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Selective betainization of 2-(dimethylamino)ethyl methacrylate residues in tertiary amine methacrylate diblock copolymers and their aqueous solution properties

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Abstract

2-(dimethylamino)ethyl methacrylate (DMA) was block copolymerized in turn with three other tertiary amine methacrylate comonomers, namely 2-(diethylamino)ethyl methacrylate (DEA), 2-(diisopropylamino)ethyl methacrylate (DPA) and 2-(*N*-morpholino)ethyl methacrylate (MEMA), using group transfer polymerization (GTP). The DMA residues of each of these diblock copolymers were selectively betainized using 1,3-propane sultone under mild conditions to yield a series of novel betaine diblock copolymers. These selectively betainized copolymers could be dissolved molecularly without co-solvents in aqueous media at room temperature, with micellization occurring reversibly on judicious adjustment of the solution pH, temperature or electrolyte concentration. In all three cases, stable block copolymer micelles were formed with betainized-DMA coronas and hydrodynamic diameters of 10–46 nm. The selective betainization of the DMA residues dramatically reduces the surface activity and increase the solubility of the tertiary amine methacrylate block copolymers (DMA–DEA, DMA–DPA and DMA–MEMA).

Keywords: Copolymers; Betainization; Micelles

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1. Introduction

The considerable interest in polyelectrolytes arises because of their technological applications. For example, cationic polyelectrolytes have increasing applications in areas such as flocculation, adhesives, emulsion stabilizers, corrosion inhibitors, dye improvers, plastifiers, macroinitiators in the radical polymerization of vinyl monomers, ion-exchangers and catalyst matrices [1–9]. Polybetaines, which have both negative and positive charge on every monomer residue, have been used in areas such as production of fungicides, synthesis of fire-resistant polymers, lubricating oil additives and emulsifying agents.

Betaine polymers can be divided into two groups, in which the N atom is located either in the main chain or in the pendant groups. Poly(aminoalkyl methacrylates), poly(vinyl amine)s and poly(vinyl pyridine)s belong to the second group. The reactive nature of the primary, secondary and tertiary amine groups makes it possible to obtain strong polyelectrolytes by quaternization and/or betainization chemistry. Another approach to obtain polyelectrolytes is the direct polymerization of the quaternary N-containing monomeric salts or betainized monomers. The first examples of polybetaines, which were polycarboxybetaines and polysulfobetaines based on poly(vinylpyridine)s, were reported in the 1950s [10,11]. The vinyl pyridine monomers were first betainized and then polymerized using free radical polymerization chemistry. In the last two decades, many different betaines including surfactants [12–15] and polymers based on (meth)acrylates, (meth)acrylamides, vinylpyridines, vinylimidazole, 4,5-dicyanoimidazole etc. have been reported [16–21].

Galin and Monroy-Soto have synthesized many polysulfobetaines by either polymerizing various betainized monomers or betainizing precursor tertiary amine polymers via free radical polymerization [16,17]. The relatively low solubility of these betaine monomers in organic solvents and the broad molar mass distributions of the resulting (co)polymers are severe limitations if controlled structure

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polybetaines are required [22]. An alternative route to polybetaines involves the synthesis of precursor aminopolymers, followed by betainization using either 1,4 butane sultone or 1,3-propane sultone. Cardoso and Manero have synthesized poly(vinylpyridine sulfopropyl betaine)s by reacting precursor polymers with 1,3-propane sultone [19]. Both poly(2-vinylpyridine) and poly(4-vinylpyridine) were prepared by free radical polymerization, at 60 °C in methanol, and followed by betainization in acetonitrile at 60 °C. The degree of betainization was varied from 3 to 100%. Many different polybetaines were reported recently, such as poly(aminoalkoxydicyano ethenolates) [23,24], poly(4-vinylpyridine betaines) derived from 4,5-dicyanoimidazole [25]. However, according to the literature, these derivation reactions usually require rather extreme conditions (e.g. prolonged heating at 120 °C in propylene carbonate or tetramethylene sulfone) and often do not go to completion [16,17,26]. Aqueous solution properties of polybetaines, such as poly(ammonioalkoxydicyano ethenolates) [23,24], poly(vinylpyridine sulfopropyl betaine)s [16, 19], poly(tertiary amine methacrylate sulfobetaine)s [17], poly(N-vinylimidazolium sulfobetaine) [21], were studied and the effect of salt concentration on the solubility of these polyelectrolytes was determined.

The direct synthesis of betaine (co)polymers with narrow molecular weight distributions and controlled diblock architecture, under mild conditions, was reported for the first time by Lowe et al. in 1996 [27–30]. DMA monomer was polymerized by GTP and then reacted with 1,3-propane sultone. The resulting polysulfopropyl betaines are water-soluble and exhibit little or no surface activity. In contrast, the corresponding precursor (co)polymers showed marked surface activity. The effect of increasing salt concentration indicated anti-polyelectrolyte behaviour in the low salt regime (10^{-2}–10^{-1} M NaCl). In addition, the betainized DMA–MMA block copolymers were also successfully employed as stabilizers in the emulsion polymerization of either styrene or *n*-butyl acrylate. A series of hydrophilic–hydrophobic sulfobetaine statistical (co)polymers were subsequently synthesized by Vamvakaki et al. [31].

More recently, we described [32–36] the block copolymerization of DMA with three other tertiary amine methacrylate comonomers, DEA, DPA and MEMA, using GTP. These block copolymers exhibit strong pH dependent surface activity and can form well-defined micelles in aqueous solution depending on solution pH, temperature and salt concentration. In a later paper, we also demonstrated that the DMA residues, in a range of tertiary amine methacrylate-based diblock copolymers, can be selectively quaternized using methyl iodide and benzyl chloride [34].

In the present work we have synthesized the homopolymers of each tertiary amine methacrylate monomer and a series of each DMA–MEMA, DMA–DEA and DMA–DPA diblock copolymers by differing comonomer compositions and M_n's. After investigation of the betainization of each DMA, DEA, DPA and MEMA homopolymer, the selective betainization of the DMA residues of these diblock copolymers were successfully carried out in THF by using 1,3-propane sultone (see Fig. 1). The aqueous solution properties of these materials have been assessed using dynamic light scattering, surface tensiometry and ^{1}H NMR spectroscopy. These studies confirmed reversible pH-, temperature- and salt-induced micellization, with the betainized DMA block forming the micelle corona. A short communication reporting our preliminary results for the selective betainization of DMA–DEA copolymers has been published in J Mater Chem [36].

