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Marked Effect of Aromatic Solvent on Unfolding Rate of Helical Ethynylhelicene Oligomer

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Abstract: Optically active acyclic ethynylhelicene oligomers were synthesized in high yields by a two-directional method involving Sonogashira coupling and deprotection. Their CD spectra in chloroform exhibited large differences between the oligomers with less than seven helicenes and their higher homologues, which indicated the formation of helical structures for the latter and random coil structures for the former. The helical heptamer gradually unfolded to a random coil structure in chloroform at room temperature. The unfolding rate was examined by CD in several aromatic solvents as well, and the rate constant k was found to be highly dependent on the type of aromatic substituent: k differed by seven orders of magnitude between iodobenzene and trifluoromethylbenzene. Several features of the rates are notable: The reaction rates in halobenzenes were in the order of iodobenzene > bromobenzene > chlorobenzene > benzene > fluorobenzene > *m*-difluorobenzene, those in alkylbenzenes were styrene > phenylacetylene > ethylbenzene > toluene > benzene, and those in heteroatom-substituted arenes were thioanisole > benzonitrile > anisole > ethyl benzoate > benzene > trifluoromethylbenzene. The log k values exhibited good correlation with the absolute hardness, η, of the arenes, and higher unfolding rates were observed in the soft arenes. Vapor pressure osmometry studies indicated that the helical structure of the heptamer is dimeric in benzene, fluorobenzene, and trifluoromethylbenzene, while the random coil structure of the heptamer is monomeric in chloroform and toluene. When a chloroform solution of the random coil structure was concentrated to a small volume, the helical structure could be regenerated.

The solvent is one of the essential factors that affects the conformation of molecules in solution, and a number of biological or synthetic oligomers are known to exhibit different structures in different solvents.[1−3] The solvent also affects conformational changes. The rates of structural changes of polypeptides, proteins, and oligonucleotides between random coils and helixes were compared, for example, in protic solvents such as water and water/alcohol mixtures.[4] Since intramolecular hydrogen bonding is essential to helix formation, protic solvents can affect the rate of conformational changes. The conformational changes of synthetic molecules with low molecular weights in some cases exhibit large solvent dependences, as exemplified by a calixarene[5] and an organoantimony compound.[6] Structural changes based on intermolecular interactions have also been examined with regard to the solvent effect, and the rates of crystallization,[7] gel formation,[8] and fiber formation[9] were compared between different solvents. The differences in the rates of such changes are related to the polarity, viscosity, or electron-donating ability of the solvents. Extensive studies of the solvent effect have been conducted on the rate of chemical reactions[10] such as the decarboxylation,[11] alkene bromination,[12]

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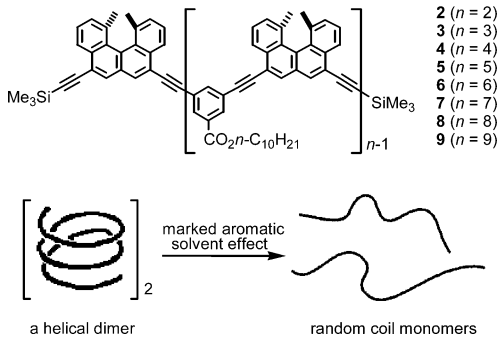
or solvolysis of tertiary halides.[13] They exhibit large solvent dependences on the reaction rates, when the solvent was changed, for example, from an organic solvent to water; in some cases, the rate constants range over five orders of magnitude. It should be noted, however, that the effects of the diverse structures of solvents on the rates of conformational changes and chemical reactions are generally complex, since multiple sums of the various properties of solvent molecules, such as solvation, dipole interactions, and hydrogen bonding, are exhibited at rates. Understanding of the solvent effect in the structural changes of molecules is still premature. Thus, this effect is an important issue to resolve in chemistry.

During our studies on the synthesis and properties of ethynylhelicene oligomers, the cyclic trimer [3+3]cycloalkyne was found to form a strong and selective bimolecular aggregate in organic solvents,[14] and its oligomeric derivatives exhibited diverse aggregation behaviors depending on the structure of the linker moiety.[15] Its aggregate formation was ascribed to strong $\pi-\pi$ interactions by the nonplanar π electron system of helicene. As an extension of the study, a series of acyclic ethynylhelicene oligomers, that is, from the dimer **2** to the nonamer **9**, possessing two to nine (*P*)-helicenes, was synthesized in this study. It was found that higher oligomers, namely, the heptamer **7**, the octamer **8**, and the nonamer **9**, containing more than six helicenes, form helical and dimeric structures in solution, and those with less than seven helicenes form random coil structures. Several synthetic oligomers have been reported to form helical structures in solution, which employ noncovalent bonding interactions, such as the hydrophobic effect,[3] hydrogen bonding,[16] or coordination bonding,[17,18] as the major driving force. The helix formation of the present ethynylhelicene oligomers **7**, **8**, and **9** in nonpolar solvents may also be due to $\pi-\pi$ interactions, since the compounds lack strongly interactive functional groups. It was also observed that helical **7** gradually unfolds to a random coil structure in solution, where a marked effect of the aromatic solvent was observed: A change in the benzene substituent changed the rate constant *k* by seven orders of magnitude. This is an interesting solvent effect on the structural change of molecules, which is directly related to the chemical structure of the solvent.



