Aqueous Solution Properties of pH-Responsive AB Diblock Acrylamido Copolymers Synthesized via Aqueous RAFT[†]

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ABSTRACT: AB diblock and AB statistical copolymers of sodium 2-acrylamido-2-methylpropanesulfonate (AMPS) and sodium 3-acrylamido-3-methylbutanoate (AMBA) have been prepared via aqueous reversible addition−fragmentation chain transfer (RAFT) polymerization. Such AB diblock copolymers were tailored to undergo reversible pH-induced self-assembly given the tunable hydrophilic/hydrophobic nature of the AMBA species. Using a combination of ^{1}H NMR spectroscopy, dynamic light scattering, and fluorescence spectroscopy, it has been shown that these AB diblock copolymers exhibit reversible micellization below pH 5.5 with the aggregate sizes dependent on the block copolymer composition.

Introduction

Block copolymers in selective solvents—those which are thermodynamically good for one block but poor for the other—self-assemble to form multimolecular micelles.[1,2] Recent reports detailing such behavior in aqueous solution include the 2-(dimethylamino)ethyl methacrylate−methyl methacrylate block copolymers reported by Baines, Billingham, and Armes,[3,4] the styrene−acrylic acid block copolymers reported by Zhang and Eisenberg,[5] and the 3-[*N*-(2-methacroyloyethyl)-*N*,*N*-dimethylammonio]propanesulfonate−alkyl methacrylate block copolymers reported by Armes, Lowe, and co-workers.[6,7] The preparation of such well-defined block copolymer micelles in aqueous media from inherently hydrophilic−hydrophobic block copolymers typically requires the use of an organic cosolvent. This cosolvent is nonselective and is normally employed initially to *molecularly* dissolve the block copolymer being studied prior to the addition of water, which induces copolymer self-assembly. In the examples above, THF or methanol was used for the 2-(dimethylamino)ethyl methacrylate−methyl methacrylate copolymers[4] and DMF in the studies concerning the styrene−acrylic acid copolymers;[5] 2,2,2-trifluoroethanol was necessary for the preparation of near-monodisperse sulfobetaine-based block copolymer micelles.[7] While these organic cosolvents can be readily removed, by dialysis for example,[8] it is desirable to both prepare well-defined blocks and assemble functional micelles in aqueous media *without* having to employ organic cosolvents.

One approach with such potential utility is to employ of stimuli-responsive water-soluble block copolymers[9] in which one block is permanently hydrophilic while the second is tunably hydrophilic/hydrophobic or “smart”. Thus, the block copolymer may be molecularly dissolved in aqueous media under conditions in which both blocks are hydrophilic—this may be at low temperature or at a specific pH, for example. Subsequent alteration of the environmental conditions (raising the temperature or changing the solution pH) results in a phase transition by the “smart” block and self-assembly into polymeric micelles.

Perhaps the most widely studied examples of such copolymers are the poly(ethylene oxide) (PEO)/poly(propylene oxide) (PPO) di- and triblock copolymers, more commonly known as poloxamers or pluronics.[2,10,11] Both PEO and PPO are water-soluble at low temperatures ($T < \sim 15$ °C). However, upon raising the temperature above this value, the solvent quality is reduced dramatically for the PPO block rendering it hydrophobic, thus allowing the di- or triblock copolymer to self-assemble into polymeric micelles. Recently, there have been a number of reports detailing stimuli-induced block copolymer micellization. For example, Webber and co-workers[12] reported the pH-dependent micellization of block copolymers comprised of 2-vinylpyridine and ethylene oxide. Under acidic conditions, these block copolymers exist in aqueous solution as unimers, while under basic conditions they self-assemble into polymeric micelles. Armes and co-workers have reported numerous examples of AB diblock tertiary amine methacrylates prepared by group transfer polymerization capable of stimuli-induced self-assembly. In these systems, 2-(dimethylamino)ethyl methacrylate is the permanently hydrophilic block with 2-(diethylamino)ethyl, 2-(*N*-morpholino)ethyl, and 2-(diisopropylamino)ethyl methacrylates, respectively, behaving as the “smart” comonomers in the responsive blocks.[13−15] Micellization may be induced employing a number of stimuli such as temperature, pH, and added electrolyte.

