Association of Fluorocarbon and Hydrocarbon End-Capped Poly(ethylene glycol)s: NMR and Fluorescence Studies

Jicang Zhou,† Dongqing Zhuang,‡ Xiaofeng Yuan,† Ming Jiang,*,† and Yunxiang Zhang‡

Department of Macromolecular Sciences and the Key Laboratory of Molecular Engineering of Polymers, Fudan University, Shanghai 200433, China, and Shanghai Institute of Organic Chemistry, Chinese Academy of Sciences, Shanghai, 200032, China

Received March 17, 2000. In Final Form: July 27, 2000

Poly(ethylene glycol)-based associating polymers with fluorocarbon and hydrocarbon hydrophobes (F-PEG & H-PEG) were synthesized. Their association behavior in aqueous solutions was investigated by NMR and a fluorescent probe technique. NMR results demonstrate that besides the hydrophobe, the urethane linkage connecting the hydrophobe and PEG chain is incorporated into the hydrophobic core as well. Thus, the F-PEG micelles consisting of both the fluorocarbon chain and urethane linkage possess a dual H/F character, whereas a pure H one exists for H-PEG micelles. Three types of fluorescent probes, that is, pyrene, 9-(anthrylmethyloxymethyl)pyrene (AMOP), and 1-(perfluorooctanoyl)pyrene (PyCORf), have been used to monitor the association, with emphasis on comparing their probing abilities for different microdomains. As for H-PEG, both pyrene and AMOP are effective in monitoring the association and measuring the critical aggregation concentration (CAC). In addition, AMOP presents information about the microviscosity of the micelles. Nevertheless, pyrene and AMOP cannot serve as effective probes for the association of small-molecular fluorocarbon surfactant FC143 because of their limited solubility in pure fluorocarbon microdomains. Compared with the surfactant case, the probing abilities of both pyrene and AMOP are markedly improved for F-PEG. This is attributed to the dual H/F character of F-PEG micelles, which enhances their affinity to the probes. PyCORf, the probe carrying a fluorocarbon chain, is effective and informative in the studies of F-PEG association as a result of its good affinity to fluorocarbon microdomains. The variation of excimer intensity of PyCORf at 465 nm is suggested as a criterion for association and estimating the CAC of F-PEG.

Introduction

Hydrophobically modified polymers, also known as associating polymers, are synthetically derived water-soluble polymers that contain a small amount of hydrophobic moieties, which may be randomly attached to the main chain or appended to one or both ends of the chain. In aqueous solutions, these hydrophobic moieties aggregate to minimize their exposure to water and consequently, hydrophobic microdomains form. The hydrophobic association of polymers often leads to a dramatic increase of the solution viscosity, which makes them effective rheology modifiers.[1−4]

Among the associating polymers such as hydrophobically modified poly(ethylene glycol)s (HM-PEGs), hydrophobically modified cellulose and its derivatives, and copolymers of water-soluble monomers with hydrophobe-containing ones, HM-PEG, especially those with hydrocarbon chains as the hydrophobe (H-PEG), have been most extensively studied, as they can serve as model-associating polymers for the association studies because of their relatively well-defined structures.[5−23] Experimental techniques including viscosity and rheological measure-

* To whom correspondence should be addressed.
† Fudan University.
‡ Shanghai Institute of Organic Chemistry.

(1) *Polymers in Aqueous Media: Performance Through Association*; Glass, J. E., Ed., Advances in Chemistry Series 223; American Chemical Society: Washington, DC, 1989.
(2) *Water-Soluble Polymers: Beauty with Performance*; Glass, J. E., Ed.; Advances in Chemistry Series 213; American Chemical Society: Washington, DC, 1986.
(3) *Polymers as Rheology Modifiers*; Schuldz, D. N., Glass, J. E., Eds.; American Chemical Society Symposium Series 462; American Chemical Society: Washington, DC, 1991.
(4) *Hydrophilic Polymers: Performance with Environment Acceptability*; Glass, J. E., Ed.; Advances in Chemistry Series 248; American Chemical Society: Washington, DC, 1996.
(5) Tarng, M.-R.; Kaczmarski, J. P.; Lunderberg, D. J.; Glass, J. E. In *Hydrophilic Polymers: Performance with Environmental Acceptability*; Glass, J. E., Ed.; Advances in Chemistry Series 248; American Chemical Society: Washington, DC 1996; chapter 17.
(6) Kaczmarski, J. P.; Glass, J. E. *Macromolecules* **1993**, *26*, 5149.
(7) Annable, T.; Buscall, R.; Ettelaie, R.; Whittlestone, D. *J. Rheol.* **1993**, *37*, 695.
(8) Jenkins, R.; Bassett, D. R.; Silebi, C. A.; El-Aasser, M. S. *J. Appl. Polym. Sci.* **1995**, *58*, 209.
(9) Wang, Y.; Winnik, M. A. *Langmuir* **1990**, *6*, 1437.
(10) Duhamel, J.; Yekta, A.; Hu, Y.-Z.; Winnik, M. A. *Macromolecules* **1992**, *25*, 7024.
(11) Yekta, A.; Duhamel, J.; Adiwidjaja, H.; Brochard, P.; Winnik, M. A. *Langumir* **1993**, *9*, 881.
(12) Yekta, A.; Duhamel, J.; Brochard, P.; Adiwidjaja, H.; Winnik, M. A. *Macromolecules* **1993**, *26*, 1829.
(13) Yekta, A.; Xu, B.; Duhamel, J.; Adiwidjaja, H.; Brochard, P.; Winnik, M. A. *Macromolecules* **1995**, *28*, 956.
(14) Char, R.; Frank, C.; Gast, A.; Tang, W. *Macromolecules* **1987**, *20*, 1833.
(15) Maechling-Strasser, C.; Clouet, F.; Fransois, J. *Polymer* **1992**, *33*, 1021.
(16) Nystrom, B.; Walderhaug, H.; Hansen, F. K. *J. Phys. Chem.* **1993**, *97*, 7743.
(17) Chassenireux, C.; Nicolai, T.; Durand, D. *Macromolecules* **1997**, *30*, 4952.
(18) Maechling-Strasser, C.; Fransois, J.; Clouet, F.; Tripette, C. *Polymer* **1992**, *33*, 1021.
(19) Persson, K.; Abrahmsen, S.; Stilbs, P.; Hansen, F. K.; Walderhaug, H. *Colloid Polym. Sci.* **1992**, *270*, 465.
(20) Abranhsen-Alami, S.; Persson, K.; Stilbs, P.; Alami, E. *J. Phys. Chem.* **1996**, *100*, 4598.
(21) Macdonald, P. M.; Uemura, L. D.; Dyke, R.; Zhu, X. In *Hydrophilic Polymers: Performance with Enviromental Acceptability*; Glass, J. E., Ed.; Advances in Chemistry Series 248; American Chemical Society: Washington, DC 1996; chapter 20.
(22) Walderhaug, H.; Hansen, F. K.; Abrahmsen, S.; Persson, K.; Stilbs, P. *J. Phys. Chem.* **1993**, *97*, 8336.
(23) Thuresson, K.; Nilsson, S.; Kjoniksen, A.-L.; Walderhaug, H.; Lindman, B.; Nystrom, B. *J. Phys. Chem. B* **1999**, *103*, 1425.

10.1021/la000412l CCC: $19.00
Published on Web 10/31/2000

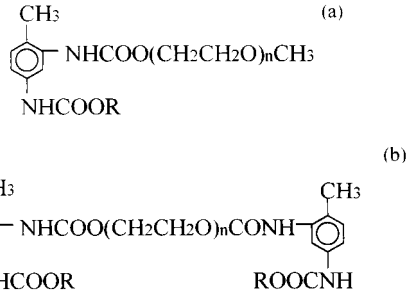
ments,[5−8] static and dynamic fluorescence,[9−14] light scattering,[15−20] and NMR[18−23] have been widely used in these studies.