Ethynylhelicene oligomers were synthesized by repeated Sonogashira couplings and deprotections by a two-directional method, which was previously developed for the synthesis of the cyclic trimers [3+3]cycloalkynes.[14] The silylated trimer **3**,[14] which was a synthetic precursor of [3+3]cycloalkyne, was treated with Bu_4NF in THF, giving the deprotected trimer **11**. Then, coupling with two equivalents of (*P*)-**1** under the rapid Sonogashira coupling condition[19] yielded the pentamer **5** in 99% yield from the trimer **3**. The subsequent deprotection and Sonogashira coupling converted the pentamer **5** to the heptamer **7** and then to the nonamer **9** in 86% and 64% yields, respectively. The series of syntheses provided oligomers containing odd numbers of helicenes. The tetramer **4**, hexamer **6**, and octamer **8** possessing even numbers of helicenes were synthesized starting from the deprotected dimer **10**, which was prepared by the coupling of the monosilylated helicene (*P*)-**16** and the ditriflate **17** followed by desilylation (Scheme 1).

The CD ($CHCl_3$, 25 °C, 5 μM) spectra of the ethynylhelicene oligomers were obtained immediately (5 min) after dissolving the oligomers in chloroform (Figure 1). As will be discussed later, a rapid measurement was required, since these compounds gradually changed their structures in solution. While the compounds dimer **2** to hexamer **6** possessing less than seven helicenes showed a monotonic increase in $\Delta\epsilon$ in accordance with the number of helicenes (Figure 1a), the CD spectra of the higher homologues heptamer **7,** octamer **8**, and nonamer **9** possessing more than six helicenes markedly changed: An extremely large $\Delta\epsilon$ with an inverted sign of the Cotton effect was observed between 300 and 400 nm (Figure 1b). This can be ascribed to the formation of highly ordered structures, most probably helical structures, for the latter compounds. As will be shown later, **7** possesses a dimeric structure as indicated by the vapor pressure osmometry (VPO) analysis.

In chloroform (5 μM), the Cotton effect of **7** gradually decreased at 25 °C, and a steady state was reached after 24 h (Figure 2). The resulting CD spectrum was similar to those of the dimer **2** to hexamer **6**, except in terms of intensity. The UV absorption also exhibited time dependence, and ϵ at 340 nm increased with the structural change. These observations can be explained by the slow transition of the helical structure of **7** to the random coil structure. Such a spectral change was also observed by ^{1}H NMR ($CDCl_3$). The aromatic signals of **7** were broadened immediately after dissolution at 25 °C and exhibited high field absorptions up to δ 5.0 (Figure 3). When the solution was heated at 60 °C for 1 h, the absorptions between δ 5.0 and 7.0 disappeared, and peaks at the lower field of δ 7.0 were sharpened. The latter, therefore, should be a random coil

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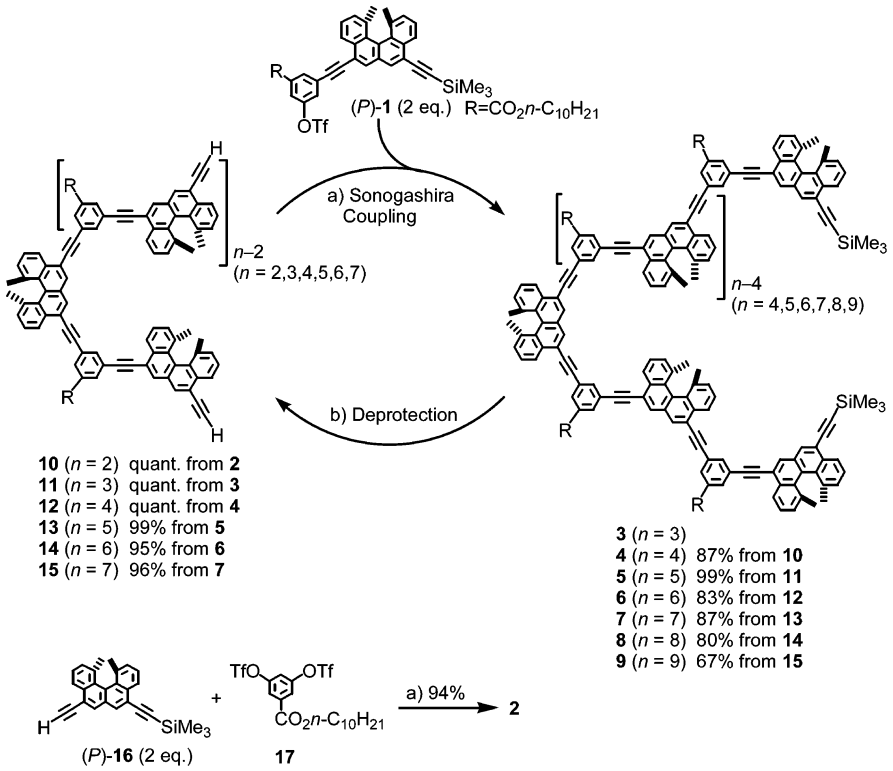
Scheme 1 [a]



[a] Conditions: (a) (*P*)-**1**, $Pd_2(dba)_3$·$CHCl_3$, CuI, Mes_3P, Ph_3P, Bu_4NI, Et_3N, DMF/toluene or DMF/THF, 45 °C, 2 h. (b) Bu_4NF, THF, 0 °C, 10 min.

