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Sol–Gel Processes

Two-Component Gel Formation by Pseudoenantiomeric Ethynylhelicene Oligomers**

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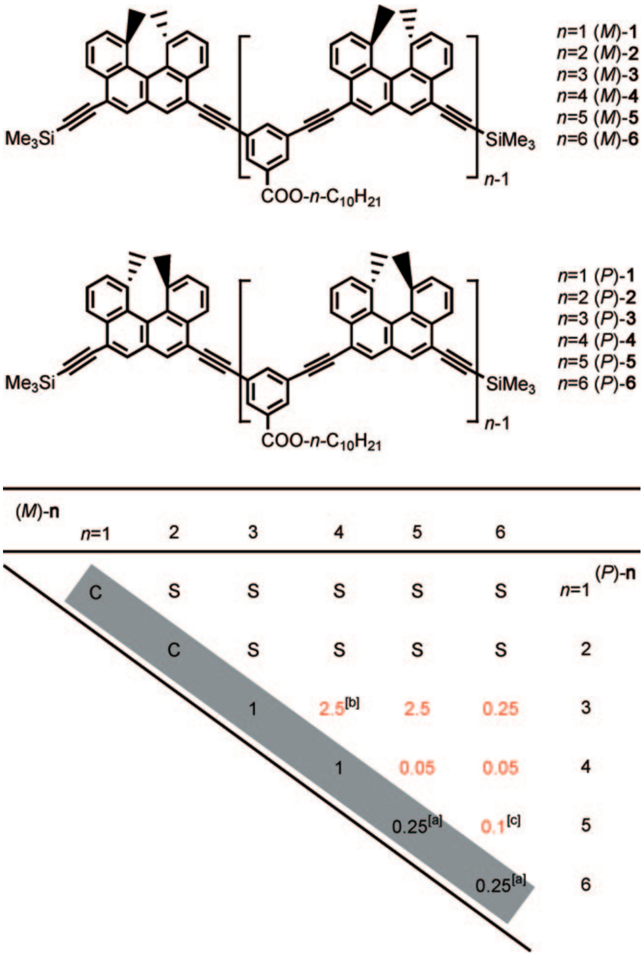
Substantial interest has been expressed in the field of low-molecular-weight gelators, which contain self-assembled structures of small molecules held together by noncovalent interactions.[1] Along with the single low-molecular-weight gel systems, two-component gelators have been developed, in which an individual component forms an isotropic solution, and a gel is formed only in the presence of both components.[2] Fibrous aggregates are formed from two components associated by metal–ligand coordination,[3] salt formation,[4] or hydrogen bonding.[5] The two-component gel system confers tunability and controllability, because the gel properties can be varied by changing the components. However, systematic understanding of the relationship between gelation ability or gel properties and the structure of each component is still preliminary, and it is desirable to develop general and versatile methods for two-component gel formation as well as methods to control gel properties.

With regard to chirality, which is generally critical for gelation, racemates are poor gelators because they tend to crystallize.[6] Therfore, very few examples are known of racemic mixtures which form gels more effectively than single enantiomers.[7] Herein, we reveal two-component organogel formation using chiral oligomers, each containing a different number of repeating 1,12-dimethylbenzo[c]phenanthrene units, namely helicene, which are referred to as pseudoenantiomeric oligomers in this study. This is a novel and general methodology for two-component gel formation, and various gel systems can be obtained by changing the combinations of the oligomers.[8] In addition, the gel formation is thought to proceed with nonplanar π–π interactions between helicenes,[9] a driving force which is different from that of conventional gels.[10]

This study was initiated after the observation that racemic oligomers formed gels, but optically pure oligomers did not (Figure 1). When toluene solutions of (*M*)-**3** (2 mM) and (*P*)-**3** (2 mM),[11] ethynylhelicene trimers containing (*M*)- and (*P*)-helicene units, respectively, were mixed in a 1:1 ratio at 25 °C, a turbid gel was formed. The gel turned into a clear yellow solution when heated to 110 °C, and a gel was formed after cooling to room temperature. No solution of (*M*)-**3** and (*P*)-**3** formed again after cooling to room temperature. This thermoreversible gel formation was observed at a concentration of greater than or equal to 1 mM for each component.



