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Amphiphilic Nanofibers

Self-Assembly of T-Shaped Aromatic Amphiphiles into Stimulus-Responsive Nanofibers**

Kyung-Soo Moon, Ho-Joong Kim, Eunji Lee, and Myongsoo Lee*

Supramolecular assemblies formed by self-associating block molecules have attracted considerable attention as a means of creating well-defined nanostructured materials with tunable properties.[1–6] Among the nanostructures formed by self-assembly of designed molecules, a 1D fibrillar assembly has proved to be particularly interesting for applications such as nanowires and biomimetic macromolecules.[3] The 1D structures with stimulus-responsive features are likely to further enhance their scope as intelligent materials. Although stimulus-responsive nanostructures have been extensively studied with spherical objects,[4] switching of the properties triggered by external stimuli with 1D fibrillar objects remains challenging.[5,6]

The hierarchical assembly of such 1D structures could result in the formation of 3D networks through interconnecting the extended micelles.[7,8] For example, conjugated-rod segments containing flexible alkyl chains self-assemble into 1D fibrils that are entangled with each other to form reversible gels.[9] We have also shown that discrete cylindrical micelles can be interconnected by addition of a bridging agent to form reversible gels in aqueous solution.[10] Recently, we demonstrated that facial amphiphiles consisting of a laterally extended aromatic segment self-assemble into elongated nanofibers coated by oligo(ethylene oxide) dendrons.[11] One can envision that aromatic amphiphiles based on oligo(ethylene oxide) dendrons lead to the formation of thermoresponsive nanofibers, because ethylene oxide chains become dehydrated with increasing temperature.[12] With this idea in mind, we prepared T-shaped aromatic amphiphiles containing oligo(ethylene oxide) dendrons.

Herein, we present the formation of thermoresponsive nanoscale fibrils from the aqueous self-assembly of T-shaped aromatic amphiphiles based on oligo(ethylene oxide) dendrons (Figure 1). The amphiphiles contain dibranched oligo(ethylene oxide) (**1a**) and tetrabranched oligo(ethylene oxide) dendrons (**1b**) with a similar volume fraction ($f_{\mathrm{dendron}} = 0.67 \approx 0.68$) as hydrophilic side chains (Scheme 1). For comparison, we also prepared an anisole-branched T-shaped aromatic amphiphile (**2b**).

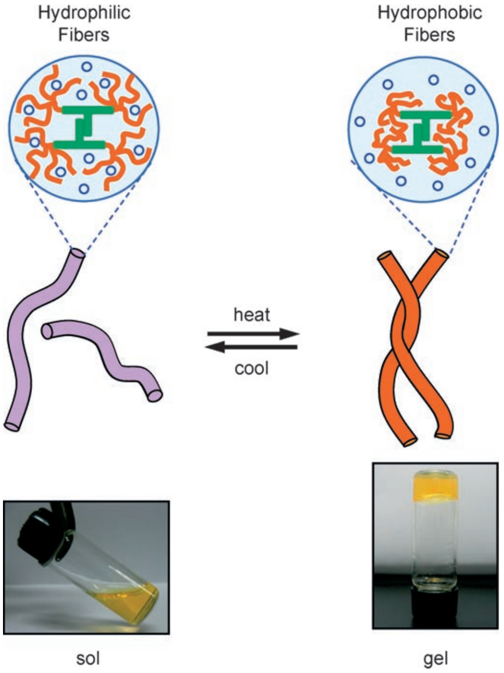

Figure 1. Stimulus-responsive sol–gel phase transition of self-assembled supramolecular nanofibers.

The aggregation behavior of **1a** and **1b** was studied in aqueous solution by using fluorescence spectroscopy. The emission maxima of both amphiphiles in aqueous solution (0.001 wt %) were red-shifted with respect to those observed in dichloromethane solution, and the intensities were significantly reduced, indicative of aggregation of the conjugated aromatic segments (Figure 2a).[13] Dynamic light scattering (DLS) experiments were performed with the amphiphiles in aqueous solution (0.1 wt %) to further investigate the aggregation behavior.[14–16] The CONTIN analysis of the autocorrelation function for both solutions showed a broad peak corresponding to average hydrodynamic radii (R_{H}) of approximately 80 and 110 nm for **1a**[14] and **1b** (Figure 2b), respectively.