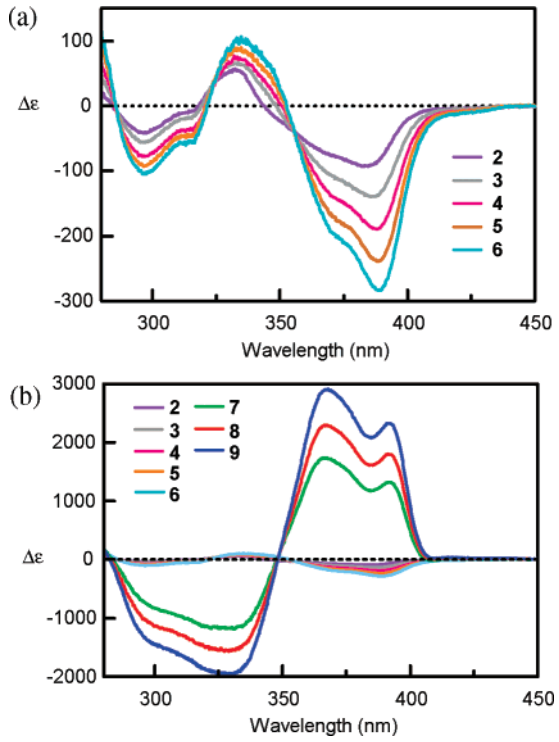


Figure 1. CD spectra ($CHCl_3$, 25 °C, 5 μM) of **2** to **6** (a) and CD spectra of **2** to **9** (b). The spectra were obtained 5 min after dissolution.

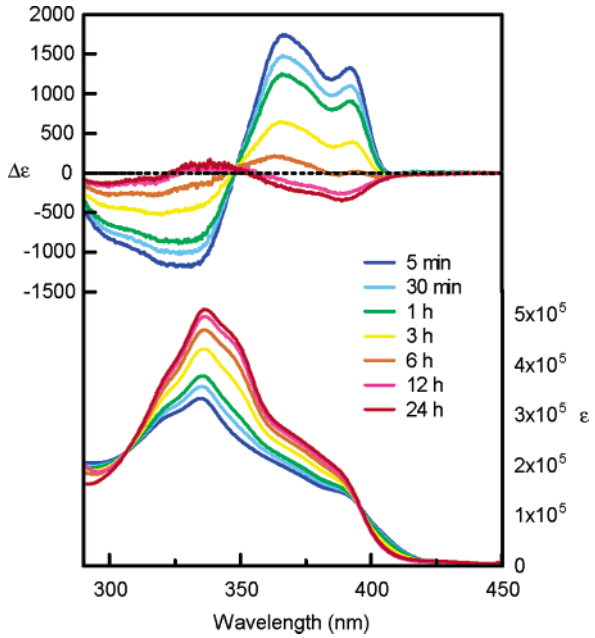


Figure 2. Time dependences of CD (top) and UV−vis (below) spectra ($CHCl_3$, 5 μM, 25 °C) of **7** after dissolution.

structure with a high degree of freedom in motion. In contrast, the spectroscopic behaviors of the former are consistent with the formation of a folded structure with a slow exchange and with aggregate formation involving extensive $\pi-\pi$ interactions. The CD spectra of the octamer **8** also slowly changed after dissolution. It should be noted that marked differences in the CD spectrum of the hexamer **6** from that of the heptamer **7** suggest that **6** can also exhibit a similar structural change under forced conditions. It is likely that all of these chiral ethynylhelicene oligomers have helixes and random coils in equilibrium.

To qualitatively study the unfolding of **7**, the rate constant *k* for this process was obtained. The *k* in chloroform was analyzed by CD employing $\Delta\epsilon$ at 370 nm. A 5 μM solution of **7** was prepared by rapidly dissolving **7** in chloroform within 60 s, and the time dependence of $\Delta\epsilon$ at 370 nm was measured by CD at

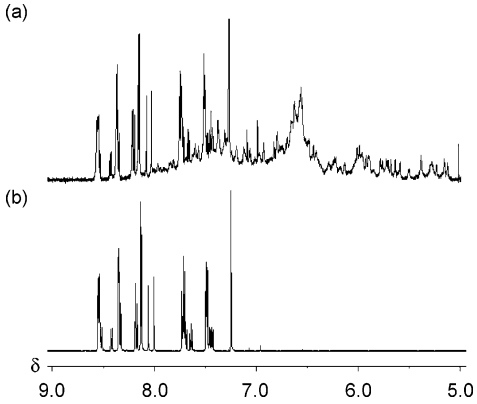


Figure 3. ^{1}H NMR (600 MHz, 1 mM, $CDCl_3$) spectra of **7** observed at 25 °C 10 min after dissolution (a) and observed at 60 °C after being heated at 60 °C for 1 h (b).

