Do Fluorocarbon, Hydrocarbon, and Polycyclic Aromatic Groups Intermingle? A Study of the Interactions in Water between Fluorocarbon- and Hydrocarbon-Modified Poly(*N*-isopropylacrylamides)

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Received: December 12, 2001

Fluorescence spectroscopy and isothermal titration calorimetry (ITC) have been used to study the intermixing in water of fluorescently labeled poly(*N*-isopropylacrylamides) grafted at random with low levels of either fluorocarbon or hydrocarbon chains. In aqueous solution, the copolymers form micellar structures consisting of a loose corona of hydrated poly(*N*-isopropylacrylamide) chains and a hydrophobic core rich in hydrocarbon or fluorocarbon groups. From fluorescence experiments using nonradiative energy transfer between excited naphthalene and pyrene and from changes in the ratio of pyrene excimer to monomer emission intensity, it has been established that polymeric chains exchange among micelles of hydrocarbon-modified polymers, but not among hydrocarbon- and fluorocarbon-modified polymers. Hydrocarbon- or fluorocarbon-modified polymers were also added to solutions of a copolymer carrying both hydrocarbon and fluorocarbon chains, which in water forms assemblies where the fluorocarbon and hydrocarbon groups segregate into distinct nanodomains within a hydrophobic core. Evidence of fluorescence spectroscopy indicated that intermixing of hydrocarbon-modified polymers with bis(fluorocarbon/hydrocarbon)-poly-(*N*-isopropylacrylamide) perturbs the hydrocarbon-rich nanodomains but not the fluorocarbon-rich ones. The conclusions were corroborated by ITC experiments, which in addition provided strong evidence that intermixing takes place among fluorocarbon-modified poly(*N*-isopropylacrylamides).

Introduction

Like their hydrocarbon counterparts, fluorocarbon amphiphiles self-assemble in water. Several characteristics unique to fluorocarbons not only pose challenging fundamental questions but also make this class of amphiphiles attractive for industrial and biomedical applications.[1,2] Fluorine, the most electronegative of all elements has a high ionization potential and a very low polarizability. The fluorine atom is small, yet it is much larger than hydrogen (van der Waals radius 1.47 Å vs 1.20 Å).[3] Therefore fluorocarbon chains occupy a larger volume (∼1.5 times larger) than the corresponding hydrocarbons.[4] Another consequence of the larger size of the fluorine atom is the greater stiffness of perfluorinated chains.[5] To minimize steric hindrance, perfluorinated chains adopt a helical conformation.[6] Fluorinated amphiphiles show lower critical micellar concentration (cmc) and higher surface activity than their hydrocarbon analogues.[7] The most fascinating property of fluorocarbon chains is their simultaneous hydrophobic and lipophobic nature. As a consequence, fluorinated amphiphiles exhibit limited miscibility with hydrocarbon amphiphiles[8] or organic solvents;[9] thus, macro- or microphase separation takes place in mixed hydrocarbon/fluorocarbon amphiphiles.

This peculiar behavior has stimulated interest in "hybrid" amphiphiles bearing hydrocarbon and fluorocarbon groups in the same molecule. Pioneering work in this area originates in the group of Kunitake, who reported the preparation and properties of various double- and triple-chain amphiphiles combining fluorocarbon and hydrocarbon chains.[10] Other examples of hybrid amphiphiles include families of "gemini" cationic surfactants having a hydrocarbon and fluorocarbon chain connected at their headgroups.[11] Hybrid amphiphiles tend to enhance the miscibility of hydrocarbon surfactants with fluorocarbon surfactants, which in the absence of hybrid amphiphiles have limited mutual miscibility. Like their low molecular analogues, hybrid amphiphilic polymers consisting of a water-soluble segment carrying both fluorocarbon and hydrocarbon groups are expected to exhibit unique properties in aqueous solution. Conceptually, they may form multicompartment micelles, a phrase coined by Ringsdorf[12] and de Gennes,[13] who compared their assembly to that of multidomain proteins and pointed out that the ability to constrain two different micellar domains in close spatial proximity may provide new solutions to problems associated with molecular recognition and catalysis.

Several examples of hybrid hydrophobically modified (HM) polymers have been described recently, including HM-polyacrylamides prepared by micellar terpolymerization of acrylamide with hydrocarbon and fluorocarbon monomeric surfactants incorporated in demixed fluorocarbon and hydrocarbon micelles,[14] polysoaps carrying fluorocarbon and hydrocarbon side chains in a block copolymer structure,[15] poly(*N*-acylethyleneimine) end-capped with a fluorocarbon and a hydrocarbon chain,[16] and HM-polymers consisting of a poly(*N*-isopropylacrylamide) (PNIPAM) backbone grafted randomly with $^{1}H,^{1}H$-perfluorooctyl groups and *N*-(*n*-octadecyl)-*N*-[4-(1-pyrenyl) butyl] groups (PNIPAM-F/HPy; Figure 1).[19] Studies of aqueous

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10.1021/jp0145053 CCC: $22.00 © 2002 American Chemical Society
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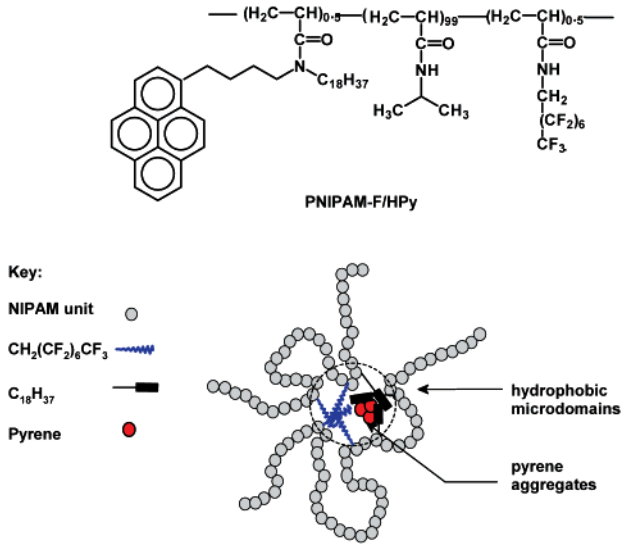

Figure 1. Chemical structure of the hybrid HM-copolymer PNIPAM-F/HPy and pictorial representation of the micellar assemblies of this polymer in water.

solutions of this polymer by fluorescence spectroscopy and isothermal titration calorimetry (ITC) have indicated that it forms multipolymeric micelles where the hydrocarbon, fluorocarbon, and polycyclic aromatic groups assemble into distinct nanodomains coexisting within a hydrophobic core surrounded by the hydrophilic polymer main chains (Figure 1).[19] To satisfy the definition of multicompartment micelles, assemblies of PNIPAM-F/HPy in water should be able to promote reactions taking place only within the fluorinated sites or only within the hydrocarbon sites.

