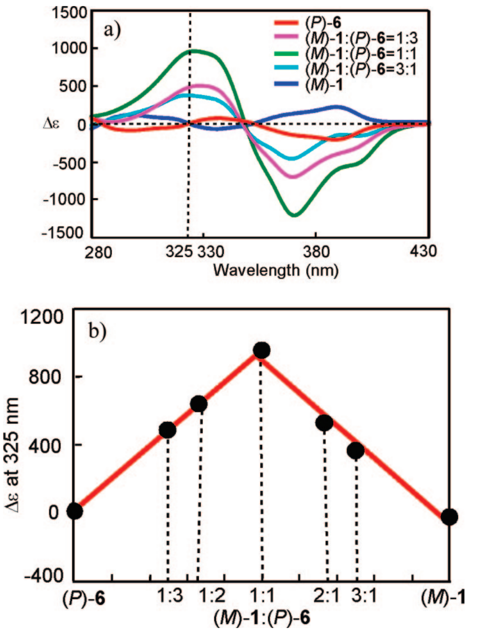

FIGURE 14. (a) CD spectra (chloroform, total concentration 5 × 10^{-6} M, 25 °C, obtained within 30 min of mixing) of mixtures of (*M*)-**1** and (*P*)-**6** at various ratios. The spectra of (*M*)-**1** and (*P*)-**6** under the same conditions are also shown. (b) Plots of $\Delta\epsilon$ (chloroform, total concentration 5 × 10^{-6} M, 25 °C) at 325 nm against the ratio of (*M*)-**1** to (*P*)-**6**. Approximated lines are also shown.

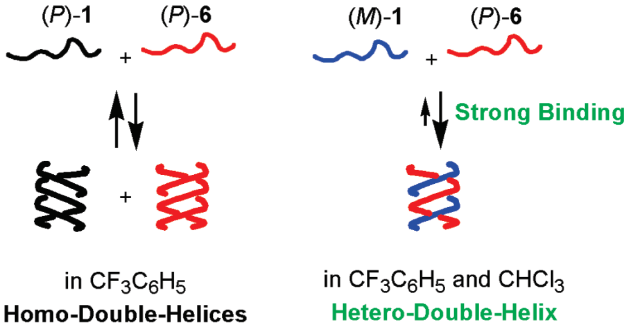

FIGURE 15. Heterodouble-helix formation between (*P*)-**6** and (*M*)-**1**.

Experimental Section

Pentamer (*P*)-6. Under an argon atmosphere, a mixture of (*P*)-**9** (59.3 mg, 0.0582 mmol), tris(dibenzylideneacetone)dipalladium(0) chloroform adduct (6.03 mg, 5.82 × 10^{-3} mmol), cuprous iodide (13.3 mg, 0.0698 mmol), tris(2,4,6-trimethylphenyl)phosphine (13.6 mg, 0.0349 mmol), triphenylphosphine (9.16 mg, 0.0349 mmol), tetrabutylammonium iodide (172 mg, 0.466 mmol), triethylamine (0.48 mL), *N*,*N*-dimethylformamide (1.6 mL), and tetrahydrofuran (2.0 mL) was freeze-evacuated three times in flask A. In flask B, a solution of (*P*)-**12** (55.2 mg, 0.0291 mmol) in tetrahydrofuran (7.0 mL) was freeze-evacuated three times and was added dropwise to flask A. The mixture was stirred for 24 h at room temperature, and insoluble materials appeared. The reaction was quenched by adding saturated aqueous ammonium chloride. The solid was filtrated and washed with water, methanol, ethyl acetate, and hexane on the filter. The organic materials in the residual solution were extracted with toluene. The organic layer was washed with brine and dried over magnesium sulfate. The filtered solid was dissolved in toluene and was mixed with the organic layer. The solvent was evaporated under a reduced pressure, and separation by silica gel chromatography and recycling gel permeation chromatography gave (*P*)-**6** (37.8 mg, 0.0104 mmol, 36% from (*P*)-**12**): mp 230 °C dec (toluene−methanol); $[\alpha]^{21}_{D}$ −335 (*c* 0.05, $CHCl_3$); MALDI TOF-

