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Synthesis and self-assembly of propeller-shaped amphiphilic molecules†

Kyung-Soo Moon, Eunji Lee and Myongsoo Lee*

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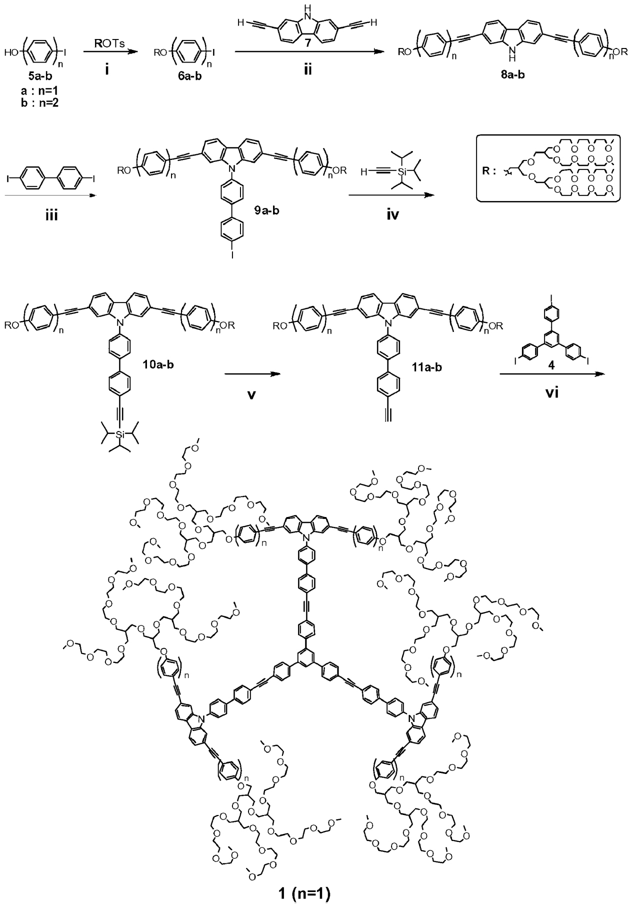
Propeller-shaped aromatic amphiphiles based on a conformationally flexible aromatic segment are shown to self-assemble into well-defined discrete nanostructures with high fluorescence characteristic.

Self-assembly of aromatic π-conjugated systems in solution can be widely utilized to construct unique, complex supramolecular structures.[1] In particular, incorporation of highly flexible chains into a rigid aromatic segment can give rise to a variety of well-defined nanoscopic architectures including cylinders,[2] ribbons[3] and vesicles.[4] These self-assembled architectures can be manipulated by variation of molecular shape and volume fraction of specific segments. For example, the aromatic rod segments in dumbbell-shaped molecules self-assemble into toroids and 2-D networks depending on the rod length.[5] Furthermore, rod segments in rigid/flexible macrocycles are shown to form well-defined tubular nanostructures.[6] In addition, we have reported that T-shaped aromatic amphiphiles self-assemble into long cylindrical micelles which further entangle to form 3-D networks.[7] These results imply that flat aromatic segments, irrespective of molecular shape, have a strong propensity to form long 1-D nanostructures due to strong π–π stacking interaction. One can envision that aromatic segments able to undergo conformational change may frustrate the formation of such long 1-D structures. With this in mind, we have synthesized novel amphiphilic molecules based on a propeller-shaped aromatic segments with conformational flexibility.

In this communication, we describe the synthesis of propeller-shaped aromatic amphiphiles (**1** and **2**) consisting of an aromatic core with a three-way junction, and three peripheral moieties containing a rigid rod and oligo(ethylene oxide) dendrons, and their self assembling behavior in solution. The strategy for preparation of the propeller-shaped aromatic amphiphiles is outlined in Scheme 1 and starts with the preparation of 4-iodo-4-hydroxybiphenyl (**5b**), carbazole 2,7-diacetylene (**7**), and oligoether dendrons according to the procedures described previously.[7,8] The resulting iodide-substituted compounds **5a,b** were coupled with oligo(ethylene oxide) dendrons to yield **6a,b**. Importantly, the peripheral moiety of the propeller-shaped molecules **8a,b** was obtained by a direct Sonogashira cross-coupling of iodo-compounds **6a,b** with N-unprotected carbazole 2,7-diacetylene (**7**) in 70% yield. Then, copper-catalyzed Buchwald amination[9] of an excess of diiodobiphenyl with the carbazole amines of **8a,b** using a 1 : 10 ratio of CuI–1,2-*trans*-diaminocyclohexane as a catalyst afforded the target mono-aminated compounds **9a,b** in 80% yield.