To test this hypothesis, we designed a study by fluorescence spectroscopy and isothermal titration calorimetry (ITC) of the interactions between the hybrid HM-polymer PNIPAM-F/HPy and various HM-PNIPAM samples carrying either hydrocarbon chains or fluorocarbon chains. The fluorescence measurements relied on two photophysical processes: pyrene excimer formation[17] and nonradiative energy transfer (NRET) between naphthalene (Np, energy donor) and pyrene (Py, energy acceptor).[18] The structure of the polymers used in the fluorescence experiments was such that the chromophores, linked in close proximity to a hydrocarbon chain, sense changes in the hydrocarbon domains of the hybrid micelles. The ITC experiments were designed to assess the interactions of the fluorocarbon-rich microdomains with themselves or with hydrocarbon-rich microdomains.

Experimental Section

Materials and Solution Preparation. Water was deionized with a Millipore Milli-Q water purification system. The polymers were prepared by AIBN-initiated free radical polymerization in dioxane as described previously: (PNIPAM-F, PNIPAM-F/HPy),[19] (PNIPAM-H, PNIPAM-HPy),[20] and (PNIPAM-HNp, PNIPAM-HPy/HNp).[21] Their structures are shown in Figure 2. Important physical properties are listed in Table 1.

Fluorescence Spectroscopy. Steady-state fluorescence spectra were recorded on a SPEX Industries Fluorolog 212 spectrometer equipped with a GRAMS/32 data analysis system. Temperature control of the samples was achieved using a water-jacketed cell holder connected to a Neslab circulating bath. The temperature of the sample fluid was measured with a thermocouple immersed in a water-filled cuvette placed in one of the four cell holders in the sample compartment. All measurements

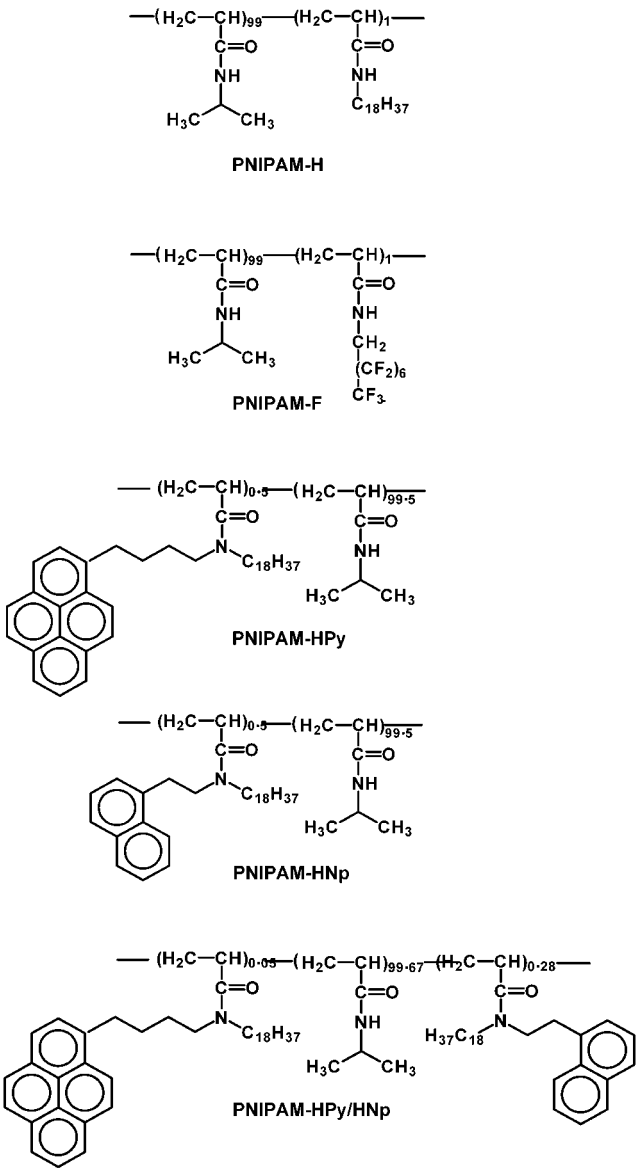

Figure 2. Chemical structure and composition of the polymers used in this study.

were carried out at 25 °C unless otherwise stated. The slit settings were 1.0 (excitation) and 1.0 mm (emission). Emission spectra were recorded with an excitation wavelength of 346 (pyrene) or 290 nm (naphthalene). They are not corrected. Excitation spectra were measured in the ratio mode. They were monitored at 378 (monomer emission) and 485 nm (excimer emission). Solutions were not degassed. Samples for analysis were prepared from stock solutions (5.0 or 0.5 g L^{-1}) kept first at 5 °C for 24 h to ensure complete dissolution of the polymer and then at room temperature for at least 3 h. Mixed solutions were obtained by dilution of polymer stock solutions. They were kept in the dark at room temperature for 12 h prior to measurements.

The pyrene excimer-to-monomer ratio (I_E/I_M) was calculated by taking the ratio of the intensity (peak height) at 480 nm to the intensity of the half sum of the intensities at 380 and 400 nm. The extent of pyrene emission because of NRET from naphthalene was assessed from the value of the ratio I_{Py}/I_{Np} of the emission intensity at 380 nm (pyrene) to the emission intensity at 340 nm (naphthalene).