(*M*)-n	n=1	2	3	4	5	6
(*P*)-n n=1	C	S	S	S	S	S
2		C	S	S	S	S
3			1	2.5[b]	2.5	0.25
4				1	0.05	0.05
5					0.25[a]	0.1[c]
6						0.25[a]

Figure 1. Minimal thermoreversible gelation concentration in mM for 1:1 mixtures of (*M*)-**n** and (*P*)-**n** (*n* = 1–6) in toluene. [a] Minimal gelation concentration as mixed. The gel formation was not thermoreversible. [b] A mixture of (*P*)-**4** and (*M*)-**3** was used. [c] A mixture of (*P*)-**6** and (*M*)-**5** was used. S = soluble at room temperature (solubility > 5 mM), C = crystallization.

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The use of monomers (*M*)-**1**/(*P*)-**1** and dimers (*M*)-**2**/(*P*)-**2** resulted in the formation of needle-like crystals and not a gel, which indicated the critical role of the number of helicene units upon gel formation. The combination of (*M*)-**4**/(*P*)-**4** provided a turbid gel (≥ 0.25 mM) when the mixture was heated to 110 °C, and then cooled to ambient temperature. Higher oligomers (*M*)-**5**/(*P*)-**5** and (*M*)-**6**/(*P*)-**6** formed turbid gels (≥ 0.25 mM) when mixed at room temperature.[12] These are notable examples of two-component gels formed by enantiomers.[7]

We then examined gel formation using enantiomeric oligomers possessing different numbers of helicene units, which are referred to as pseudoenantiomeric oligomers in this study. When (*M*)-**5** and (*P*)-**4** (0.5 mM each) were mixed in toluene in a 1:1 ratio at 25 °C, a clear yellow gel was formed within 30 minutes. This gel thermoreversibly changed sol–gel state by heating to 110 °C and cooling to room temperature. Such changes were observed at ≥ 0.05 mM. The structure change could be monitored by circular dichroism (CD) spectroscopy by taking advantage of the pseudoenantiomers. Each 0.5 mM solution of (*M*)-**5** and (*P*)-**4** in toluene at 25 °C was in a random-coil state having small Cotton effects. After mixing these solutions in a 1:1 ratio at 25 °C, the magnitude of the Cotton effect increased considerably, and attained a steady state after 12 hours, having $\Delta\varepsilon$ -1500 dm^3 mol^{-1} cm^{-1} at 370 nm and $\Delta\varepsilon$ 1130 at 337 nm (Figure 2). This data show that the structure slowly changed after gel formation. When the mixture was heated to 85 °C, the intensity of the peak in the CD spectrum decreased rapidly, and provided a spectrum corresponding to the sum of the spectra for each oligomer in a random-coil state (Figure 3 a). This sol–gel cycle could be repeated reproducibly by heating to 90 °C and cooling to 25 °C as indicated by the change in $\Delta\varepsilon$ at 337 nm (Figure 3 b). The UV/vis absorption shifted bathochromicaly with gel formation, and the absorption maxima at 335 nm shifted to 350 nm (Figure 3 c). Accordingly, the pale yellow solution changed to a deep yellow gel. The morphology of the dried (*M*)-**5**/(*P*)-**4** gel (xerogel) was examined by atomic force microscopy (AFM) and scanning electron microscopy (SEM; Figure 4). The gel exhibited a regular structure of fibers, which were approximately 50 nm in diameter.