Fluorocarbon-modified water-soluble polymers were first reported by Zhang et al.[24] and have received widespread interest in recent years. It is well-known that fluorocarbons are more hydrophobic than their hydrocarbon analogues, for example, as far as the association ability is concerned, one CF_2 group equals ca. 1.7 CH_2 groups.[25] A few studies on the association of fluorocarbon-modified poly(ethylene glycol)s (F-PEGs) have been reported. Zhang et al.[26] studied the association of PEGs mono end-capped with fluorocarbons by ^{19}F NMR and found that the F chemical shift of the CF_3 group in the fluorocarbon hydrophobes shows a pronounced concentration dependence. Namely, at low polymer concentrations, only one peak at ca. 82.1 parts per million (ppm) is observed, whereas a new peak at ca. 80.2 ppm appears as the polymer concentration is increased, indicating association of the fluorocarbons. Xu et al.[27] studied the association of double fluorocarbon end-capped PEGs by pulsed-gradient spin-echo (PGSE) NMR and rheological measurements. Cathebras et al.[28] reported the effects of polymer concentration, temperature, and the hydrophilic PEG chain length on the viscoelastitcity of the aqueous solutions. Very recently, Preuscheu et al.[29] reported a ^{19}F NMR relaxation study of the association of F-PEG in aqueous solutions. However, to our knowledge, no studies concerning fluorescent probing of the association of these polymers have been reported.

In this study, both H-PEG and F-PEG with well-defined structures were synthesized. Here, in the synthesis of F-PEG, telomer alcohols [$H(CF_2CF_2)_nCH_2OH$] instead of perfluoro alcohols [$CF_3(CF_2)_nCH_2OH$] were chosen as the hydrophobes. The telomer alcohols, being the tetrafluoroethylene−methanol telomerization products in the presence of a radical initiator, are cheaper and more easily available than perfluoro alcohols. Though the ω-H in telomer alcohols may show some effects on their properties in comparison with the ω-F perfluoro alcohols,[30] the telomer alcohol end-capped PEGs are expected to maintain the basic association behavior of ω-F perfluoro alcohol end-capped ones.

In this article, we present our NMR and fluorescent studies on the hydrophobic association of H-PEG and F-PEG in water. Here, we are particularly interested in comparing the characters of F-PEG and H-PEG micelles as well as the probing abilities of three different probes, that is, pyrene, 9-(anthrylmethyloxymethyl)pyrene (AMOP),[31] and 1-(perfluorooctanoyl)pyrene (PyCORf).[32,33] This study, to some extent, is an extension of our previous studies on fluorocarbon-modified water-soluble polymers.[32,33]

Scheme 1. Structures of Mono-Hydrophobe End-Capped PEG (a) and Double-Hydrophobe End-Capped PEG (b). R is the Fluorocarbon or Hydrocarbon Hydrophobe

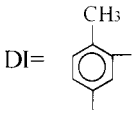


Scheme 2. Synthesis of Fluorocarbon End-Capped PEG

excess OCN-DI-NCO + R_f-OH → R_fOOCNH-DI-NCO 【1】

2 【1】 + HO-$(CH_2CH_2O)_m$-H →

R_fOOCNH-DI-NHCOO-$(CH_2CH_2O)_m$-COHN-DI-NHCOOR_f



R_f = $H(CF_2CF_2)_4CH_2$—

Experimental Section

Materials. PEGs [molecular weight (MW) = 10 000, 20 000] and PEG monomethyl ether (MW = 5000) (Aldrich) were used as received. Pyrene (Aldrich, 99%), 9-chloromethylanthracene (Aldrich, 98%), and 1-hydroxymethylpyrene (Aldrich, 98%) were used as received. 1-Dodecanol was recrystallized twice in ethanol before use. 1-Octanol and toluene 2,4-diisocyanate (TDI) were distilled under reduced pressure before use. Toluene and hexane were dried in the presence of CaH_2 and distilled before use. *N*,*N*-Dimethylformamide (DMF) was dried over 4A sieves and distilled before use. Tetrahydrofuran (THF) was refluxed in the presence of benzophenone/sodium and distilled. Ammonium perfluorooctanoate (FC143) (3M Co.) was used as received. αH, αH, ωH-perfluoro alcohols [i.e., telomer alcohols with the formula of $H(CF_2CF_2)_nCH_2OH$], the telomer alcohols with n = 1, 3, and 4, were commercial products and distilled before use. All other solvents were of analytical grade and used without further purification.

Preparation of Fluorescence Probes. PyCORf was synthesized and purified as reported.[32] AMOP was prepared through the reaction of 9-chloromethylanthracene with 1-hydroxymethylpyrene in DMF using NaH as the catalyst.[34,35] The synthesis and purification of AMOP has been described elsewhere.[31]

Polymer Synthesis and Characterizations. The hydrophobically modified PEGs (Scheme 1) were prepared according to a two-step procedure proposed by Xu et al.[27] Typically, the synthesis of 1H, 1H, 9H-perfluorononyl alcohol (i.e., telomer alcohol with n = 4) end-capped PEG (MW = 10 000) proceeded as follows (Scheme 2).

End-Capping of Telomer Alcohol (n = 4) by TDI. In a three-necked 250-mL round-bottom flask equipped with a magnetic stirrer, a condenser, and a dropping funnel, a solution of 17.4 g (0.1 mol) toluene 2,4-diisocyanate in anhydrous THF (50 mL) was added. It was heated to 60 °C and a solution of 21.6 g (0.05 mol) of telomer alcohol (n = 4) in anhydrous THF (100 mL) was slowly dropped in. The reaction continued for at least 12 h under nitrogen. THF was then distilled out at ambient pressure followed

(24) Zhang, Y.; Da, A.; Hogen-Esch, T. E. *J. Polym. Sci. Part A: Polym. Chem.* **1992**, *30*, 1383.
(25) Ravey, J. C.; Stebe, M. *Colloids Surf., A* **1994**, *84*, 11.
(26) Zhang, H.; Pan, J.; Hogen-Esch, T. E. *Macromolecules* **1998**, *31*, 2815.
(27) Xu, B.; Li, L.; Yekta, A.; Masoumi, Z.; Kanagalingam, S.; Winnik, M. A.; Zhang, K.; Macdonald, P. M.; Menchen, S. *Langmuir* **1997**, *13*, 2447.
(28) Cathebras, N.; Collet, A.; Viguier, M. *Macromolecules* **1998**, *31*, 1305.
(29) Preuscheu, J.; Menchen, S.; Winnik, M. A.; Heuer, A.; Spiess, H. W. *Macromolecules* **1999**, *32*, 2690.
(30) See, for example: Donald, R. B. *Ind. Eng. Chem.* **1959**, *51*, 829.
(31) Zhou, J.; Yuan, X.; Jiang, M.; Zhang, Y. *Macromol. Rapid Commun.* **2000**, *21*, 579.
(32) Li, M.; Jiang, M.; Zhang, Y.; Fang, Q. *Macromolecules* **1997**, *30*, 470.
(33) Chen, J.; Jiang, M.; Zhang, Y.; Zhou, H. *Macromolecules* **1999**, *32*, 4861.
(34) Desvergne, J.-P.; Bitit, N.; Castelllan, A.; Bouas-Laurent, H. *Tetrahedron Lett.* **1981**, *22*, 3529.
(35) Desvergne, J.-P.; Castelllan, A.; Bouas-Laurent, H.; Soulignac, J. C. *J. Lumin.* **1987**, *37*, 175.

by removal of the excess TDI through distillation under reduced pressure. Finally, the product was extracted by anhydrous hexane (3×100 mL) for further removal of the residual TDI. About 28.0 g of a yellow, waxlike solid was obtained.