We have a long-standing interest in water-soluble polymers and have recently been examining reversible addition−fragmentation chain transfer (RAFT)[16] polymerization as a means for synthesizing neutral,[17−19] anionic,[20,21] cationic,[20] and zwitterionic (betaine)[22,23] water-soluble (co)polymers. We previously reported the synthesis of pH-responsive styrenic-based anionic and cationic block copolymers which were shown to undergo reversible self-assembly in aqueous media as a function of solution pH.[20] (Similar anionic block copolymers have

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also been reported by Armes and co-workers and were synthesized by TEMPO-mediated polymerization.[24]) Of particular interest to our group are controlled structure acrylamido polymers. Currently, RAFT is the only technique suitable for the preparation of acrylamido polymers in a controlled/living manner. For example, Rizzardo and co-workers[25] and Schilli, Lanzendörfer, and Müller[26] have reported the RAFT polymerization of *N*-isopropylacrylamide; Favier et al.[27] have disclosed the synthesis of *N*-acryloylmorpholine homopolymers; and Baum and Brittain[28] have reported the surface-initiated polymerization of *N*,*N*-dimethylacrylamide. Recently, we disclosed the synthesis of *N*,*N*-dimethylacrylamide homopolymers in both organic[17] and aqueous media[18] and have accomplished the controlled polymerization of acrylamide in aqueous media.[19] We previously communicated the controlled polymerization of anionic acrylamido monomers in which the homopolymerization of both sodium 2-acrylamido-2-methylpropanesulfonate (AMPS) and sodium 3-acrylamido-3-methylbutanoate (AMBA) was accomplished in aqueous media employing 4-cyanopentanoic acid dithiobenzoate as the RAFT chain transfer agent.[21] We also demonstrated the ability to synthesize both AMPS−AMBA and AMBA−AMPS AB diblock copolymers. Importantly, these block copolymers were hypothesized to undergo pH-induced self-assembly since the AMBA block is tunably hydrophilic/hydrophobic, whereas the AMPS block is permanently hydrophilic.

Herein we describe the pH-dependent aqueous solution properties of a series of well-defined AMPS−AMBA AB diblock copolymers and AB statistical copolymers of varying molar composition as a function of solution pH. We demonstrate, using a combination of ^{1}H NMR spectroscopy, dynamic light scattering, and fluorescence spectroscopy, that these block copolymers are indeed capable of reversible, pH-induced micellization with the resulting size of the aggregates being dependent on the block copolymer composition.

Experimental Section

Materials. All reagents were purchased from Aldrich at the highest purity available and used as received unless otherwise stated. 4,4′-Azobis(4-cyanopentanoic acid) (V-501) was donated by Wako Chemicals and was recrystallized twice from methanol prior to use. AMPS was recrystallized twice from methanol prior to use. AMBA was synthesized as previously reported[29] and recrystallized twice from methyl ethyl ketone. 4-Cyanopentanoic acid dithiobenzoate (CTP) was synthesized and purified as previously reported.[20] Pyrene was recrystallized from benzene.

Block and Statistical Copolymer Syntheses. Block copolymers of AMPS and AMBA were prepared as previously reported.[21] Briefly, a homopolymer of AMPS was prepared in water at 70 °C with V-501 and CTP as the initiator and RAFT chain transfer agent (CTA), respectively. The [CTP]:[V-501] ratio was 5:1 (mole basis) with [V-501] = 6.11 mM. An equimolar amount of NaOH was added prior to the polymerization to fully neutralize the acid form of AMPS, and the pH was then adjusted to 8.0. The [AMPS]:[CTA] ratio was chosen such that, at quantitative conversion, a number-average degree of polymerization (DP$_n$) of 73 (M_n = 16 700 g/mol) would be obtained. The polymerization was conducted for 6 h under a nitrogen atmosphere in a 25 mL round-bottomed flask equipped with a magnetic stir bar and sealed with a rubber septum. The product was purified by dialysis against deionized water and isolated by lyophilization.

The resulting PAMPS homopolymer was employed as a macro-CTA for the synthesis of block copolymers comprised of AMPS and AMBA. All polymerizations were conducted in water (pH 8.0 ± 0.1) at 70 °C with V-501 as the initiator. The [PAMPS]:[V-501] ratio was 5:1 (mole basis) with [V-501] = 2.84 mM for all polymerizations. An equimolar amount of NaOH was added prior to the polymerization to fully neutralize the AMPS. The [AMBA]:[PAMPS] ratio was varied in order to prepare block copolymers with a range of compositions. The polymerizations were conducted for 12 h under a nitrogen atmosphere in 25 mL round-bottomed flasks equipped with magnetic stir bars and sealed with rubber septa. The products were purified by dialysis against deionized water and isolated by lyophilization.