2. Experimental

2.1. Polymer synthesis

2.1.1. The synthesis of tertiary amine methacrylate precursor (co)polymers

All homopolymers and diblock copolymers were synthesized using GTP as described previously [32,33]. In the latter case of block copolymerization, DMA monomer was always polymerized first, followed by the addition of DEA, DPA, or MEMA, respectively.

2.1.2. The synthesis of tertiary amine methacrylate-based polysulfobetaines

The betainization of all homopolymers was examined in THF by using 1,3-propane sultone. Experimental conditions for the betainization reaction in THF have been described previously [27–29]. For the first time, the betainization of the DMA and MEMA homopolymers was also examined in water with the same agent. For the betainization in water, one of the homopolymers (2 g) was dissolved in water (40 ml) and a 10 mol% excess of betainizing reagent was then added to the solution at room temperature. Betainization of DMA homopolymer in water was completed within 1–2 h. Since the resulting betainized DMA homopolymer was soluble in water and insoluble in THF, the betainized homopolymer was precipitated in THF from water in order to remove excess betainizing agent.

Selective betainization of DMA residues in the DMA–DEA, DMA–DPA and DMA–MEMA block copolymers (1–2 g) was carried out in THF using a 10 mol% excess of 1,3-propane sultone based on DMA residues at room temperature. The solution was stirred for 2 days and gelation occurred within 10–24 h, depending on the DMA content of the block copolymer. The copolymers were generally purified by soxhlet extraction with THF to remove excess betainizing agent. In the case of betainized DMA–MEMA block copolymer, purification was achieved by precipitation into *n*-hexane. The resulting selectively betainized block copolymer was dried in a vacuum oven at 55 °C for at least 2 days. The extent of betainization was assessed by ^{1}H NMR spectroscopy.

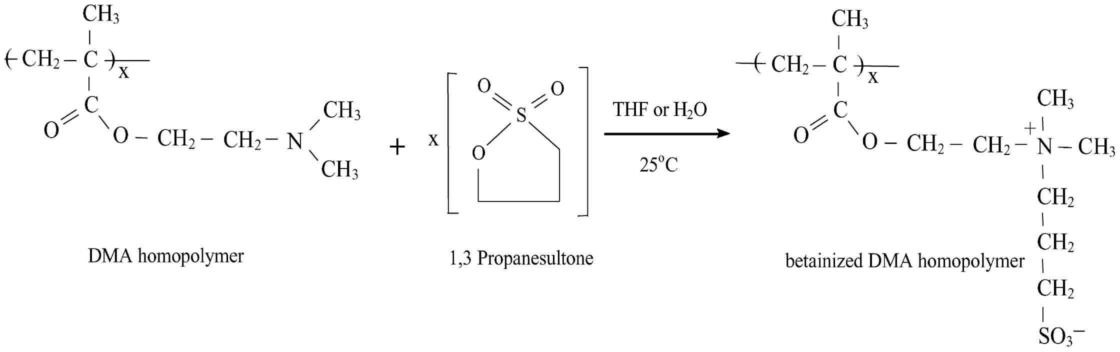

Fig. 1. Reaction scheme for the betainization of the 2-(dimethylamino)ethyl methacrylate homopolymer.

2.2. Polymer characterization

Molecular weights and molecular weight distributions of all precursor (co)polymers were determined using gel permeation chromatography (GPC). The GPC set-up consisted of a Perkin Elmer LC pump and a RI detector, the columns used were either Mixed 'E' or Mixed 'D' (Polymer Labs), and calibration was carried out using PMMA standards (Polymer Labs). The GPC eluent was HPLC-grade THF stabilized with BHT, at a flow rate of 1.0 ml min^{-1}. Molecular weights of the selectively betainized diblock copolymers were calculated assuming 100% betainization.

The compositions of all precursor block copolymers, the degree of betainization and the micellization behaviour of the selectively betainized diblock copolymers in aqueous solution were investigated using a Bruker AC-P 250 or 300 MHz instrument in D_2O/NaOD and D_2O/DCl.

The hydrodynamic size of the selectively betainized block copolymer micelles in aqueous solution was measured using dynamic light scattering instrument, a Malvern 4700 spectrometer equipped with a 80 mW argon ion laser operating at $\lambda_o = 632.8$ nm and a series 7032 Multi-8 Correlator. The measurements were performed at a fixed angle of 90° and data were fitted using both monomodal cumulants analysis and the CONTIN algorithm. All measurements were carried out using 1 w/v% solutions. The solution temperature was controlled to within ±0.1°C.

The surface tension measurements depending on both the concentration of selectively betainized block copolymers and the solution pH (0.2 w/v%) were carried out using a Kruss K10ST surface tensiometer equipped with a platinum ring.

3. Results and discussion

3.1. Betainization of tertiary amine methacrylate homopolymers

Tertiary amines are weak bases. Their basicity and reactivity depend on the polar effects of alkyl groups and also on steric factors. The base strength rises in the series ammonia, methylamine and ethylamine [37–39]. On the other hand, their reactions with alkyl halides show the opposite trend. This is presumably due to steric effects as studied by Menschutkin [40,41]. He first reported the quaternization of tertiary amines with alkyl halides in the 1890s. Significant steric effects were noted in these original small-molecule studies, with tertiary amines reacting much more slowly than secondary or primary amines. In addition, the effect of changing the alkylating reagent was also determined and the reaction was faster with smaller alkyl halides. Polymer-analogous reactions are also well-documented, particularly for the betainization of DMA homopolymers [27–31] and various vinylpyridine homopolymers [16,19]. However, as far as we are aware, there have been no systematic studies in the literature concerning the betainization of polymeric tertiary amines with alkyl sultones, which examine the effect of varying steric hindrance, basicity strength, inductive effects etc. In this paper, we will demonstrate that DMA residues are significantly more reactive toward betainization than DEA, MEMA, or DPA residues. This allows the selective betainization of the DMA residues in DMA–DEA, DMA–MEMA and DMA–DPA diblock copolymers, which in turn leads to pronounced changes in both surface activity and also the property for these new cationic polymeric surfactants to undergo micellization.

