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ARTICLE *in* MACROMOLECULES · AUGUST 2005

Impact Factor: 5.8 · DOI: 10.1021/ma0510082

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Chain Mixing and Segregation in B−C and C−D Diblock Copolymer Micelles

Jiwen Hu and Guojun Liu*

Department of Chemistry, Queen's University, 90 Bader Lane, Kingston, Ontario, Canada K7L 3N6

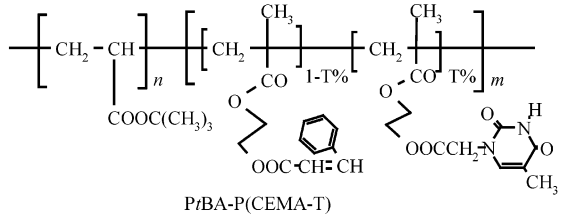
Received May 16, 2005; Revised Manuscript Received July 3, 2005

ABSTRACT: In a block-selective solvent for the B and D blocks of two diblock copolymers B−C and C−D, both diblocks should form micelles. Normally chains of the different diblocks do not mix significantly or comicellize for repulsion between the B and D coronal chains. This paper describes the tagging of the C blocks by adenine (A) and thymine (T), a H-bonding nucleic acid pair, to enhance mixing of the different diblock chains in a micelle. This enhancement effect has been observed in the premixed micelles prepared by first mixing the two diblocks in a solvent good for all of the three blocks and then adding a block-selective solvent for B and D. The A and T tagging has been shown also to enhance mixing of chains of different diblocks among the premade or the initially pure B−C and C−D micelles. While the A and T tagging helped give mixed micelles or micelles consisting of chains of both diblocks, the intrinsic repulsion between the B and D chains made them segregate into interesting patterns, including being two-faced and flowerlike in the coronas of the mixed premade micelles. Mixed micelles with surface-segregated chains may have intriguing applications.

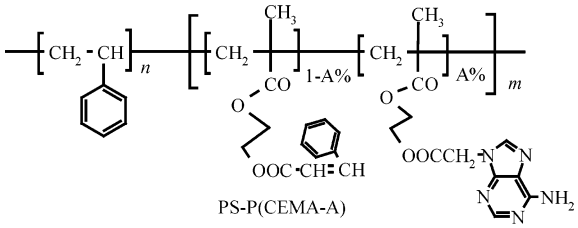
I. Introduction

Mixed micelles of B−C and C−D diblock copolymers with the insoluble C block as the core possess B and D chains in their coronas. Since the B and D chains are likely to be incompatible, the distribution of these chains in the confined 2-d space of the micelle corona can be very intriguing. In principle, this distribution should be affected by the degree of incompatibility between B and D, the relative B and D amount, solvency, etc. If the B and D chains do segregate to form B- and D-rich domains, we anticipate interesting applications for such mixed micelles. Despite the possible fascinating physical chemistry of chain mixing in such a micelle and the potential applications of the mixed micelles, these micelles have been rarely studied, mainly because they do not form easily for repulsion between the B and D chains. This paper reports a new strategy to facilitate B−C and C−D chain mixing in a micelle. The strategy works well in enhancing chain mixing in the "comicelles" or "premixed micelles" that are prepared by first mixing the two diblocks in a solvent good for all of the three blocks and then adding a block-selective solvent for B and D. It enhances as well chain mixing in the "mixed premade micelles" that are prepared by mixing and equilibrating the initially pure B−C and C−D micelles. Also reported in this paper are some fascinating coronal chain segregation patterns in the mixed premade micelles.

The proposed strategy relies on compensating the repulsion between the B and D blocks by increasing the affinity between the C blocks of the different diblocks. We achieved the latter by tagging the C blocks of the different diblocks with a H-bonding pair adenine and thymine. More specifically, we have prepared for this project the diblocks poly(*tert*-butyl acrylate)-*block*-poly{(2-cinnamoyloxyethyl methacrylate)-*ran*-[2-(1′-thyminylacetoxyethyl methacrylate)]}, P*t*BA-P(CEMA-T), and polystyrene-*block*-poly{(2-cinnamoyloxyethyl methacrylate)-*ran*-[2-(1′-adeninylacetoxyethyl methacrylate)]}, PS-P(CEMA-A):



P*t*BA-P(CEMA-T)



PS-P(CEMA-A)

P*t*BA was chosen here as the B block for its ready hydrolysis to poly(acrylic acid) or PAA, which was then stained by uranyl acetate for differentiation by transmission electron microscopy (TEM) from PS. PCEMA was chosen as the C block for its photo-cross-linkability. The cross-linking of the PCEMA core allowed the locking of the micellar structure and thus the subsequent hydrolysis of the P*t*BA block with minimal chain position shuffling in the micelles.

There have been several precedents on the preparation of block copolymers micelles with mixed corona chains. Shi and co-workers[1] claimed, on the basis of dynamic light scattering (DLS) observations alone, chain mixing among the premade B−C and C−D micelles in water where the B block consisted of PAA and the D block consisted of poly(amino propylene−glycol methacrylate). The driving force for chain mixing in this case was attributed to H-bond formation between the B and D blocks in the coronas. Gohy et al.[2] prepared comicelles from two triblock copolymers B−C−D and E−F−E with the C and F blocks being poly(2-vinylpyridine), P2VP, and PAA. The driving force for comicellization was polyelectrolyte complex (PEC) formation

10.1021/ma0510082 CCC: $30.25
Published on Web 08/20/2005

between the C and F blocks. Since the PEC was insoluble, it made up the core of the micelles. For this special case with B, D, and E being polystyrene (PS), poly(ethylene glycol), and a comb copolymer with ethylene glycol oligomers as the combs, the authors were able to discern by TEM the formation of segregated circular PS domains in the corona. Luo and Eisenberg[3] prepared covesicles from polystyrene-*block*-poly(4-vinylpyridine), PS-P4VP, and PS-PAA. To suppress PEC formation between P4VP and PAA, they used pH = 3 at which PAA was protonated. The driving force for covesicle formation in water in this case was the thermodynamic requirement for the shorter water-soluble chains, e.g. PAA, to segregate into the inside and the longer water-soluble chains, i.e., P4VP, on the outside of the vesicular wall. Schrage et al.[4] have also claimed the preparation of diblock covesicles with segregated corona chains recently. The driving force for covesicle formation in THF in this case was due to PEC formation between poly(cesium methacrylate) and poly(*N*-methyl-4-vinylpyridinium iodide).