Compounds **10a,b** were obtained from a Sonogashira cross-coupling reaction of the iodide of **9a,b** with triisopropylsilyl acetylene and subsequently deprotected into terminal alkyne molecules **11a,b** for the final coupling reaction. The final propeller-shaped molecules **1** and **2** were obtained from a Sonogashira cross-coupling reaction of 5 equivalents of **11a,b** with triiodo compound **4**. It should be noted that the base activity of piperidine is remarkably higher than that of triethylamine in this coupling reaction. The resulting propeller-shaped molecules were purified by column



1 (n=1)
2 (n=2)

Scheme 1 Synthesis of propeller-shaped aromatic amphiphiles. *Reagents and conditions*: (i) K_2CO_3, CH_3CN, 80 °C, 12 h; (ii) $Pd(PPh_3)_4$, CuI, Et_3N, 60 °C, 24 h; (iii) CuI, Na^{t}OBu, 1,2-*trans*-diaminocyclohexane, 1,4-dioxane, 110 °C, 12 h; (iv) $Pd(PPh_3)_4$, CuI, Et_3N, 50 °C, 12 h; (v) TBAF, THF, r.t., 1 h; (vi) $Pd(PPh_3)_4$, CuI, piperidine, 50 °C, 20 h.

Center for Supramolecular Nano-Assembly, Department of Chemistry, Yonsei University, Shinchon 134, Seoul, 120-749, Korea.
E-mail: mslee@yonsei.ac.kr; Fax: 82 2 393 6096; Tel: 82 2 2123 2647

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chromatography (silica gel) and subsequent preparative HPLC to yield **1** and **2** as a brown sticky liquid and yellow solid, respectively. Compounds were characterized by ^{1}H and ^{13}C NMR spectroscopy, elemental analysis and MALDI-TOF mass spectroscopy, and shown to be in full agreement with the structures presented.

The aggregation behavior of the propeller-shaped molecules was subsequently studied in mixed solutions of water and THF using fluorescence spectroscopy. In a pure THF solution, the amphiphilic molecules were shown to be molecularly dissolved (Fig. 1(a)). This was also confirmed by dynamic light scattering (DLS) experiments which showed a non-aggregated state from the autocorrelation function of 0.01 wt% of **1** (Fig. 1(b)). Upon addition of water into the THF solution, the emission maxima of both amphiphiles were significantly red-shifted above a specific point of the water : THF ratio (see ESI†) (Fig. 1(a) and (c)) indicative of aggregation of the conjugated aromatic segments.[10,11] Interestingly, the emission intensity of the aggregated state such as in a water–THF (9 : 1) solution of **1** shows a fluorescence increase rather than quenching with respect to that of THF solution (Fig. 1(a)). This result implies that the twisted conformation of the peripheral moieties gradually changes into the planar structure induced by self-assembly and relatively weak π–π stacking interaction between the aromatic segments also leads to a fluorescence increase rather than quenching.[12] Molecule **2**, based on longer peripheral rods, shows a similar solution behavior to that of **1**, but the fluorescence of a water–THF (9 : 1) solution of **2** shows quenching with respect to that of a THF solution, suggesting that the longer peripheral aromatic rods of **2** allow stronger π–π stacking interactions with respect to that of **1**, thus resulting in fluorescence quenching (Fig. 1(c)).

DLS experiments were performed with **1** in water–THF (9 : 1) solution to further investigate the aggregation behavior at a concentration of 0.01 wt%. The CONTIN analysis of the autocorrelation function at a scattering angle of 90° showed a sharp peak corresponding to an average hydrodynamic radius (R_h) of approximately 2.5 nm (Fig. 1(d)) which indicates the formation of nanoaggregates with molecular length scale. **2** showed similar aggregation behavior to that of **1** and its R_h value was 3.3 nm.[12]

