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Water-soluble poly(aryl ether) dendrimers as a potential fluorescent detergent to form micelles at very low CMC

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Abstract—The self-assembly of amphiphilic pyrene-cored poly(aryl ether) dendrimers has been studied. Pyrene excimer emission at 500 nm from the higher generation **6** is observed in KOH aqueous solution at the concentration as low as 1.8×10^{-5} M, while the excimer emission from lower generation **5** could not be detected at 3.5×10^{-5} M. The results indicate that the self-aggregation in higher generation dendrimer takes place more efficiently than in lower generation in aqueous solution.

Dendrimers can offer two different chemical environments: an interior and a surface.[1] The surface of the dendrimers represents the molecular features such as solubility. When a hydrophilic substituent is introduced to the periphery, it can be dissolved in water. The interior of these water-soluble dendrimers is shielded from the outside and gives a hydrophobic environment to incorporate organic molecules. Thus, the difference between the outside environment and the dendrimer's interior can be emphasized in water by using dendrimers with hydrophobic interior and hydrophilic surface groups. When the cone-shaped dendrimers are dissolved in water, self-aggregation to form a micelle-like structure can be expected because of the distinct hydrophobic branching units and hydrophilic outside. In addition, the generation effect of the dendrimers on the formation of aggregates would also be of interest. We have reported the photochemistry of water-soluble dendrimers where the photoresponsive moiety, such as stilbenes or azobenzenes, is placed at the core of the dendrimer.[2–5] Now we are focusing our attention on the photochemical studies of a poly(aryl ether)-type dendrimer possibly acting as a surfactant. The self-assembly process of dendrimers has been studied by a number of groups.[6] Pyrene seems to be a good candidate as a probe for the self-assembly process of the dendrimers because of its well-known fluorescent properties including excimer emission. Pyrene-cored dendrimers have been prepared and fluorescence properties were studied in organic solvents.[7] However, the excimer fluorescence was not detected even at high concentration (0.5 mM).[7b] We have started to prepare water-soluble pyrene dendrimers with poly(aryl ether)-type dendron having carboxylate group at the periphery. Just after we have finished our work on fluorescent and aggregation properties of water-soluble pyrene dendrimers, excimer emission of pyrene-labeled dendrimers with polyacrylamide group have been reported.[8] Polyacrylamide is soluble in water and therefore the reported dendrimer may have hydrophilic dendron and hydrophobic pyrene.[8,9] However, since our compounds have hydrophobic pyrene and benzyl-ether-type dendron group with hydrophilic part only at the peripheral carboxylate group, it seems worthwhile to publish the photochemical properties of our pyrene-labeled dendrimers. We wish to report here the self-aggregation of fluorescent poly(aryl ether)-type dendrimers as a novel type of detergent to form micelles in aqueous solution. In this respect, we have performed a photochemical study on the generation-concentration dependent aggregation of pyrene-labeled dendrimers in aqueous solution. The excimer fluorescence of pyrene was observed at the concentration as low as 1.8×10^{-5} M. Thus, pyrene excimer fluorescence can be used as a probe for the aggregation of poly(aryl ether) dendrons at very low concentration.

Compounds **1–3** were obtained by coupling reaction of pyrenol and the corresponding dendritic bromide in the presence of K_2CO_3 and 18-crown-6 in refluxing

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Keywords: Dendrimers; Excimer fluorescence; Self-assembly.

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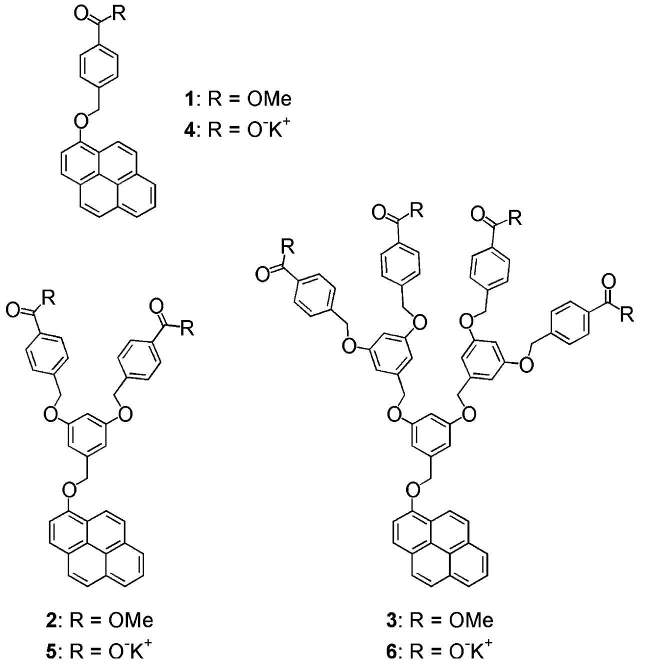