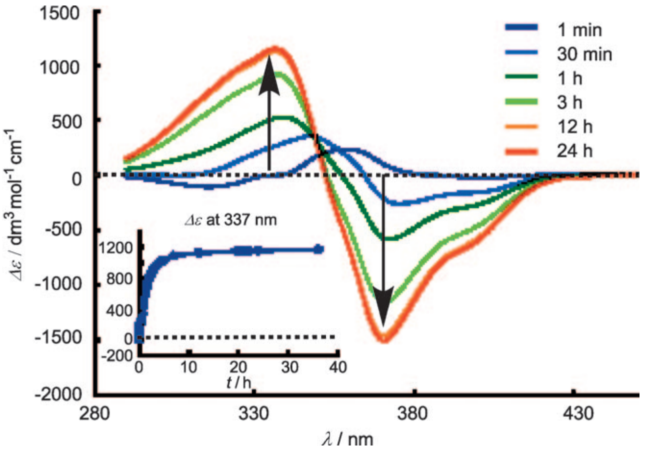

Figure 2. Time dependence of CD spectra (toluene, 0.25 mM each, 25 °C) of the mixture of (*M*)-**5** and (*P*)-**4**. Inset shows plots of $\Delta\varepsilon$ at 337 nm.

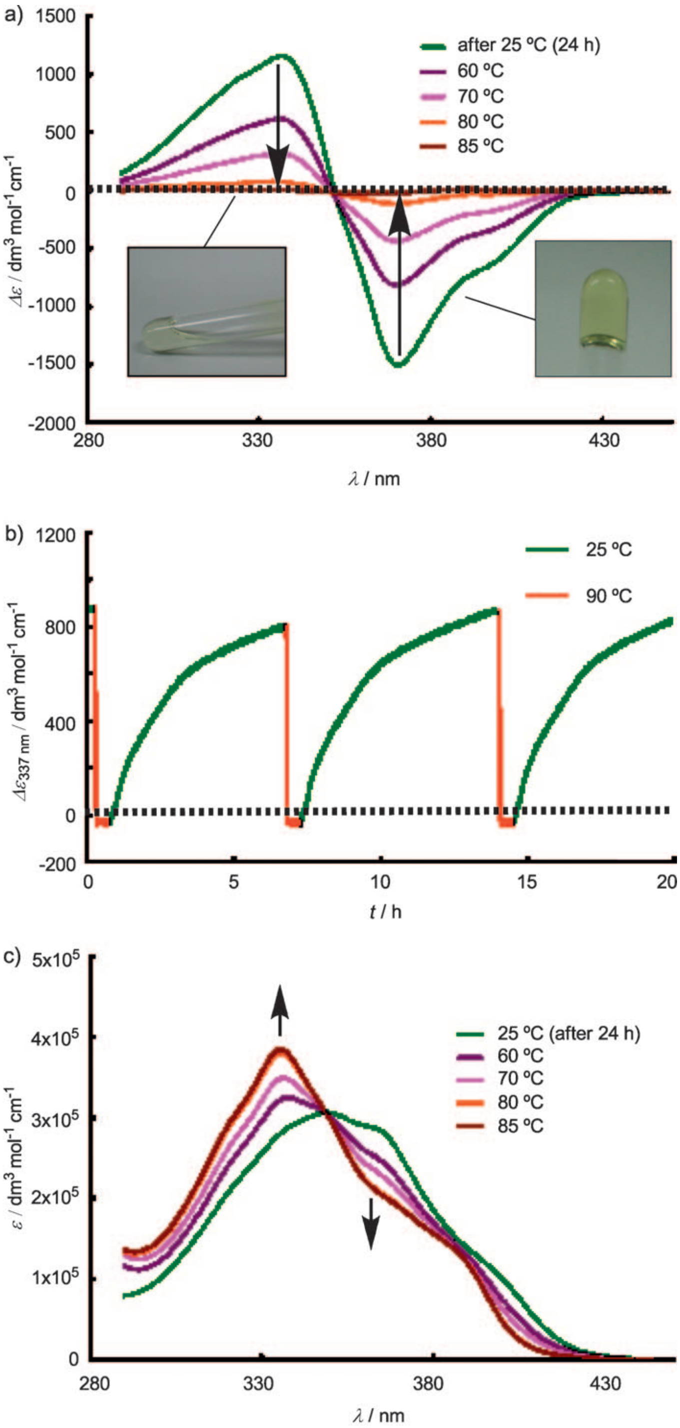

Figure 3. a) The CD spectra (toluene, 0.25 mM each, 25 °C) of the (*M*)-**5**/(*P*)-**4** gel formed at 25 °C after 24 h, and the results of a heating experiment. Insets show pictures of the gel and the solution. b) Plots of $\Delta\varepsilon$ at 337 nm for the mixture of (*M*)-**5** and (*P*)-**4** (0.1 mM each, toluene) in the repeating cycles of heating at 90 °C for 0.5 h and cooling at 25 °C for 6 h. c) UV/vis spectra (toluene, 0.25 mM each) of the mixture of (*M*)-**5** and (*P*)-**4** at various temperatures.

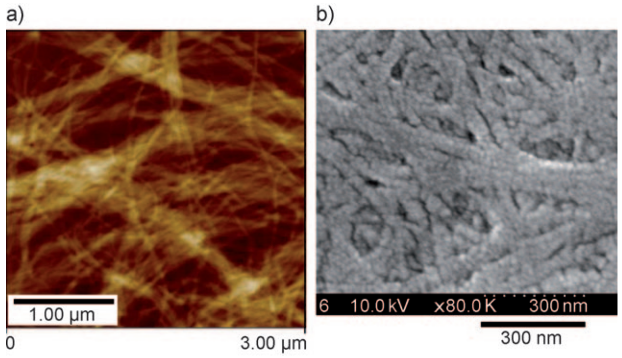

Figure 4. a) AFM image (height mode) of the dried (*M*)-**5**/(*P*)-**4** gel (xerogel) obtained in toluene (0.05 mM each). b) SEM image of the dried (*M*)-**5**/(*P*)-**4** gel (xerogel) obtained in toluene (0.25 mM each).

This methodology of forming a two-component gel using pseudoenantiomers of oligomeric compounds has an advantage over the method using enantiomers. The use of pseudoenantiomers can suppress crystal formation, which is often observed in mixtures of enantiomers. The different chain length of each oligomer probably enhances the formation of polymeric aggregates.

Various combinations of the pseudoenantiomeric oligomers formed thermoreversible gels provided that both oligomers were longer than a trimer. The minimal concentrations, for thermoreversible gel formation are summarized in Figure 1. A mixture of (*P*)-**6** and (*M*)-**5** (0.25 mM each) formed a clear yellow gel at room temperature in toluene. The CD spectra of (*P*)-**6**/(*M*)-**5** gel were similar to the CD spectra of (*M*)-**5**/(*P*)-**4** gel between 350 and 430 nm, but with weaker Cotton effects of opposite sign (Figure 5a). A bathochromic shift upon gel formation was observed in UV/vis spectra as well as for the (*M*)-**5**/(*P*)-**4** gel (Figure 5b).