Statistical copolymers of AMPS and AMBA were prepared in water at 70 °C with V-501 and CTP as the initiator and RAFT CTA, respectively. The [CTP]:[V-501] ratio was 5:1 (mole basis) with [V-501] = 5.13 mM. An equimolar amount of NaOH was added prior to the polymerization to fully neutralize both monomers, and the pH was then adjusted to 8.0 ± 0.1. The polymerizations were conducted for 6 h under a nitrogen atmosphere in 25 mL round-bottomed flasks equipped with magnetic stir bars and sealed with rubber septa. The products were purified by dialysis against deionized water and isolated by lyophilization.

Micellar Solution Preparation. Each block copolymer sample was dissolved in an equimolar (based on acidic functionality) amount of NaOH, and the pH was adjusted to 9.0 ± 0.1. The resulting solutions were gently agitated for 36 h and subsequently filtered with 0.1 μm Whatman Anotop syringe filters. Each solution was slowly titrated with aqueous HCl to yield 1% w/v block copolymer solutions at pH 1.0 ± 0.1. After 6 days of gentle agitation, the resulting solutions were filtered (×4) with 0.2 μm Whatman Anotop syringe filters.

Aqueous Size Exclusion Chromatography. Molecular weights were determined by aqueous size exclusion chromatography (ASEC) at 25 °C using Viscotek TSK Viscogel mixed-bed G3000 and G4000 PW$_{XL}$ columns (molecular weight range 0−50K and 2K−300K in PEO equivalents, respectively). The mobile phase consisted of 20% acetonitrile/80% 0.05 M Na_2SO_4. The flow rate was maintained at 0.5 mL/min with an Agilent 1100 series isocratic pump. The detectors included a Wyatt Optilab DSP interferometric refractometer, a Wyatt DAWN EOS multiangle laser light scattering (MALLS) detector operating at λ = 690 nm, and a Polymer Labs LC1200 UV/vis. The d*n*/d*c* values of AMPS and AMBA in the above eluent were determined to be 0.121 and 0.123 mL/g, respectively, at λ = 690 nm and 25 °C. The molecular weight and polydispersity data were determined using the Wyatt ASTRA SEC/LS software package.

^{1}H NMR Spectroscopy. All ^{1}H NMR spectra were recorded with a Bruker AC-200 spectrometer using a 2 s recycle time. Samples were prepared as 1% w/v solutions in D_2O (HOD internal standard) with DCl or NaOD added for pH adjustment.

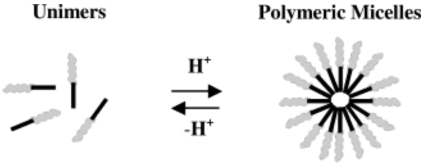
Dynamic Light Scattering. Dynamic light scattering (DLS) experiments were performed with 1% w/v copolymer solutions using a Brookhaven Instruments 128-channel BI-2030 AT digital correlator equipped with a 25 mW Spectra-physics He−Ne laser operating at λ = 633 nm. Measurements were made at 90°. CONTIN and CUMMULANTS analyses were used to fit the data.

Fluorescence Spectroscopy. Fluorescence emission spectra were measured at 25 °C with an excitation wavelength of 330 nm using an Edinburgh FS900CDT T-Geometry fluorometer. A sufficient amount of a stock solution of pyrene in methanol (4.50×10^{-5} M) was added to a vial and dried under a nitrogen flow. A sufficient amount of polymer solution (1% w/v) was added such that the final [pyrene] = 9.00×10^{-6} M. Solutions were allowed to equilibrate with gentle agitation for 72 h and were sparged by vigorous bubbling with nitrogen for 15 min immediately prior to measurement.

Results and Discussion

Block Copolymer Synthesis and Characterization. In the present study, we first synthesized a homopolymer of AMPS to be used as a macro-CTA for

Scheme 1. pH-Responsive Reversible Micellization of Block Copolymers Comprised of 2-Acrylamido-2-methylpropanesulfonate (AMPS) (Gray) and 3-Acrylamido-3-methylpropanebutanonate (AMBA) (Black) in Aqueous Solutions



subsequent RAFT copolymerizations with AMBA. This blocking order was chosen due to the pH-insensitive nature of the AMPS units, allowing the preparation of a range of AB block copolymers that contained a constant length of a permanently hydrophilic A block. The length of the AMBA block was systematically varied in order to study the effects of copolymer composition on the self-assembly of the resulting copolymers in aqueous solutions as a function of pH (Scheme 1).