Aside from mixed diblock micelles, micelles containing different types of chains in the corona can also be prepared from a triblock copolymer B−C−D in a solvent with the C block insoluble. While there have been many reports on the preparation of core−shell−corona micelles from B−C−D triblocks in a solvent with either the B block insoluble or both the B and C blocks insoluble,[5,6] there have been only a few reports on micelles with the middle C block insoluble.[7] The possibility for corona chain segregation in these cases was not addressed until very recently.[8,9]

A variation of the spherical micelles, i.e., block copolymer nanospheres or cross-linkeed spherical micelles, with surface-segregated chains has been prepared recently via the solid-state synthesis approach.[10] In this approach, a B−C−D triblock was so designed that C formed a spherical domain decorating the interface between the B and D lamellae. The nanospheres were obtained after cross-linking the C block and dispersing the cross-linked spherical domains in a solvent good for the B and D blocks. In this case, the B and D chains are segregated with each type occupying one hemisphere on the C core surface.

II. Experimental Section

Materials and Reagents. Only one PS-PHEMA sample and one P*t*BA-PHEMA sample were used in this project, where PHEMA denotes poly(2-hydroxyethyl methacrylate). These samples were derived from PS-P(HEMA-TMS) and P*t*BA-P(HEMA-TMS) with P(HEMA-TMS) denoting poly(2-trimethylsiloxyethyl methacrylate). PS-P(HEMA-TMS)[11] and P*t*BA-P(HEMA-TMS)[12] were prepared by anionic polymerization. PS-PCEMA,[11] P*t*BA-P(CEMA-T),[13] and 6-*N*-(benzyloxycarbonyl)-9-(carboxymethyl) adenine,[14] **1**, were prepared following literature methods. Reagents 1,3-dicyclohexylcarbodiimide (DCC, 99%), *p*-toluenesulfonic acid monohydrate (TSA·H_2O, 98.5%), cinnamoyl chloride (98%), 4-(dimethylamino)pyridine (DMP, 99%), trifluoroacetic acid (99%), and cyclopentane (CP, 99+%) were all purchased from Aldrich and used as received. Pyridine (Aldrich, 99+%) was dried by refluxing and distillation over CaH_2. CH_2Cl_2 and $CHCl_3$, both of ACS grade, were purchased from Fisher Scientific. $CHCl_3$ was purified by washing with water to remove ethanol. It was then dried over $CaCl_2$ overnight before distillation.

PS-P(HEMA-1). Compound **1** was attached to the PHEMA block of PS-PHEMA via esterification of the hydroxyl groups of PHEMA by the carboxyl groups of **1**. In an example run, PS-PHEMA, 0.70 g containing 0.93 mmol of hydroxyl groups, and **1**, 0.0605 g or 0.186 mmol, were dissolved in 50 mL of pyridine. Then added was 0.0071 g or 0.037 mmol of the catalyst TSA, which was obtained from dehydrating TSA·H_2O.[15] This mixture was cooled to 0 °C before DCC, 0.0766 g or 0.371 mmol dissolved in 5 mL of dry pyridine, was added dropwise. After stirring at room temperature for 20 h, the mixture was dialyzed against methanol changed four times over 2 days in a tube with a molar mass cutoff of 12 000−14 000 g/mol. PS-P(HEMA-**1**), 0.730 g, was obtained after its precipitation in hexanes and drying under vacuum.

PS-P(CEMA-A). PS-P(HEMA-**1**), 0.70 g containing 0.74 mmol of hydroxyl groups, was dissolved in 45 mL of pyridine. To it was added cinnamoyl chloride, 0.232 g or 1.39 mmol, dissolved in 5 mL of pyridine. The mixture was stirred overnight, centrifuged to remove pyridinium chloride, and then added dropwise into excess methanol to precipitate the polymer. After drying under vacuum, 0.813 g of PS-P(CEMA-*r*-**1**) solid was obtained.

PS-P(CEMA-A) was prepared by removing the benzyloxycarbonyl (Cbz) protective groups from PS-P(CEMA-**1**). In an example procedure, 0.80 g of PS-P(CEMA-**1**) was dissolved in 20 mL of CH_2Cl_2. To it was added 20 mL of TFA. The mixture was refluxed under nitrogen for 4 h. TFA was then removed by vacuum distillation, and the remaining volatiles were removed by azeotropic distillation under nitrogen with chloroform thrice to give a solid. The sample was lastly dissolved in 5 mL of pyridine to neutralize the amino groups of the adenine groups before it was added dropwise into excess methanol to precipitate the polymer. After vacuum-drying 0.78 g of PS-P(CEMA-A) was obtained.

Polymer Characterization. Proton NMR analysis was performed on a Bruker 300 spectrometer. The analysis of PS-P(CEMA-*r*-**1**) was done in deuterated *N*,*N*-dimethylformamide (DMF-d_7), and those of the other samples were done in $CDCl_3$. All size exclusion chromatographic (SEC) analyses were performed on a Waters system equipped with one Styragel HT4 and one μStyragel column. The eluant used was tetrahydrofuran, and calibration standards used were monodisperse PS samples. Light scattering was done using a Brookhaven model 9025 instrument equipped with a 632.8 nm He−Ne laser. The difference, Δn_r, between the refractive index of a diblock solution and its solvent was determined using a differential refractometer (Precision Instruments Co.) with light that had passed a band-pass filter centered around 633 nm. The specific refractive index increments, dn_r/dc, were obtained from the intercept of a $\Delta n_r/c$ vs c plot, where c denotes polymer concentration.