Initially, near-monodisperse homopolymers of DMA, DEA, DPA and MEMA were readily synthesized by GTP [32,33]. Betainization of these four homopolymers with 1,3 propane sultone was examined in both THF and water (see Fig. 1). The results are summarized in Table 1. Although both the DMA and the MEMA homopolymers are soluble in water, the DEA and DPA homopolymers are insoluble in neutral and basic water but are soluble in acidic media due to protonation of their tertiary amine residues [32,33]. Thus, betainization of the DMA and MEMA homopolymers was attempted in both THF and water, but betainization of the both DEA and DPA homopolymers was only evaluated in THF.

Betainization of the DMA homopolymer was carried out with 1,3-propane sultone in both THF and aqueous medium at room temperature and betainization was complete after 24 h. Although the MEMA homopolymer did not react with

Table 1
Number-average molecular weights, calculated number-average molecular weights, degree of betainization, observed precipitation (gel) time and reaction conditions for the four betainized tertiary amine methacrylate homopolymers (betainization was carried out using 1,3-propane sultone)

Sample code	Betainized homopolymer	Precursor M_n (g mol^{-1})[a]	Calcd. M_n (g mol^{-1})[b]	Solvent	Degree of betain (mol %)[c]	Observed gellation time	Reaction conditions
VB95	bet-DMA	12,450	22,000	THF	100	8 h	24 h at 25 °C
VB147	bet-DMA	4,000	7100	H_2O	100	Soluble[d]	24 h at 25 °C
VB162	bet-DEA	3,550	9350	THF	0	–	48 h at 25 °C
VB162	bet-DEA	3,550	9350	THF	61	24 h	84 h at 65 °C
VB102	bet-DEA	5,650	–	THF/H_2O (1/1)	0	24 h	48 h at 25 °C
VB111	bet-MEMA	12,100	19,500	THF	Side reac.	24 h	48 h at 65 °C
VB111	bet-MEMA	12,100	–	THF	0	–	24 h at 25 °C
VB111	bet-MEMA	12,100	–	H_2O	Side reac.	–	48 h at 25 °C
VB97	bet-DPA	4,800	–	THF	0	–	96 h at 65 °C
VB97	bet-DPA	4,800	–	THF/H_2O (2/1)	0	–	48 h at 25 °C

[a] As determined by GPC (calibrated with poly(methyl methacrylate) standards).
[b] As calculated from GPC results of precursor homopolymers.
[c] As determined by ^1H NMR spectroscopy.
[d] Both precursor and betainized DMA homopolymers are soluble in H_2O.

the betainizing reagent in THF at room temperature, it reacted with the betainizing reagent both in water at room temperature and in refluxing THF (see Table 1). But side reactions were observed in both cases, possibly due to ring-opening of the morpholine groups of the MEMA residues and/or oligomerization or ring opening polymerization of the betainizing agent [42,43]. An unexpected product was obtained according to ^1H NMR studies (not shown). The disappearance of the three methylene protons bound to nitrogen at δ 2.6–2.8, the decrease in the peak integral of the $-CH_2-O-CH_2-$ protons at δ 3.7 and the appearance of three equal new peaks at δ 3.3, 3.9 and 4.4 confirmed that the morpholine ring was at least partially destroyed during the reaction. Betainization of the DEA homopolymer was also problematic. Significantly longer reaction times (48–96 h) and elevated temperature were required for any significant degree of betainization, as judged by the onset of gelation. ^1H NMR studies suggested that degree of betainization of DEA homopolymer is 61 mol% even after 84 h in refluxing THF (Table 1). Purification difficulties of the betainized DEA homopolymer suggested that side reactions, such as polymerization of the betainizing reagent, had occurred. On the other hand, the DPA homopolymer remained completely unbetainized even after 96 h in refluxing THF. Presumably, this much reduced reactivity is due to steric crowding of the tertiary amine residues.

For the betainized DMA homopolymer, the degrees of betainization (see Table 1) were calculated using ^1H NMR spectroscopy. Fig. 2(a) shows the corresponding ^1H NMR spectrum of the DMA homopolymer in D_2O with the relevant signals labeled. Peak A at δ 4.1–4.2 represents the $-OCH_2-$ protons, peak B at δ 2.7 represents the $-CH_2-NR_2$ protons and peak C at δ 2.3 represents the six dimethylamino protons. After betainization of this homopolymer with 1,3-propane sultone in THF (see Fig. 2(b)), the peaks A, B and C shifted to δ 4.5, 3.8 and 3.1–3.2, respectively. After betainization, the new peaks (D, E and F) at δ 3.6 (D), 2.3 (E) and 3.0 (F) correspond to the propylsulfonate group (see Fig. 2(b)). The absence of any unbetainized DMA protons in (which would appear at δ 2.7) 'spectrum b' indicates 100% betainization, but also a comparing of the peak integrals of C and F indicates 100% betainization. Thus, betainization of DMA homopolymer was successfully carried out with 1,3-propane sultone at room temperature within 24 h in THF. On the other hand, for the first time, betainization of the DMA homopolymer was also carried out in water at room temperature (see Fig. 2(c), compare with spectrum b). The betainized DMA homopolymers was precipitated from water in THF to remove the excess of betainizing reagent. The spectrum c is identical to spectrum b and indicates that the betainization reaction proceeds almost quantitatively.

The majority of the polybetaine (co)polymers reported in the literature were synthesized via free-radical polymerization of the betaine monomers [11,16,22]. Near-monodisperse DMA based (co)polymers were betainized in THF at room temperature using 1,3-propane sultone for the first time by Lowe et al. [27–29]. Our observations are in excellent agreement with the quantitative degrees of betainization of the DMA homopolymers previously reported by Lowe and co-workers.

In summary, fully betainized DMA homopolymer was obtained with using 1,3-propane sultone in both THF and water at room temperature within 24 h. Under the same mild conditions, the DEA, MEMA and DPA homopolymers underwent little or no reaction in either solvents. These observations suggested that the DMA residues in the DMA–DEA, DMA–MEMA and DMA–DPA block copolymers could be selectively betainized at room temperature in THF by restricting the reaction time to 24 h and by using near-stoichiometric quantities of 1,3-propane sultone (relative to the DMA residues). This proved to be the case, as is demonstrated in Section 3.2.