The homopolymerization of AMPS was conducted in water at 70 °C with V-501 and CTP as the initiator and RAFT CTA, respectively. The PDI of the resulting PAMPS homopolymer was 1.17, and the experimentally determined M_n of 16 100 ($DP_n = 70$) was in excellent agreement with the theoretical value of 16 800 ($DP_n = 73$). After purification and isolation, the PAMPS homopolymer was employed as a macro-CTA for four RAFT polymerizations of AMBA, thus leading to block copolymers with various AMPS/AMBA ratios (Scheme 2). It has been our experience that the best results for RAFT polymerizations conducted in aqueous media are obtained with systems involving charged monomers.[18,20−23] Therefore, the copolymerizations were conducted at pH 8.0 ± 0.1 to ensure the complete ionization of AMBA. Figure 1 shows the ASEC traces for the macro-CTA and the resulting block copolymers. A small fraction of dead chains are inevitable in all controlled radical polymerizations; however, as evidenced by the molecular weight distributions and the excellent agreement between the theoretical and experimental molecular weights, there appear to be no significant homopolymer impurities in the block copolymers, implying a large majority of the PAMPS chains were functionalized with dithioester groups and were reactivated, thus facilitating high blocking efficiencies. Additionally, the block copolymer traces show only minimal signs of termination products which could potentially lead to ABA triblock copolymers.

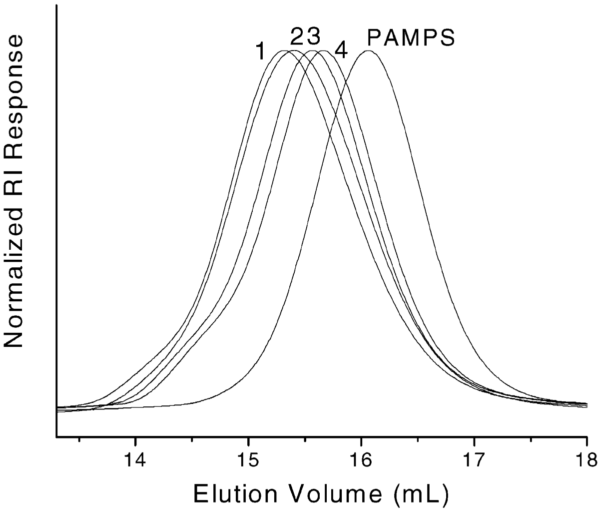


Figure 1. RI traces for block copolymers of sodium 2-acrylamido-2-methylpropanesulfonate (AMPS) and 3-acrylamido-3-methylbutanoate (AMBA) obtained by aqueous size exclusion chromatography: P(AMPS$_{70}$-*block*-AMBA$_{62}$) (**1**), P(AMPS$_{70}$-*block*-AMBA$_{40}$) (**2**), P(AMPS$_{70}$-*block*-AMBA$_{25}$) (**3**), P(AMPS$_{70}$-*block*-AMBA$_{16}$) (**4**), and the corresponding AMPS homopolymer macro-CTA (PAMPS).

Table 1 summarizes the results obtained from the analysis of the block and statistical copolymers by ASEC and ^1H NMR spectroscopy. Again, excellent agreement between the experimentally determined and theoretical molecular weights is observed, and all of the samples are near-monodisperse with the PDIs ≤ 1.21. The molecular weights discussed in this report were determined by online MALLS and are therefore absolute. For the block copolymers, the corresponding DP_n of the AMBA block was calculated by subtracting the M_n of the macro-CTA from the M_n of the block copolymer and then dividing by the molecular weight of AMBA. The copolymer compositions were determined independently by ASEC and ^1H NMR spectroscopy and are in excellent agreement.[21] For the statistical copolymers, the molecular weights determined by ASEC, coupled with the copolymer compositions determined by ^1H NMR spectroscopy, were used to calculate the DP_n for both AMPS and AMBA.

Solution Characterization. Micellar solutions of each block copolymer were prepared by first dissolving the copolymer in sufficient NaOH to ensure full neutralization of the AMBA units. The pH was then adjusted to 9.0 ± 0.1, and the solutions were filtered before being allowed to equilibrate with gentle agitation. Thus, complete molecular dissolution should have been obtained, resulting in the block copolymers existing only as unimers in solution. The copolymer solutions were then slowly titrated with HCl to pH 1.0 ± 0.1 and allowed to age for an extended period.