Evidence for the formation of the fibrillar aggregates was also provided by transmission electron microscopy (TEM) experiments. The micrographs with negatively stained samples showed fibrillar aggregates with lengths up to several hundred nanometers for **1a** (Figure 2c) and several micro-

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[*] K.-S. Moon, H.-J. Kim, E. Lee, Prof. M. Lee
Center for Supramolecular Nano-Assembly and
Department of Chemistry
Yonsei University
Shinchon 134, Seoul 120-749 (Korea)
Fax: (+82) 2-393-6096
E-mail: mslee@yonsei.ac.kr

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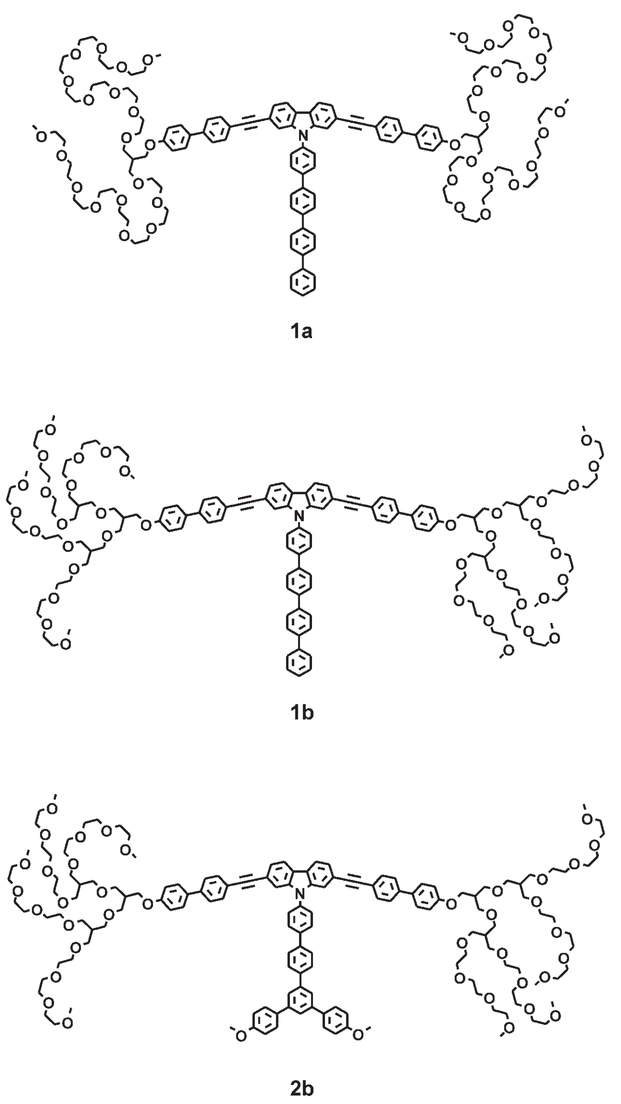

Scheme 1. Molecular structure of the T-shaped aromatic amphiphiles.

meters for **1b** (Figure 2d). The formation of the much longer fibrillar aggregates in **1b** is consistent with the results obtained from DLS measurements described above, thus indicating that the tetrabranched oligoether dendrons, compared to the dibranched ones, endow the T-shaped aromatic segments with better aggregation ability. A dendritic architecture with a higher generation is known to exhibit a more hydrophobic nature because of the dendritic effect,[17] which results in a higher ability to form aggregates in aqueous solution. By considering the extended molecular lengths (about 7 nm by the Corey–Pauling–Koltun (CPK) model), the images indicate that the diameter of the elementary cylindrical objects corresponds to one molecular length. All of these data suggest that the T-shaped aromatic amphiphiles self-assemble into a fibrillar structure consisting of aromatic cores surrounded by hydrophilic dendritic segments that are exposed to the aqueous environment (Figure 1). Within the core, the T-shaped aromatic segments are stacked with dimeric association to maximize π–π interactions. Note that **1b**, in the solid state, self-assembles into a 2D oblique columnar structure with lattice constants $a = 5.7$ and $b = 2.5$ nm and a characteristic angle of 100°, thus implying that the cross section of a cylinder consists of two molecules.

To gain insight into the role of the π–π stacking interactions between T-shaped aromatic segments in the formation of a 1D fibrillar structure, compound **2b**, based on a branched T-shaped aromatic unit, was prepared with the aim of frustration of π–π stacking interactions through steric hindrance. As expected, **2b** showed no apparent aggregation behavior, which was confirmed by DLS measurements. Furthermore, **2b** was an amorphous solid. This result suggests that the primary driving force for the formation of stable fibrillar aggregates in **1b** in aqueous solution is π–π stacking interaction of the T-shaped aromatic segments.