Gel formation occurred for various combinations of oligomers and different ranges of concentrations, when mixtures were heated once to 110 °C and then cooled to room temperature: (*M*)-**6**/(*P*)-**4** and (*M*)-**5**/(*P*)-**4** ($\geq$ 0.05 mM); (*P*)-**6**/(*M*)-**5** ($\geq$ 0.1 mM); (*M*)-**5**/(*P*)-**3** and (*P*)-**4**/(*M*)-**3** ($\geq$ 2.5 mM). When one of the oligomers was shorter than a trimer, however, the combination did not form a gel, even when the other oligomer was a hexamer. Longer oligomers tend to form more stable gels at lower concentrations. All these gels exhibited negative Cotton effects between 350 and 430 nm when *M* oligomers were used for the longer oligomer, although the absolute $\Delta\varepsilon$ values differed considerably (Figure 6). The Cotton effects between 290 and 350 nm were case dependent. The results indicated similar but slightly different helical polymeric structures of the pseudoenantiomeric oligomer gels depending on the combination. The following are the $\Delta\varepsilon$ values ($dm^3\,mol^{-1}\,cm^{-1}$) at 400 nm after the first-formed gel was heated to form a solution and then cooled to 25 °C: (*P*)-**6**/(*M*)-**5**, $\Delta\varepsilon$ 400 (0.25 mM, heated to 90 °C); (*M*)-**5**/(*P*)-**4**, $\Delta\varepsilon$ −570 (0.25 mM, heated to 85 °C); (*M*)-**4**/(*P*)-**3**, $\Delta\varepsilon$ −180 (2.5 mM, heated to 70 °C); (*M*)-**6**/(*P*)-**4**, $\Delta\varepsilon$ −230 (0.05 mM, heated to 70 °C); (*M*)-**5**/(*P*)-**3**, $\Delta\varepsilon$ −90 (2.5 mM, heated to 60 °C).