^1H NMR spectroscopy was employed to study the hydration of the block copolymers in D_2O.[3,15,30] Figure

Scheme 2. Synthetic Outline for the Preparation of Block Copolymers of Sodium 2-Acrylamido-2-methylpropanesulfonate (AMPS) and Sodium 2-Acrylamido-2-methylbutanoate (AMBA) via Aqueous Reversible Addition−Fragmentation Chain Transfer (RAFT) Polymerization

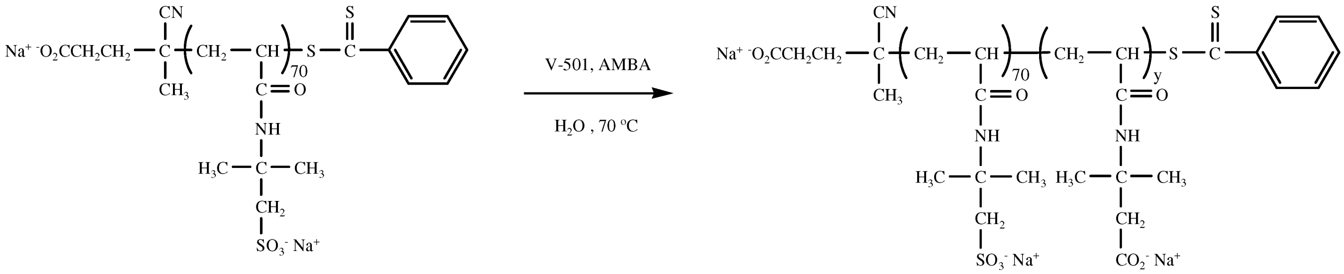


Table 1. Data for the RAFT Polymerization of Sodium 3-Acrylamido-3-methylbutanoate (AMBA) Employing a Sodium Poly(2-acrylamido-2-methylpropanesulfonate) (PAMPS) Macro-Chain Transfer Agent (Macro-CTA) in Water (pH 8) at 70 °C with a [Macro-CTA]/[Initiator] Ratio of 5/1 (Mole Basis); [4,4′-Azobis(4-cyanopentanoic acid)] = 2.84 mM, Time = 6 h

sample	conv (%)[a]	M_n (theory)[b]	M_n (expt)[c]	M_w/M_n[c]	DP_n AMPS	DP_n AMBA	comp ASEC[c] (AMPS/AMBA)	comp NMR[e] AMPS/AMBA
P(AMPS$_{70}$-*block*-AMBA$_{62}$)	87	28 300	29 000	1.15	70[c]	62[c]	53/47	50/50
P(AMPS$_{70}$-*block*-AMBA$_{40}$)	85	24 200	24 500	1.10	70[c]	40[c]	64/36	64/36
P(AMPS$_{70}$-*block*-AMBA$_{25}$)	84	21 300	21 300	1.15	70[c]	25[c]	75/25	77/23
P(AMPS$_{70}$-*block*-AMBA$_{16}$)	94	19 600	19 700	1.21	70[c]	16[c]	82/19	82/19
P(AMPS$_{106}$-*stat*-AMBA$_{40}$)	84	28 700	32 000	1.15	106[d]	40[d]		73/27
P(AMPS$_{35}$-*stat*-AMBA$_{112}$)	89	27 100	29 800	1.14	35[d]	112[d]		24/76
P(AMPS$_{79}$-*stat*-AMBA$_{89}$)	87	29 400	35 300	1.13	79[d]	89[d]		47/53

[a] Determined from the residual monomer concentration obtained from the RI detector during ASEC. [b] Determined using $M_n(\text{theory}) = [M] \times [MW_{\text{mon}}] \times \text{conversion}/[CTA] + MW_{\text{macro-CTA}}$. [c] Calculated by ASEC. [d] Determined by using the M_n determined from ASEC and the copolymer composition determined by ^{1}H NMR spectroscopy. [e] Determined using ^{1}H NMR spectroscopy.