25 °C (Figure 4). The value $\Delta\epsilon_0 = 1860$ was estimated by extrapolating to the time 0, and $\Delta\epsilon_\infty = -220$ was obtained from $\Delta\epsilon$ in the steady state, which was reached after 24 h (Figure 2).

The rate constant k was obtained using the $\Delta\epsilon$ values at less than 15% conversion. The observed $\Delta\epsilon$ is described as shown in eq 1, where [H] is the helical dimer concentration and [R] is the random coil monomer concentration. The heptamer **7** is treated to be under equilibrium between a helical dimer (H) and two random coil monomers (2R) (vide infra).

$$\mathrm{H} \rightleftarrows 2\mathrm{R}$$

$$\Delta\epsilon = \Delta\epsilon_0([\mathrm{H}]/[\mathrm{H}]_0) + \Delta\epsilon_\infty([\mathrm{R}]/2[\mathrm{H}]_0) \quad (1)$$

The initial concentration $[H]_0$ is defined as shown in eq 2.

$$[\mathrm{H}]_0 = [\mathrm{H}] + {}^1/_2[\mathrm{R}] \quad (2)$$

The rearrangement of eq 2 gives

$$[\mathrm{H}] = [\mathrm{H}]_0 - {}^1/_2[\mathrm{R}] \quad (2')$$

Substituting [H] into eq 1 and solving for 1/2[R] gives

$${}^1/_2[\mathrm{R}] = [\mathrm{H}]_0(\Delta\epsilon_0 - \Delta\epsilon)/(\Delta\epsilon_0 - \Delta\epsilon_\infty) \quad (3)$$

From eq 3, conversion (%) is calculated using

$$\text{conversion (\%)} = ({}^1/_2[\mathrm{R}])/[\mathrm{H}]_0 \times 100 = (\Delta\epsilon_0 - \Delta\epsilon)/(\Delta\epsilon_0 - \Delta\epsilon_\infty) \times 100 \quad (4)$$

Assuming a first order reaction, the helix−random-coil transition rate is defined as shown in eq 5.

$$\ln[\mathrm{H}] = \ln([\mathrm{H}]_0 - {}^1/_2[\mathrm{R}]) = -kt + \ln[\mathrm{H}]_0 \quad (5)$$

From eqs 3 and 5, eq 6 is given.

$$\ln[\mathrm{H}]_0\{1 - (\Delta\epsilon_0 - \Delta\epsilon)/(\Delta\epsilon_0 - \Delta\epsilon_\infty)\} = -kt + \ln[\mathrm{H}]_0$$

$$\ln(\Delta\epsilon - \Delta\epsilon_\infty) = -kt + \ln(\Delta\epsilon_0 - \Delta\epsilon_\infty) \quad (6)$$

Then, $\ln(\Delta\epsilon - \Delta\epsilon_\infty)$ was plotted against time after dissolution, and the slope of the plot was calculated by the least squares method, giving $k = 5.7 \times 10^{-3}$ min^{-1} in chloroform (Figure 5). The reproducibility was confirmed by conducting the same experiment, giving $k = 5.5 \times 10^{-3}$ min^{-1}.

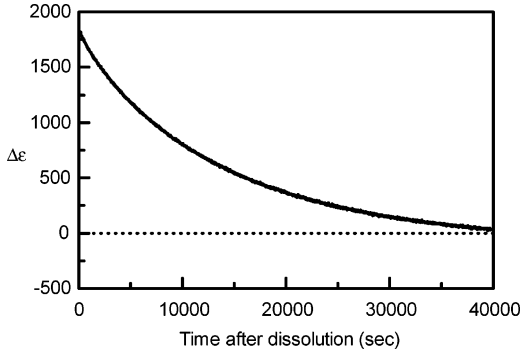


Figure 4. Time dependence of $\Delta\epsilon$ at 370 nm by CD (5 μM, 25 °C) in unfolding of **7** after dissolution in chloroform. $\Delta\epsilon_0 = 1860$ was obtained.

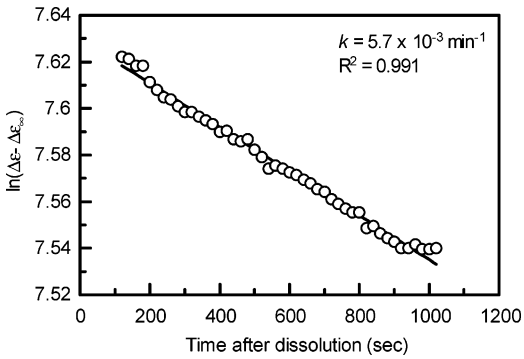


Figure 5. Plots of $\ln(\Delta\epsilon - \Delta\epsilon_\infty)$ of **7** (5 μM) at less than 10% conversion versus time after dissolution in chloroform at 25 °C, which gave $k = 5.7 \times 10^{-3}$ min^{-1}.

