

# Nanofibers from self-assembly of an aromatic facial amphiphile with oligo(ethylene oxide) dendrons<sup>†</sup>

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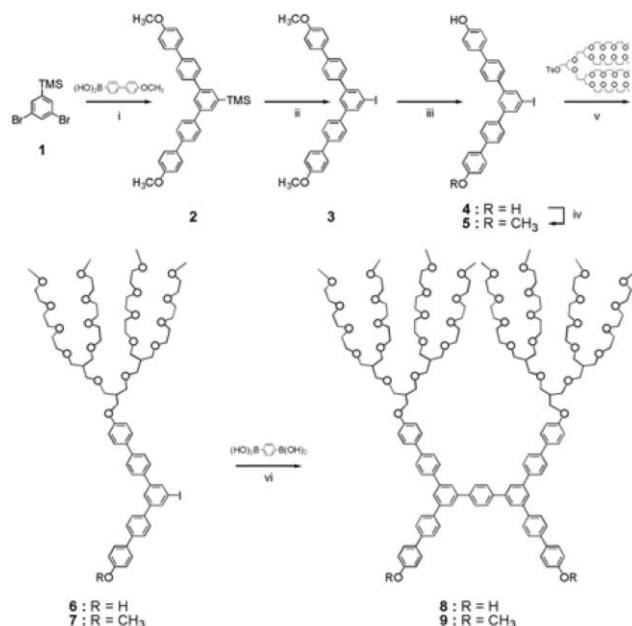
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Novel block facial amphiphiles consisting of a laterally extended aromatic segment and oligo(ethylene oxide) dendrons as a flexible segment were synthesized in a stepwise fashion and their aggregation behavior was investigated in aqueous solution; self-assembly into elongated nanofibers with a uniform diameter of  $7 \pm 0.5$  nm and lengths up to several hundred nanometers was observed.

Supramolecular assemblies formed by self-associating block molecules have attracted considerable attention as a means of creating well-defined nanostructured materials with tunable properties.<sup>1</sup> In most cases, amphiphilic block molecules consist of different immiscible coil segments.<sup>2</sup> These molecules are dissolved in a selective solvent for one constituent, which results in aggregates that consist of a core formed by the insoluble blocks surrounded by a shell of the solvated block. Block molecules based on rigid aromatic segments represent a unique class of self-assembling systems due to their capability to render desired functions.<sup>3,4</sup> Recently, we have been devoted to developing novel amphiphilic block molecules based on rigid aromatic segments that self-assemble into various supramolecular structures in aqueous solution. For example, we have shown that incorporation of a conjugated rod into an amphiphilic dumbbell-shaped molecular architecture gives rise to the formation of a helical nanostructure, consisting of hydrophobic aromatic cores surrounded by hydrophilic flexible chains.<sup>5</sup> We have also shown that rod building blocks in rigid–flexible macrocycles self-assemble into discrete barrel or long tubular structures depending on the relative rod volume fraction.<sup>6</sup> In a recent publication, we have demonstrated that tree-shaped amphiphilic molecules based on octa-*p*-phenylene self-assemble into a stable cage-like structure in aqueous solution.<sup>7</sup> Although rod-like aromatic amphiphiles have been extensively studied, the design of facial amphiphiles based on laterally extended aromatic segments remains a challenge.<sup>8</sup>

In this communication, we describe the synthesis of facial amphiphiles (**8** and **9**) consisting of a laterally extended aromatic segment and oligo(ethylene oxide) dendrons as a flexible segment, and their self-assembling behavior in aqueous solution. The synthesis of the amphiphilic molecule is outlined in Scheme 1 and starts with the preparation of 1-trimethylsilyl-3,5-dibromobenzene and oligoether dendrons according to the procedures



**Scheme 1** Synthesis of block facial amphiphiles. (i) Pd(0), 2M Na<sub>2</sub>CO<sub>3</sub>, THF, 80 °C, 12 h (ii) ICl, CH<sub>2</sub>Cl<sub>2</sub>, -78 °C, 0.5 h (iii) BBr<sub>3</sub>, CH<sub>2</sub>Cl<sub>2</sub>, 0 °C, 6 h (iv) CH<sub>3</sub>I, acetone–ethanol, 70 °C, 2 h (v) excess K<sub>2</sub>CO<sub>3</sub>, CH<sub>3</sub>CN, 70 °C, 12 h (vi) Pd(0), 2M Na<sub>2</sub>CO<sub>3</sub>, THF, 80 °C, 12 h.