Self-assembly of T-shaped amphiphiles into a long fibrillar structure with a hydrophilic oligoether dendritic exterior suggests that they may lead to temperature-dependent solution behavior, because the degree of hydration of the ethylene oxide chains decreases with increasing temperature.[12] To investigate the thermoresponsive solution behavior, viscosities were measured with a capillary viscometer as a function of temperature (Figure 3a). The aqueous solution of **1a** (0.5 wt%) showed essentially no change in viscosity with heating. This result suggests that the hydrophobicity of the surfaces and the length of the micelles in **1a** are not sufficient to interconnect adjacent cylindrical micelles. Indeed, **1a** was highly soluble and no gels were produced under standard conditions. In great contrast, the solution viscosity of **1b** (0.5 wt%) increases abruptly above 30 °C and results in

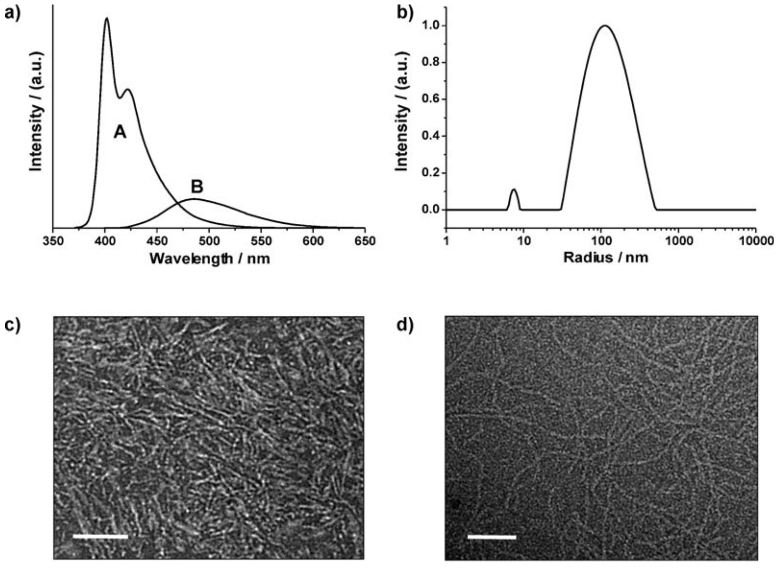

Figure 2. a) Fluorescence emission spectra of **1b** in CH_2Cl_2 (0.001 wt%, curve A) and aqueous solution (0.001 wt%, curve B). $\lambda_{ex} = 350$ nm. b) Size distribution of **1b** at a scattering angle of 90° (from CONTIN analysis of the autocorrelation function; 0.1 wt% in aqueous solution). c,d) TEM images of **1a** and **1b**, respectively, with negative staining (0.01 wt%); scale bars: 100 nm.

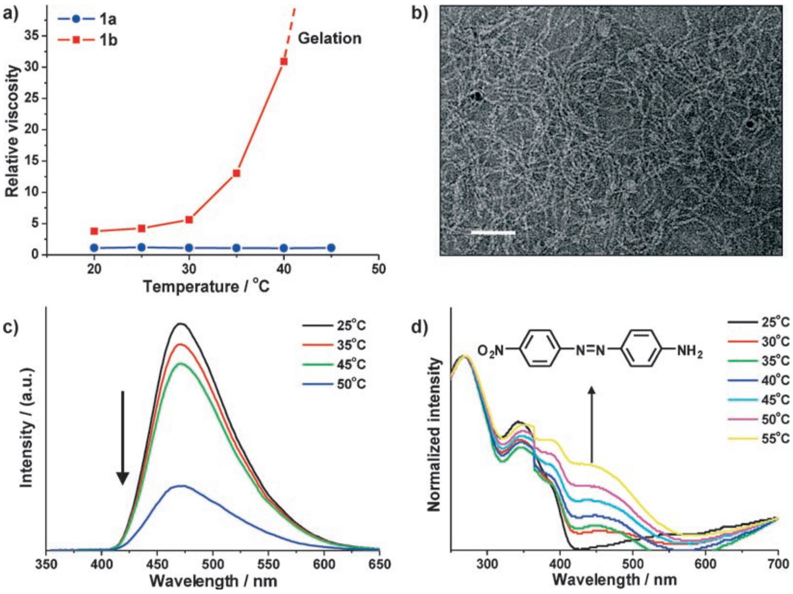

Figure 3. a) Relative viscosities of **1a** and **1b** in aqueous solution (0.5 wt%) with increasing temperature. b) TEM image of gel with 0.5 wt% **1b** at 45 °C; scale bar: 100 nm. c) Changes in the emission ($\lambda_{ex} = 350$ nm) spectrum of **1b** in aqueous solution (0.05 wt%) with increasing temperature. d) Changes in the absorption spectrum of **1b** in aqueous solution (0.001 wt%) containing five equivalents of Disperse Orange 3 with increasing temperature.

gelation at 45 °C. This transition temperature decreases to 0 °C with increasing concentration up to 4.0 wt% (see the Supporting Information).