Fluorescence lifetimes were measured on a Fluorolog-Tau-3 multifrequency phase modulation fluorimeter (Jobin-Yvon

TABLE 1: Molecular and Physical Properties of the Polymers

	composition (mol %)							
polymer	NIPAM	$C_{18}H_{37}$	$CH_2C_7F_{15}$	Py	Np	M_v	cloud point (°C)	ref
PNIPAM-F	99		1			180 000	30.0	19
PNIPAM-H	99	1				360 000	31.5	20
PNIPAM-HPy	99	1		1		390 000	30.6	20
PNIPAM-F/HPy	99.5	0.5	0.5	0.5		130 000	30.4	19
PNIPAM-HNp	99.5	0.5			0.5	279 000	30.4	21
PNIPAM-HPy/HNp	98.18	1.82		1.55	0.27	235 000	30.8	21

Horiba Inc.). The excitation light from a 450 W xenon lamp was modulated with a Pockels cell. Phase and modulation values were determined relative to a glycogen aqueous solution. The excitation wavelength was set at 346 nm. Pyrene monomer and excimer emissions were monitored at 376 and 480 nm, respectively. The frequency of the analyzing light was chosen in the range of 0.1−100 MHz. All measurements were carried out at 25 °C. Data were analyzed with the Datamax Spectroscopy software based on GRAMS/32 from Galactic Ind. Data were fit to a multiexponential decay law, where a_i and τ_i are the preexponential factors and the lifetime of the i th component, respectively. The goodness of the fit was determined by the χ^2 value ($\chi^2 < 1.1$) and examination of the residuals. The preexponential factors a_i are related to the observed fractional intensity contribution f_i by the relation $f_i = a_i\tau_i/\sum_j a_j\tau_j$. The average lifetime $\langle\tau\rangle$ was calculated from $\langle\tau\rangle = \sum a_i\tau_i^2/\sum a_i\tau_i$.

Isothermal Titration Calorimetry (ITC). ITC measurements were performed using a VP−ITC titration microcalorimeter (MicroCal Inc.). The sample cell had a volume of 1.43 mL. A solution of a polymer (5.0 g L^{-1}) was titrated into water or into a polymer solution placed in the sample cell. The injection volume was 5 μL. A total of 58 consecutive injections were performed. The delay time between two consecutive injections was 300 s. All measurements were carried out at 25 °C. Data were analyzed using the Microcal ORIGIN software. The results are presented in terms of the enthalpy evolved per mol of injectant (NIPAM unit) as a function of the total injectant concentration. The principles and basic thermodynamic conventions of ITC are discussed in a recent publication.[22] Solutions for analysis were prepared by dilution of polymer stock solutions (5.0 g L^{-1}). They were kept in the dark at room temperature for 24 h prior to measurements.

Results and Discussion

Spectroscopy of the Labeled Polymers: A Brief Review. The steady-state fluorescence spectra of dilute aqueous solutions of PNIPAM-HPy and PNIPAM-F/HPy consist of two contributions: a well-resolved emission with the (0,0) band located at 376 nm due to locally isolated excited pyrene (pyrene monomer emission, intensity I_M) and a strong, broad, and featureless emission centered at 478 nm attributed to the emission of pyrene excimer (intensity I_E; Figure 3). The fact that pyrene excimer emission is so strong, even though the pyrene solution concentration is low ($\sim 10^{-6}$ mol L^{-1}) implies that the pyrene groups are in close spatial proximity, constrained within hydrophobic microdomains. From a combination of steady-state and time-resolved measurements, it was ascertained that the excimer observed in spectra of aqueous PNIPAM-HPy solutions forms via the dynamic encounter of an excited pyrene and a ground-state pyrene.[20,23] On the contrary, the excimer emission recorded from aqueous solutions of PNIPAM-F/HPy originates from preformed ground-state pyrene aggregates.[19] This disparity in pyrene photophysics indicates differences in the microstructure of the hydrophobic cores of PNIPAM-F/HPy

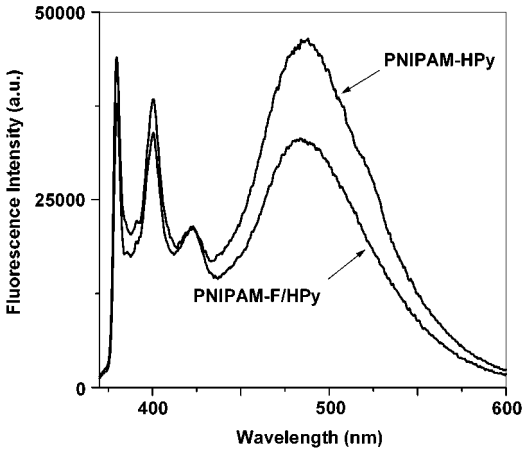

Figure 3. Fluorescence spectra of PNIPAM-HPy and PNIPAM-F/HPy in water; polymer concentration, 0.05 g L^{-1}; temperature, 25 °C; λ_{exc} = 346 nm.

and PNIPAM-HPy. Even though the pyrene groups of PNIPAM-F/HPy are attached to the same amide nitrogen as the hydrocarbon chains, they sense the presence of fluorocarbon chains, which have a poor affinity toward aromatic groups.[24,25] Thus, within hydrophobic microdomains, pyrene groups assemble in close proximity to avoid unfavorable interactions with the fluorocarbon chains (Figure 1).[19]

The pyrene−naphthalene pair of chromophores is known to interact as an energy donor (naphthalene) and energy acceptor (pyrene) by NRET with a characteristic distance, R_0, of 29 Å.[26] Using an excitation wavelength of 290 nm, a wavelength at which most of the light is absorbed by naphthalene, one can detect both the direct emission of naphthalene and the emission of pyrene excited through NRET from Np*. Thus, under circumstances where the pyrene and naphthalene groups are in close enough proximity to satisfy the NRET requirements, excitation at 290 nm will result in a complex emission consisting of the emission from Np* (310−400 nm) and the emission of Py* excited by transfer of energy from Np*. Excitation at 346 nm will result in an emission that is due exclusively to directly excited pyrene, with no contribution from the naphthalene chromophores which do not absorb light of this wavelength. The emission spectrum of the doubly labeled polymer PNIPAM-HPy/HNp dissolved in water, upon excitation at 290 nm, exhibits features characteristic of efficient energy transfer between Np* and Py (Figure 4): a strong pyrene emission ($\lambda_{em} > 370$ nm) and a naphthalene emission (300 nm $< \lambda_{em} <$ 360 nm). The latter emission is lower in intensity than that of a solution of a polymer labeled with naphthalene only, present in identical concentration as in the solution of PNIPAM-HPy/HNp ([Np] $= 5.4 \times 10^{-4}$ mol L^{-1}). Fluorescence lifetimes of the pyrene and naphthalene chromophores confirmed the occurrence of energy transfer: (1) The decay of Np* is extremely fast ($\tau \sim 1$ ns), especially by comparison with the fluorescence lifetime ($\tau \sim 60$ ns) of Np* linked to PNIPAM-HNp, where energy transfer cannot occur, and (2) the time-dependent-profile of Py* presents