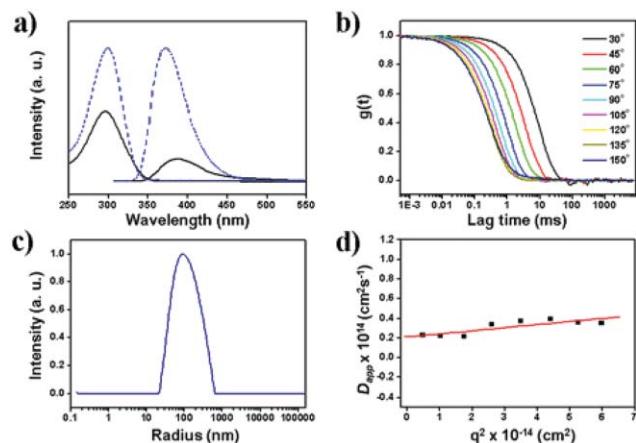
described previously.<sup>7,9</sup> The resulting silyl-substituted compound **1** was coupled with 2 equiv. of 4'-methoxybiphenyl-4-boronic acid by a Suzuki cross-coupling reaction to yield **2**. The silyl group of **2** was subsequently substituted into iodine which is the most active group for the next aromatic coupling. To increase the solubility, aliphatic chains should be introduced to the aromatic building block prior to further extension of the aromatic block of **3**. Along this line, dihydroxy compound **4** obtained from demethylation in the presence of boron tribromide was coupled with oligo(ethylene oxide) dendron in the presence of potassium carbonate to yield **6**. As expected, **6** was readily soluble in common organic solvents methylene dichloride, acetonitrile, and methanol. The final amphiphilic molecules **8** and **9** based on a laterally extended aromatic segment were obtained from a Suzuki coupling reaction of excess amounts of **6** and **7** with benzene-1,4-diboronic acid in the presence of Pd(0) catalysis, respectively. The resulting facial amphiphile was purified by column chromatography (silica gel) and subsequent preparative HPLC to yield a waxy solid, and characterized by <sup>1</sup>H and <sup>13</sup>C-NMR spectroscopy, elemental analysis and MALDI-TOF mass spectroscopy, and showed to be in full agreement with the structure presented.

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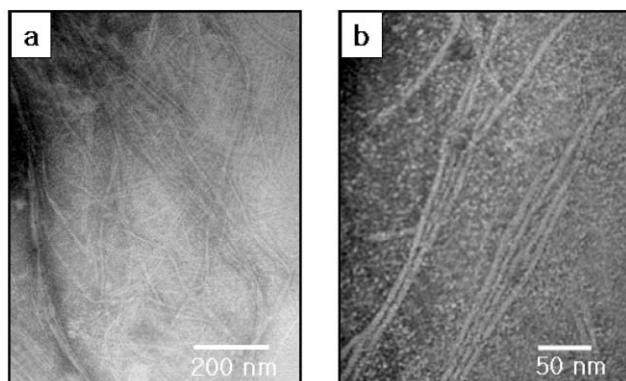
Block molecule **8** can be considered as a novel class of amphiphile because it consists of hydrophilic flexible dendrons and a hydrophobic rigid aromatic segment. Aggregation behavior of both block molecules **8** and **9** was subsequently studied in aqueous solution using UV/vis and fluorescence spectra (Fig. 1a). The absorption spectrum of **8** in aqueous solution (0.002 wt%) exhibits a broad transition with a maximum at 296 nm, resulting from the conjugated rod block. The fluorescence spectrum of **8** in methylene dichloride solution (0.002 wt%) exhibits a strong emission maximum at 372 nm. However, the emission maximum in aqueous solution is red-shifted with respect to that observed in methylene dichloride solution, and the fluorescence is significantly quenched, indicative of aggregation of the conjugated rod segments (Fig. 1b).