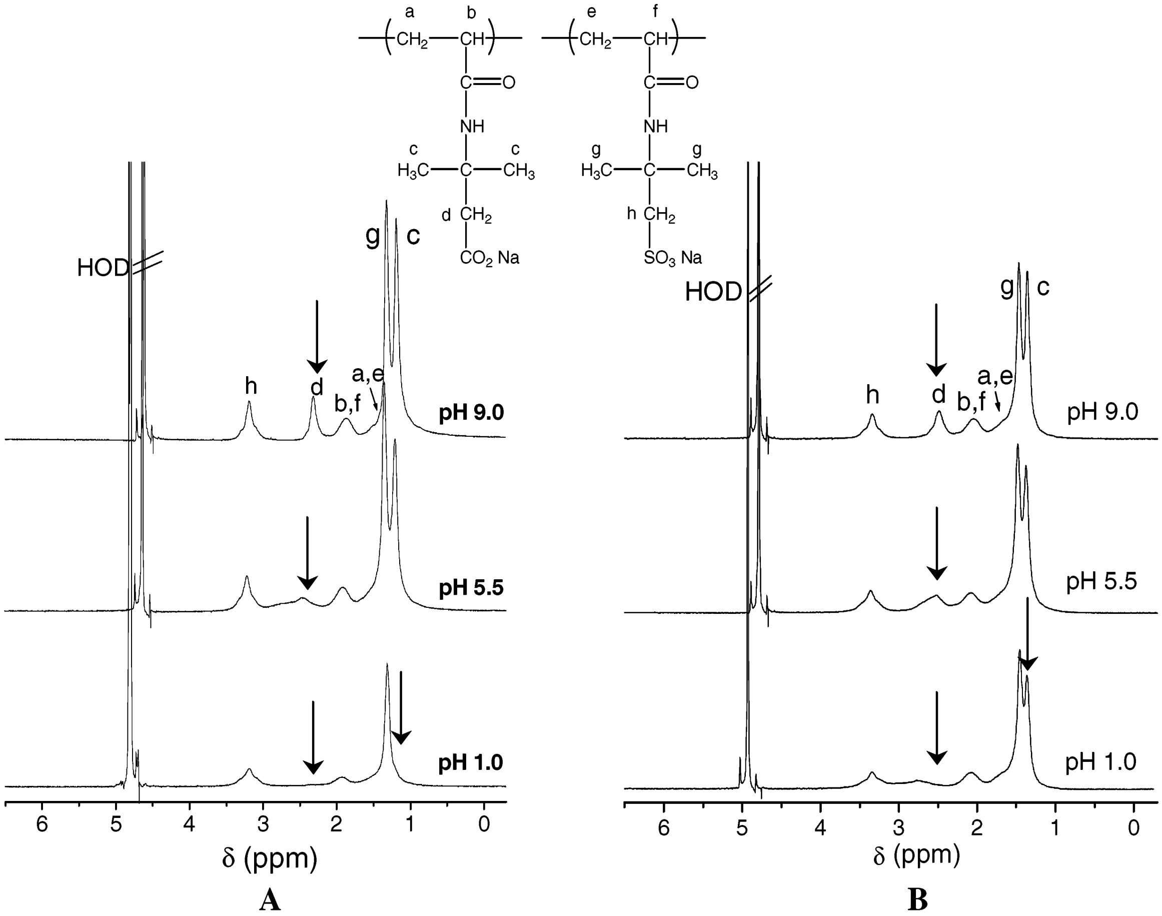


Figure 2. ^{1}H NMR spectra and peak assignments for copolymers of sodium 2-acrylamido-2-methylpropanesulfonate and sodium 3-acrylamido-3-methylbutanoate (AMBA) in D_2O as a function of solution pH (adjusted with NaOD or DCl): P(AMPS$_{70}$-*block*-AMBA$_{62}$) (A) and P(AMPS$_{79}$-*stat*-AMBA$_{89}$) (B).

2 shows the spectra for a 1% w/v solution of P(AMPS$_{70}$-*block*-AMBA$_{62}$) at pH values of 9.0, 5.5, and 1.0. The signals associated with the AMBA units ($\delta = 1.23$, 1.90, and 2.34 ppm) diminish noticeably with a decrease in solution pH (Figure 2A). This is consistent with the gradual protonation of carboxyl groups and dehydration of the AMBA block, which is a prerequisite for supramolecular self-assembly. No noticeable decrease in the intensity of the signals associated with the AMPS units is observed as would be expected since PAMPS remains hydrophilic, even at very low solution pH. When the same block copolymer sample is exposed to changes in pH from 1.0 to 9.0 and back to 1.0, the hydration of the AMBA block is seen to be reversible. Interestingly, pH 5.5 is close to the expected pK_a of the AMBA units, and the signals are accordingly diminished by approximately 50% under these conditions, as would be predicted. When a statistical copolymer (P(AMPS$_{79}$-*stat*-AMBA$_{89}$)) was exposed to the same analysis, the AMBA units did not appear to be completely dehydrated at pH 1.0 (Figure 2B). This can be attributed to the presence of intermittent AMPS units, which may help to solvate adjacent protonated AMBA units.