End-Capping of PEG. In a three-necked 500-mL round-bottom flask equipped with a magnetic stirrer, a water trap, and a dropping funnel, a solution of 10.0 g of PEG (MW = 10 000, 0.001 mol) in dried toluene (300 mL) was added. It was heated to about 120 °C to azeotropically distill out the possible residual water in PEG until about 200 mL of toluene was removed. The solution was then cooled to 70 °C and several drops of dibutyltin dilaurylate as well as a solution of 3.0 g (0.005 mol, 200 mL) of TDI end-capped telomer alcohol in dried toluene were added. The reaction continued for at least 12 h. Finally, the resultant reaction mixture was precipitated in diethyl ether followed by Soxhelt extraction with diethyl ether for further purification. The product was dried at 40 °C under vacuum for 72 h.

The polymers end-capped with hydrocarbons were synthesized in a similar way. However, in the first reaction step, no hexane extraction was performed for removal of the excess TDI, as the reaction products of TDI and hydrocarbon alcohols are soluble in hexane as well.

Characterizations. The molecular weight and molecular weight distributions of the products were characterized by size exclusion chromatography (SEC) using THF as the mobile phase and polystyrene as standard. The end-capping degree of the polymers with hydrocarbon and fluorocarbon hydrophobes was determined by ^{1}H NMR and F elemental analysis, respectively.

Fluorescent Measurements. Polymer (0.5 g) was dissolved in 25 mL of deionized water to get a stock solution (2.0 wt %). The final solutions for measurements were prepared by proper dilution to desired concentrations. Into these solutions a probe solution in acetone was added by a microsyringe to give a final concentration of 6×10^{-7} M for pyrene, 1×10^{-6} M for AMOP, and 2×10^{-6} M for PyCORf. The solutions with pyrene and AMOP, as the probe were ultrasonically treated for 20 min and then allowed to stand for at least 24 h at room temperature before the measurements. Those with PyCORf as the probe were ultrasonically treated for 20 min and then allowed to stand for about 48 h in a 60 °C bath before the measurements.

Steady-state measurements were performed on an FZ-1 fluorescence spectrometer. For solutions using pyrene as the probe, a slit of 7.5 nm for excitation and 2.5 nm for emission was used. The excitation and emission wavelengths were 333 and 393 nm for the emission and excitation measurements, respectively. For solutions using AMOP and PyCORf as the probe, a slit of 7.5 nm for both excitation and emission was used. For the emission spectra, the excitation wavelengths were 366 nm for AMOP and 340 nm for PyCORf.

^{19}F NMR and ^{1}H NMR Measurements. Weighed amounts of polymer samples were added into the NMR testing tube and dissolved in D_2O and $CDCl_3$, respectively. The final polymer concentration was ca. 1 wt %, which is well above the critical aggregation concentration (CAC) of these polymers in water as determined by fluorescent spectroscopy.

Both ^{19}F NMR and ^{1}H NMR spectra were recorded on a Bruker AM300 spectrometer. As for ^{19}F NMR, CF_3COOH is used as external standard. Acquisition parameters were as follows: Spectral width: 71425 Hz (250 ppm); acquisition time: 0.46 s including relaxation delay of 2 s; pulse width: 3 μs (45° angle). The number of acquisitions was ca. 200−2000.

Tetramethylsilane is used as the external standard for ^{1}H NMR measurements. Acquisition parameters are as follows: Spectral width: 3906 Hz (13 ppm); acquisition time: 0.26 including relaxation delay of 5 s; pulse width: 3.5 μs; number of acquisitions: 1000−2000.

Results and Discussion

Synthesis and Characterization of HM-PEG. In hydrophobically modified PEGs, the hydrophobe can be linked to the hydrophilic PEG chain through either ether bond, ester bond, or urethane bond. The urethane bond is the most widely used linkage and the corresponding polymers are usually named hydrophobe-modified ethoxylated urethanes (HEURs). Several synthetic procedures for HEURs have been reported.[5] In our experiments we found that the procedure proposed by Xu et al.[27] (Scheme 2) is most suitable to prepare HEURs with a high degree of hydrophobe end-capping and narrow molecular weight distribution. In this study, all the polymers were prepared according to this scheme.

Table 1. Characterization Results of Hydrophobically Modified Poly(ethylene glycol)s (PEGs)

sample code[a]	M_n ($\times 10^{-4}$)[b]	M_w/M_n	end-capping degree
F^3-10K			1.0[c]
F^7-10K	1.57	1.17	0.98[c]
F^9-10K	1.58	1.13	1.0[c]
H^{12}-10K	1.47	1.15	1.0[d]
H^{12}-ME5K	0.99	1.16	
H^{12}-20K			
H^8-10K	1.36	1.22	

[a] In the sample code F and H respectively represent the polymers carrying fluorocarbon and hydrocarbon hydrophobes and the superscript number refers to the carbon atom number in the hydrophobes. 10K, 20K, and ME5K mean that the hydrophilic chain is PEG10000, PEG20000, and PEGME5K, respectively. For example, in F^9-10K, the hydrophobe is $H(CF_2CF_2)_4CH_2OH$, i.e., the telomer alcohol with $n = 4$, and the hydrophilic chain is PEG10000. [b] The measured molecular weight is much larger than expected. This can be attributed to the fact that polystyrene was used as the standard in our SEC experiments, which causes a large error in estimating the MW of PEG and modified PEG. In fact, SEC gave a MW of 6700 for PEGME5k, which has the absolute molecular weight of 5000. [c] Determined by ^{19}F elemental analysis. [d] Determined by ^{1}H NMR according to a procedure proposed by Winnik and co-workers.[36]

It was found that the molar ratio of isocyanate group to hydroxyl group (n_{NCO}/n_{OH}) in the feed of the second reaction step should be kept at ca. 2−3 to obtain products with a high degree of end-capping (i.e., close to 100%). This leads to contamination of the products with low-molecular-weight impurities. The impurities can be removed by repeatedly dissolving/precipitating the products or recrystallizing them in solvents such as ethyl acetate.[36] In our experiments we found that extraction of the product by diethyl ether is also an effective way, as evidenced by the SEC traces of the extracted products.

The molecular weight and its distribution as well as the end-capping degree of the purified products obtained by SEC, ^{19}F elemental analysis, and ^{1}H NMR are listed in Table 1. It shows that the polymers prepared have well-defined structure, for example, narrow molecular weight distributions and high degree of hydrophobe end-capping. The meaning of the sample codes is illustrated in the note of Table 1.

Association of H-PEG and F-PEG: NMR Results. Both H-PEG and F-PEG have been studied by a variety of NMR techniques including PGSE-NMR,[18−23] NMR chemical shift,[26] and relaxation.[29] In this study, we measured the NMR spectra of H-PEG and F-PEG in both the nonselective solvent ($CDCl_3$) and selective solvent (D_2O). Our attention mainly concentrated on the signal band broadening of the water-insoluble blocks. As is well known, signal band broadening in a NMR spectrum, which is often accompanied by loss of the signal sharpness and intensity, reflects the environmental changes of the nuclei. This has been used as an indication for the association of amphiphilic polymers in water.[37,38]

(36) Yekta, A.; Nivaggioli, T.; Kanagalingam, S.; Xu, B.; Masoumi, Z.; Winnik, M. A. In *Hydrophilic Polymers: Performance with Environment Acceptability*; Glass, J. E., Ed.; Advances in Chemistry Series 248; American Chemical Society: Washington, DC, 1996; Chapter19.

(37) Kriz, J.: Massar, B.; Pospisil, H.; Plestil, J.; Tuzzar, Z.; Kiselev, M. A. *Macromolecules* **1996**, *29*, 7853.

(38) Mizusaki, M.; Morishima, Y.; Winnik, F. M. *Macromolecules* **1999**, *32*, 4317.