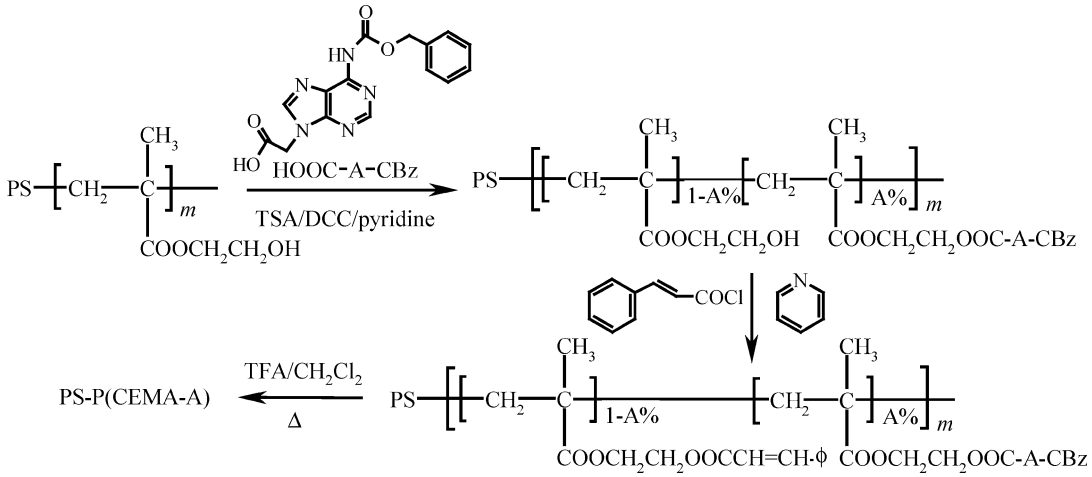
Preparation of Diblock Micelles. Micelles of all diblocks were prepared in chloroform and cyclopentane (CP) at v/v = 1/5 or a CP volume fraction of f_{CP} = 83%. An example procedure involved dissolving 6.0 mg of a diblock in 1.0 mL of chloroform. The mixture was stirred for at least 4 h before 5.0 mL of CP was added dropwise. Micelles were stirred for at least 24 h for equilibration before physical examination. The critical micellar concentration (cmc) of PS-PCEMA was considerably lower than those of the other diblocks. To facilitate dynamic light scattering (DLS) studies, micelles of this sample were prepared at 3.0 mg/mL.

Mixing of Premade Micelles. Premade micelles of different polymers were mixed always at an equal concentration and volume. PS-P(CEMA-A) and P*t*BA-P(CEMA-T) micelles were mixed at c = 1.0 mg/mL. PS-PCEMA and P*t*BA-P(CEMA-T) micelles were mixed at c = 3.0 mg/mL.

Premixed Micelles. Premixed micelles were obtained by dissolving the premixed diblocks in $CHCl_3$ and then adding CP. To prepare premixed micelles from PS-P(CEMA-A) and P*t*BA-P(CEMA-T), PS-P(CEMA-A) and P*t*BA-P(CEMA-T) each at 3.0 mg were dissolved in 1.0 mL of chloroform. The mixture was stirred for at least 24 h before 5.0 mL of CP was added dropwise. Micelles were stirred for at least another 24 h before study. Premixed PS-PCEMA and P*t*BA-P(CEMA-T) micelles were prepared similarly but with a concentration that was 3 times higher.

Micelle Cross-Linking and Hydrolysis. The micelles were cross-linked in a UV cell by a focused light beam from a

Scheme 1. Preparation of PS-P(CEMA-A)



500 W Hg lamp passed through a 270 nm cutoff filter for 60−100 min. The PCEMA double bond conversion measured from the absorbance decrease at 274 nm was between 30% and 35% for all samples.

To hydrolyze the P*t*BA chains of the cross-linked micelles or nanospheres, the spheres were dried and then redispersed in CH_2Cl_2. TFA at v/v = 1/3 relative to CH_2Cl_2 was added to the nanosphere solution. The resultant mixture was stirred for 4 h. Solvents were removed from the hydrolyzed sample by rotaevaporation first and then under vacuum. The dried sample was redispersed in DMF for storage or further processing.

DLS Measurements. Micelle solutions at a concentration of either 1.0 or 3.0 mg/mL were used for DLS measurements at a scattering angle of 90° at 22 °C. The samples were clarified by passing through 0.2 μm filters. The viscosity for the solvent mixture $CHCl_3$/CP at f_{CP} = 83% was determined to be 0.453 cP by comparing the flow times and densities of the solvent mixture and chloroform, which has a viscosity of 0.558 cP at 22 °C.[16] The refractive index of the mixture was estimated from the sum of the individual component's value each multiplied by its volume fraction. The instrument used was of a Brookhaven 9025 model equipped with a He−Ne laser operated at 632.8 nm. The data were analyzed by the cumulant method to yield the average hydrodynamic diameter d_h and polydispersity K_1^2/K_2, where K_1 and K_2 denote the first- and second-order cumulants, respectively.[17]

TEM Measurements. A Hitachi-7000 instrument was operated at 75 kV to obtain the TEM images. Micelle samples were sprayed onto carbon-coated copper grids using a home-built device[18] and stained with OsO_4 vapor for 4 h before observation. The PAA-bearing nanosphere samples were first dispersed in DMF before they were aspirated onto mica-supported carbon films. After DMF evaporation, drops of a uranyl acetate solution at 0.05 g/mL were added on the films to stain the PAA groups of the nanospheres for 10 min. The excess staining agent was removed with a filter paper. The samples were then rinsed with drops of methanol 6 times before carbon films were floated off the mica surface in water and picked up by TEM copper grids for observation.

III. Results and Discussion

In this section, we start by describing the synthesis and characterization of the diblocks used. We then show enhancement in the degree of chain mixing by TEM in the PS-P(CEMA-A)/P*t*BA-P(CEMA-T) premixed micelles relative to the PS-PCEMA/P*t*BA-P(CEMA-T) premixed micelles. This is followed by a discussion of chain mixing among the premade micelles.

Polymer Synthesis. Of the PS-P(CEMA-A), P*t*BA-P(CEMA-T), and PS-PCEMA samples used, the syntheses of PS-PCEMA[11] and P*t*BA-P(CEMA-T)[13] have been reported before. Thus, only the preparation of PS-P(CEMA-A) is discussed in some length here. Scheme 1 shows the reaction steps involved.