The helix−coil transition examined in several substituted benzenes revealed a large solvent dependence.[20] When **7** was dissolved in toluene at 25 °C (5 μM), the steady state was reached after 12 h, and the same analysis by CD provided $k = 1.9 \times 10^{-2}$ min^{-1}, which is about three times more rapid than in chloroform. Analogously, the rate constants in phenylacetylene, ethylbenzene, ethyl benzoate, pyridine, benzene, and fluorobenzene were obtained, which were slower in this order ranging from $k = 9.3 \times 10^{-2}$ to $k = 5.6 \times 10^{-5}$ min^{-1}.[21] In the case of iodobenzene, $\Delta\epsilon = -170$ at 370 nm was obtained 40 s after dissolution at 25 °C, which suggested a very rapid unfolding.[21] When the same experiment was conducted at −5 °C, the unfolding could be monitored by CD (Figure 6a), and $k = 4.8 \times 10^{-1}$ min^{-1} was obtained (Figure 6b). The rate constants k were obtained at −10 and −15 °C as well (Figure 6, parts c and d), and $k = 28$ min^{-1} at 25 °C with an activation energy = 88 kJ mol^{-1} was estimated by extrapolation using the Arrhenius plots (Figure 7). The structural changes in styrene, thioanisole, bromobenzene, benzonitrile, anisole, and chlorobenzene were also rapid, and the extrapolation method gave $k =$ 9.3 to 5.1 $\times 10^{-1}$ min^{-1} (25 °C) in this order with activation energies between 66 and 130 kJ mol^{-1}.[21]

The unfolding was slow in *m*-difluorobenzene, and only a 10% change occurred after 7 days at 25 °C.[21] Then, $\Delta\epsilon_\infty = -157$ was obtained by heating the solution at 60 °C for 16 h, and the analysis of $\Delta\epsilon$ gave $k = 5.8 \times 10^{-6}$ min^{-1} at 25 °C

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(21) See Supporting Information.

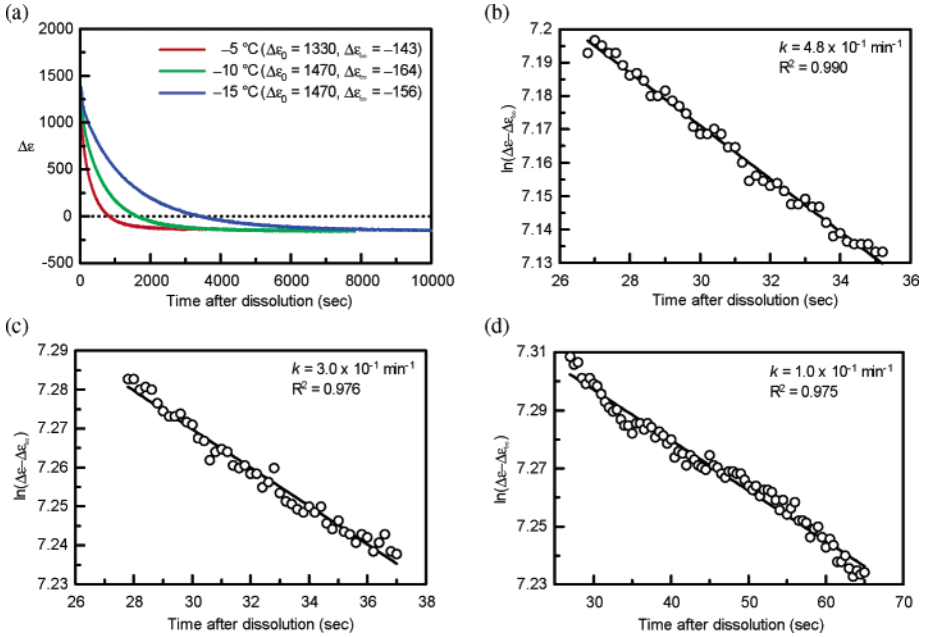

Figure 6. (a)Time dependences of $\Delta\epsilon$ at 370 nm by CD (5 μM) in unfolding of **7** after dissolution in iodobenzene at −5 °C ($\Delta\epsilon_0 = 1330$, $\Delta\epsilon_\infty = -143$), −10 °C ($\Delta\epsilon_0 = 1470$, $\Delta\epsilon_\infty = -164$), and −15 °C ($\Delta\epsilon_0 = 1470$, $\Delta\epsilon_\infty = -156$). Plots of $\ln(\Delta\epsilon - \Delta\epsilon_\infty)$ of **7** (5 μM) at less than 15% conversion versus time after dissolution in iodobenzene at −5 °C (b), −10 °C (c), and −15 °C (d), which gave $k = 4.8 \times 10^{-1}$ min^{-1} (−5 °C), 3.0×10^{-1} min^{-1} (−10 °C), and 1.0×10^{-1} min^{-1} (−15 °C). Reproducibility was confirmed by conducting the same experiments, giving $k = 4.6 \times 10^{-1}$ min^{-1} (−5 °C), 3.4×10^{-1} min^{-1} (−10 °C), and 9.4×10^{-2} min^{-1} (−15 °C).