Dynamic light scattering (DLS) experiments were performed with **8** in aqueous solution to further investigate the aggregation behavior with a concentration of 0.01 wt% over a scattering angular range of 30–150° (Fig. 1b). The CONTIN analysis of the autocorrelation function at a scattering angle of 90° showed a broad peak corresponding to an average hydrodynamic radius ( $R_h$ ) of approximately 117 nm (Fig. 1c). The angular dependence of the apparent diffusion coefficient ( $D_{app}$ ) was measured because the slope is related to the shape of the diffusing species. As shown in Fig. 1d, the slope is 0.02, consistent with the value predicted for elongated non-spherical micelles (0.03).<sup>11</sup> Compound **9** based on dimethoxy groups showed similar aggregation behavior to that of **8** and its  $R_h$  value showed to be 125 nm.<sup>12</sup>

To further confirm the aggregation structure, transmission electron microscopy (TEM) experiments have been performed with an aqueous solution of **8**. Fig. 2 shows micrographs obtained from a 0.01 wt% aqueous solution of **8** cast onto a TEM grid. The negatively stained sample with uranyl acetate clearly shows 1-dimensional nanofibers with a uniform diameter of 7 nm. Most of the strands have lengths up to several hundred nanometers. Considering that from molecular modeling the fully extended molecular length of the amphiphilic molecule is estimated to be ~4 nm, the 7 nm width is consistent with a bilayer packing of aromatic segments.



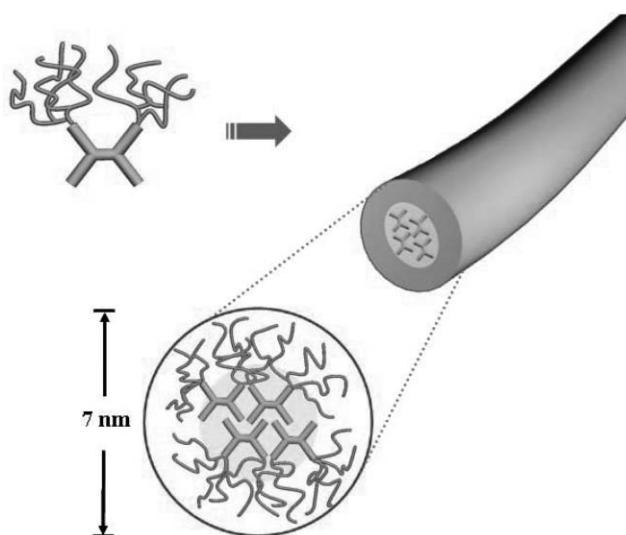
**Fig. 1** (a) Absorption and emission spectra of **8** in  $\text{CH}_2\text{Cl}_2$  (0.002 wt%, blue dot line) and aqueous solution (0.002 wt%, black line). (b) Autocorrelation functions of **8** in aqueous solution (0.01 wt%). (c) Hydrodynamic radius distribution of **8**. (d) Angular dependence of diffusion coefficient for **8**.



**Fig. 2** TEM images of nanofibers formed by self-assembly of **8** in aqueous solution (a) with low magnification and (b) with high magnification.

On the basis of the results described above, the aromatic facial amphiphile can be considered to self-assemble into elongated nanofibers with a uniform diameter of  $7 \pm 0.5$  nm and several micrometers long. The nanofibers consist of hydrophobic aromatic inner cores surrounded by hydrophilic flexible dendritic segments that are exposed to the aqueous environment. Within the core, the laterally extended aromatic segments are stacked with a bilayer packing to release steric crowding between bulky dendritic chains (Fig. 3).<sup>13</sup> This estimation is supported by molecular dimensions and the diameter of the single strand in TEM.

In conclusion, we have successfully synthesized a novel block facial amphiphile based on a laterally extended rigid aromatic segment that shows a unique aggregation behavior in aqueous solution. TEM along with dynamic light scattering studies demonstrated that the amphiphilic molecule self-assembles into elongated nanofibers with a uniform diameter of molecular length scale, and lengths up to several hundred nanometers. The synthetic approach described here can be extended to the preparation of a series of amphiphilic molecules with control over the rigid-to-flexible volume ratio to create tunable nanostructures. Such



**Fig. 3** Schematic representation of the proposed self-assembly of facial amphiphile **8**.

amphiphilic molecules are believed to be of interest for biological applications due to the formation of well-defined supramolecular nanostructures based on a highly hydrophobic aromatic core in aqueous solution.

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- 12 See supporting Information†.
- 13 The hydrophobic nature of the core was also confirmed by dye encapsulation experiments. See Supporting Information†.