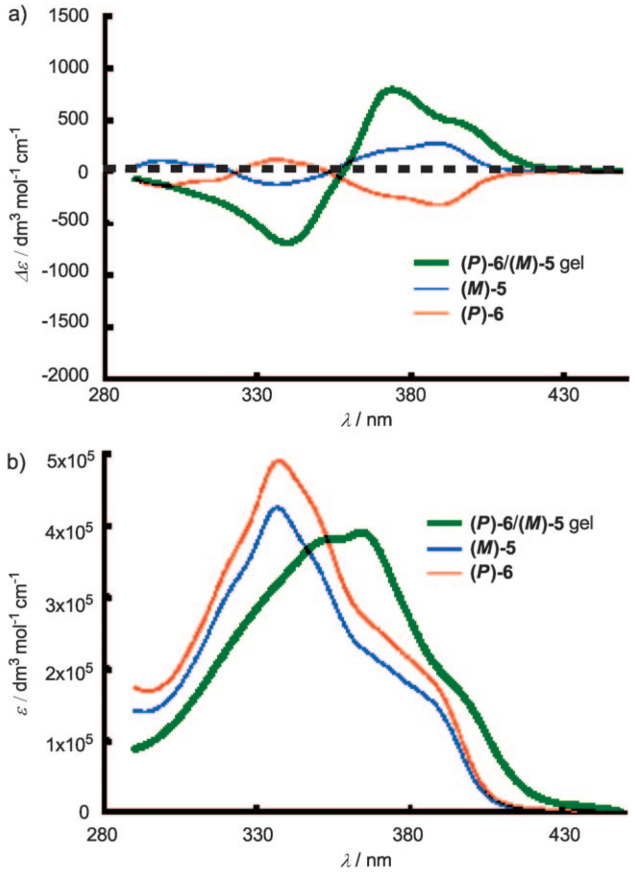

Figure 5. a) CD spectra (toluene, 25 °C) of (*M*)-**5** (0.5 mM, blue line), (*P*)-**6** (0.5 mM, red line), and their mixture (0.25 mM each, heated at 90 °C for 30 min, and then cooled to 25 °C for 30 h, green line). b) UV/vis spectra (toluene, 25 °C) of (*M*)-**5** (0.5 mM, blue line), (*P*)-**6** (0.5 mM, red line), and their mixture (0.25 mM each, heated at 90 °C for 30 min, and then cooled to 25 °C for 30 h, green line).