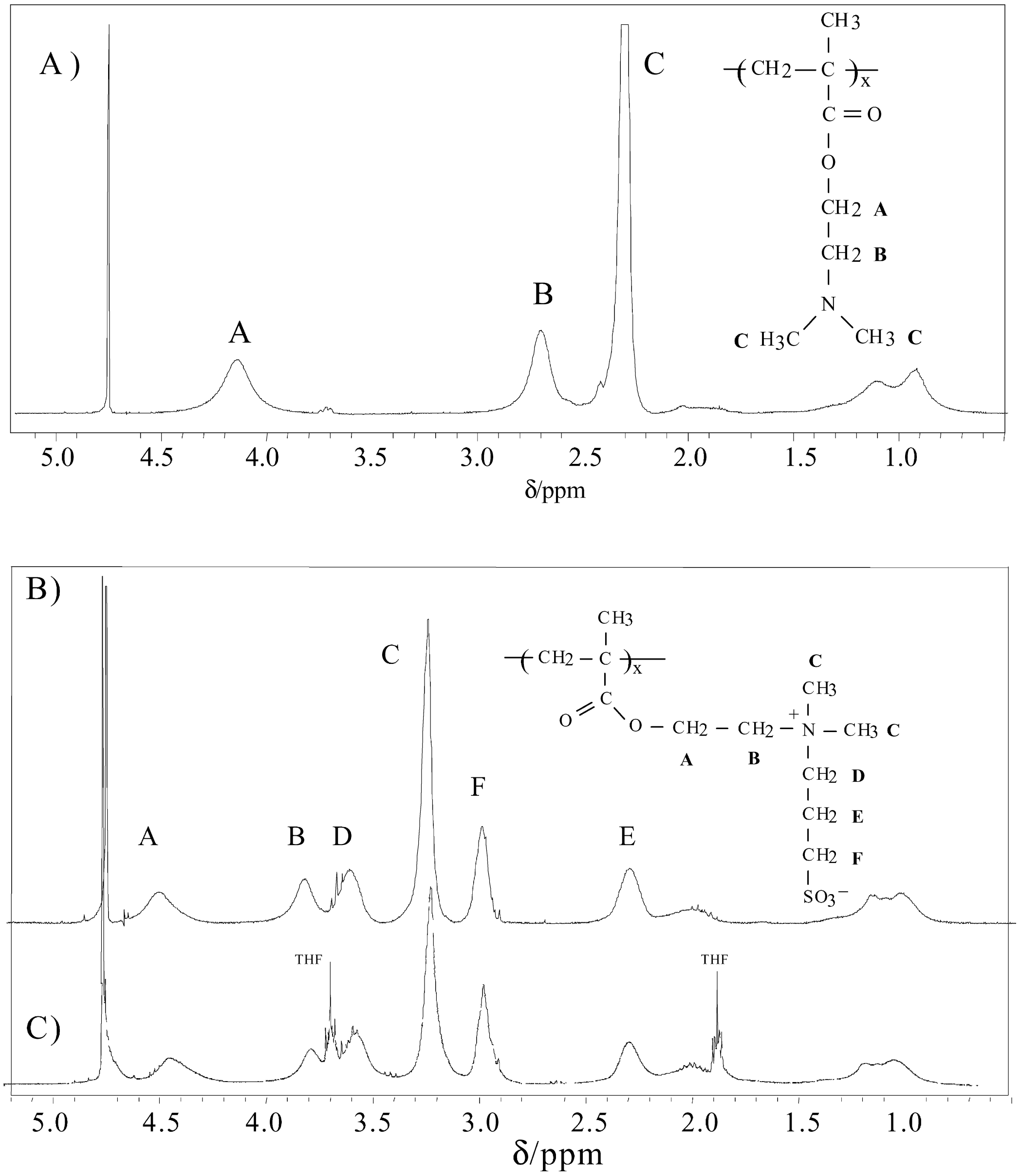

Fig. 2. ^{1}H NMR spectra (in D_2O) of DMA homopolymer (VB95): (a) before betainization; (b) after betainization in THF; and (c) after betainization in H_2O.

3.2. Selective betainization of the tertiary amine methacrylate block copolymers and subsequent micellization studies

Micelles of DMA–DEA and DMA–DPA block copolymers precipitated from aqueous media at around pH 7–9 due to the reduced in solubility of the DMA corona with increasing solution pH. As the water solubility of the betainized DMA block is much higher than that of the precursor, micelles formed from the betainized block copolymer should be stable across a much wider pH range with the betainized DMA forming solvated corona and the DEA, DPA or MEMA forming micelle cores (see Fig. 3). Thus, selective betainization of DMA residues in DMA–DEA, DMA–DPA and DMA–MEMA block copolymers was attempted using 1,3-propane sultone (see Fig. 4).

3.3. Selective betainization of DMA residues in DMA–DEA block copolymers

Preliminary betainization experiments on the DMA, DEA, DPA and MEMA homopolymers confirmed that only the DMA homopolymer was quantitatively betainized at room temperature in THF within 16–24 h. This suggested that the DMA residues in the DMA–DEA block copolymer could be selectively betainized under the same conditions by restricting the reaction time to 24 h. The degrees of betainization of the DMA blocks were determined by ^{1}H

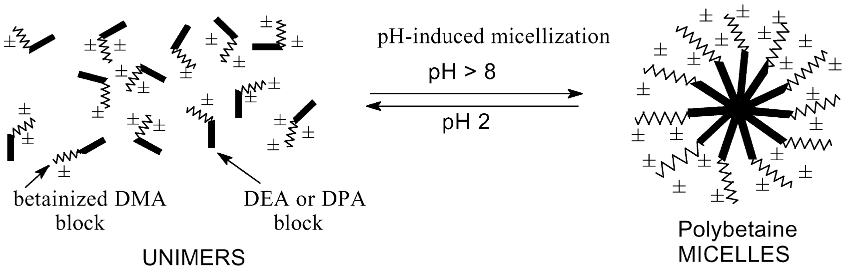

Fig. 3. Schematic representation of the formation of polybetaine-based micelles from selectively betainized DMA–DEA and DMA–DPA block copolymers.