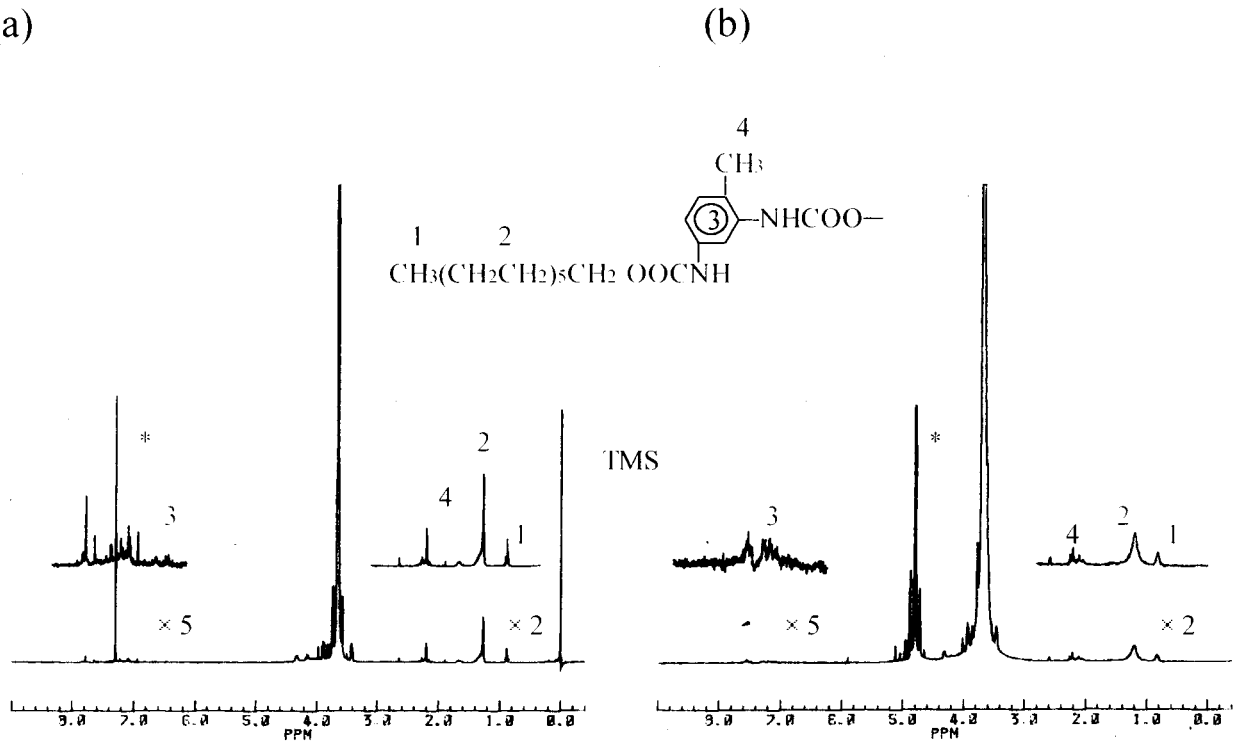


Figure 1. ^{1}H NMR spectra of H^{12}-10K in $CDCl_3$ (a) and D_2O (b); (*), solvent peak. Polymer concentration: 1.0×10^{-2} g/mL.

Figure 1 shows the ^{1}H NMR spectra of H^{12}-10K in $CDCl_3$ and D_2O. It can be seen that when the polymer is in a nonselective solvent ($CDCl_3$), the signal bands corresponding to the hydrophobe (lauryl), the urethane linkage, and the hydrophilic PEG chain are all well resolved. However, in a selective solvent (D_2O), the signal bands corresponding to the hydrophobe become broadening, although those associated with the PEG hydrophilic chain almost do not change. For example, the CH_3 group in the hydrophobe shows a triplet in $CDCl_3$, while only a broadened peak in D_2O. Furthermore, it is interesting to find that the signal bands of the urethane linkage exhibit apparent broadening as well. We have also measured the ^{1}H NMR spectra of other H-PEG samples listed in Table 1; the same results were obtained. Obviously, the broadening of the proton signals for the hydrophobe and urethane linkage is caused by the severe restriction of the proton motion due to association.[38] Therefore, it can be concluded that both the hydrophobe and urethane linkage contribute to the association. In other words, the urethane linkage actually exists in the hydrdphobic microdomains.

This conclusion also holds for F-PEG. Figure 2 shows the ^{1}H NMR spectra of F^9-10K in $CDCl_3$ and D_2O. The signal bands corresponding to the urethane linkage can be clearly seen in the nonselective solvent $CDCl_3$ but show apparent broadening in the selective solvent D_2O. For F^3-10K and F^7-10K, the same results were obtained.

^{19}F NMR measurements of F-PEG in $CDCl_3$ and D_2O were performed as well. As an example, Figure 3 shows the ^{19}F NMR spectra of F^9-10K in $CDCl_3$ and D_2O. The signals associated with the hydrophobes in $CDCl_3$ are well resolved (Figure 3a). However, the spectrum in D_2O (Figure 3b) exhibits a striking difference in both broadness and resolution of the signals compared with that measured in $CDCl_3$. Here, the remarkable signal broadening in D_2O, accompanied by the loss of signal sharpness, clearly indicates association of the fluorocarbon chains.

In summary, ^{1}H and ^{19}F NMR studies conclude that, regardless of whether hydrocarbon or fluorocarbon serves as the hydrophobe, both the hydrophobe and urethane linkage are incorporated into the associating regions. This implies that F-PEG micelles may possess a dual H/F character, as their hydrophobic cores are composed of both the fluorocarbon hydrophobe and urethane linkage, whereas those of H-PEG have only a pure H character because both the hydrophobe and urethane linkage are hydrocarbon chains. This difference is very important for us to understand the fluorescence results to be presented below. However, we still lack understanding of the detailed internal structure of such hydrophobic microdomains. Specifically, we do not know whether the perfluorinated chains segregate from the urethane linkage because of their mutual repulsion or mix together as they are closely bonded. Further work is needed to clarify this point.

Association of H-PEG Probed by Pyrene and AMOP. Pyrene has been widely used as a polarity probe because of its unique photophysical properties. Because of its strong hydrophobicity, pyrene has a very low solubility in water (7×10^{-7} M) and is preferentially solubilized into the hydrophobic region or microphase existing in aqueous medium. The change in the microenvironment surrounding the probe molecules is reflected by variations in both its emission and excitation spectra. First, in the emission spectrum, the intensity ratio of the first vibronic band to the third one, I_1/I_3, is sensitive to the polarity of its environment and thus can be used as an indication of local environment that pyrene molecules experience.[39,40] Second, the (0, 0) band of the excitation spectrum of pyrene shifts from 333 to 338.5 nm when pyrene molecules are transferred from a hydrophilic environment to a hydrophobic one.[41,42] Thus, the ratio of I_{338}/I_{333} can show the onset of micellization as well.

In this study, both emission and excitation spectra of

(39) Kalyanasundaram, K.; Thomas, J. K. *J. Am. Chem. Soc.* **1977**, *99*, 2039.
(40) Dong, D. C.; Winnik, M. A. *Can. J. Chem.* **1984**, *62*, 2566.
(41) Wilhelm, M.; Zhao, C.; Wang, Y.; Xu, R.; Winnik, M. A.; Mura, J.; Reiss, G.; Croucher, M. *Macromoleculaes* **1991**, *24*, 1033.
(42) Astafieva, I.; Zhong, X.; Eisenberg, A. *Macromolecules* **1993**, *26*, 7339.