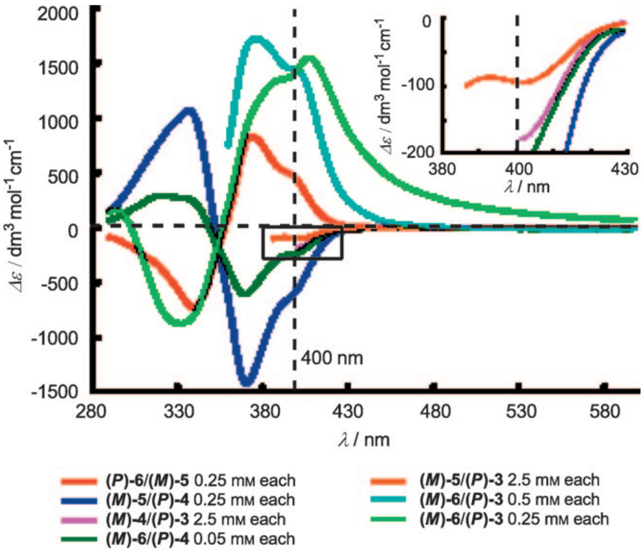

Figure 6. CD spectra of gels derived from a 1:1 mixture of oligomers; used different combinations of oligomers. The spectra were obtained after heating at 90 °C ((*P*)-**6**/(*M*)-**5**), 85 °C ((*M*)-**5**/(*P*)-**4**), 70 °C ((*M*)-**4**/(*P*)-**3**, (*M*)-**6**/(*P*)-**4** and (*M*)-**6**/(*P*)-**3**), 60 °C ((*M*)-**5**/(*P*)-**3**), and then cooling to 25 °C. The inset shows the expansion of the spectra from 380 to 430 nm.

Gel formation occurred even with a combination of (*M*)-**6** and (*P*)-**3** ($\geq$ 0.25 mM), with one oligomer being twice the length of the other. The gel property, however, was different from those of the other two-component gels noted above. The UV/vis spectra of the (*M*)-**6**/(*P*)-**3** gel did not show large changes upon aggregation (Figure 7 a). The CD spectra exhibited strong positive Cotton effects at 400 nm with $\Delta\varepsilon$ 2300 dm^3 mol^{-1} cm^{-1}, despite the use of (*M*)-**6** as the longer component (Figure 7 b and c), which is the opposite of the observations in other gels.