TABLE 2: Composition of the Solutions Used in the Energy Transfer Experiments

polymer	[Py] (mol L^{-1})	[Np] (mol L^{-1})	[$C_{18}H_{37}$] (mol L^{-1})	[$CH_2C_7F_{15}$) (mol L^{-1}]
PNIPAM-F/HPy (0.125 g L^{-1}) and PNIPAM-HNp (0.125 g L^{-1})	5.3×10^{-6}	5.4×10^{-6}	10.7×10^{-6}	5.3×10^{-6}
PNIPAM-HPy/HNp (0.05 g L^{-1}) and PNIPAM-H (0 to 0.45 g L^{-1})	0.2×10^{-6}	1.2×10^{-6}	$(1.4-40) \times 10^{-6}$	
PNIPAM-HPy/HNp (0.05 g L^{-1}) and PNIPAM-F (0 to 0.45 g L^{-1})	0.2×10^{-6}	1.2×10^{-6}	1.4×10^{-6}	$(0-38.6) \times 10^{-6}$

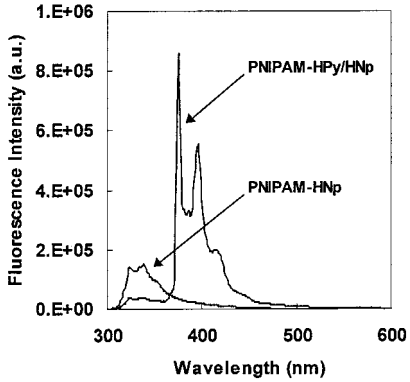

Figure 4. Fluorescence spectra of PNIPAM-HPy/HNp (0.225 g L^{-1}) and PNIPAM-HNp (0.125 g L^{-1}) in water; temperature, 25 °C; $\lambda_{exc} =$ 290 nm.

a short-lived ($\tau \sim 3$ ns) growing-in component corresponding to the energy transfer process.

Mixing Behavior. In the following sections, we describe the mixing behavior of PNIPAM-F, PNIPAM-H, or PNIPAM-HNp with either PNIPAM-HPy or PNIPAM-F/HPy. We report also changes in the emission spectrum of the doubly labeled polymer PNIPAM-HPy/HNp upon mixing with either PNIPAM-F or PNIPAM-H. In all cases, the concentration of the pyrene-labeled polymer was kept constant, and the second component was added in increasing amounts. The compositions of the solutions used in NRET experiments are reported in Table 2.

(a) Mixing PNIPAM-HPy and PNIPAM-F or PNIPAM-H. In this experiment, the emission of the pyrene-labeled polymer, the "host" polymer (concentration 0.05 g L^{-1}), was measured in aqueous solutions containing increasing amounts of unlabeled "guest" polymer, PNIPAM-H or PNIPAM-F. The presence of the hydrocarbon-modified guest, PNIPAM-H, drastically affected the fluorescence of PNIPAM-HPy. The monomer emission increased at the expense of the excimer emission, which all but disappeared when the host and guest polymers are present in equimolar concentration in terms of NIPAM units. This result is presented in Figure 5a where the values of the ratio I_E/I_M of the excimer emission intensity, I_E, and of the monomer emission intensity, I_M, are plotted as a function of the guest polymer concentration. The ratio decreases from a value of 1.30 in the absence of PNIPAM-H to a plateau value of ~0.15 in mixed solutions of equimolar PNIPAM-H and PNIPAM-HPy concentration. This spectroscopic observation is taken as an indication of the dilution of the hydrophobic core of PNIPAM-HPy micelles by PNIPAM-H octadecyl chains that provide a solubilizing environment for the pyrene chromophores. In mixed polymer micelles, pyrene groups are separated from each other, and with sufficient added chains, they are kept apart from each other at distances too large for efficient excimer formation.

In contrast, addition of PNIPAM-F to a solution of PNIPAM-HPy caused only minor changes in the emission of PNIPAM-HPy, namely, a small decrease in excimer emission intensity with concomitant increase in monomer emission intensity. The corresponding ratio I_E/I_M decreased to a value approximately

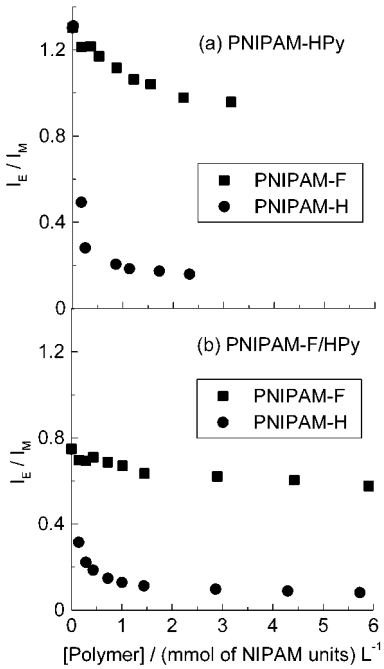

Figure 5. Plot of the changes as a function of guest polymer concentration of the ratio I_E/I_M of pyrene excimer emission intensity to pyrene monomer emission intensity for solutions of PNIPAM-HPy (a) and PNIPAM-F/HPy (b); labeled polymer concentration, 0.05 g L^{-1}; full circle, guest, PNIPAM-H; full square, guest, PNIPAM-F.

80% of the starting value, even in solutions containing up to a 7-fold excess of PNIPAM-F (Figure 5a). The failure of PNIPAM-F to alter the emission of PNIPAM-HPy is a consequence of the incompatibility of the hydrophobic cores of PNIPAM-F and PNIPAM-HPy. We tested the reluctance to mix of the two types of polymeric micelles by subjecting mixed solutions to prolonged standing in the dark at room temperature (up to 36 h) or by heating them to 35 °C, a temperature higher than their cloud point. Neither treatment resulted in changes in the emission of PNIPAM-HPy, independently of the total polymer concentration or the number of heating/cooling cycles.