MS m/z calcd for $^{12}C_{180}{}^{13}C_2H_{100}F_{68}Si_2$ 3634.9, found 3635.6; UV−vis ($CHCl_3$, 5×10^{-6} M) λ_{max} (ϵ) 336 nm (3.5×10^5); CD ($CHCl_3$, 5×10^{-6} M) λ ($\Delta\epsilon$) 297 nm (−96), 337 nm (89), 389 nm (−245); IR (KBr) 2209, 2151, 1242, 1211, 1150 cm^{-1}; ^{1}H NMR (600 MHz, $CDCl_3$) δ 0.36 (18H, s), 1.92 (6H, s), 1.93 (6H, s), 1.97 (12H, s), 1.98 (6H, s), 7.44 (2H, d, J = 7.2 Hz), 7.46 (2H, d, J = 7.2 Hz), 7.49−7.51 (6H, m), 7.65 (2H, dd, J = 7.2, 7.8 Hz), 7.70 (2H, dd, J = 7.2, 7.8 Hz), 7.72−7.75 (6H, m), 7.88−7.90 (4H, m), 7.91 (4H, s), 8.01 (2H, s), 8.08 (2H, s), 8.15 (4H, s), 8.16 (2H, s), 8.20 (2H, s), 8.22 (2H, s), 8.41 (2H, d, J = 7.8 Hz), 8.49 (2H, d, J = 7.8 Hz), 8.52−8.53 (6H, m); ^{13}C NMR (150 MHz, $CDCl_3$, observed at 50 °C) δ 1.00, 23.1, 23.2, 23.3, 29.7, 105−119 (m, br), 119.4, 119.7, 119.8, 120.6, 123.5, 123.6, 123.8, 124.7, 125.0, 125.1, 127.0, 127.2 (2 peaks), 127.3, 129.2, 129.3, 129.4, 129.8, 129.9, 130.1, 130.2, 131.0, 131.1, 131.3, 132.2, 132.3, 137.8; ^{19}F NMR (565 MHz, $CDCl_3$) δ −127.3 (8F, s, br), −123.8 (8F, s, br), −123.0 (8F, s, br), −122.9 (8F, s, br), −122.5 (8F, s, br), −122.3 (8F, s, br), −112.2 (8F, t, J = 12.4 Hz), −81.9 (12F, t, J = 9.6 Hz). Anal. ($C_{182}H_{100}F_{68}Si_2$) Calcd: C, 60.14; H, 2.77; F, 35.54. Found: C, 59.85; H, 3.08; F, 35.28.

Pentamer (*M*)-1. The compound was prepared by the method discussed for the synthesis of (*P*)-**1**:[8a] $[\alpha]^{20}_D$ −455 (c 0.10, $CHCl_3$). ^{1}H NMR spectrum is shown in the Supporting Information.

Complex of (*M*)-1 and (*P*)-6. To a solution of (*P*)-**6** in trifluoromethylbenzene (5×10^{-6} M, 2 mL) was added a solution of (*M*)-**1** in trifluoromethylbenzene (5×10^{-6} M, 2 mL) at 25 °C. The mixture was cooled at 5 °C for 2 h. The precipitate was separated by centrifugal separator (6400 rpm, 30 min), and the top liquid layer was removed by decantation. To the resulting solid was added trifluoromethylbenzene (2 mL), and the solid was separated again by a centrifugal separator. The solid was washed twice by this method. The resulting precipitate was put between the two quartz plates, and the CD spectrum was obtained (Figure 13b): MALDI TOF-MS m/z calcd for (*P*)-**6** $^{12}C_{181}{}^{13}CH_{100}F_{68}Si_2$ 3633.9, (*M*)-**1** $^{12}C_{193}{}^{13}CH_{184}O_8Si_2$ 2698.4, found 3634.7, 2699.7; UV−vis ($CF_3C_6H_5$, 5×10^{-6} M, 25 °C, observed within 5 min of mixing) λ_{max} (ϵ) 343 nm (2.6×10^5); CD ($CF_3C_6H_5$, 5×10^{-6} M, 25 °C, observed within 5 min of mixing) λ ($\Delta\epsilon$) 323 nm (705), 368 nm (−856), 396 nm (−397); CD (precipitation obtained from $CF_3C_6H_5$, with an arbitrary scale) λ ($\Delta\epsilon$) 310 nm (419), 382 nm (−788), 400 nm (−818). Anal. ($C_{376}H_{284}F_{68}O_8Si_4$) Calcd: C, 71.29; H, 4.52. Found: C, 68.80; H, 4.71. A solution of (*P*)-**6** and (*M*)-**1** in chloroform was treated by the same procedures. The CD spectrum of the precipitate is shown in Figure 14b: UV−vis ($CHCl_3$, 5×10^{-6} M, 25 °C, observed within 30 min of mixing) λ_{max} (ϵ) 337 nm (3.1×10^5); CD ($CHCl_3$, 5×10^{-6} M, 25 °C, observed within 30 min of mixing) λ ($\Delta\epsilon$) 326 nm (959), 370 nm (−1213), 397 nm (−541); CD (precipitation obtained from $CHCl_3$, with an arbitrary scale) λ ($\Delta\epsilon$) 326 nm (554), 372 nm (−1349).

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Supporting Information Available: Synthesis and characterization date of spacer **7**, characterization date for (*P*)-**3**-**5**, **11**, and **12**, CD spectra of (*P*)-**1**, (*P*)-**6**, and a 1:1 mixture of (*P*)-**1** and (*P*)-**6**, ^{1}H and ^{13}C NMR spectra of new compounds, and ^{1}H NMR spectra of (*M*)-**1**. This material is available free of charge via the Internet at http://pubs.acs.org.

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