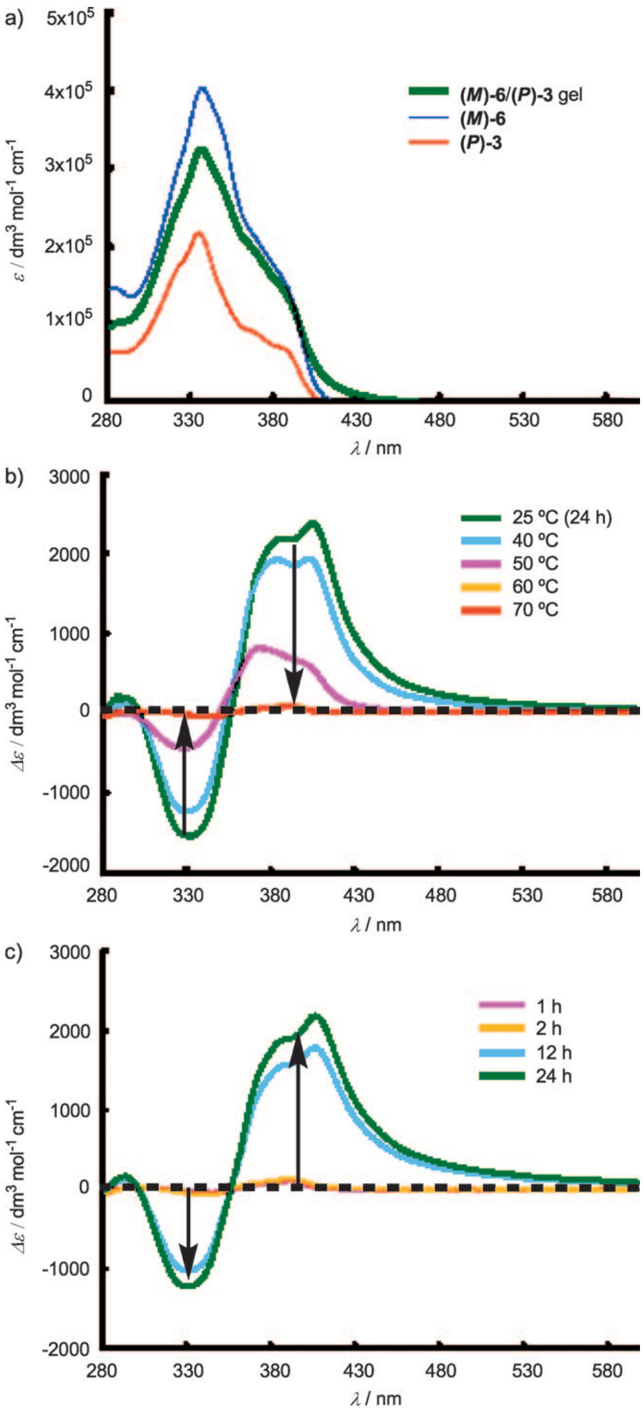

Figure 7. a) UV/vis spectra (toluene, 25 °C) of (*M*)-**6** (0.5 mM, blue line), (*P*)-**3** (0.5 mM, red line), and their mixture (0.25 mM each, 24 h after mixing, green line). b) CD spectra (toluene, 0.25 mM each) of (*M*)-**6**/(*P*)-**3** gel obtained at 25 °C after 24 h, and the results of a heating experiment. c) CD spectra (toluene, 0.25 mM each) of (*M*)-**6**/(*P*)-**3** gel formation at 25 °C at various time.

The ratio of the components in (*M*)-**6**/(*P*)-**3** gels could also be changed. Keeping the total concentration at 1 mM, (*M*)-**6** and (*P*)-**3** were mixed in 2:1, 1:1, 1:2, and 1:9 ratios, all of which provided thermoreversible gels. Even the 1:9 mixture provided a gel, indicating that a small amount of (*M*)-**6** could induce the gel formation of (*P*)-**3**, which itself did not form gel. Different CD spectra were obtained depending on the ratio of the relative $\Delta\varepsilon$ values at 370 and 400 nm, and these gels appear to possess somewhat different structures (Figure 8). Accordingly the calculated CD spectra of the gel having the 1:9 ratio, obtained by adding the spectra of the 1:1 gel and random-coil (*P*)-**3**, did not coincide with the experimental data. This is another advantage of this two-component gel, which can provide a diversity of gels by changing the ratio of the two components as well as the combination.[13]

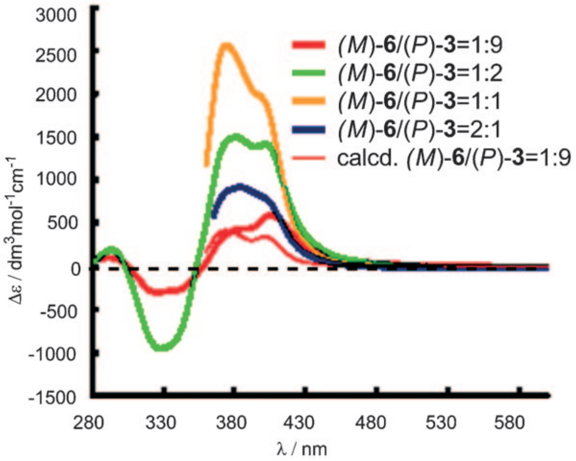

Figure 8. CD spectra (toluene, 25 °C, 1 mM total) of mixtures of (*M*)-**6** and (*P*)-**3** at various ratios. A calculated spectrum, obtained by adding the spectra of 2/10 of 1:1 (*M*)-**6**/(*P*)-**3** gel and 8/10 of (*P*)-**3** (1 mM) is also shown.

In conclusion, pseudoenantiomeric ethynylhelicene oligomers formed two-component organogels in toluene, whereas homochiral compounds did not. Thermoreversibility of the pseudoenantiomeric two-component gels was improved over that of the enantiomeric gels. Gels were formed using various combinations of a *P* oligomer and an *M* oligomer, each having different numbers if helicene monomer units, provided that both oligomers were longer than trimers. Changes in the ratio of the pseudoenantiomers also provided various gel systems. This methodology is a new and general, providing a diversity of two-component gels.

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[1] a) P. Terech, R. G. Weiss, *Chem. Rev.* **1997**, *97*, 3133–3159; b) *Molecular Gels*, (Eds.: R. G. Weiss, P. Terech), Springer, Dodrecht, **2006**; c) P. Dastidar, *Chem. Soc. Rev.* **2008**, *37*, 2699–2715.