NMR spectroscopy. Fig. 5 shows the NMR spectra of a 50:50 DMA–DEA block copolymer before and after betainization. Both precursor and betainized block copolymers were dissolved in DCl–D_2O, which is a good solvent for both block and all protons are visible in the spectra (see Fig. 5, spectrum a). The block composition of a 50:50 DMA–DEA precursor was determined by comparing the peak integrals of C (at δ 3.0) with that of peak G (at δ 1.2). After betainization of the DMA residues, the signal at δ 3.2–3.3 is due to the six dimethylamino protons of the DMA residues, whereas the signal at δ 1.3–1.5 corresponds to the six methyl protons of the diethyl groups of the DEA residues (see Fig. 5, spectrum b). Comparing the peak integrals of peak C and peak G gives the same 50:50 copolymer composition as determined for the original DMA–DEA precursor prior to betainization. In addition, while the signal due to the six dimethylamino protons, after betainization, shifted to δ 3.2–3.3 and new signals of the propylsulfonate group appeared at δ 2.3, 3.0 and 3.6, the signals of the DEA residues remained unchanged. Thus betainization of the DMA residues is both selective and near-quantitative (>95%). Fig. 5 also shows the NMR spectra of the betainized DMA–DEA block copolymer in both acidic and alkaline media.

As we have reported in our recent papers, the DMA–DEA and DMA–DPA block copolymers exhibited highly pH-dependent surface activity and micellization [32,33]. It was suggested that the more hydrophobic DEA (or DPA) block adsorbed at the air–water interface and also formed the interior of the copolymer micelles. This NMR study of the betainized 50:50 DMA–DEA block copolymer now supports this hypothesis. Initially, this copolymer was molecularly dissolved in DCl–D_2O (see Fig. 5, spectrum b). On addition of excess NaOD, the strong signal at δ 1.4–1.5 observed in 'spectrum b' due to the six methyl protons of the diethylamino groups in the DEA residues completely disappears (see Fig. 5, spectrum c), indicating that this deprotonated block sequence is no longer solvated. This is strong evidence for the DEA block forming a hydrophobic micellar core, as expected. It is noteworthy that the formation of stable micelles for the DMA–DEA and DMA–DPA precursor blocks only occurs over a rather narrow pH range; precipitation occurs above pH 8–9 due to deprotonation of the hydrophilic DMA residues. In contrast, since the betainized DMA residues remain soluble in alkaline media, the betainized block copolymer micelles remain in solution up to pH 12–13.

Dynamic light scattering studies of pH-induced micellization were carried out on dilute aqueous solutions of the betainized block copolymers. Micelle diameters depend on

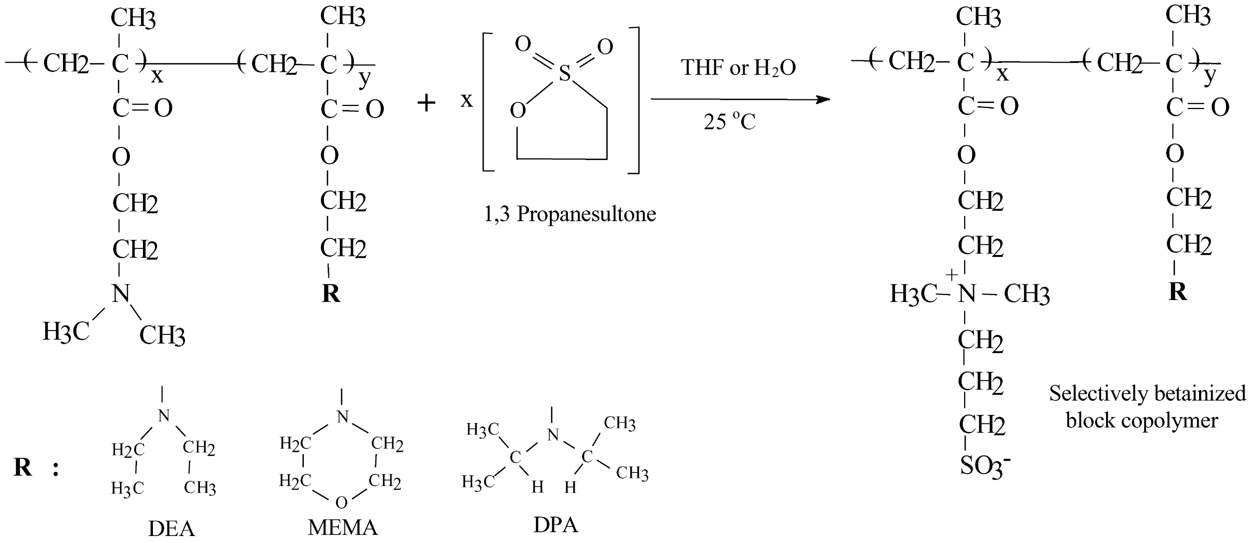

Fig. 4. Reaction scheme for the selective betainization of the 2-(dimethylamino)ethyl methacrylate residues in the tertiary amine methacrylate diblock copolymers using 1,3-propane sultone under mild conditions.