With the use of dry PS-PHEMA and dry pyridine, the reaction between the hydroxyl groups of PHEMA and **1** or HOOC-A-CBz (Scheme 1) was efficient at ∼80%. Since **1** was the limiting reagent with a feed molar ratio of 20% relative to HEMA, this corresponded to a hydroxyl group labeling efficiency or A% of 16%. This labeling efficiency was readily determined from ^{1}H NMR analysis of PS-P(HEMA-**1**) using unique peaks such as peaks G, O, and P for adenine in Figure 1.

The cinnamation of the hydroxyl groups of PHEMA was essentially quantitative. The removal of the benzylcarboxyl (−CBz) group required the refluxing of PS-P(CEMA-**1**) in CH_2Cl_2/TFA. The quantitative removal of the −CBz group under the stated conditions was established from the disappearance of the methylene proton NMR absorption peak at ∼5.3 ppm for −CBz. Figure 1 shows the ^{1}H NMR spectrum of the final

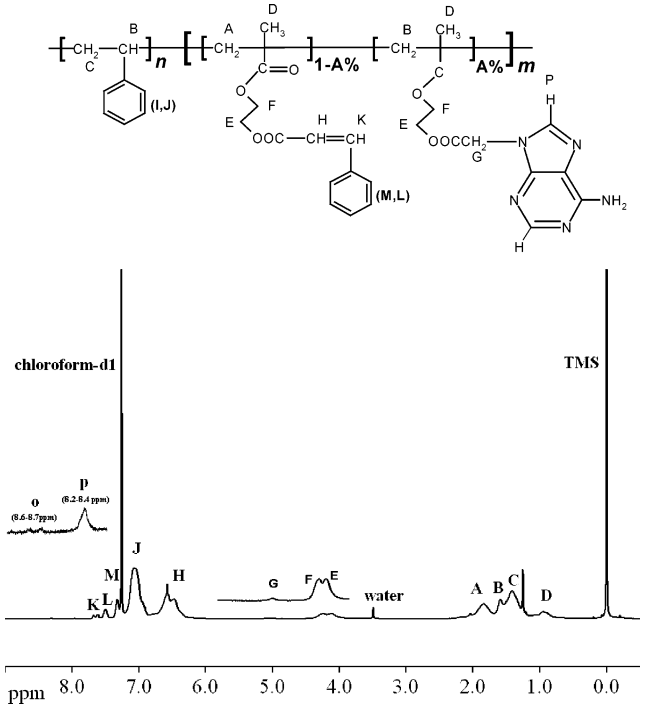


Figure 1. NMR spectra of PS-P(CEMA-A) with peak assignments.

Table 1. Characteristics of the Diblocks Used

sample	SEC M_w/M_n	SEC M_w	dn_r/dc (mL/g)	LS M_w (g/mol)	NMR n/m	n_w	T% or A%
PS-P(CEMA-A)	1.25	5.0×10^4	0.158[a]	5.1×10^{4a}	6.5	360	16
PS-PCEMA	1.17	5.8×10^4					
P*t*BA-P(CEMA-T)	1.11	4.7×10^4	0.114 [b]	6.4×10^{4b}	3.2	305	10

[a] Measured in DMF. [b] Measured in butanone.

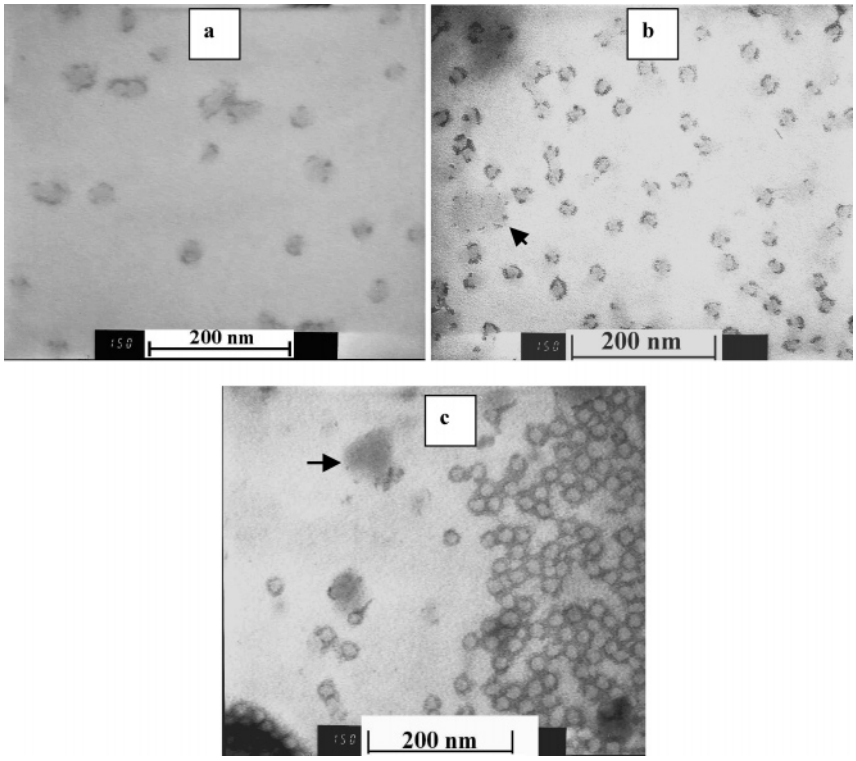


Figure 2. TEM images of nanospheres derived from premixed micelles of PS-P(CEMA-A)/P*t*BA-P(CEMA-T) **(a)** and PS-PCEMA/P*t*BA-P(CEMA-T) **(b)**. Also shown is a TEM image of the pre-cross-linked and then mixed PS-P(CEMA-A) and P*t*BA-P(CEMA-T) nanospheres **(c)**. For all samples the P*t*BA block had been hydrolyzed and stained by uranyl acetate.

product measured in $CDCl_3$ with all proton peaks assigned.