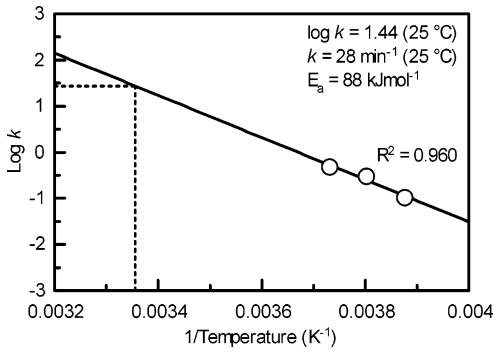

Figure 7. Estimation of $k = 28$ min^{-1} with activation energy = 88 kJ mol^{-1} in iodobenzene at 25 °C using Arrhenius plots. Reproducibility was confirmed by conducting the same experiment, giving $k = 33$ min^{-1} at 25 °C.

(Figure 8). Since the unfolding was much slower in trifluoromethylbenzene than in *m*-difluorobenzene at 60 °C (Figure 9), k was estimated to be less than 10^{-6} min^{-1}.

The rate constants k (25 °C, 5 μM) of the unfolding of **7** in aromatic solvents are summarized in Table 1; they ranged from $<10^{-6}$ to 10 min^{-1}. It is notable that the variation in the type of benzene substituent changed the rate constants k by seven orders of magnitude. Such a large effect of the aromatic solvent in a conformational change or a chemical reaction has not been reported yet. Apparently, the electronic or steric effect of the substituents does not correlate well with k. Several trends are worth noting; the rate constants (k) of unfolding in halobenzenes exhibited the following order of the substituent: −I (28 min^{-1}) > −Br (2.9 min^{-1}) > −Cl (5.1×10^{-1} min^{-1}) > −H (3.6×10^{-4} min^{-1}) > −F (5.6×10^{-5} min^{-1}) > *m*-F_2 (5.8×10^{-6} min^{-1}); those in alkylbenzenes: −CH=CH_2 (9.3 min^{-1}) > −C≡CH (9.3×10^{-2} min^{-1}) > −C_2H_5 (9.2×10^{-2} min^{-1}) > −CH_3 (1.9×10^{-2} min^{-1}) > −H (3.6×10^{-4} min^{-1}); and those in heteroatom-substituted benzenes: −SCH_3 (4.6 min^{-1}) > −CN (1.3 min^{-1}) > −OCH_3 (9.0×10^{-1} min^{-1}) > −$CO_2C_2H_5$ (7.1×10^{-2} min^{-1}) > −H (3.6×10^{-4} min^{-1}) > −CF_3 ($<10^{-6}$ min^{-1}).

Since the soft Lewis basic groups appeared to exhibit higher unfolding rates, log k values were plotted against the absolute hardnesses η of the aromatic molecules, which were obtained

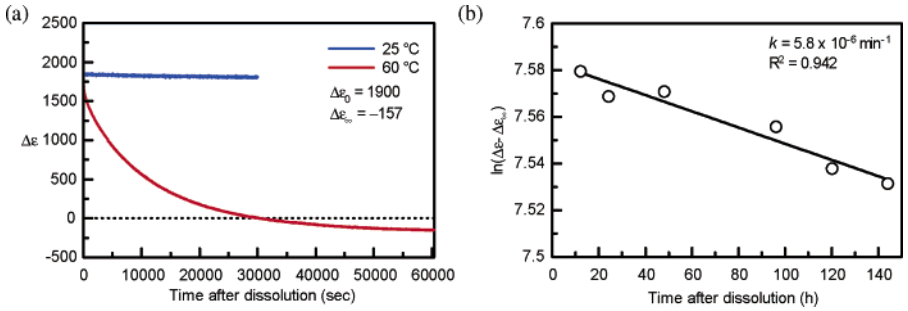

Figure 8. (a) Time dependences of $\Delta\epsilon$ at 370 nm by CD (5 μM) in unfolding of **7** after dissolution in *m*-difluorobenzene at 25 °C (blue line) and 60 °C (red line). $\Delta\epsilon_0 = 1900$ and $\Delta\epsilon_\infty = -157$ were obtained. (b) Plots of $\ln(\Delta\epsilon - \Delta\epsilon_\infty)$ of **7** (5 μM) at less than 10% conversion versus time after dissolution in *m*-difluorobenzene at 25 °C, which gave $k = 5.8 \times 10^{-6}$ min^{-1}. Reproducibility was confirmed by conducting the same experiment, giving $k = 7.9 \times 10^{-6}$ min^{-1}.

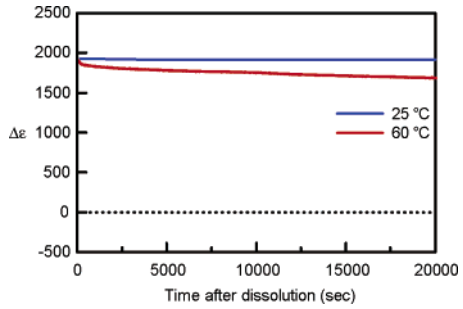

Figure 9. Time dependences of $\Delta\epsilon$ at 370 nm (5 μM) in unfolding of **7** after dissolution in trifluoromethylbenzene at 25 °C (blue line) and 60 °C (red line).