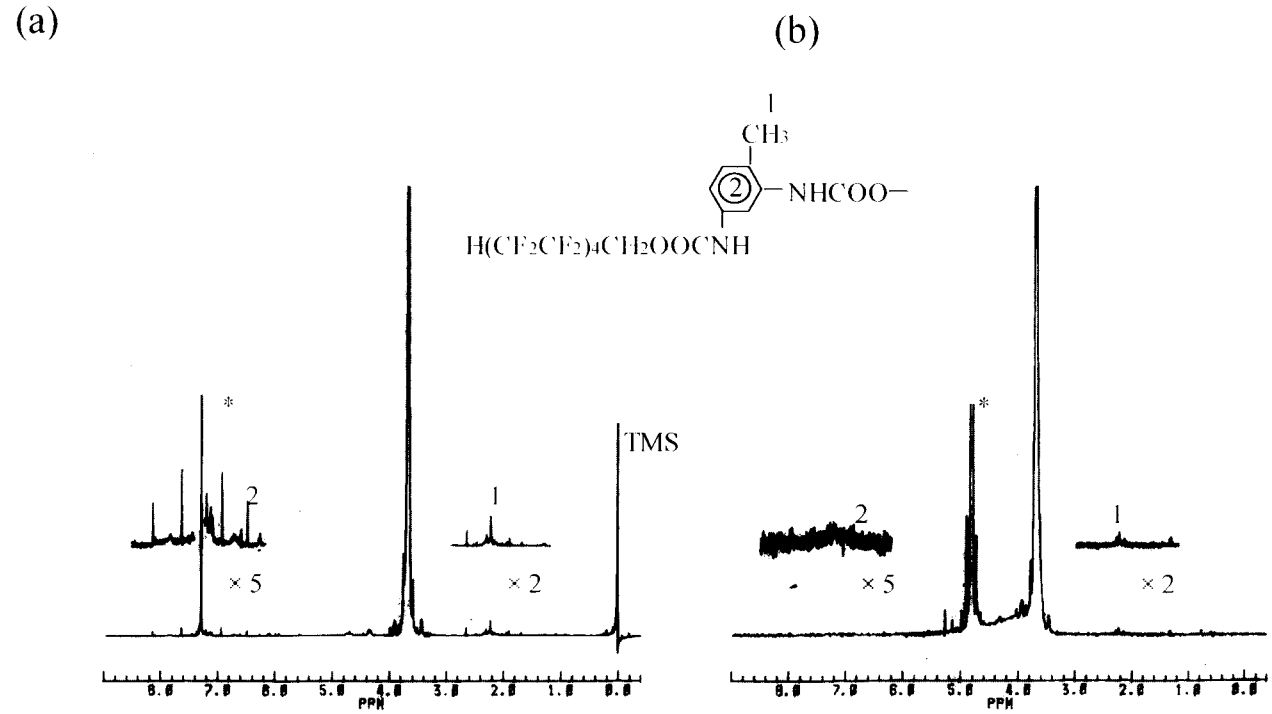


Figure 2. ^{1}H NMR spectra of F^{9}-10K in $CDCl_3$ (a) and D_2O (b); (*), solvent peak. Polymer concentration: 1.0×10^{-2} g/mL.

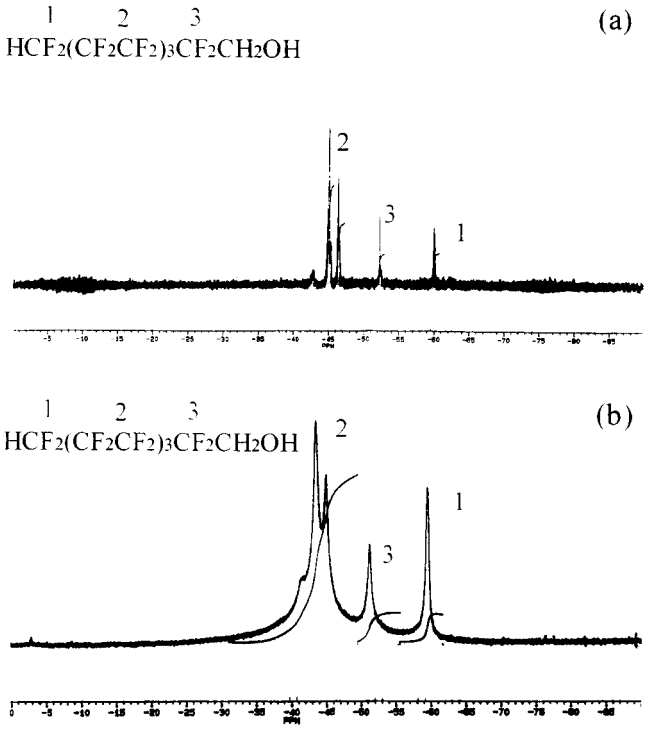


Figure 3. ^{19}F NMR spectra of F^{9}-10K in $CDCl_3$ (a) and D_2O (b). Polymer concentration: 1.0×10^{-2} g/mL.

pyrene in aqueous solutions of H-PEG were measured. As an example, Figure 4 shows a plot of I_1/I_3 and I_{338}/I_{333} for pyrene versus the polymer (H^{12}-10K) concentrations. The I_1/I_3 curve shows a sigmoidal shape. At very low polymer concentrations, I_1/I_3 takes the value of ca. 1.8, typical for pyrene in water. This indicates that pyrene molecules are mainly in aqueous phase. However, when the polymer concentration reaches a certain value, the curve shows an abrupt decrease of I_1/I_3. Finally, it reaches a plateau with the I_1/I_3 value of ca. 1.2, characteristic of a nonpolar medium, indicating that most of pyrene molecules partition into the hydrophobic microdomains formed. From

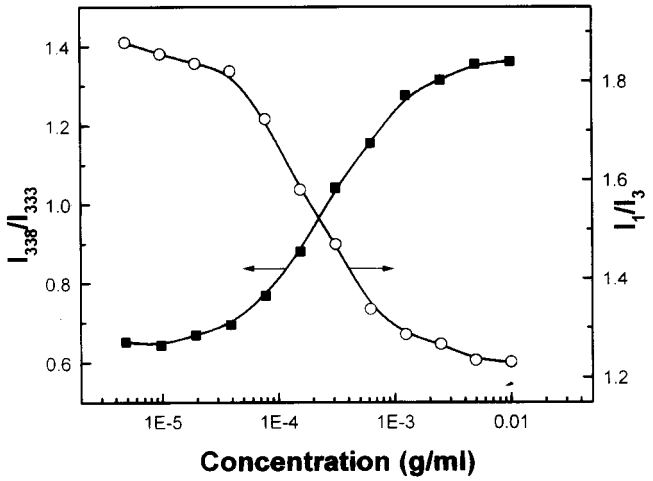


Figure 4. Plot of I_1/I_3 and I_{338}/I_{333} of pyrene versus H^{12}-10K concentrations.

the I_1/I_3 curve, the CAC of H^{12}-10K can be determined to be ca. 7.8×10^{-5} g/mL.

The plot of I_{338}/I_{333} against polymer concentrations also shows the association. At low polymer concentrations, the I_{338}/I_{333} ratio takes a value around 0.5−0.6, relatively higher than that of pyrene entirely in a hydrophilic environment (0.3−0.4).[41,42] The ratio shows an abrupt increase at the concentration of ca. 6.6×10^{-5} g/mL, indicating the onset of aggregation and finally reaches the highest value of ca. 1.2−1.3, which is still much lower than the value for pyrene in micelles (2.1−2.4) [41,42] of amphiphilic block copolymers in aqueous solutions. The results may imply that the microdomains formed in the present case are relatively open ones with some water molecules incorporated in.

We have investigated the structural effect of H-PEG on their association behavior by using pyrene as the probe. The results can be summarized as follows: (1) H^{12}-20K shows a CAC of ca. 8.3×10^{-4} g/mL, 1 order of magnitude higher than that of H^{12}-10K (7.8×10^{-5} g/mL). This means

that, with the same hydrophobe, an increase of the hydrophilic PEG chain length greatly weakens the association. (2) When the hydrophilic PEG chains are equal in length, an increase of the chain length of the hydrophobes strengthens the association, as is evidenced by comparing the CAC of H^{12}-ME5K and H^{8}-ME5K, that is, 9.3×10^{-5} g/mL and 1.9×10^{-4} g/mL, respectively. (3) When the hydrophobes are identical, mono end-capped H^{12}-ME5K shows a similar CAC (9.3×10^{-5} g/mL) to the double end-capped H^{12}-10K (7.8×10^{-5} g/mL); this may be attributed to their similar hydrophile-lipophile balance (HLB) value, as the PEG molecular weight of the latter is double that of the former.