Polymer Characterization. Of the three samples used, PS-PCEMA and PS-P(CEMA-A) were derivatives of the same PS-PHEMA sample. Table 1 compares the SEC results for the two samples. PS-P(CEMA-A) has a higher polydispersity than PS-PCEMA probably for the stronger interaction between the adenine groups and the column packing material and thus the slight tailing of the PS-P(CEMA-A) peak. Despite this, the weight-average molar masses M_w of the two samples agree with each other. We thus assume that the extra reaction steps taken to prepare PS-P(CEMA-A) did not degrade or cross-link the original PS-PHEMA sample and that the n and m values were the same for the two polymers.

PS-P(CEMA-A) and P*t*BA-P(CEMA-T) were further analyzed by a differential refractometer to determine the specific refractive index dn_r/dc, by LS to determine the weight-average molar mass M_w, and by ^{1}H NMR to obtain n/m, A%, and T%. Table 1 summarizes the characterization results for these samples. The A% and T% values are 16% and 10%, respectively. Since the weight-average m or m_w values for PS-P(CEMA-A) and P*t*BA-P(CEMA-T) are 55 and 95, respectively, the weight-average numbers of A and T groups per chain for both samples are ~9.

Chain Mixing in Premixed Micelles. We prepared the premixed micelles by premixing the two diblocks in $CHCl_3$ for 24 h before CP addition. The samples were stirred in $CHCl_3$ for 24 h mainly to facilitate and allow time for H-bond formation between the different diblock chains. To check whether T and A tagging helped improve diblock chain mixing, we examined by TEM the distribution of the PS and P*t*BA chains in the coronas of the premixed micelles of PS-P(CEMA-A)/P*t*BA-P(CEMA-T) and of PS-PCEMA/P*t*BA-P(CEMA-T). This required a selective staining agent for either PS or P*t*BA. While the phenyl rings of PS could be selectively stained by RuO_4,[19] this staining method was nonideal because it gave a very messy background and a low contrast between PS and P*t*BA. For better results, we took advantage of the cross-linkability of PCEMA. After PCEMA cross-linking to yield permanent structures that we call nanospheres, we hydrolyzed the P*t*BA chains and then stained the resultant PAA with $UO_2(OOCCH_3)_2$ to bring out the contrast between the two polymers. Because of structural locking afforded by PCEMA cross-linking, we expected minimal chain position shuffling in a micelle before and after P*t*BA hydrolysis.

Figure 2 compares the TEM images of the PS-P(CEMA-A)/PAA-P(CEMA-T) and PS-PCEMA/PAA-P(CEMA-T) nanospheres derived from the corresponding premixed micelles. To facilitate discussion, we have prepared also micelles separately from PS-P(CEMA-A) and P*t*BA-P(CEMA-T). These micelles were then cross-linked before they were mixed, subjected to P*t*BA hydrolysis, and stained with uranyl acetate before TEM

Table 2. DLS Results for the Diblock Micelles and Nanospheres in $CHCl_3$/CP at f_{CP} = 83%

sample	d_h/nm	K_1^2/K_2	c/(mg/mL)
PS-P(CEMA-A) micelles	36.6 ± 0.8	0.051 ± 0.021	1.0
PS-P(CEMA-A) nanospheres	35.9 ± 0.2	0.054 ± 0.006	1.0
P*t*BA-P(CEMA-T) micelles	45.8 ± 0.7	0.049 ± 0.009	1.0
P*t*BA-P(CEMA-T) nanospheres	45.0 ± 0.4	0.048 ± 0.004	1.0
PS-P(CEMA-A)/P*t*BA-P(CEMA-T) micelles ~10 min after mixing	39.9 ± 0.9	0.064 ± 0.046	1.0
PS-P(CEMA-A)/P*t*BA-P(CEMA-T) nanosphere mixture	39.8 ± 0.7	0.061 ± 0.005	1.0
PS-P(CEMA-A)/P*t*BA-P(CEMA-T) micelles 4 days after mixing	41.8 ± 0.3	0.032 ± 0.010	1.0
PS-PCEMA micelles	31.3 ± 0.3	0.103 ± 0.021	3.0
PS-PCEMA/P*t*BA-P(CEMA-T) micelles ~10 min after mixing	40.0 ± 0.4	0.061 ± 0.016	3.0
PS-PCEMA/P*t*BA-P(CEMA-T) nanosphere mixture	39.6 ± 0.5	0.066 ± 0.007	3.0
PS-PCEMA/P*t*BA-P(CEMA-T) micelles 4 days after mixing	40.2 ± 0.2	0.057 ± 0.011	3.0

observation. We notice the following features about the particles in the three TEM images. First, the discernible particles in Figure 2c for the pre-cross-linked nanospheres and Figure 2b for the PS-PCEMA/PAA-P(CEMA-T) nanospheres appear similar and have a clear core−shell structure with the core lighter and shell darker. While the shell is uniformly dark in Figure 2c, light dents are found in the shells of the particles in Figure 2b. The particles in Figure 2c have a darker shell and a lighter core because the shell consisted of the stainable PAA and the core consisted of the nonstainable cross-linked P(CEMA-T). The reason for the formation of such 2-D TEM images from the 3-D core−shell nanospheres has been explained by many researchers before for vesicles,[20] where the "nonstainable core" consisted of void space. The core−shell contrast is reduced in Figure 2b, and most of the shells are not uniformly dark because there had been some mixing between the PS-P(CEMA-A) and P*t*BA-P(CEMA-T) chains.

Second, the PS-P(CEMA-A)/PAA-P(CEMA-T) nanospheres in Figure 2a look very different from those in Figure 2b,c. For those which still have a recognizable shell, the shells are badly segmented, and the core−shell contrast is drastically reduced. Instead of the core−shell particles, we see some particles that are almost uniformly gray or particles whose images are not circular at all. Third, the average diameters of the core−shell particles in parts c and b of Figure 2 are ~23 and ~22 nm, respectively. This value increased to ~30 nm for the "spherical" particles in Figure 2a.