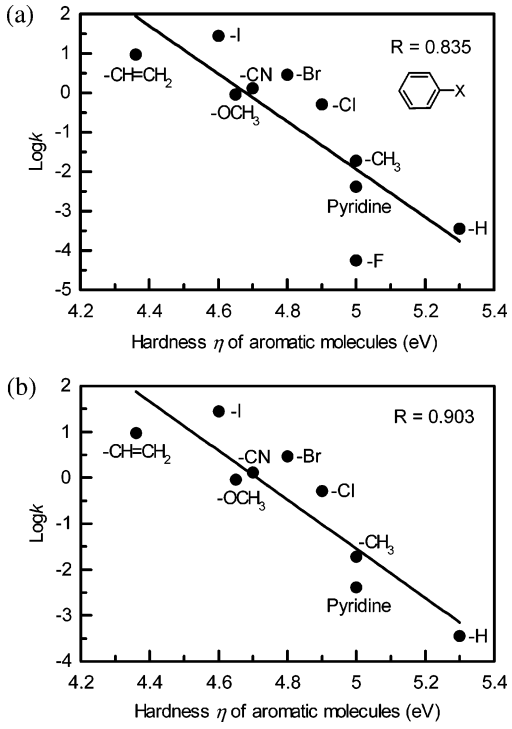

Figure 10. Correlation between log k of **7** in Table 1 and the hardness η of aromatic molecules[22] (eV) including (a) or excluding fluorobenzene (b).

by Pearson[22] employing the ionization potential and electron affinity (Figure 10a). It turned out that log k exhibited good correlation with η, and k decreased with the increase in η of the solvents. These data were analyzed using linear least squares regression, and a correlation coefficient R of 0.835 was obtained. It was noted that log k in fluorobenzene considerably deviated from the line, and the calculation excluding fluorobenzene provided a better R of 0.903 (Figure 10b). It is reasonable to conclude that the unfolding rate is strongly influenced by the hardness and softness of aromatic solvents, which may be related to the nature of $\pi-\pi$ interactions.

The helix structure of **7** could be regenerated from the random coil structure. A solution of unfolded **7** in chloroform (0.1 mM, Figure 11b), which was obtained by allowing the solution to stand for 12 h at 25 °C, was concentrated to approximately 10 mM. Then, the solution was rapidly diluted to 0.1 mM in chloroform to obtain the CD spectrum, which turned out to be identical to that of the helix structure (Figure 11c). Thus, **7** undergoes a reversible helix−random-coil transition in solution by changing its concentration. The observation suggested the involvement of intermolecular interactions in helix formation (vide infra).

(22) Pearson, R. G. *J. Org. Chem.* **1989**, *54*, 1423−1430.

Table 1. Rate Constant k (25 °C, 5 μM) for Unfolding of **7** in Various Aromatic Solvents, Obtained from $\Delta\epsilon$ at 370 nm by CD

solvent	k/min^{-1}
iodobenzene[a]	28
styrene[a]	9.3
thioanisole[a]	4.6
bromobenzene[a]	2.9
benzonitrile[a]	1.3
anisole[a]	9.0×10^{-1}
chlorobenzene[a]	5.1×10^{-1}
phenylacetylene	9.3×10^{-2}
ethylbenzene	9.2×10^{-2}
ethyl benzoate	7.1×10^{-2}
toluene	1.9×10^{-2}
chloroform	5.7×10^{-3}
pyridine	4.1×10^{-3}
benzene	3.6×10^{-4}
fluorobenzene	5.6×10^{-5}
m-difluorobenzene	5.8×10^{-6}
trifluoromethylbenzene	$<10^{-6}$

[a] Estimated by low temperature experiment.

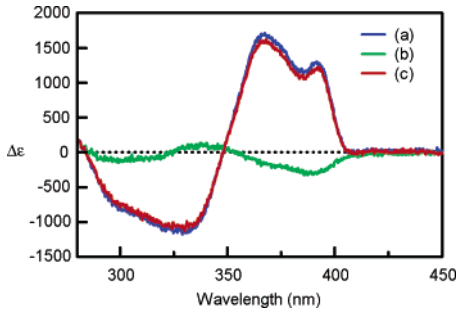

Figure 11. Refolding experiment on **7**. CD spectra ($CHCl_3$, 25 °C, 0.1 mM) of **7** obtained 5 min after dissolution (a) and 12 h after dissolution (b). The spectrum (c) was obtained after the solution (b) was concentrated to approximately 10 mM followed by dilution to 0.1 mM.