Fluorescent probes sensitive to the surrounding microviscosity can also be used for studying micellization of surfactants and hydrophobic association of amphiphilic polymers in water. For example, auramine O exhibits enhanced fluorescence in a rigid environment and consequently, a dramatic increase in fluorescence intensity when it's transferred from aqueous phase to a micelle. It was reported that Dipyme[11−13,43−45] and 1,3-dipyrenylpropane[46,47] capable of forming *intramolecular excimers* can also probe the microviscosity of its environment. Recently, we have successfully used AMOP which can form *intramolecular exciplex* as a friction-sensitive probe to study the association of amphilphilic molecules in water.[31]

We found that the emission spectra of AMOP in cyclohexane and liquid paraffin, whose viscosity is 1.02 and 30 cp, respectively, have similar features, that is, show monomer emission at about 388, 411, and 434 nm as well as an exciplex emission at about 464 nm. However, as the exciplex formation of AMOP in the highly viscous liquid paraffin is substantially suppressed, the ratio of the exciplex intensity (I_e at 364 nm) to the monomer intensity (I_m at 411 nm), I_e/I_m, of AMOP in liquid paraffin (0.39) is only one-third of that in cyclohexane (1.12). In water, AMOP exhibits a quite different emission spectrum. It shows a weak and blurred monomer emission but a strong exciplex emission at about 476 nm. Here, the blurring of monomer emission has been attributed to the self-quenching as a consequence of the aggregation of AMOP molecules because of its low solubility in water.[31]

Figure 5A shows a series of emission spectra of AMOP in H^{12}-10K solutions, displaying a regular change with polymer concentrations. At low polymer concentrations, the emission spectra are almost the same as that found in water, indicating that the probe molecules are in aqueous medium. At high polymer concentrations, the spectra become similar to those found in the highly viscous nonpolar solvent. This means that the probe molecules transfer from aqueous phase to H^{12}-10K micelles. We also tried to use I_e/I_m as an indicator for the association transition (Figure 5B). It can be seen that I_e/I_m takes the value of ca. 3−3.4 at very dilute polymer concentrations. The curve shows an abrupt decrease at the concentration of ca. 4.3×10^{-5} g/mL. Finally the I_e/I_m value reaches a plateau of ca. 0.26. This variation of I_e/I_m clearly reveals the micellization process of H^{12}-10K as its concentration increases. For reference, the results of micellization of H^{12}-10K monitored by pyrene are also shown in Figure 5B. Obviously, the two probes present similar results. Moreover, AMOP provides more information than pyrene does, as it gives the microviscosity of its environment as well. For example, the I_e/I_m value of AMOP in H^{12}-10K micelles is ca. 0.26, apparently lower than that in sodium dodecyl sulfate (SDS) micelles (I_e/I_m=0.58). This means that the microviscosity of H^{12}-10K micelle cores is even higher than that of SDS micelle cores. This conclusion is in good agreement with the results obtained by Winnik and co-workers[11−13] by using the friction-sensitive probe ($PyCH_2OCH_2Py$) based on *intramolecular excimer* formation. In addition, we also measured the effect of structural factors such as the molecular weight of PEG and the chain length of the hydrophobes on the association behavior of H-PEG using AMOP as the probe. Once again, the results are in accordance with those obtained using the probe of pyrene mentioned above.

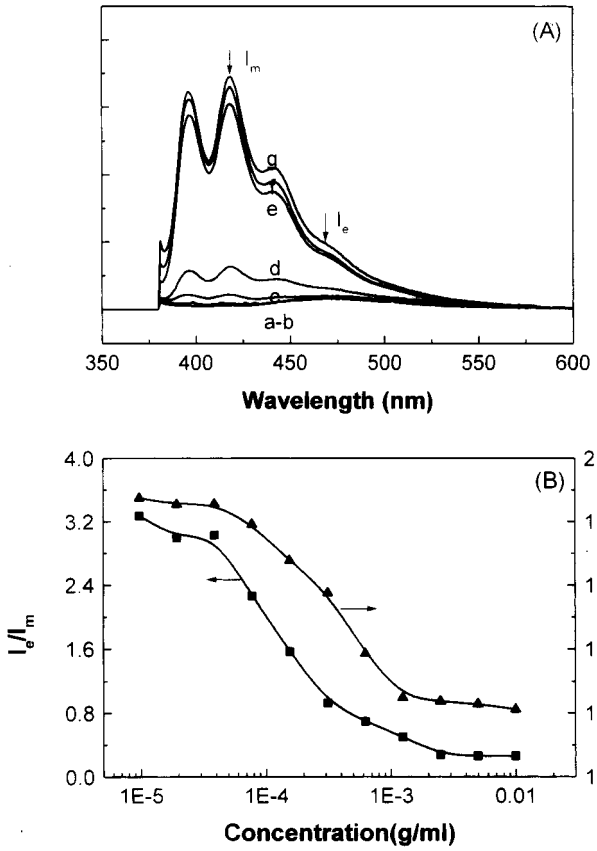


Figure 5. (A) Typical fluorescence emission spectra of AMOP in aqueous solutions of H^{12}-10K. The polymer concentrations (g/mL) are: (a) 4.75×10^{-6}, (b) 1.9×10^{-5}, (c) 7.8×10^{-5}, (d) 3.12×10^{-4}, (e) 1.25×10^{-3}, (f) 5.0×10^{-3}, and (g) 1.0×10^{-2}. (B) Plot of I_e/I_m of AMOP and I_1/I_3 of pyrene against H^{12}-10K concentrations.

In short, the above results clearly demonstrate that both pyrene and AMOP can serve as effective probes for micellization of H-PEG, whose associative region is only composed of hydrocarbon chains.

Association of F-PEG Probed by Pyrene and AMOP. In this section, the association of F-PEG (e. g., F^{9}-10K) as well as a fluorocarbon surfactant FC143 was studied using pyrene and AMOP as the probes. We are particularly interested in comparing and understanding the different fluorescent characteristics of pyrene and AMOP in micelles of H-PEG, F-PEG as well as FC143.

Figure 6 shows I_1/I_3 of pyrene against F^{9}-10K concentration. Although I_1/I_3 decreases with the polymer concentration continuously as a result of the hydrophobic

(43) Nivaggioli, T.; Tsao, B.; Alexandridis, P.; Hatton, T. A. *Langmuir* **1995**, *11*, 119.
(44) Winnik, F. M.; Winnik, M. A.; Ringsdorf, H.; Venzmer, J. *J. Phys. Chem.* **1991**, *95*, 2583.
(45) Georgescauld, D.; Desmasez, R.; Lapouyade, R.; Babeau, A.; Richard, H.; Winnik, M. A. *Photochem. Photobiol.* **1980**, *31*, 539.
(46) Szajdzinska-Pietek, M.; Wolszczak, A.; Plonka, S.; Schlick, J. *J Am. Chem. Soc.* **1998**, *120*, 4215.
(47) Zachariasse, K. A. *Chem. Phys. Lett.* **1978**, *57*, 429.