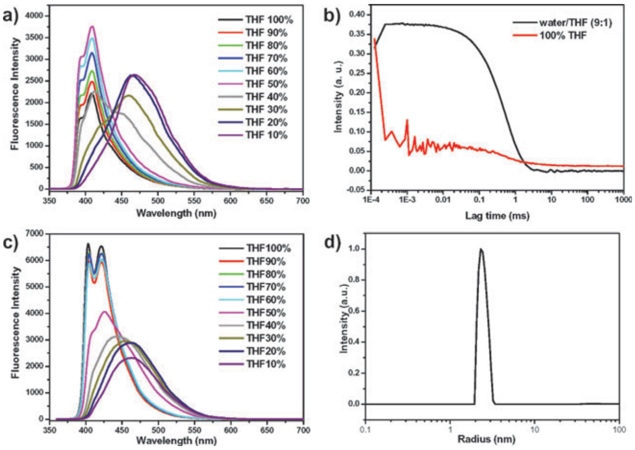

Fig. 1 (a) Changes in the emission (λ_ex = 345 nm) spectra of 0.01 wt% of **1** at different water–THF solvent ratios. (b) Autocorrelation functions of 0.01 wt% of **1** at different water–THF solvent ratios at a scattering angle of 90°. (c) Changes in the emission (λ_ex = 350 nm) spectra of 0.01 wt% of **2** in different water–THF solvent ratios. (d) Mass weighted hydrodynamic radius distribution of 0.01 wt% of **1** in a water–THF (9 : 1) solution.

To further confirm the aggregation structure, transmission electron microscopy (TEM) experiments have been performed with a water–THF (9 : 1) solution of **1** and **2**, respectively. Fig. 2 shows the micrographs obtained from a 0.01 wt% solution cast onto a TEM grid. The negatively stained samples with uranyl acetate clearly show that both molecules self-assemble into spherical micelles with a uniform diameter of about 6 nm. By considering the extended molecular lengths (about 6 nm by the Corey–Pauling–Koltun (CPK) model), this result indicates the formation of discrete aggregates with a molecular length scale.

All of these experimental results clearly demonstrate that the propeller-shaped aromatic amphiphiles self-assemble into discrete spherical nanostructures with fluorescence increase in the case of **1** and only a little fluorescence quenching for **2**, in contrast to conventional disc-shaped aromatic amphiphiles that, in general, form long cylindrical structures.[13] This result can be explained by considering the unique conformational flexibility of the aromatic segments. Within the core, the flat aromatic segments with a three-way junction are assembled in a random manner, most probably due to steric hindrance caused by dynamic conformational change in which the peripheral rigid-flexible moieties rotate with respect to the aromatic core plane (Fig. 3). Consequently, this conformational flexibility of the aromatic segments enforces the molecules to form only discrete, very small nanoaggregates.

In conclusion, we have successfully synthesized novel aromatic amphiphilic molecules based on a conformationally flexible aromatic core and peripheral flexible chains that show a unique aggregation behavior in water–THF mixed solutions. TEM along with dynamic light scattering studies demonstrated that the aromatic amphiphiles self-assemble into well-defined spherical aggregates with a uniform diameter of molecular length scale. The formation of discrete, fluorescent nanostructures from the aromatic amphiphiles can be assumed to arise from a very weak π–π stacking interaction caused by dynamic conformational change between the three-way aromatic core and peripheral moieties. Our strategy to frustrate strong π–π interactions between aromatic segments described

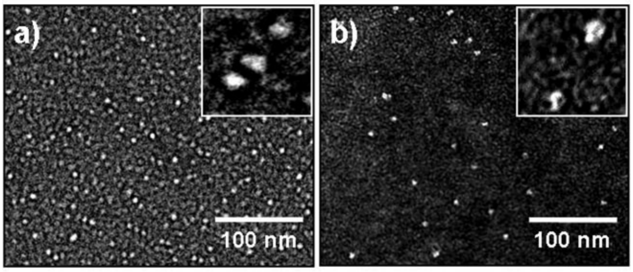

Fig. 2 TEM images of discrete nanostructures formed by self-assembly of a water–THF (9 : 1 v/v) solution of (a) **1** and (b) **2** (insets: high magnification images).

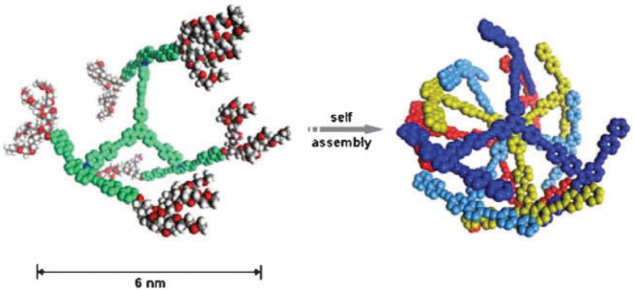

Fig. 3 Schematic representation of the proposed self-assembly of propeller-shaped aromatic amphiphiles. Oligo(ethylene oxide) dendron moieties are omitted for clarity.

here can be extended to the preparation of large and bulky aromatic molecules by a convergent method to produce highly fluorescent discrete aggregates.