(b) Mixing PNIPAM-F/HPy and PNIPAM-F or PNIPAM-H. The next set of mixing experiments focuses on the emission of Py linked to a polymer chain modified with *fluorocarbon and hydrocarbon chains*. Addition of the hydrocarbon-modified polymer PNIPAM-H to solutions of this polymer triggered changes in pyrene emission similar to those already described in the mixed PNIPAM-HPy and PNIPAM-H system. The monomer emission intensity increased, whereas the excimer emission intensity decreased accordingly with increasing amounts of PNIPAM-H. The results are presented in Figure 5b, where the spectroscopic changes are reported in terms of the dependence on guest polymer concentration of the ratio, I_E/I_M, of pyrene excimer to monomer emission intensities of the chromophore linked to the host polymer. The fluorocarbon-modified guest polymer, PNIPAM-F, only modestly affected the emission of PNIPAM-F/HPy solutions: the ratio I_E/I_M declined by ~20% of its value in a PNIPAM-F/HPy solution even in the presence

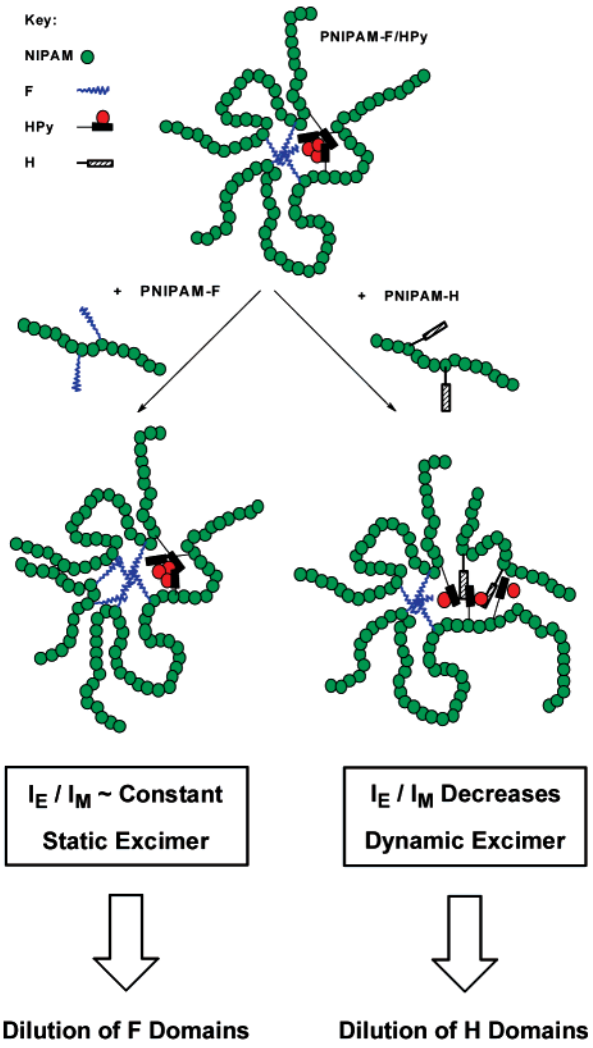

Figure 6. Conceptual representation of the interactions occurring in aqueous solutions of PNIPAM-F/HPy in the presence of PNIPAM-F or PNIPAM-H.

of a vast excess of PNIPAM-F (up to 14 molar excess, Figure 5b). Additional treatments effected on mixed solutions, such as heating/cooling cycles, resulted in no further changes of the I_E/I_M values. A conceptual representation of the interactions between host and guest polymers is given in Figure 6, which highlights the incompatiblity of hydrocarbon and fluorocarbon domains.

(c) Mixing of PNIPAM-F/HPy and PNIPAM-HNp. Excitation of naphthalene (λ_{exc} 290 nm) in a mixed solution of PNIPAM-F/HPy and PNIPAM-HNp resulted in an emission with a very strong contribution from the pyrene monomer (360−400 nm) and a weak contribution from excited naphthalene (maximum at 340 nm). By comparing this emission to the spectra recorded for solutions of individual polymers, one observes concurrent quenching of naphthalene emission and enhancement of pyrene monomer emission (Figure 7), implying that the polymers intermix placing Py and Np* linked to different polymers in close enough proximity to permit NRET. The extent of energy transfer, assessed by the ratio I_{Py}/I_{Np} (see the Experimental Section), increases with PNIPAM-HNp concentration (Figure 8, bottom). Pyrene excimer emission intensity, recorded from direct pyrene excitation (λ_{exc} 346 nm), also depends on PNIPAM-HNp concentration. The ratio I_E/I_M decreases abruptly upon addition of small amounts of PNIPAM-HNp and reaches

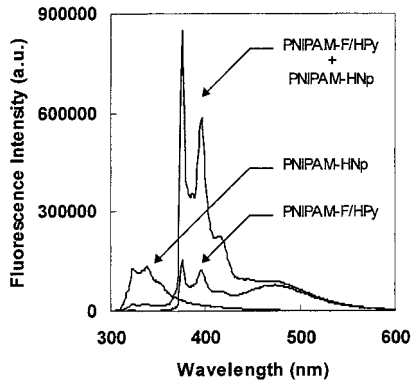

Figure 7. Fluorescence spectra of solutions in water of PNIPAM-HNp (0.125 g L^{-1}), PNIPAM-F/HPy (0.125 g L^{-1}), and of a mixture of PNIPAM-F/HPy (0.125 g L^{-1}) and PNIPAM-HNp (0.125 g L^{-1}); λ_{exc} = 290 nm.

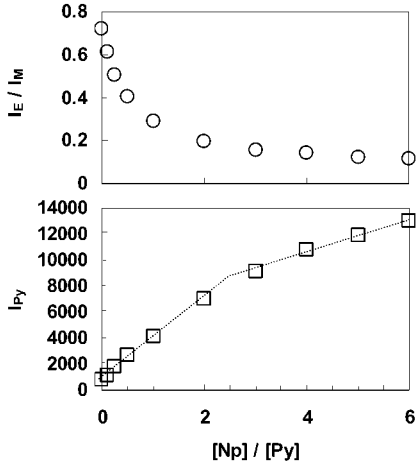

Figure 8. Changes in I_E/I_M (top) and in pyrene monomer emission intensity (bottom) as a function of the molar ratio of Np and Py in mixed aqueous solutions of PNIPAM-HNp and PNIPAM-F/HPy.

a near constant value for [PNIPAM-HNp] > 0.125 g L^{-1} (Figure 8, top).

The time-resolved profile of the Py* monomer (λ_{exc} 290 nm) in mixed solutions of PNIPAM-F/HPy and PNIPAM-HNp features a rising component (τ = 35 ns) corresponding to the process of energy transfer from Np* to Py (Table 3). The decay profile of Py* can be fitted with two components. The average decay time (~156 ns) is similar to the value recorded upon direct pyrene excitation (λ_{exc} 346 nm). The pyrene excimer profile exhibits a growing-in component (τ = 11.6 ns) followed by a decaying component, consistent with the dynamic excimer formation process. Therefore, addition of PNIPAM-HNp relieves the pyrene ground-state aggregation observed in solutions of PNIPAM-F/HPy,[19] presumably via insertion of the octadecyl chains in the pyrene-rich microdomains formed in solutions of PNIPAM-F/HPy.