Figure 1. Structures of dendrimers **1**–**6**.

acetone. The following ester hydrolysis with KOH in EtOH gave the corresponding potassium salts **4**–**6**, respectively (Fig. 1).[14] Compound **4**, however, did not show enough solubility (less than 1×10^{-6} M) in aqueous solution for the aggregation study. Therefore, we will discuss **5** and **6** in aqueous solution. Figure 2a shows the UV absorption spectra of **1**–**3** in $CHCl_3$. The peaks around 275–285 nm increased in higher generation due to the absorption of dendron groups. Unlike the absorption spectra for higher-generation dendrimer **3** in $CHCl_3$, the dendron peak at 280 nm of **6** in aqueous solution did not increase but slightly red-shifted compared to that of **5**, despite the fact that the number of phenyl rings increased (Fig. 2b). We have observed the extinction coefficients of water-soluble dendrimers in aqueous solution are smaller than those of the corresponding dendrimer in organic solvents.[2] One can suppose that the molecular size of the dendrimers in aqueous solution probably becomes smaller than that in organic solvents due to hydrophobic interaction of the branching units and the core moiety. However, this is the first case that the extinction coefficient for the dendron part in higher generation did not increase compared to that in lower generation and the reason would be molecular aggregation. Therefore, the experimental results are unusual, but the reason is not clear at this stage.

When the dendrimers take sphere shape and have the hydrophobic interior and hydrophilic end groups at the periphery, the molecule would shrink by itself in water, while when the molecule takes a cone-like shape like **5** and **6**, the intermolecular hydrophobic interaction, or self-aggregation, might occur in aqueous solution. Figure 3 shows the fluorescence spectra of **5** and **6** at different concentrations in 0.1 M KOH aqueous solution at room temperature. The peaks at 387, 407, and 430 nm with vibrational progression are attributed to the fluorescence emission from the pyrene monomer. The broad signals peaking around 500 nm are the fluorescence from the pyrene excimer. The intensity of the excimer fluores-

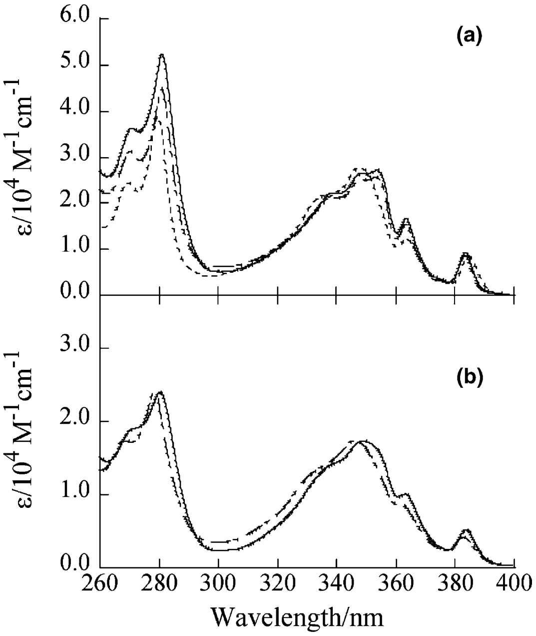

Figure 2. UV absorption spectra of (a) **1** (dotted line), **2** (dot-dash line), and **3** (solid line) in $CHCl_3$ and (b) **5** (dot-dash line) and **6** (solid line) in 0.1 M KOH aqueous solution.

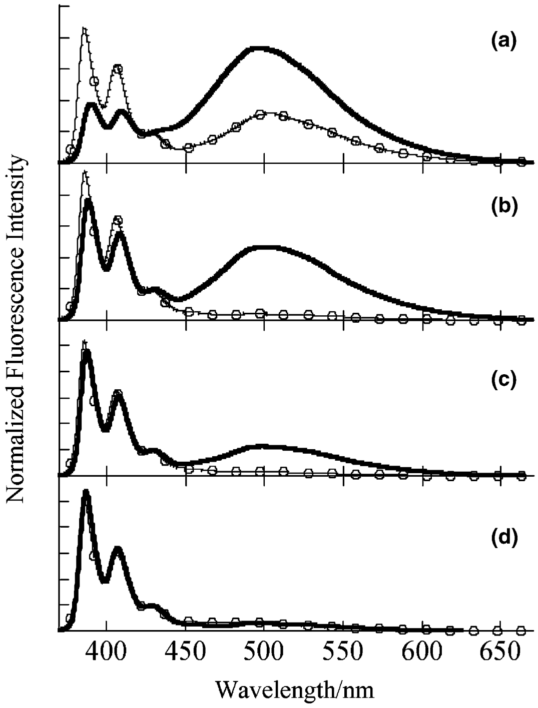

Figure 3. Change in the fluorescence spectra upon the concentration of **5** (—○—) and **6** (solid line) in 0.1 M KOH aqueous solution: (a) 1.5×10^{-4} M, (b) 3.5×10^{-5} M, (c) 1.8×10^{-5} M, (d) 4.5×10^{-6} M. Excitation wavelength are 346 nm for **5** and 349 nm for **6**, respectively.