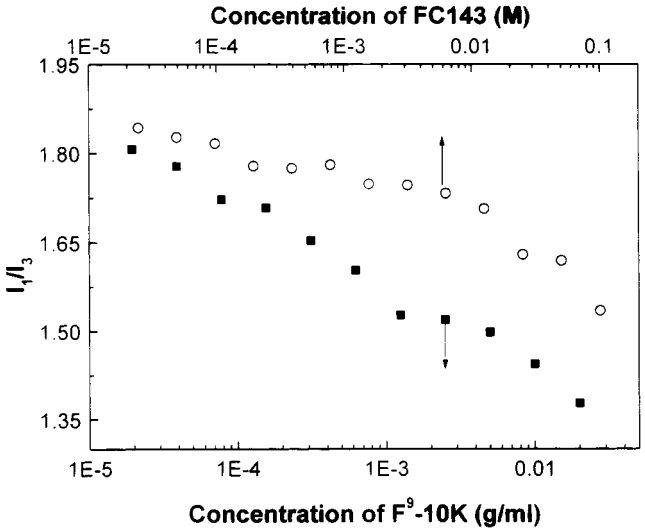


Figure 6. Plot of I_1/I_3 of pyrene as a function of the concentrations of F^9-10K and FC143.

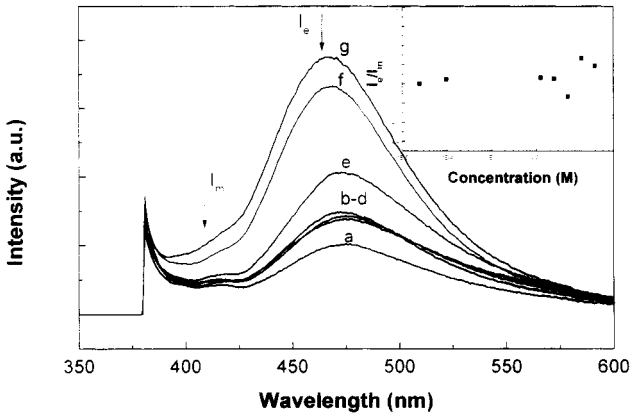


Figure 7. Typical fluorescence emission spectra of AMOP in aqueous solutions of FC143. The polymer concentrations (M) are: (a) 4.75×10^{-6}, (b) 1.9×10^{-5}, (c) 7.8×10^{-5}, (d) 3.12×10^{-4}, (e) 1.25×10^{-3}, (f) 1.0×10^{-2}, and (g) 2.0×10^{-2}. The *inset* shows a plot of I_e/I_m of AMOP against FC143 concentrations.

microdomain formation, no distinct break can be found in the curve. Besides, the lowest I_1/I_3 value of pyrene (1.3−1.4) observed here at the polymer concentration as high as 2×10^{-2} g/mL is still higher than that in micelles of hydrocarbon surfactants, for example, SDS (ca. 1.1−1.2) and H-PEG (1.2−1.3) mentioned above. Figure 6 also shows I_1/I_3 of pyrene against concentration of FC143. The curve follows the same trend and reaches the lowest I_1/I_3 value of ca. 1.5, which is even higher than that in F-PEG micelles, when the concentration of FC143 is as high as 0.2 M, almost 1 order of magnitude higher than its CMC (2.7×10^{-2} M).

The high I_1/I_3 value of pyrene in FC143 micelles can be attributed to its poor solubility in fluorocarbon microdomains. In fact, there have been some reports in the literature showing poor affinity of pyrene to fluorocarbon microdomains. Muto et al.[48] and Kalyanasundaram[49] have reported that the I_1/I_3 value of pyrene in fluorocarbon surfactant micelles (1.5−1.6) is apparently larger than that in normal hydrocarbon surfactants (e.g., 1.1−1.2 in SDS micelles). Almgren et al.[50] measured the solubilities of pyrene in fluorocarbon and hydrocarbon surfactant micelles and found that pyrene shows evident preference for micelles of hydrocarbon surfactants. For example, pyrene was found to prefer C(16)TAC (*N*-hexadecylpyridinium chloride) micelles to HFDePC [*N*−(1,1,2,2-tetrahydroperfluorodecanyl) pyridinium chloride] micelles by a factor of ca. 60. In addition, Stahler et al.[51] recently studied the solubilization of pyrene in polymeric multicompartment micelle systems containing both fluorocarbon and hydrocarbon domains. It was found that pyrene is only solubilized in hydrocarbon domains.

The apparent difference among the I_1/I_3 value of pyrene in H-PEG, F-PEG, and FC143 micelles turns out to be understood if both the different affinity of pyrene to fluorocarbon and hydrocarbon environments and the different composition of the corresponding associative regions are considered. Pyrene shows good affinity to H-PEG micelles, whose associative regions are pure hydrocarbon chains, leading to the lowest I_1/I_3. It shows poor affinity to FC143 micelles comprising pure fluorocarbon chains, leading to the highest I_1/I_3 and it exhibits fair affinity to F-PEG micelles, as the associative regions are composed of both fluorocarbon and hydrocarbon chains, resulting in I_1/I_3 in between.

We have also measured the fluorescence spectra of AMOP in solutions of FC143 and F-PEG. As can be seen from Figure 7, in FC143 solutions, though AMOP does show enhanced emission intensity as the concentration is increased, the general feature of the spectra at FC143 concentration as high as 0.2 M still remains the same as that of AMOP in water. This indicates that most of AMOP molecules are still in aqueous phase as a result of the very low solubility of AMOP in fluorocarbon micelles. Besides, the I_e/I_m value of AMOP actually fails to monitor the micellization of FC143, as it does not show any regular changes with the surfactant concentrations (see the inset of Figure 7).

The emission spectra of AMOP in F-PEG (F^9-10K) show quite different features from those in FC143, displaying a regular change as the polymer concentration increases. Moreover, the plot of I_e/I_m of AMOP against polymer concentrations possesses the same shape as that found in the case of H-PEG, clearly indicating the association of F^9-10K. Once again, this can be attributed to the dual H/F character of the F-PEG microdomains. In other words, compared with the pure fluorocarbon micelles of FC143, the urethane linkage in the microdomains of F^9-10K micelles remarkably enhances the affinity to AMOP molecules.

As a conclusion, the above results show that both pyrene and AMOP are not effective probes for micellization of fluorocarbon surfactants, for example, FC143, because of their poor affinity to the fluorocarbon microdomains. However, F-PEG micelles show an enhanced affinity to pyrene and AMOP because of their dual H/F character and consequently, the association can be fairly monitored by both pyrene and AMOP, although they are not ideal probes.

Fluorocarbon-Modified Probe PyCORf. In previous work, we confirmed that fluorescent probes with enhanced affinity to fluorocarbon domains were effective in monitoring the association of fluorocarbon-modified water-soluble polymers.[32,33] Li et al. successfully used a pyrene derivative with a fluorocarbon chain, that is, PyCORf, to monitor the association of fluorocarbon-modified PNIPAM.[32] Later, It was found that this probe was even capable of probing the very weak association of fluorocarbon-modified poly(acrylic acid) at high pH val-

(48) Muto, Y.; Esurmi, K.; Meguro, K.; Zana, R. *J. Colloid Interface Sci.* **1987**, *120*, 162.
(49) Kalyanasundaram, K. *Langmuir* **1988**, *41*, 942.
(50) Almgren, M.; Wang, K.; Asakawa, T.*Langmuir* **1997**, *13*, 4535.
(51) Stahler, K.; Selb, J.; Candau, F. *Langmuir*, **1999**, *15*, 7565.

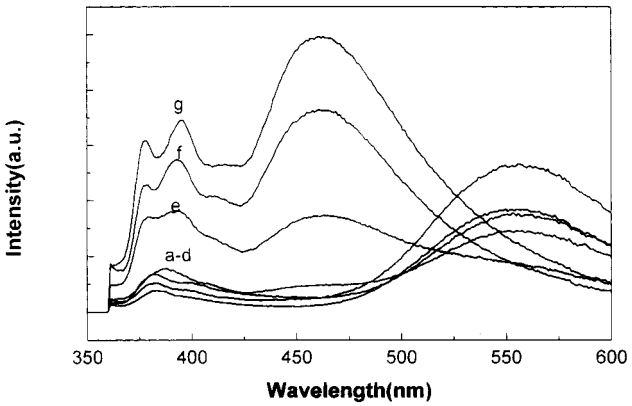


Figure 8. Fluorescence emission spectra of PyCORf in aqueous solutions of F^9-10K. The polymer concentrations (g/mL) are: (a) 1.9×10^{-5}, (b) 7.8×10^{-5}, (c) 3.12×10^{-4}, (d) 1.25×10^{-3}, (e) 5.0×10^{-3}, (f) 1.0×10^{-2}, and (g) 2.0×10^{-2}.