(d) Mixing of PNIPAM-HPy/HNp and PNIPAM-F or PNIPAM-H. In this last set of experiments, the host polymer was the doubly labeled polymer PNIPAM-HPy/HNp (concentration, 0.05 g L^{-1}). It was brought in contact with an unlabeled "guest" polymer, PNIPAM-H or PNIPAM-F. Addition of increasing amounts of PNIPAM-H to a solution resulted in a gradual decrease in the extent of intrapolymeric Np* to Py energy transfer, as observed in Figure 9, which presents emission spectra (λ_{exc} 290 nm) of PNIPAM-HPy/HNp solutions containing increasing amounts of PNIPAM-H, and in Figure 10, which

TABLE 3: Fluorescence Lifetimes of Pyrene and Naphthalene in Aqueous Solutions of PNIPAM-HNp, PNIPAM-HPy, and PNIPAM-F/HPy and in Mixed Polymer Solutions

sample	λ_{exc} (nm)	λ_{em} (nm)	τ_1 (ns)	a_1	τ_2 (ns)	a_2	τ_3 (ns)	a_3	$\langle\tau\rangle$ (ns)
PNIPAM-HNp	290	340	4.5	0.04	55.4	0.96			55.2
PNIPAM-HPy	346	380	28.1	0.29	121	0.71			94
		480	24.0	−0.28	29.5	0.28	80.8	0.72	66
PNIPAM-F/HPy	346	380	24.6	0.22	118.4	0.77			113.1
		480	83.8	1.0					
PNIPAM-F/HPy + PNIPAM-HNp	290[a]	380	35.3	−0.31	36.0	0.43	169.1	0.87	156.4
([Np]/[Py] =1)	346	380	10.0	0.04	62.8	0.25	165.2	0.75	154.9
		480	11.6	−0.04	96.4	1.0			96.4

[a] The emission at 340 nm (Np*) was too weak to allow accurate lifetime determinations.

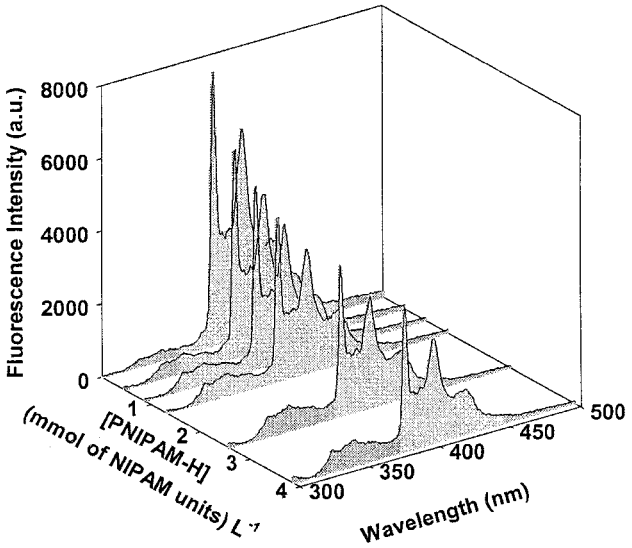

Figure 9. Fluorescence spectra of PNIPAM-HPy/HNp (0.05 g L^{-1}) measured at several PNIPAM-H concentrations; λ_{exc} = 290 nm.

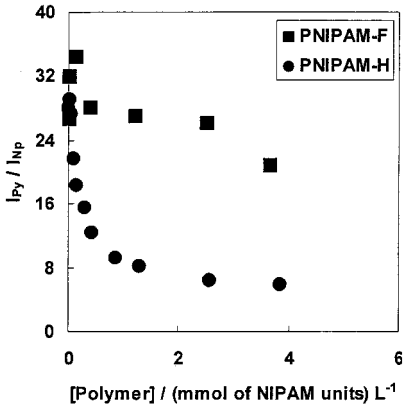

Figure 10. Changes in the ratio I_{Py}/I_{Np} of pyrene monomer to naphthalene emission intensities for aqueous PNIPAM-HPy/HNp solutions (0.05 g L^{-1}) in the presence of different amounts of PNIPAM-F (full squares) or PNIPAM-H (full circles); λ_{exc} = 290 nm.

displays the dependence of the ratio I_{Py}/I_{Np} on PNIPAM-H concentration. The decrease in the extent of energy transfer reflects a dilution of existing Py- and Np-containing hydrophobic domains by the octadecyl chains linked to PNIPAM-H and corroborates the effect of added PNIPAM-H on the extent of Py excimer formation in solutions of PNIPAM-HPy (see section a). The ratio I_{Py}/I_{Np} of the host polymer was hardly affected by the presence of increasing amounts of the fluorinated polymer PNIPAM-F (Figure 10). This trend is yet another consequence of the paucity of the interactions of hydrocarbon-rich microdomains with fluorocarbon-rich microdomains, as depicted in Figure 11, which provides a pictorial representation of the microstructures formed in various polymer solutions before mixing (left-hand side) and in mixed solutions (right-hand side).

Overall, these findings confirm the incompatibility of the fluorocarbon core of PNIPAM-F micelles with the pyrene-rich domains of the hydrophobic core of PNIPAM-F/HPy micelles. However, they give no information on a possible mixing of fluorocarbon chains of PNIPAM-F and PNIPAM-F/HPy, as they could occur without affecting the photophysics of pyrene. The ITC experiments described next were aimed at assessing interactions of fluorocarbon chains and hydrocarbon chains.

Isothermal Titration Calorimetry (ITC) Studies. In a typical ITC experiment, aliquots of a concentrated solution of PNIPAM-F were injected into either water or an aqueous polymer solution kept at 25 °C. The heat evolved after each injection was measured, and the area under each peak was plotted against the polymer concentration. The enthalpogram obtained by dilution of PNIPAM-F in water (Figure 12a, open squares) exhibited marked concentration dependence. In the low concentration regime (<4 mmol NIPAM units L^{-1}), the heat evolved was large, but it decreased rapidly with increasing concentration to level off at high concentration. The enthalpogram reflects the following events. After the first few injections, the large enthalpic effect corresponds to the dilution of polymeric micelles, demicellization, and dissolution of individual polymer chains. As more polymer solution is added, there comes a point, beyond a critical aggregation concentration, for which the polymeric micelles no longer dissociate and the heat evolved is due only to the dilution of polymeric micelles. The process is analogous to the demicellization of surfactants, a process studied extensively by ITC. The enthalpogram provides estimates of the enthalpy of demicellization of PNIPAM-F [−10 cal (mol^{-1} NIPAM)][19] and of the critical aggregation concentration ($\sim 1.5 \times 10^{-3}$ mol NIPAM L^{-1} or 0.17 g L^{-1}).[19]