Table 1. Fluorescence lifetimes and fluorescence quantum yields of **2** and **3** in $CHCl_3$ and **5** and **6** in 0.1 M KOH aqueous solution

Compounds	Concentration /M	Solvents	τ/ns	Φ_f
2	4.5×10^{-6}	$CHCl_3$	7.4	0.27
3	4.7×10^{-6}	$CHCl_3$	7.4	0.33
5	4.4×10^{-6}	KOH aqueous solution	9.8/53.7	0.032
6	4.5×10^{-6}	KOH aqueous solution	9.7/59.3	0.082

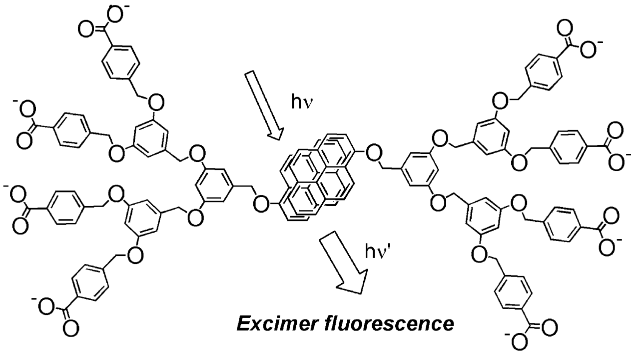

Figure 4. Excimer fluorescence from **6** in aggregation form in aqueous solution.

cence from both **5** and **6** increased in higher concentrations. The fluorescence lifetimes (λ_{ex} = 349 nm) and fluorescence quantum yields in $CHCl_3$ for **2** and **3**, and in 0.1 M KOH aqueous solution for **5** and **6**, respectively, are shown in Table 1. Esters **2** and **3** gave a fluorescence lifetime of 7.4 ns with single exponential decay, which indicates that **2** and **3** exist as a monomer or a dissociation form in $CHCl_3$. On the other hand, the fluorescence decay curves either for **5** or **6** do not fit a single exponential function, but fit two exponential functions to give 9.8 and 57.3 ns for **5** and 9.7 and 59.3 for **6**, respectively (Table 1). These results indicate that the environment for the pyrene moiety is not uniform in **5** and **6** in aqueous solution. We assigned the fluorescent species of ~10 ns lifetime and ~58 ns lifetime to pyrene monomer and pyrene excimer, respectively. In fact, multiexponential decay models were required to describe the time-resolved intensity decay data for pyrene-labeled poly(amido) dendrimers[8] in aqueous solution. Furthermore, the time-resolved fluorescence intensity decay of pyrene bound to another species is often multiexponential.[8,10–12] Fluorescence quantum yields for **2** and **3** in $CHCl_3$ were 0.27 and 0.33. Those in aqueous solution are lower than in an organic solvent and were 0.032 for **5** and 0.082 for **6**, respectively (Table 1). The reasons of the decrease of the fluorescence quantum yield and the increase of the fluorescence lifetime for **5** and **6**, compared to those of **2** and **3**, are still unclear and the further investigation is needed.

The results shown in Figure 3 indicate that aggregation of both **5** and **6** tends to occur at the higher concentration. However, there is a clear generation effect on the molecular aggregation. The excimer fluorescence in **6** is much stronger than that in **5** as shown in Figure 3a–c. In addition, the pyrene monomer fluorescence in **6** obviously decreased at the concentration of 1.5×10^{-4} M (Fig. 3a), suggesting that the molecules aggregate quite effectively at that concentration. From the results, we can deduce that the aggregation takes place more easily in higher generation **6** than in lower generation **5** in aqueous solution (Fig. 4). In addition, the excimer is formed in **6** at the concentration as low as 1.8×10^{-5} M, which is very much lower than the critical micelle concentration of other anionic surfactants such as SDS (8.1×10^{-3} M).[13] Furthermore, we found that the excimer fluorescence of **6** was diminished by the addition of organic solvents, such as EtOH or THF (data not shown), indicating that the excimer formation is inhibited by the added organic solvents, which weaken the intermolecular hydrophobic interaction of the pyrene core and the dendron part.

In summary, we have shown the possibility of poly(aryl ether) dendrimers as a surfactant, which aggregates at quite low concentration in aqueous solution (1.8×10^{-5} M) to form micelles which is very different from the CMC of usual detergents (~10^{-2} M), depending upon the generation. A comparison of the fluorescence spectra of **5** and **6** indicates that the higher generation dendrimer **6** easily forms molecular aggregates and induces π–π interaction among the pyrene rings and emits excimer fluorescence much more efficiently than that of **5**.