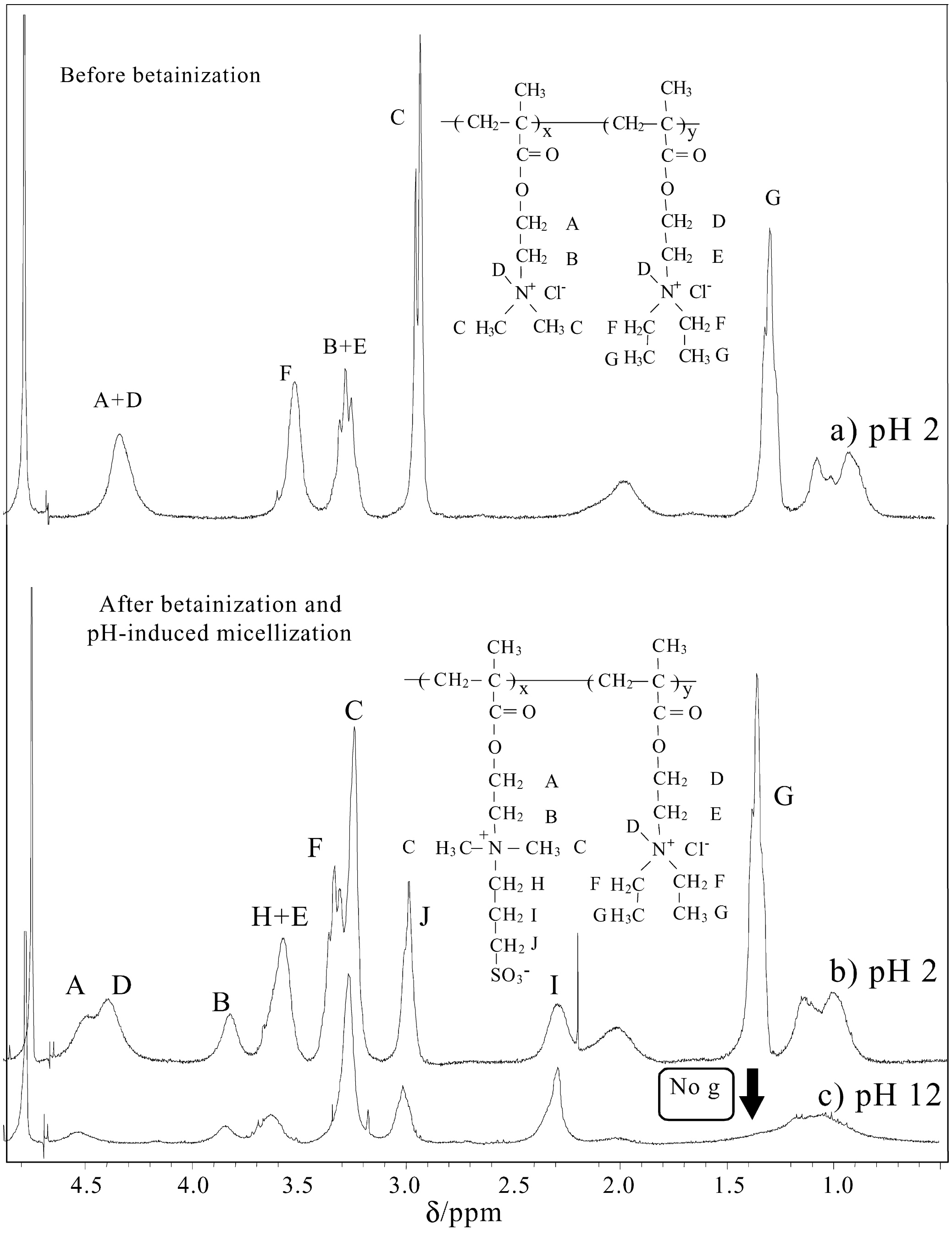

Fig. 5. ^{1}H NMR spectra of a selectively betainized 50:50 DMA–DEA block copolymer in D_2O–DCl (VB127): (a) precursor block copolymer pH 2; (b) after betainization at pH 2; (c) after betainization at pH 12 (micellar solution of the betaine block copolymer achieved by adjusting the solution pH with NaOD to pH 12). Note the disappearance of the D, F and G signals due to the micellization of the unquaternized DEA block.

both the copolymer molecular weights and the comonomer compositions of the selectively betainized block copolymers. When the DMA content of the DMA–DEA block copolymer is higher than 80 mol%, micellization is not possible. Unimer state exists even for pH > 8. On the other hand, if the DMA content of precursor copolymer lower than 30 mol%, macroscopic precipitation occurs when the solution pH is increased over pH 7 without micellization. Thus, for betainized DMA–DEA copolymer micelles, the DMA content should be lower than 80%. As the overall molecular weight was kept constant, the hydrodynamic diameter of the betainized DMA–DEA copolymer micelles slightly increased from 20 to 24 nm with increasing DEA content (see entries VB103, VB116 and VB118 in Table 2). At constant comonomer composition, the hydrodynamic diameters dramatically increased from 22 to 37 nm with increasing copolymer molecular weight (see VB100, VB124 and VB125 in Table 2). When the solution pH was acidic, only unimers exist due to protonation of DEA residues. When the pH was increased from pH 8.6 to pH

Table 2
A summary of copolymer compositions, molecular weights, polydispersities (PD) of selectively betainized DMA–DEA, and DMA–DPA diblock copolymers and their micelle diameters, PD's and solution conditions

Sample code	Selectively betainized block copolymer type	DMA content[a] (mol%)	Precursor M_n[b] (g mol^{-1})	Precursor PD[b] (M_w/M_n)	Calculated M_n[c] (g mol^{-1})	pH	Temp. (°C)	Micelle diameter[d] (nm)	Micelle PD[d]
103	bet-DMA–DEA	78	12,400	1.10	19,600	12.0	23	4	0.580
116	bet-DMA–DEA	67	11,070	1.10	16,500	12.0	23	20	0.210
118	bet-DMA–DEA	61	13,700	1.10	19,700	11.5	20	24	0.160
100	bet-DMA–DEA	49	9,550	1.15	12,850	11.0	20	22	0.066
124	bet-DMA–DEA	50	18,350	1.17	25,000	12.0	20	29	0.056
125	bet-DMA–DEA	51	32,600	1.10	44,000	12.0	20	37	0.064
127	bet-DMA–DEA	36	12,000	1.09	15,000	11.0	24	22	0.060
127	bet-DMA–DEA	36	12,000	1.09	15,000	8.6	24	21	0.090
127	bet-DMA–DEA	36	12,000	1.09	15,000	6.5	24	2	0.150
107	bet-DMA–DPA	80	11,550	1.10	18,250	11.0	20	21	0.126
101	bet-DMA–DPA	72	12,050	1.12	18,100	11.0	20	22	0.132
105	bet-DMA–DPA	61	15,750	1.11	22,400	11.0	20	22	0.170

[a] As determined by ^{1}H NMR spectroscopy.
[b] As determined by GPC (calibrated with poly(methyl methacrylate) standards).
[c] As calculated from GPC analyses of precursor polymers (assuming 100% betainization of the DMA residues).
[d] As determined by DLS on 1.0% aqueous solutions.

11.0, the micelle diameter slightly increased from 21 to 22 nm and narrower micellar size distributions were obtained at high pH (see VB127 in Table 2). The betainized DMA–DEA block copolymer micelles had reasonably narrow size distributions (see Table 2). Addition of acid caused complete dissociation of the betainized DMA–DEA block copolymer micelles. Under similar conditions, the micelle diameter of 22 nm of the betainized DMA–DEA diblock copolymer (VB100 in Table 2) is much higher than that of the quaternized DMA–DEA block copolymer (10 nm) synthesized from the same precursor by reacting with benzyl chloride as reported in our previous paper [34].