We carried out next a titration of PNIPAM-F under the same conditions, except that the sample cell did not contain water but aqueous solutions of a "host" polymer of concentration higher than the critical aggregation concentration. Thus, PNIPAM-F was titrated into solutions of either PNIPAM-F or PNIPAM-F/HPy. It was expected that, if the injected polymer, PNIPAM-F, intermixes with the host polymer, the heat of interaction should be reflected in the corresponding enthalpogram. Indeed, the enthalpograms recorded (Figure 12a, full circles and full inverted triangles) were different from the enthalpogram recorded upon dilution of PNIPAM-F in water (Figure 12a, open squares). Enthalpograms recorded upon injection of PNIPAM-F into solutions of PNIPAM-H and of PNIPAM-HPy are presented in Figure 12b (full triangles and full diamonds, respectively). Both enthalpograms were identical, within experimental error, to the curve recorded upon titration of PNIPAM-F in water. This result implies that the dilution of PNIPAM-F micelles and the demicellization of PNIPAM-F proceeds without disruption of the host polymer aggregates. It

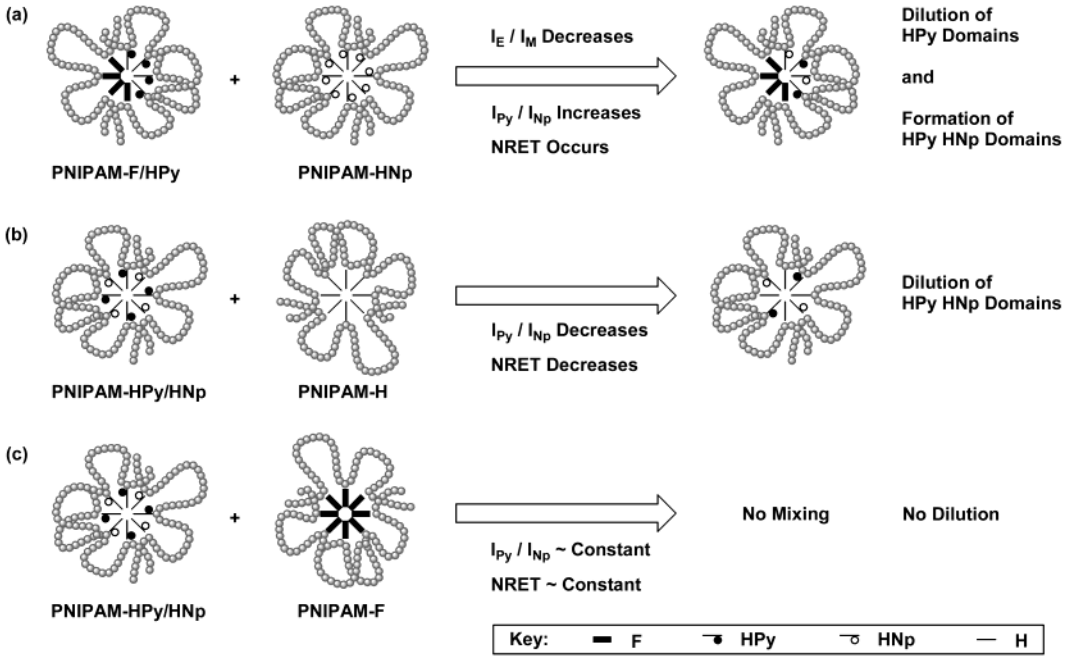

Figure 11. Conceptual representation of the interactions between fluorocarbon and hydrocarbon microdomains of the polymeric micelles under study, as detected by nonradiative energy transfer between naphthalene and pyrene linked to two different polymer chains (a) or to the same polymer chain (b) and (c).

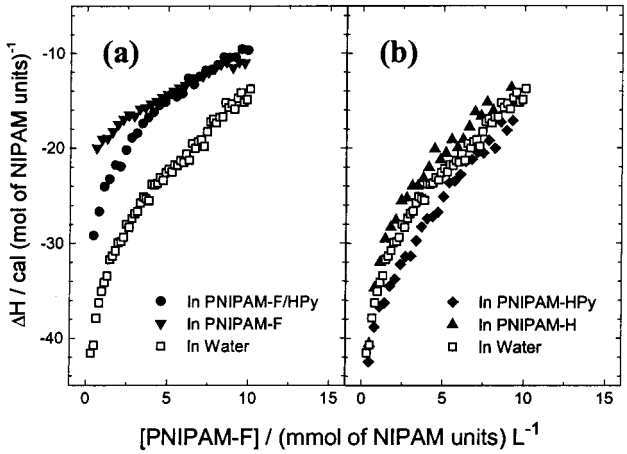

Figure 12. Dilution enthalpograms for a solution of PNIPAM-F (5 g L^{-1}) in water (open squares) and in aqueous solutions of PNIPAM-F (inverted full triangle), PNIPAM-F/HPy (full circle), PNIPAM-H (full triangle), and PNIPAM-HPy (full diamond); polymer concentration in the cell, 0.5 g L^{-1}; temperature, 25 °C.

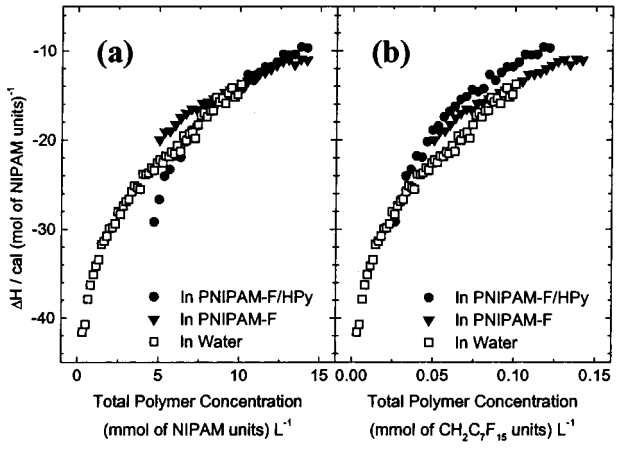

Figure 13. Dilution enthalpograms for a solution of PNIPAM-F (5 g L^{-1}) in water and in aqueous solutions of PNIPAM-F and PNIPAM-F/HPy as a function of total polymer concentration (a, NIPAM monomer units; b, $CH_2C_7F_{15}$ units); polymer concentration in the cell, 0.5 g L^{-1}; temperature, 25 °C.

corroborates the results of fluorescence measurements indicating that fluorocarbon and hydrocarbon microdomains within polymeric micelles do not intermix.