DLS was employed to characterize 1% w/v solutions of the copolymers in water at pH 9.0 and 1.0 (Table 2). Under basic conditions, there should be no intermolecular aggregation for the block or statistical copolymer systems. Indeed, the intensity-average hydrodynamic diameter (D_h) values obtained at high pH are in the region expected for molecularly dissolved polymers with the molecular weights considered. A marked increase in D_h at pH 1.0 is observed for the block copolymer

Table 2. Hydrodynamic Diameters (D_h) and Size Distribution Polydispersities (ρ) As Determined by Dynamic Light Scattering of Block and Statistical Copolymers of Sodium 2-Acrylamido-2-methylpropanesulfonate (AMPS) and Sodium 3-Acrylamido-3-methylpropanesulfonate (AMBA) as a Function of Solution pH

	D_h (nm)		ρ
sample	pH 9.0	pH 1.0	pH 1.0
$PAMPS_{70}$	5	4	0.07
P($AMPS_{70}$-*block*-$AMBA_{62}$)	6	25	0.11
P($AMPS_{70}$-*block*-$AMBA_{40}$)	5	24	0.14
P($AMPS_{70}$-*block*-$AMBA_{25}$)	6	21	0.11
P($AMPS_{70}$-*block*-$AMBA_{16}$)	6	18	0.12
P($AMPS_{106}$-*stat*-$AMBA_{40}$)	11	7	0.10
P($AMPS_{35}$-*stat*-$AMBA_{112}$)	11	9	0.08
P($AMPS_{79}$-*stat*-$AMBA_{89}$)	13	9	0.06

systems. Importantly, aggregation is reversible as evidenced by alternation between unimers and micelles of specific sizes being observed during pH hysteresis experiments. The results from DLS, coupled with those obtained by ^{1}H NMR spectroscopy for the block copolymer solutions, are consistent with the reversible formation of uniform micelle-like structures with AMPS coronas and dehydrated AMBA cores. The average aggregate diameters increase with increasing length of the AMBA block. This would be expected since it has been previously reported that the hydrophobic block controls the association behavior of amphipathic block copolymers in aqueous solutions.[31] Additionally, because of the polyelectrolyte nature of the AMPS−AMBA copolymers, the aggregation behavior is expected to be dependent on the ionic strength of the surrounding medium.[32]

Interestingly, the statistical copolymers exhibit a slight decrease in D_h as the solution pH is lowered. Several explanations can be offered for this behavior. Because a majority of the AMBA units are ionized at pH 9.0, the statistical copolymers exist as polyelectrolytes. As the pH is lowered, AMBA units are protonated, leading to a lower effective charge density and reduced electrostatic repulsion. This would result in the copolymer collapsing to yield a smaller D_h. The decrease in D_h might also be attributed to intramolecular aggregation of the hydrophobic AMBA units at pH 1.0. Finally, because of the higher ionic strength of the solution at pH 1.0 as compared to pH 9.0, the polyelectrolyte effect should cause a smaller D_h for the copolymers at the former pH.

Further information concerning the micellization of the block copolymers was obtained by steady-state fluorescence pyrene probe experiments. The solubility of pyrene in water is very low, and as a result, it is selectively solubilized in hydrophobic microphases such as those found in solutions containing polymeric micelles.[31] The vibrational fine structure of its monomer fluorescence spectra in solution makes pyrene an excellent probe of local environment polarity changes.[33,34] The intensity of the highest energy emission peak (I_1) at 373 nm is dependent on solvent polarity, while that of the third highest energy emission peak (I_3) at 383 nm is relatively solvent-insensitive. Therefore, the ratio of intensities of the two (I_1/I_3) correlates well with solvent polarity. For example, Winnik and co-workers have shown that I_1/I_3 varies from 1.86 for water to 0.58 for hexane.[35]

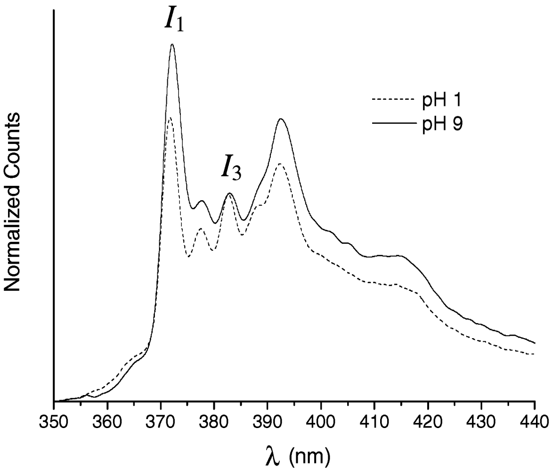


Figure 3. Fluorescence spectra of pyrene (9.00 × 10^{-6} M) in aqueous solutions of sodium P((2-acrylamido-2-methylpropanesulfonate)$_{70}$-*block*-(3-acrylamido-3-methylbutanoate)$_{62}$) (1% w/v) at pH 1 and 9. The spectra are baseline-adjusted and normalized to give equal peak heights at I_3.