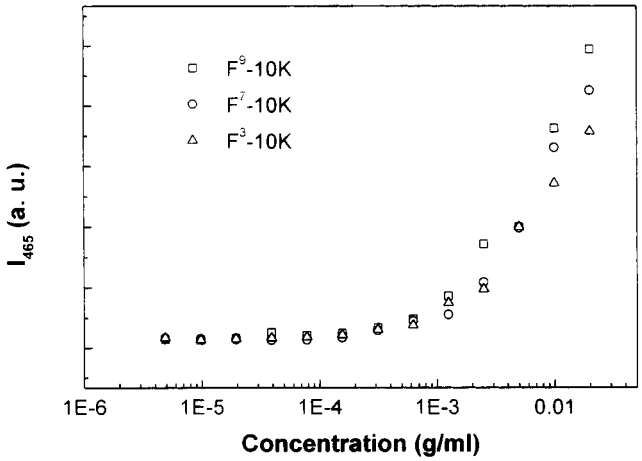


Figure 9. Plot of excimer emission intensity (I_{465}) of PyCORf as a function of polymer concentrations.

ues.[33] In a recent paper dealing with the multicompartmental polymeric micelles, Stahler et al.[51] found that PyCORf showed an enhanced solubility in the F compartment as compared with pyrene, which can only be selectively solubilized in the H compartment. Besides, it was found that though PyCORf can be solubilized in hydrocarbon micelles, it obviously prefers a fluorocarbon environment to a hydrocarbon one.

PyCORf shows different emission characteristics in methanol and water.[32] In methanol, at the low concentration range (10^{-7}–10^{-5} M), three maxima at 374, 394, and 415 nm, characteristic of monomer emission, are present. When the concentration is increased to 10^{-4} M, a new broad, structureless peak centered at 445 nm appears, which can be attributed to excimer emission. In water, there is no monomer emission with fine structure at very low concentrations. Instead, a single peak at about 385 nm is present. The monomer intensity varies slightly as the probe concentration is increased. However, a new broad emission band at ca. 550 nm appears as the probe concentration is increased above 10^{-7} M. This band is associated with the excimer emission from the dimers of PyCORf molecules as a result of aggregation of the fluorocarbon chains in water. This type of excimer emission of PyCORf in water may belong to "static excimers", whereas the excimer emission in methanol belongs to "dynamic excimers", which comes from the dynamic collision of the singlet excited-state probe molecules with the ground-state probe molecules, that is, the Birk's mechanism.[52]

Figure 8 shows a series of emission spectra of PyCORf in aqueous solutions of F^9-10K. It can be seen that the spectra show regular changes as the polymer concentrations increase continuously. At very low polymer concentrations, the spectra are almost the same as that in water. This indicates the aggregation of the probe molecules in water, as the probe concentration used here is 2×10^{-6} M, well above its critical aggregation concentration (1×10^{-7} M).[32] As the polymer concentration is increased, the monomer emission strengthens considerably and a fine-structural monomer emission appears. Meanwhile, the excimer emission peak centered at ca. 550 nm gradually disappears. This clearly reflects the diffusion of PyCORf molecules from the bulk aqueous phase to the microregion with higher hydrophobicity, leading to an increase of the emission quantum efficiency and enhancement of the fluorescent lifetime. In addition, this increase of the monomer emission is accompanied by the growth of a new peak centered at ca. 465 nm, similar to the excimer emission of PyCORf in methanol. This emission around 465 nm has been attributed to the excimer of PyCORf in the hydrophobic environment of the micelles.[32,33] Li et al.[32] reported that this peak centered at about 450 nm in the micelles of fluorocarbon-modified PNIPAM. The discrepancy may be due to the difference in hydrophobicity between the two kinds of micelles.[33]

We also attempted to use the concentration dependence of the excimer emission intensity (I_{465}) as an indication of the association. The results are summarized in Figure 9. It can be seen that all the curves exhibit the same trend, that is, at low polymer concentrations, I_{465} does not change much. However, the curves show an abrupt increase of I_{465} at a certain polymer concentration, indicating the onset of aggregation of these polymers in water. From Figure 9, CAC of F^9-10K, F^7-10K, and F^3-10K were found to be very close to one another, around 8×10^{-4} g/mL. In addition, at high polymer concentrations, the excimer emission at 465 nm strengthens in the sequence of F^3-10K, F^7-10K, and F^9-10K, which implies that the longer the CF_2 chain length, the better is the affinity to PyCORf molecules. These results demonstrate that PyCORf possesses a good targeting ability to fluorocarbon domains, and this renders the probe effective in monitoring the association of fluorocarbon-modified water-soluble polymers.

We have also used PyCORf to monitor the association of H-PEG. It was found that the monomer emission of PyCORf in water solutions of H^{12}-10K shows an obvious increase as the polymer concentration increases to a critical value, which indicate the association of H-PEG. This success of using PyCORf for micelles of H-PEG can be attributed to the dual H/F character of the probe, which contains both the fluorocarbon chain and polycyclic aromatic hydrocarbon. However, differing from the case of F-PEG, almost no excimer emission at about 465 nm was observed, even at H^{12}-10K concentration as high as 1×10^{-2} g/mL. This may imply that the probe molecules cannot be solubilized in micelles of H^{12}-10K as abundant as in micelles of F-PEG. The results provide further evidence concerning the targeting abilities of PyCORf to fluorocarbon microdomains.

Conclusions

In this study, fluorocarbon- and hydrocarbon-modified PEGs with well-defined structure have been synthesized,

(52) Winnik, F. M. *Chem. Rev.* **1993**, *93*, 587.

and their association in aqueous solutions has been investigated by NMR and a fluorescent probe technique.

It is found that, in the NMR spectra, the signal bands corresponding to the hydrophobe and urethane linkage exhibit pronounced broadening and loss in the intensity and sharpness in selective solvent (D_2O), which demonstrates that both the hydrophobe and urethane linkage contribute to hydrophobic association. Thus, the hydrophobic microdomains of F-PEG micelles consist of both the perfluorinated chains and urethane linkage and therefore bear a dual H/F character, whereas those of H-PEG only have a pure H character.

Three types of fluorescent probes, that is, the polarity-sensitive pyrene, friction-sensitive AMOP, and fluorocarbon microdomains targeting PyCORf were used to monitor the hydrophobic association. As for H-PEG, both pyrene and AMOP can serve as effective probes to monitor the association, and AMOP provides more information about the microviscosity of the microdomains. Experiments on fluorocarbon surfactant FC143 showed that both pyrene and AMOP are not effective in monitoring the association because of the low solubility of the probes in the pure fluorocarbon micelles. However, much better probing ability of the two probes were found in the case of F-PEG. This can be attributed to the H/F character of the microdomains, which markedly improves the affinity between the probes and the microdomains. PyCORf, carrying a fluorocarbon chain, shows an excellent affinity to the fluorocarbon micelles and consequently serves as an effective probe of F-PEG. The excimer characteristics of PyCORf in micelles of F-PEG indicate that the longer the CF_2 chains of the hydrophobe in F-PEG, the higher the solubility of PyCORf in the microdomains.

Acknowledgment. This work was supported by National Natural Science Foundation of China (NNSFC, 29992590, 59773023) and the National Basic Research Project−Macromolecular Condensed State.

LA000412L