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Notes and references

1. (*a*) F. J. M. Hoeben, P. Jonkheijm, E. W. Meijer and A. P. H. J. Schenning, *Chem. Rev.*, 2005, **105**, 1491; (*b*) J. P. Hill, W. Jin, A. Kosake, T. Fukushima, H. Ichihara, T. Shimomura, K. Ito, T. Hashizume, N. Ishii and T. Aida, *Science*, 2004, **304**, 1481; (*c*) J.-H. Ryu, D.-J. Hong and M. Lee, *Chem. Commun.*, 2008, ASAP.
2. (*a*) J.-H. Ryu and M. Lee, *J. Am. Chem. Soc.*, 2005, **127**, 14170; (*b*) H. Wang, H. H. Wang, V. S. Urban, K. C. Littrell, P. Thiyagarajan and L. Yu, *J. Am. Chem. Soc.*, 2000, **122**, 6855.
3. (*a*) E. R. Zubarev, M. U. Pralle, E. D. Sone and S. I. Stupp, *J. Am. Chem. Soc.*, 2001, **123**, 4105; (*b*) A. Ajayaghosh, C. Vijayakumar, R. Varghese and S. J. George, *Angew. Chem., Int. Ed.*, 2006, **45**, 456.
4. (*a*) X. Zhang, Z. Chen and F. Würthner, *J. Am. Chem. Soc.*, 2007, **129**, 4886; (*b*) Y.-S. Yoo, J.-H. Choi, J.-H. Song, N.-K. Oh, W.-C. Zin, S. Park, T. Chang and M. Lee, *J. Am. Chem. Soc.*, 2004, **126**, 6294; (*c*) A. Ajayaghosh, R. Varghese, S. Mahesh and V. K. Praveen, *Angew. Chem., Int. Ed.*, 2006, **45**, 7729; (*d*) F. J. M. Hoeben, I. O. Shklyarevskiy, M. J. Pouderoijen, H. Engelkamp, A. P. H. J. Schenning, P. C. M. Christianen, J. C. Maan and E. W. Meijer, *Angew. Chem., Int. Ed.*, 2006, **45**, 1232.
5. (*a*) J.-K. Kim, E. Lee, Z. Huang and M. Lee, *J. Am. Chem. Soc.*, 2006, **128**, 14022; (*b*) J.-K. Kim, E. Lee, Y.-H. Jeong, J.-K. Lee, W.-C. Zin and M. Lee, *J. Am. Chem. Soc.*, 2007, **129**, 6082.
6. W.-Y. Yang, J.-H. Ahn, Y.-S. Yoo, N.-K. Oh and M. Lee, *Nat. Mater.*, 2005, **4**, 399.
7. K.-S. Moon, H.-J. Kim, E. Lee and M. Lee, *Angew. Chem., Int. Ed.*, 2007, **46**, 6807.
8. M. Jayaraman and J. M. J. Fréchet, *J. Am. Chem. Soc.*, 1998, **120**, 12996.
9. (*a*) J. C. Antilla, A. Klapars and S. L. Buchwald, *J. Am. Chem. Soc.*, 2002, **124**, 11684; (*b*) Z. H. Li and M. S. Wong, *Org. Lett.*, 2006, **8**, 1499.
10. B. W. Messmore, J. F. Hulvat, E. D. Sone and S. I. Stupp, *J. Am. Chem. Soc.*, 2004, **126**, 14452.
11. R. Varghese, S. J. George and A. Ajayaghosh, *Chem. Commun.*, 2005, 593.
12. B.-K. An, S.-K. Kwon, S.-D. Jung and S.-Y. Park, *J. Am. Chem. Soc.*, 2002, **124**, 14410.
13. (*a*) A. J. Fleming, J. N. Coleman, A. B. Dolton, A. Fechtenkoetter, M. D. Watson, K. Müllen, H. J. Byrne and W. J. Blau, *J. Phys. Chem.B*, 2003, **107**, 37; (*b*) N. Reitzel, T. Hassenkam, K. Balashev, T. R. Jensen, P. B. Howes, K. Kjaer, A. Fechtenkoetter, N. Tchebotareva, S. Ito, K. Müllen and T. Björnholm, *Chem.–Eur. J.*, 2001, **7**, 4894; (*c*) N. Kimizuka, T. Kawasaki, K. Hirata and T. Kunitake, *J. Am. Chem. Soc.*, 1995, **117**, 6360.