The drastically different appearance of the PS-P(CEMA-A)/PAA-P(CEMA-T) nanospheres has to be explained by the more extensive mixing between the two types of diblock chains. The contrast between the different regions of the spheres appears much reduced is in Figure 2a because the PAA chains were not concentrated in a dense thin layer around the core any more. Rather, many of the PAA chains were interspersed and trapped among the PS chains in this case. This conclusion is also reaffirmed by the size changes of the discernible particles in the three images. The TEM diameters of the particles in Figure 2b,c are essentially the same, suggesting a minimal perturbation by PS-PCEMA to P*t*BA-P(CEMA-T) micelle formation or minimal comicellization of the two types of chains. On the other hand, the size of the particles increased substantially for the PS-P(CEMA-A) and P*t*BA-P(CEMA-T) micelles.

We have so far not addressed the whereabouts of the PS-P(CEMA-A) nanospheres in Figure 2c and the PS-P(CEMA-A)-rich nanospheres in Figure 2b. These spheres should not be very legible but exist mainly as background materials. Two of such regions consisting probably of the aggregated PS-P(CEMA-A)-rich and PS-P(CEMA-A) nanospheres are marked by arrows in Figure 2b,c. Because of incorporation of some P*t*BA-P(CEMA-T) chains into the original PS-PCEMA micelles, we can vaguely delineate the contour of some PS-PCEMA-rich nanospheres in the marked region of Figure 2b, thus suggesting the validity of our claim.

DLS Study of Chain Mixing in Premade Micelles. Results of the above subsection demonstrated that tagging of the PCEMA block with T and A helped improve diblock mixing in the premixed micelles. In this subsection we show by DLS that the strategy helped enhance chain mixing in premade micelles as well. To this effect, DLS was used to follow changes in the hydrodynamic diameter d_h and polydispersity K_1^2/K_2 of the micelles with time t after their mixing.

Table 2 shows the d_h values of 36.6 ± 0.8 and 45.8 ± 0.7 nm for the individual PS-P(CEMA-A) and P*t*BA-P(CEMA-T) micelles. Approximately 10 min after their mixing the d_h value of the mixture was 39.9 ± 0.9 nm. This value increased to 41.8 ± 0.3 nm 4 days after micelle mixing. The intermediate d_h values are plotted as a function of t in Figure 3. The data clearly show an initial increasing and then a leveling-off trend. The fact that the d_h values increased with t suggests possible chain mixing among micelles of the different diblocks. If chains of the different diblocks did not mix and only chain exchange among micelles of the same diblock was possible, we would have witnessed a decrease in d_h. The d_h value would have decreased because the concentration of each diblock was decreased by a factor of 2 after micelle mixing, and some micelles should have dissociated into unimers. The decrease in d_h would have been negligible, of course, if the concentration of the diblocks used in DLS was far above their cmc.

We have determined also the d_h values for the PS-PCEMA and P*t*BA-P(CEMA-T) micelles at different times after their mixing. A higher polymer concentration was used here as the PS-PCEMA cmc was higher than 1.0 mg/mL. Approximately 10 min after micelle mixing, the d_h value of the mixture was 40.0 ± 0.4 nm. This value remained constant or changed insignificantly to 40.2 ± 0.2 nm 4 days after micelle mixing. Also plotted in Figure 3 are the d_h values at the intermediate t. The fact that the d_h values changed with t insignificantly suggests *plausibly* a low degree of chain mixing in this case.

The above conclusion is not without ambiguity because the magnitude of d_h change is not directly correlated with the degree of chain mixing. It is, for example, possible to have the final size of the perfectly chain-mixed micelles the same as that of the initial micelle mixture. In this case, a lack of net changes in d_h is not correlated with chain mixing at all. Then, a lack of significant changes in d_h within our observation time frame, i.e., between ~10 min and 4 days, does not necessarily mean that the d_h value did not experience

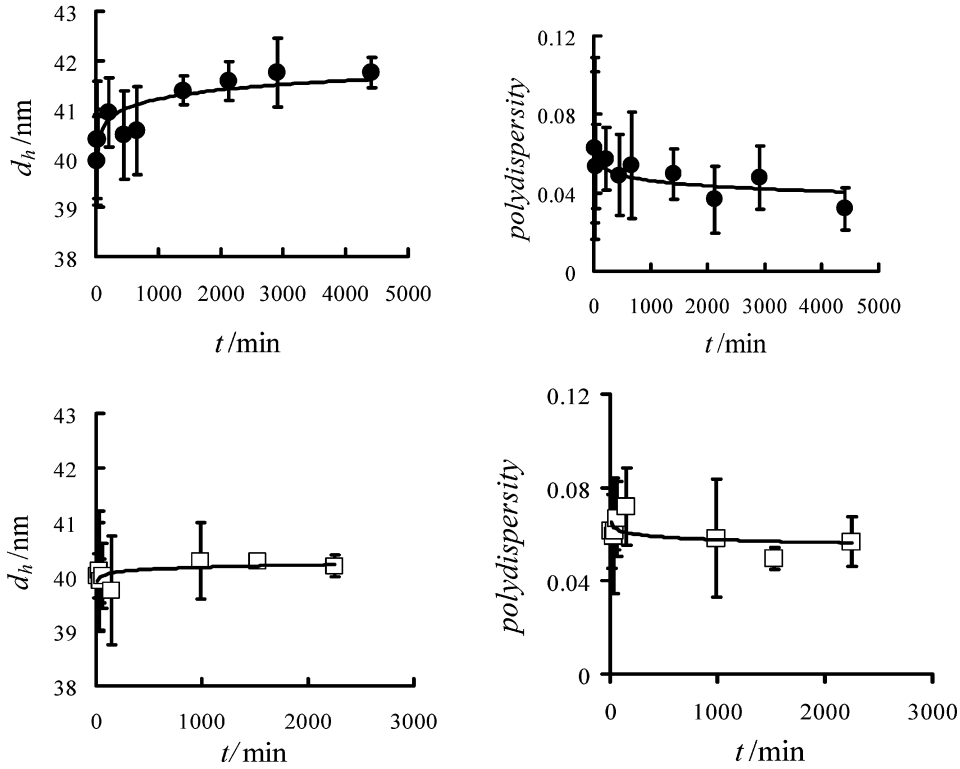


Figure 3. Variation in the hydrodynamic diameter d_h and polydispersity K_1^2/K_2 as a function of time for a PS-P(CEMA-A)/P*t*BA-P(CEMA-T) micelle mixture (●) and a PS-PCEMA/P*t*BA-P(CEMA-T) micelle mixture (□).