The TEM image of the gel dried on a carbon-coated copper grid revealed the formation of bundles of the fibrils at higher temperatures (Figure 3b), which indicates that an increase in the solution viscosity with increasing temperature and subsequent formation of gel can be attributed to the interconnection of fibrillar aggregates. These results show that heating the solution of long fibrils drives the fluid state to a gel in which the elementary fibrils are connected to each other to immobilize water molecules (Figure 1). This thermoresponsive solution behavior can be explained by considering hydrophobic interactions between oligo(ethylene oxide) dendron-coated nanofibers.[12,17,18] With increasing temperature, the oligoether dendritic chains will be dehydrated because of the breakup of hydrogen bonding. As a result, the fibrillar surfaces would become more hydrophobic, thus resulting in enhanced hydrophobic interactions between adjacent fibrils to form 3D networks.

This finding was confirmed by fluorescence spectroscopy experiments. The fluorescence of an aqueous solution of **1a** (0.05 wt%) remained nearly unaltered with increasing temperature up to 60 °C.[14] In contrast, the fluorescence of **1b** (0.05 wt%) was significantly reduced at the sol–gel transition temperature (Figure 3c). This result indicates that, upon heating, the aromatic segments are packed more closely within the core because of enhanced hydrophobic environments caused by dehydration of the oligoether dendritic surfaces. Evidence for the enhanced hydrophobicity of fibrillar surfaces was also provided by hydrophobic dye molecular-encapsulation experiments with UV/Vis spectroscopy. When Disperse Orange 3 was added to a solution of **1b** (0.001 wt%), the characteristic absorption band of the dye molecule increased gradually (Figure 3d), which indicates that the more hydrophobic nature of the fibrillar surfaces upon heating allows the more hydrophobic dye molecules to translocate into the aromatic core.

Interestingly, the gel reversibly transforms into a fluid solution with addition of a dye molecule, such as 0.2 equivalents of Nile Red. CONTIN analysis of the correlation functions in DLS experiments showed R_H to be 84 nm, which demonstrates a decrease in the fibrillar length upon addition of the dye (Figure 4a). This decrease in the length was also confirmed by TEM, which revealed discrete fibrillar objects with an average length of about 150 nm, consistent with the result obtained from DLS experiments (Figure 4b). Consequently, the structural change of **1b** to discrete micelles upon addition of guest molecules is responsible for the phase change from gel to a fluid solution. The breakup of the long fibrils of **1b** into discrete micelles seems to arise from the packing frustration of the T-shaped aromatic segments by intercalation of the guest molecules.[19]

In summary, we have demonstrated that T-shaped aromatic amphiphiles self-assemble into stimulus-responsive fibrils consisting of aromatic cores surrounded by hydrophilic oligo(ethylene oxide) dendritic segments. Upon heating, the fibrils have more hydrophobic surfaces, which results in

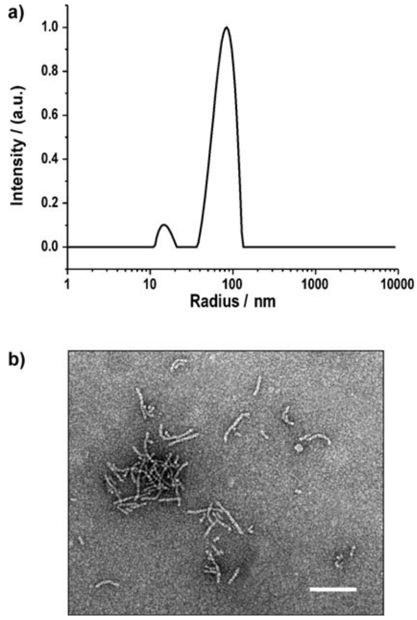

Figure 4. a) Size distribution at a scattering angle of 90° from CONTIN analysis of the autocorrelation function of a solution of **1b** (0.1 wt%) containing 0.2 equivalents of Nile Red. b) TEM image of **1b** with 0.2 equivalents of Nile Red (0.01 wt%); scale bar: 100 nm.

enhanced hydrophobic interactions between the ethylene oxide-coated nanofibrils. Consequently, this dynamic fibrillar association leads to a reversible phase transition from a fluid state to a gel with increasing temperature. In addition, the gel was transformed into a fluid solution by addition of hydrophobic guest molecules, caused by the breakup of long fibrils into discrete micelles. These stimulus-responsive features of the fibrils show a remarkable contrast to conventional fibrillar gels that dissolve upon heating.[20] The results described herein represent a significant example of nanofibrils with stimulus-responsive surfaces, which can provide a strategy for creating intelligent nanomaterials with desired functions.

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