The surface activity of the DMA–DEA block copolymer has a strong pH and concentration dependence [32–34,36]. At high pH, the block copolymer becomes significantly more surface active (the limiting surface tension is ca. 32–34 mN m^{-1}). Presumably, the deprotonated hydrophobic DEA block becomes adsorbed strongly at the air–water interface, thus lowering the surface tension of the solution. Betainization significantly reduces the surface activities of the copolymers. For example, the limiting surface tension at pH 10–12 for a 1% selectively betainized 78:22 DMA–DEA block copolymer solution is only ca. 51 mN m^{-1} at pH >8, whereas the precursor block is much more surface active, exhibiting a limiting surface tension as low as 32 mN m^{-1} (see Fig. 6(A)). This is presumably due to the increased water-solubility of the DMA block with betainization, which decreases the adsorption of the block copolymer at the air–water interface.

The critical micelle concentration (CMC) of the 72:28 DMA–DEA block copolymer is around 0.02 w/v%, as estimated from the surface tension vs. copolymer concentration curve (see Fig. 6(B)). After selective betainization of the DMA residues, the limiting surface tension vs. concentration of this copolymer decreased appreciably to 50–52 mN m^{-1} (see Fig. 6(B)), indicating reduced adsorption at the air–water interface. In addition, the CMC of the betainized DMA–DEA block copolymer is around 0.04 w/v%, which is significantly higher than the CMC of the precursor block copolymer. Clearly, betainization of these copolymers decreases their surface activity.

3.4. Selective betainization of DMA residues in DMA–DPA block copolymers

Again, the degrees of betainization of the DMA blocks were determined by ^{1}H NMR spectroscopy. Fig. 7(a) shows the NMR spectrum of a 61:39 DMA–DPA block copolymer dissolved in DCl–D_2O, which is a good solvent for both block sequences. The signal at δ 3.0 is due to the six dimethylamino protons of the DMA residues, whereas the signal at δ 1.4–1.5 corresponds to the 12 protons of the four equivalent methyl groups in each of the DPA residues. Comparing these peak integrals gives a 61:39 DMA:DPA copolymer composition. Fig. 7(b) shows the NMR spectra of the betainized DMA–DPA block copolymer in D_2O in

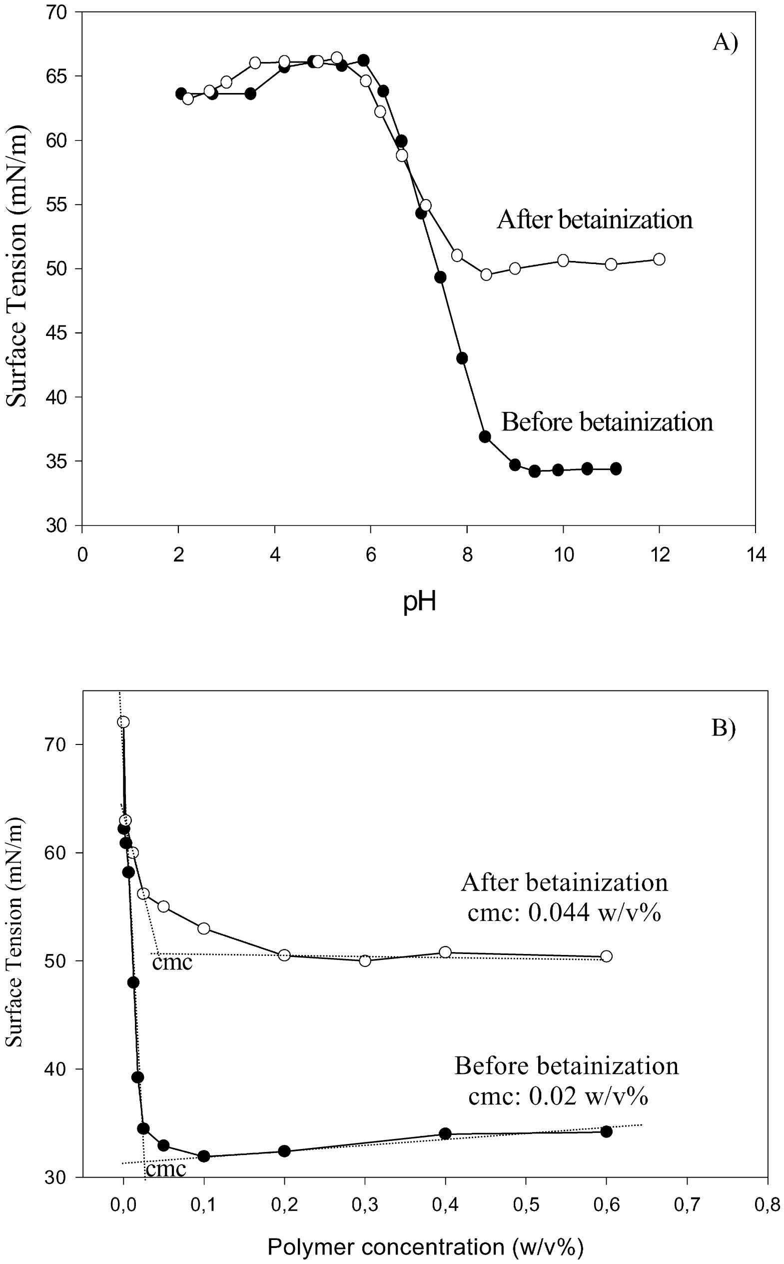

Fig. 6. Variation of surface tension with (A) pH for a 0.2 w/v% aqueous solution of a 78:22 DMA:DEA block copolymer ($M_n = 12{,}400$ g mol^{-1}) and (B) as a function of copolymer concentration at pH 8.5. Note that the selective betainization of the DMA residues dramatically reduces the surface activity of the DMA–DEA block copolymer.

both acidic and alkaline media. After betainization of the DMA residues, the signal due to the six dimethylamino protons shifted to δ 3.2–3.3 and new signals of the propylsulfonate group appeared at δ 2.3, 3.0 and 3.6. The signals due to the DPA residues remained unchanged. Comparing the peak integrals of peak C and peak G gives the same 61:39 copolymer composition as that determined for the original DMA–DPA precursor block prior to betainization. Thus betainization of the DMA residues is again both selective and near-quantitative.