a sudden change immediately after micelle mixing before we could make a first DLS measurement. This scenario is possible especially for the PS-PCEMA micelles as our previous studies[21] revealed that the chain exchange kinetics increased as the cmc of the micelles increased. To check the validity or invalidity of this hypothesis, we cross-linked the premade micelles separately and then mixed them for d_h measurement. The d_h value for the mixture of the pre-cross-linked PS-PCEMA and P*t*BA-P(CEMA-T) nanospheres was 39.6 $\pm$ 0.5 nm, which is only slightly less than the size of 40.0 $\pm$ 0.4 nm for the freshly mixed micelles. Comparing the d_h values (Table 2) of the pure PS-P(CEMA-A) micelles or those of the P*t*BA-P(CEMA-T) micelles before and after PCEMA cross-linking, we conclude that the small difference between 39.6 $\pm$ 0.5 and 40.0 $\pm$ 0.4 nm was most likely due to micelle core shrinking caused by cross-linking. Thus, there could not have been an abrupt increase in the d_h values of the PS-PCEMA and P*t*BA-P(CEMA-T) micelles immediately after their mixing.

An increase in d_h with t after the mixing of the PS-P(CEMA-A) and P*t*BA-P(CEMA-T) micelles and a negligible change in d_h with t for the PS-PCEMA and P*t*BA-P(CEMA-T) micelles suggest a possible enhancement in chain mixing in the former system due to T−A pairing. This conclusion is corroborated by the polydispersity data K_1^2/K_2 plotted in Figure 3. For the former system, a greater decrease in K_1^2/K_2 with t and a smaller final K_1^2/K_2 value were observed. These are possible only if there had been a gradual conversion from an initially bimodal system (two groups of micelles of different sizes) to a system with a narrower size distribution.

TEM Study of Chain Mixing in Premade Micelles. While the d_h and K_1^2/K_2 value variation trends suggest more chain mixing for the PS-P(CEMA-A) and P*t*BA-P(CEMA-T) micelles, these are only indirect evidences and the conclusions are tentative and conditional. We obtained more direct evidence for chain mixing from TEM.

TEM can be used to obtain the average diameter and diameter distribution of the micelles at different times after their mixing. The results can then be used similarly as the DLS results to shed light on chain mixing. Figure 4 shows the TEM images of the individual PS-P(CEMA-A) and P*t*BA-P(CEMA-T) micelles stained by OsO_4, which darkened the PCEMA core preferentially. The average diameter for the core of the PS-P(CEMA-A) micelles is ~8 nm, and that for the P*t*BA-P(CEMA-T) micelles is ~12 nm. Because of the small size of the PCEMA core and the poor quality of the TEM images, we opted to gather evidence about chain mixing from the distribution of the coronal PS and P*t*BA chains.

Figure 5 shows two TEM images for the PS-P(CEMA-A)/PAA-P(CEMA-T) and PS-PCEMA/PAA-P(CEMA-T) nanospheres stained by $UO_2(OOCCH_3)_2$. These samples were derived from the corresponding premade micelles after they had been mixed for 4 days. The CEMA units of the mixed micelles were then photo-cross-linked, and the P*t*BA block was hydrolyzed to yield PAA. The differences between the images of the PS-P(CEMA-A)/PAA-P(CEMA-T) and PS-PCEMA/PAA-P(CEMA-T) nanospheres are striking. In the TEM image for the PS-PCEMA/PAA-P(CEMA-T) nanospheres, there are still spheres, marked by arrows, with a seemingly intact PAA shell despite the fact that a large fraction of the discernible spheres do bear a dent or dents in the corona, suggesting the insertion of PS-PCEMA chains into the original P*t*BA-P(CEMA-T) micelles. In contrast, one does not see any intact PAA-P(CEMA-T) nanospheres in the left image of Figure 5. These marked by hollow arrows appear to be two-faced with PAA occupying one-half corona and PS the other half. The

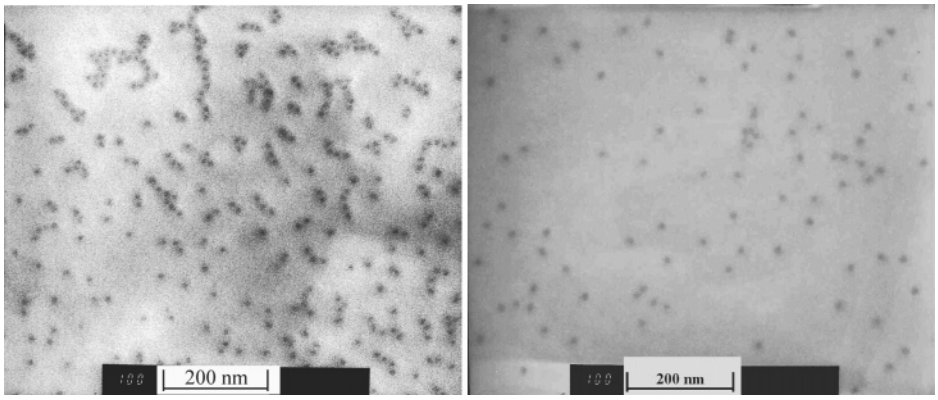


Figure 4. TEM images of PS−P(CEMA-A), left, and P*t*BA-P(CEMA-T), right, micelles. The samples were stained by OsO_4 vapor.