Table 3. Fluorescence Intensity Ratios I_1/I_3 from Pyrene Emission Spectra as a Function of Solution pH for Copolymers of AMPS Sodium 2-Acrylamido-2-methylpropanesulfonate and Sodium 3-Acrylamido-3-methylbutanoate (AMBA)

	I_1/I_3	
sample	pH 9.0	pH 1.0
P($AMPS_{70}$-*block*-$AMBA_{62}$)	1.60	1.37
P($AMPS_{79}$-*stat*-$AMBA_{89}$)	1.67	1.81

The emission fluorescence spectra for pyrene in 1% w/v solutions of P($AMPS_{70}$-*block*-$AMBA_{62}$) at pH 1.0 and pH 9.0 are shown in Figure 3. The spectra have been baseline-adjusted and normalized to give equal peak heights for I_3. The corresponding decrease in the normalized intensity of I_1 from pH 9.0 to 1.0 is indicative of the pyrene being preferentially located in a more hydrophobic environment under acidic conditions. Table 3 lists the I_1/I_3 values for P($AMPS_{70}$-*block*-$AMBA_{62}$) and P($AMPS_{79}$-*stat*-$AMBA_{89}$) at pH 9.0 and 1.0. The decrease in I_1/I_3 for the block copolymer from 1.60 to 1.37 is consistent with the presence of pyrene in polymeric micelles. For the case of the statistical copolymer, a slight increase in the value of I_1/I_3 was observed with a change in pH from 9.0 to 1.0, indicating that associates capable of significantly solubilizing pyrene are not present under acidic conditions.

To determine the pH at which polymer micelles form, fluorescence pyrene probe measurements were conducted at pH values between 1.0 and 9.0. As shown in Figure 4, a dramatic increase in I_1/I_3 is observed between pH 5.0 and 6.0 for a 1% w/v solution of P($AMPS_{70}$-*block*-$AMBA_{62}$). This is consistent with the results from ^{1}H NMR spectroscopy that support the onset of dehydration of the PAMBA block at pH 5.5. Thus, the data indicate the presence of hydrophilic−hydrophilic block copolymers under basic conditions and near-monodisperse, micelle-like structures capable of solubilizing low-molecular-weight organic molecules below pH 5.5.

Conclusions

Dithioester end-capped PAMPS was employed as a macro-CTA for the synthesis of a series of well-defined AB diblock copolymers of AMPS and AMBA directly in water via the RAFT process. Statistical copolymers of these two monomers were also prepared via aqueous

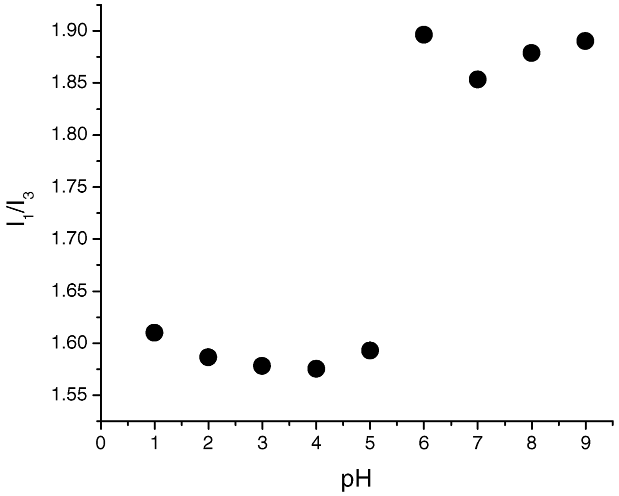


Figure 4. I_1/I_3 as a function of solution pH for a 1% w/v solution of a block copolymer of sodium 2-acrylamido-2-methylpropanesulfonate (AMPS) and sodium 3-acrylamido-3-methylpropanebutanonate (AMBA) (P(AMPS$_{70}$-*block*-AMBA$_{62}$)).

RAFT. Excellent control of the molecular weight and molecular weight distributions was attained. Aqueous solution studies of a series of block and statistical copolymers employing ^{1}H NMR spectroscopy, DLS, and fluorescence spectroscopy indicate that these AB diblock copolymers can undergo self-assembly in solution below pH 5.5 to form reversible, pH-induced polymeric micelles with dehydrated AMBA cores capable of solubilizing low-molecular-weight organic molecules.

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