To obtain information on the helical structure of **7**, VPO studies were conducted using several aromatic solvents. Since the VPO examination should be conducted at considerably higher concentrations compared with the CD studies, additional experiments were performed to confirm that the helix structures are in fact treated in the VPO studies. The CD of **7** in trifluoromethylbenzene at 1 mM confirmed that the helical structure was maintained for several hours after dissolution at this concentration (Figure 12a). Then, the VPO study of the helical structure was conducted in 5 mM trifluoromethylbenzene during 1 to 7 h after dissolution. The apparent molecular weight of helical **7** turned out to be constant during this period and corresponded to that of a dimer (Figure 12b). Although it would be appropriate to suggest a double helical structure as a possible structure of **7**, it cannot be determined at present. Dimer formation was also observed in fluorobenzene and benzene.[21] In contrast, the VPO study revealed the random coil structure to be monomeric. It was confirmed that the CD spectrum of **7** in 1 mM chloroform (Figure 13a) is that of the random coil structure after being heated at 40 °C for 3 h. Then, the apparent molecular weight was measured at several chloroform concentrations between 1 and 5 mM. It turned out that the random coil structures in chloroform (Figure 13b) are monomeric. The same experiments in toluene also showed the random coil structure to be monomeric.[21] For all the solvents used in the

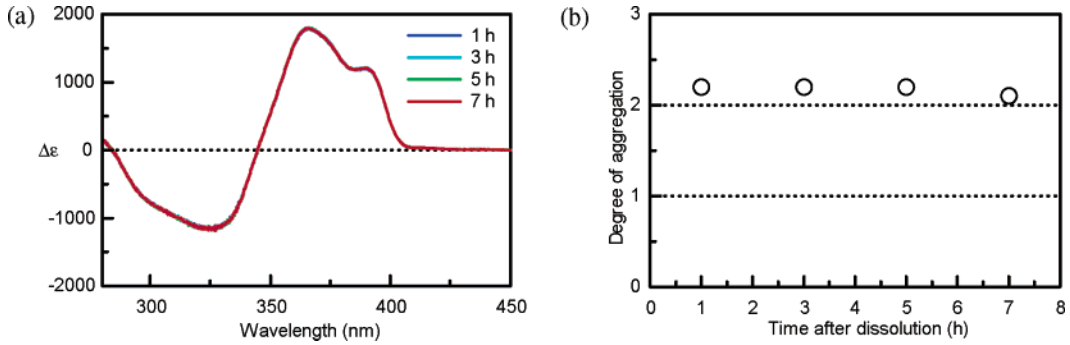

Figure 12. (a) CD spectra of **7** (1 mM, 60 °C) at various times after dissolution in trifluoromethylbenzene. (b) Degree of aggregation of **7** (5 mM, 60 °C) by VPO at various times after dissolution in trifluoromethylbenzene. Degree of aggregation = observed molecular weight/molecular weight of monomer.

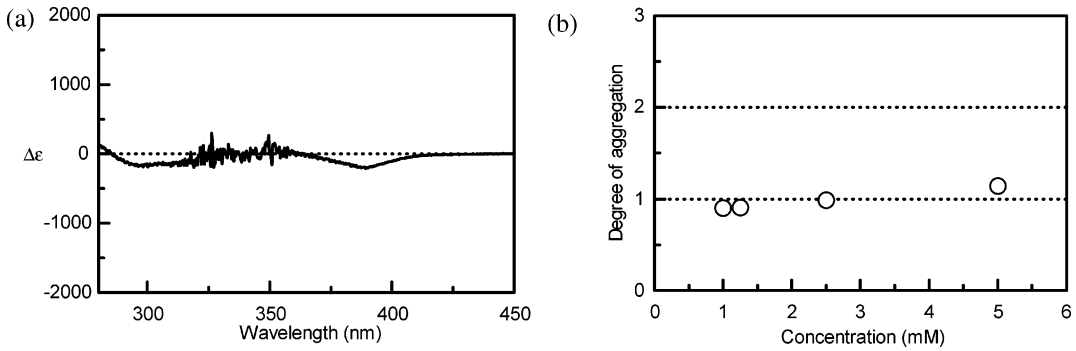

Figure 13. (a) CD spectrum of **7** ($CHCl_3$, 1 mM, 40 °C) after being heated at 40 °C for 3 h. The same sample as that used in the VPO study at 1 mM was used. (b) Degree of aggregation of **7** ($CHCl_3$, 40 °C) by VPO at various concentrations after being heated at 40 °C for 3 h.

present study, the CD spectra for helical and random coil structures are very similar. Accordingly, it may reasonably be concluded that the transition proceeds between a helical dimer and two random coil monomers in all the solvents. The present synthetic oligomer **7** exhibits a reversible transition between a helix dimer and two random coil monomers reminiscent of DNA.

In summary, a series of acyclic ethynylhelicene oligomers containing two to nine helicenes was synthesized. The CD spectra of these oligomers in chloroform considerably differed between the oligomers containing less than seven helicenes and those containing more than six helicenes. The observation indicated the formation of highly ordered chiral structures of **7**, **8**, and **9**, which are likely to be helical structures. Helical **7** gradually unfolded to its random coil structure in various solvents, and the rate of this unfolding was examined by CD. The rate was markedly affected by the type of substituent of the aromatic solvents, and the rate constants k differed by seven orders of magnitude between iodobenzene and trifluoromethylbenzene. It should be emphasized that unfolding rate correlates to the hardness and softness of the aromatic solvents, which may be related to the nature of $\pi-\pi$ interactions.

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Supporting Information Available: Experimental procedures for the synthesis of ethynylhelicene oligomers, as well as for the determination of the rate constant k for the unfolding of **7** in various solvents. ^{1}H NMR spectra of **2**, **4**−**9**. This material is available free of charge via the Internet at http://pubs.acs.org.

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