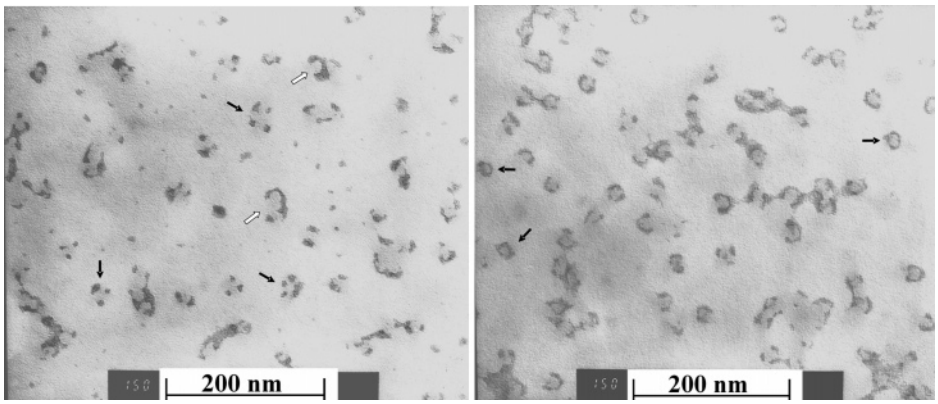


Figure 5. TEM images of the PS-P(CEMA-A)/PAA-P(CEMA-T) nanospheres (left) and PS-PCEMA/PAA-P(CEMA-T) nanospheres (right). The samples were derived from their corresponding micellar mixtures 4 days after micelle mixing.

size of these two-faced spheres suggests that they were derived from the original P*t*BA-P(CEMA-T) micelles. These marked by solid arrows are flowerlike and appear to have formed due to the insertion of the P*t*BA-P(CEMA-T) chains into the original PS-P(CEMA-A) micelles. Thus, the degree of chain mixing is higher among the PS-P(CEMA-A) and P*t*BA-P(CEMA-T) micelles, conforming unambiguously our preliminary conclusion deduced from the DLS results.

Surface Chain Segregation. An intriguing aspect of the mixed diblock micelles has been the segregation of the corona chains. Some PS and P*t*BA chain segregation was observed in Figure 2b and the right image of Figure 5 for the premixed micelles and the mixed premade micelles of PS-PCEMA and P*t*BA-P(CEMA-T). Because of the low degree of chain mixing in these cases, the contrast between the segregated regions is not as sharp as that seen in the left image of Figure 5 for the mixed premade PS-P(CEMA-A)/P*t*BA-P(CEMA-T) micelles. Despite the high degree of chain mixing in the premixed micelles of PS-P(CEMA-A) and P*t*BA-P(CEMA-T), this contrast between PS and P*t*BA was unfortunately again reduced due to a more random distribution of these chains in the corona. Thus, the optimal images for visualizing the chain segregation were obtained for the mixed premade PS-P(CEMA-A) and P*t*BA-P(CEMA-T) micelles. From this approach, we were able to prepare micelles with a range of surface segregation patterns from being two-faced to being flowerlike.

The fact that the surface chains were segregated for the mixed premade PS-P(CEMA-A) and P*t*BA-P(CEMA-T) micelles suggests that chains of a different polymer do not insert into micelles of another polymer at random locations. According to Anainsson and Wall,[22] chain exchange between different micelles takes place in a staged fashion; i.e., only one chain is expelled from or inserted into a micelle at a time. If this mechanism is valid, our TEM results suggest that once one chain of a different polymer has inserted into a micelle of another polymer, this spot becomes more labile toward later attack by the foreign chains. This nonuniform chain mixing is reasonable as the PS and P*t*BA chains are not compatible and have been shown to segregate from one another in the solid state.[23] As for the reason for the formation of different surface segregation patterns, e.g. two-faced vs flowerlike, it remains elusive.

The micelles or nanospheres with patched surface chains will have very interesting applications that remain to be explored. The two-faced nanospheres should be useful as particular surfactants. The flowerlike particles will be useful in controlling the position and number of block copolymer nanotubes attached to each sphere when we perform the chemical coupling of nano- or microspheres with nanotubes to make nanomechanical devices.[24]

The different surface chain segregation patterns between the premixed and the mixed premade micelles of PS-P(CEMA-A)/P*t*BA-(PCEMA-T) suggest that the surface chain distribution equilibrium was not necessarily reached in these systems. For the low mobility of polymer chains and thus the kinetic control of products in many cases, the morphology of aggregates or "micelles" of a pure block copolymer have been known to depend on how the final state was achieved or preparation history.[25] The history dependence of the surface chain segregation patterns of the mixed micelles should thus not be a surprise here.

IV. Conclusions

We have successfully attached adenine groups to PS-PHEMA and then cinnamated the residual HEMA units to yield PS-P(CEMA-A). The resultant block copolymer has been carefully characterized together with P*t*BA-(PCEMA-T) and PS-PCEMA by NMR, SEC, and LS. We then mixed either PS-P(CEMA-A) and P*t*BA-(PCEMA-T) or PS-PCEMA and P*t*BA-(PCEMA-T) in $CHCl_3$ and prepared premixed micelles by adding CP to the diblock mixture. By taking advantage of the photo-cross-linkability of PCEMA, we locked in the structure of the premixed micelles and hydrolyzed the P*t*BA block yielding PAA for selective staining by uranyl acetate. A comparative TEM study of the premixed PS-P(CEMA-A)/P*t*BA-(PCEMA-T) and the PS-PCEMA/P*t*BA-(PCEMA-T) micelles revealed that the tagging of the PCEMA block by A and T enhanced chain mixing. We have also carried out a comparative study of chain mixing among the premade PS-P(CEMA-A)/P*t*BA-(PCEMA-T) and PS-PCEMA/P*t*BA-(PCEMA-T) micelles in $CHCl_3$/CP at $f_{CP} = 83\%$ by DLS and TEM. The study demonstrated again an enhancement in chain mixing due to T and A tagging. More interestingly, chain mixing among the premade PS-P(CEMA-A)/P*t*BA-(PCEMA-T) micelles lead to spherical micelles with the PS and P*t*BA chains segregated in the corona. The segregation pattern ranged from being two faced to being flowerlike. These micelles should have fascinating applications.

Acknowledgment. J.W.H. thanks the Chinese Academy of Sciences for a visiting fellowship, and G.J.L. thanks NSERC of Canada for sponsoring this research. Dr. Xiaohu Yan is acknowledged for obtaining the TEM images.

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MA0510082