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14. **1**: (Typical procedure) G1Br (0.50 mmol, 116 mg) was added to the mixture of pyrenol (0.46 mmol, 100 mg), K_2CO_3 (0.68 mmol, 100 mg) and 18-crown-6 (16 mg) in dry acetone (8 mL) and the mixture was refluxed for 25 h. After cooled down to room temperature, acetone was evaporated. The residue was dissolved in dichloromethane, washed with water, and dried over Mg_2SO_4. The solvent was removed to dryness and the crude product was purified with column chromatography (SiO_2, eluting with dichloromethane/hexanes 1/1) to give product as an yellow solid (74 mg, 44% yield). ^{1}H NMR; (400 MHz, $CDCl_3$). δ 3.94 (s, 3H, OCH_3), 5.51 (s, 2H, OCH_2), 7.57 (d, 1H, $J = 8.4$ Hz, ArH), 7.68 (d, 2H, $J = 8$ Hz, ArH), 7.69–8.06 (m, 9H, ArH), 8.53 (d, 1H, $J = 9.2$ Hz, ArH). **2**: ^{1}H NMR; (400 MHz, $CDCl_3$). δ 3.92 (s, 6H, OCH_3), 5.11 (s, 4H, OCH_2), 5.37(s, 2H, OCH_2), 6.58 (s, 1H, ArH), 6.81 (s, 2H, ArH), 7.46 (d, 4H, $J = 8.0$ Hz, ArH), 7.53 (d, 1H, $J = 8.0$ Hz, ArH), 7.89–8.13 (m, 11H, ArH), 8.46 (d, 1H, $J = 9.2$ Hz, ArH). **3**: ^{1}H NMR; (400 MHz, $CDCl_3$) δ 3.90 (s, 12H, OCH_3), 5.01 (s, 4H, OCH_2), 5.06 (s, 8H, OCH_2), 5.36 (s, 2H, OCH_2), 6.51 (s, 3H, ArH), 6.66 (s, 4H, ArH), 6.80 (s, 2H, ArH), 7.43 (d, 8H, $J = 8.4$ Hz, ArH), 7.54 (d, 1H, $J = 8.4$ Hz, ArH), 7.87–8.10 (m, 15H, ArH), 8.45 (d, 1H, $J = 8.8$ Hz, ArH). **5**: 1 M KOH aqueous solution (0.4 mL) was added to the mixture of **2** (97 mg, 0.15 mmol) in ethanol/benzene (20 mL/30 mL) and the mixture was refluxed for 16 h. After the solvents were evaporated to remove benzene, water (15 mL) was added to the residue to give a red solution, which was then stirred at 80 °C for 12 h. The aqueous solution was cooled down to room temperature. HCl (1 N) was slowly dropwised to the solution to acidify to pH 3 and the obtained precipitate was filtered and washed with water to give **5** (63 mg, 68% yield). ^{1}H NMR; (400 MHz, DMSO-d_6) δ 5.27 (s, 4H, OCH_2), 5.48 (s, 2H, OCH_2), 6.75 (s, 1H, ArH), 6.93 (s, 2H, ArH), 7.59 (d, 4H, $J = 8.0$ Hz, ArH), 7.85 (d, 1H, $J = 8.0$ Hz, ArH), 7.99–8.28 (m, 11H, ArH), 8.36 (d, 1H, $J = 9.2$ Hz, ArH). Elemental analysis. Anal. Calcd for $C_{39}H_{28}O_7{\cdot}H_2O$: C, 74.8; H, 4.83. Found: C, 75.1; H, 4.89. **6**: 2 M KOH aqueous solution (10 mL) was added to the mixture of **3** (152 mg, 0.13 mmol) in ethanol/benzene (20 mL/30 mL) and the mixture was refluxed for 3 h. After the solvents were evaporated to dryness, water (15 mL) was added to the residue to give a red solution, which was then stirred at 80 °C for 5 h. The same workup gave **6** (120 mg, 83% yield). ^{1}H NMR; (400 MHz, DMSO-d_6) δ 5.10 (s, 4H, OCH_2), 5.19 (s, 8H, OCH_2), 5.47 (s, 2H, OCH_2), 6.69 (s, 3H, ArH), 6.77 (s, 4H, ArH), 6.90 (s, 2H, ArH), 7.54 (d, 8H, $J = 8.4$ Hz, ArH), 7.85 (d, 1H, $J = 8.4$ Hz, ArH), 7.95–8.28 (m, 15H, ArH), 8.40 (d, 1H, $J = 8.8$ Hz, ArH). Elemental analysis. Anal. Calcd for $C_{69}H_{52}O_{15}{\cdot}4H_2O$: C, 5.07; H, 69.5. Found: C, 4.81; H, 69.7.