[2] A. R. Hirst, D. K. Smith, *Chem. Eur. J.* **2005**, *11*, 5496–5508.

[3] For recent examples: a) S. A. Joshi, N. D. Kulkarni, *Chem. Commun.* **2009**, 2341–2343; b) M. Yamanaka, H. Fujii, *J. Org. Chem.* **2009**, *74*, 5390–5394.

[4] For recent examples: a) D. Haldar, *Tetrahedron* **2008**, *64*, 186–190; b) D. Berthier, T. Buffeteau, J.-M. Léger, R. Oda, I. Huc, *J. Am. Chem. Soc.* **2002**, *124*, 13486–13494.

[5] For recent examples: a) L. E. Buerkle, Z. Li, A. M. Jamieson, S. J. Rowan, *Langmuir* **2009**, *25*, 8833–8840; b) M. Suzuki, H. Saito, K. Hanabusa, *Langmuir* **2009**, *25*, 8579–8585.

[6] a) J.-H. Fuhrhop, P. Schnieder, J. Rosenberg, E. Boekema, *J. Am. Chem. Soc.* **1987**, *109*, 3387–3390; b) A. Brizard, R. Oda, I. Huc, *Top. Curr. Chem.* **2005**, *256*, 167–218.

[7] For examples of racemic mixtures forming better gels than enantiomers: a) J. Makarević, M. Jokić, Z. Raza, Z. Štefanić, B. Kojić-Prodić, M. Žinić, *Chem. Eur. J.* **2003**, *9*, 5567–5580; b) Y. Watanabe, T. Miyasou, M. Hayashi, *Org. Lett.* **2004**, *6*, 1547–1550. For examples of racemic mixtures forming gels but not enantiomers: c) M. de Loos, A. Friggeri, J. van Esch, R. M. Kellogg, B. L. Feringa, *Org. Biomol. Chem.* **2005**, *3*, 1631–1639; d) A. R. Borges, M. Hyacinth, M. Lum, C. M. Dingle, P. L. Hamilton, M. Chruszcz, L. Pu, M. Sabat, K. L. Caran, *Langmuir* **2008**, *24*, 7421–7431; e) T. Naota, H. Koori, *J. Am. Chem. Soc.* **2005**, *127*, 9324–9325.

[8] Effect of oligomer length on one-component gel: a) S. Kawano, N. Fujita S. Shinkai, *Chem. Eur. J.* **2005**, *11*, 4735–4742; b) A. Ajayaghosh, V. K. Praveen, *Acc. Chem. Res.* **2007**, *40*, 644–656.

[9] Y. Saiki, H. Sugiura, K. Nakamura, M. Yamaguchi, T. Hoshi, J. Anzai, *J. Am. Chem. Soc.* **2003**, *125*, 9268–9269.

[10] Use of hydrophobic interactions in a two-component gel: J.-H. Ryu, M. Lee, *J. Am. Chem. Soc.* **2005**, *127*, 14170–14171.

[11] a) H. Sugiura, Y. Nigorikawa, Y. Saiki, K. Nakamura, M. Yamaguchi, *J. Am. Chem. Soc.* **2004**, *126*, 14858–14864; b) K. Nakamura, H. Okubo, M. Yamaguchi, *Org. Lett.* **2001**, *3*, 1097–1099.

[12] We recently reported that a (*P*)-pentamer with a perfluorooctyl side chain interacted with an (*M*)-pentamer with decyloxycarbonyl side chain forming a hetero-double helix. Thus, a slight change in the side chain structure substantially affected the aggregate structure. R. Amemiya, N. Saito, M. Yamaguchi, *J. Org. Chem.* **2008**, *73*, 7137–7144.

[13] Effect of the *ee* value on gel formation: A. R. Hirst, B. Huang, V. Castelletto, I. W Hamley, D. K. Smith, *Chem. Eur. J.* **2007**, *13*, 2180–2188.