It should be noted that the enthalpograms presented in Figure 12 display the heat of dilution as a function of the concentration of polymer titrated into the cell and not as a function of total polymer concentration. This representation was justified in the case of titrations of PNIPAM-F in water. For titrations of PNIPAM-F into a solution already containing the polymer, it is more relevant to consider in the abscissa the total polymer concentration. Modified enthalpograms are presented in Figure 13, where the abscissa is the total polymer concentration in the cell (Figure 13a, NIPAM units; Figure 13b: $-CH_2C_7F_{15}$ units). We observe that the corrected dilution curves for the addition of PNIPAM-F into water and into a PNIPAM-F solution now coincide, implying that the added polymer interacts with the host polymer (itself) and that intermixing of the fluorocarbon microdomains takes place. When the enthalpograms are recorded as a function of fluorocarbon chain concentration (Figure 13b), the dilution curves of PNIPAM-F into water, aqueous PNIPAM-F, and aqueous PNIPAM-F/HPy superimpose, within experimental error. This observation, on the one hand, provides further strength to a mechanism of polymer interaction that involves mingling of the fluorocarbons microdomains. On the other hand, the fact that dilution of PNIPAM-F was not affected by the presence in solution of polymers carrying hydrocarbon chains (Figure 12b) supports our conclusion based on fluorescence measurements that fluorocarbon and hydrocarbon microdomains within polymeric micelles do not intermix.

Conclusions

We have reported a study of the interactions between hydrocarbon- and fluorocarbon-modified poly(*N*-isopropylacrylamides) using two complementary techniques: fluorescence

spectroscopy and ITC. The spectroscopic measurements relied on the photophysics of pyrene and naphthalene chromophores grafted along the polymer backbone. All of the modified polymers form multipolymeric micelles in water. From experiments assessing the energy transfer efficiency between donor and acceptor chromophores, it was concluded that micelles consisting of hydrocarbon-modified polymers freely intermix, presumably via exchange of individual polymer chains between micelles. In contrast, micelles of fluorocarbon-modified polymers do not interact with micelles of hydrocarbon modified-polymers, at least not within the time and distance scale probed by the fluorescence measurements. The ITC experiments allowed us to confirm the occurrence of specific interactions among hydrocarbon-modified polymers, among fluorocarbon-modified polymers but not between H- and F-modified polymers.

Experiments carried out with a hybrid polymer, randomly grafted with hydrocarbon and fluorocarbon groups, uncovered the distinct tendency of hydrocarbon-modified polymers to disrupt the hydrocarbon-rich nanodomains of hybrid H/F polymer micelles without affecting the fluorocarbon-rich nanodomains. The preliminary results presented here need to be strengthened through the use of hybrid H/F modified polymers that form micellar assemblies with distinct fluorocarbon and hydrocarbon compartments.

Acknowledgment. This work was supported by a grant of the Natural Sciences and Engineering Research Council of Canada to F.M.W. and by a fellowship to P.K. from the International Atomic Energy Agency, Vienna, Austria.

References and Notes

(1) Kissa, E. *Fluorinated Surfactants*; Dekker: New York, 1993.
(2) Krafft, M. P. *Adv. Drug Delivery Rev.* **2001**, *47*, 209.
(3) Bondi, A. *J. Phys. Chem.* **1964**, *68*, 441.
(4) Mukerjee, P.; Mysels, K. J. *ACS Symp. Ser.* **1975**, *9*, 239.
(5) Eaton, D. F.; Smart, B. E. *J. Am. Chem. Soc.* **1990**, *112*, 2821.
(6) Rigby, H. A.; Bunn, C. W. *Nature* **1949**, *164*, 583.
(7) Mukerjee, P.; Mysels, K. J. *Critical Micelle Concentrations of Aqueous Surfactant Systems*, NSRDS−NBS-36; U.S. Government Printing Office: Washington, DC, 1971.
(8) Elbert, R.; Folda, T.; Ringsdorf, H. *J. Am. Chem. Soc.* **1984**, *106*, 7687.
(9) Ishikawa, Y.; Kuwahara, H.; Kunitake, T. *J. Am. Chem. Soc.* **1989**, *111*, 8530.
(10) Kunitake, T.; Higashi, N. *J. Am. Chem. Soc.* **1985**, *107*, 692.
(11) Oda, R.; Huc, I.; Danino, D.; Talmon, Y. *Langmuir* **2000**, *16*, 9759.
(12) Lehmann, P.; Ringsdorf, H. *Int. Symp. Polym. Theor.* **1996**, 78.
(13) De Gennes, P. G. *C. R. Acad. Sci., Ser. II−B* **1999**, *327*, 535.
(14) Stähler, K.; Selb, J.; Candau, F. *Langmuir* **1999**, *15*, 7565.
(15) Kotzev, A.; Laschewsky, A. *Polym. Prepr. (Am. Chem. Soc. Div. Polym. Chem.)* **1998**, *39* (2), 942.
(16) Weberskirch, R.; Preuschen, J.; Spiess, H. W.; Nuyken, O. *Macromol. Chem. Phys.* **2000**, *201*, 995.
(17) Winnik, F. M. *Chem. Rev.* **1993**, *93*, 587.
(18) Lakowicz, J. R. *Principles of Fluorescence Spectroscopy*, 2nd ed.; Kluwer Academic/Plenum Publishers: New York, 1999; p 368.
(19) Kujawa, P.; Goh, C. C. E.; Calvet, D.; Winnik, F. M. *Macromolecules* **2001**, *34*, 6387.
(20) Ringsdorf, H.; Venzmer, J.; Winnik, F. M. *Macromolecules* **1991**, *24*, 1678.
(21) Ringsdorf, H.; Simon, J.; Winnik, F. M. *Macromolecules* **1992**, *25*, 5253.
(22) *Biocalorimetry, Applications of Calorimetry in the Biological Sciences*; Ladbury, J. E., Chowdhry, B. Z., Eds.; John Wiley & Sons: Chichester, U.K., 1998.
(23) Birks, J. B. *Rep. Prog. Phys.* **1975**, *38*, 903.
(24) Kalyanasundaram, K. *Langmuir* **1988**, *4*, 492.
(25) Almgren, M.; Wang, K.; Asakawa, T. *Langmuir* **1997**, *13*, 4335.
(26) Winnik, F. M. *Polymer* **1990**, *31*, 2125.