As we have reported in our recent paper, the DMA–DPA block copolymers were also shown to exhibit highly pH-dependent micellization [33]. It was suggested that the more hydrophobic DPA (or DEA) block adsorbed at the air–water interface and also formed the interior of the copolymer micelles. Our NMR studies of the betainized 61:39 DMA–DPA block copolymer now support this hypothesis. Initially, this copolymer was molecularly dissolved in DCl–D_2O (see Fig. 7, spectrum b). On addition of excess NaOD, the strong signal at δ 1.3–1.4 observed in ‘spectrum b’ due to the 12 equivalent methyl protons of the DPA residues completely disappears (see Fig. 7, spectrum c), indicating that this deprotonated block sequence is no longer solvated. This is strong evidence for the DPA block

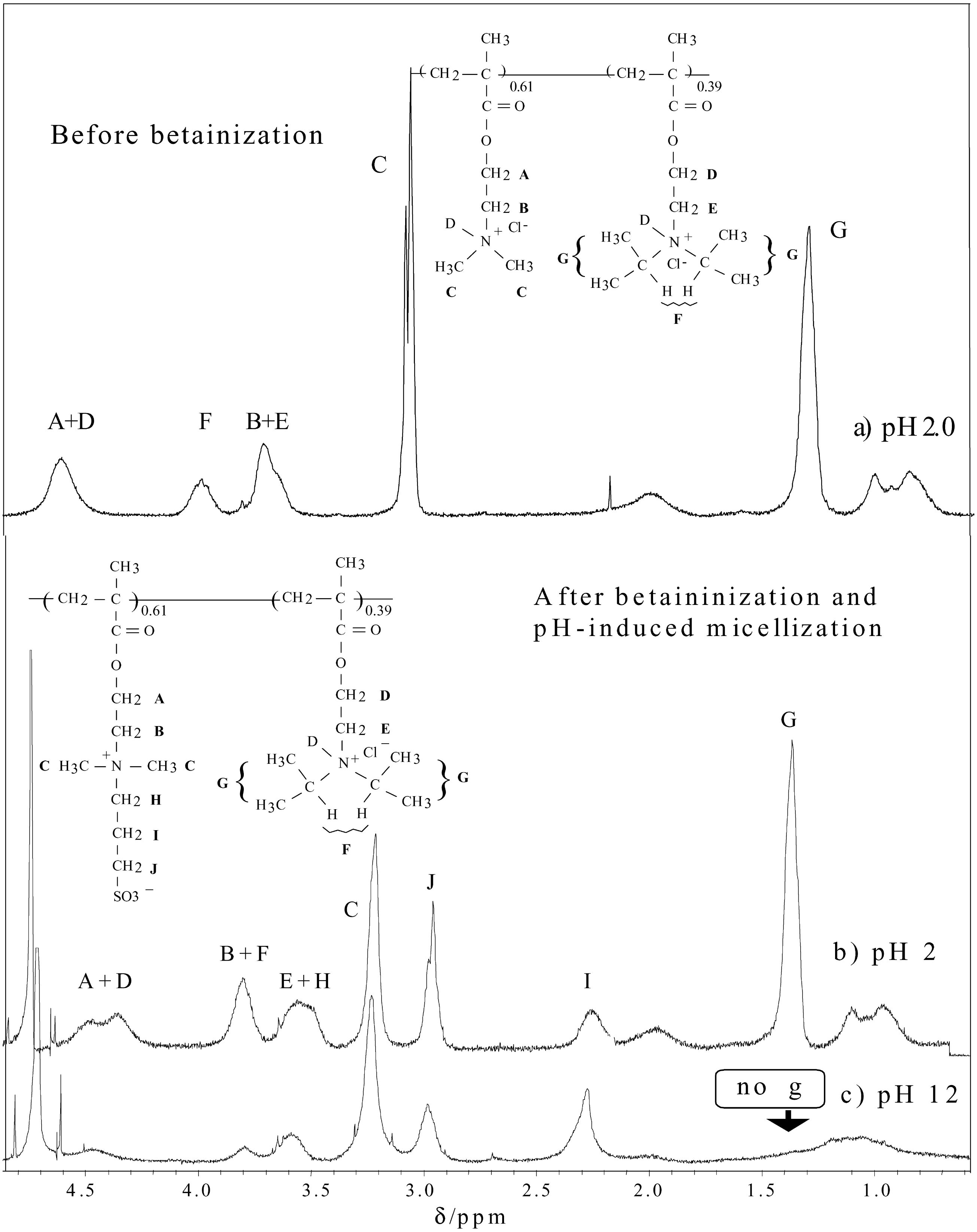

Fig. 7. ^{1}H NMR spectra of a 61:39 DMA–DPA block copolymer (VB86): (a) before betainization (DCl–D_2O, pH 2); (b) betainized DMA–DPA copolymer dissolved in DCl–D_2O at pH 2; (c) micellar solution of the same betaine block copolymer achieved by adjusting the solution pH with NaOD to pH 12.

forming a hydrophobic micellar core, as expected. Similar spectral changes are observed in the NMR spectrum of the betainized DMA–DEA block copolymer under similar conditions as reported earlier [34]. It is noteworthy that the micellization behaviour reported for the DMA–DEA and DMA–DPA precursor blocks only occur over a rather narrow pH range, since precipitation occurs above pH 8–9 due to deprotonation of the hydrophilic DMA residues [33]. In contrast, since the betainized DMA residues are soluble in alkaline media the betainized block remain in solution as micelles up to pH 12–13.

Dynamic light scattering studies of pH-induced micellization were carried out on dilute aqueous solutions of the betainized block copolymers. The betainized DMA–DPA block copolymers formed micelles of ca. 22 nm (see Table 2) with reasonably narrow size distributions. In our previous paper, we have reported that the micelle diameters of the selectively methylated DMA–DPA block copolymers strongly depended on DPA contents. As the hydrophobic DPA content was increased, larger micelle diameters were obtained [34]. In the case of betainized DMA–DPA diblock copolymer micellization, the comonomer composition of diblock copolymers did not affect the hydrodynamic diameter of the micelles, but broaden PD was obtained by decreasing molecular weight of the copolymer. Addition of acid caused complete dissociation of the betainized DMA–DPA block copolymer micelles. This micellization is completely reversible.

3.5. Selective betainization of DMA residues in DMA–MEMA block copolymers

Both DMA and MEMA homopolymers exhibit inverse temperature solubility behaviour. Their cloud points lie between 32 and 53 °C for 1% aqueous solutions, depending on molecular weight [33]. Compared to DMA and most other water-soluble polymers, MEMA homopolymer can be easily precipitated (salted out) from aqueous solution on addition of electrolytes such as Na_2SO_4, K_2CO_3, Na_3PO_4 etc. Normally, it was expected that their block copolymers should have induced micellization in aqueous media when the solution temperatures are increased above the cloud point of DMA block. This was studied by both varying DMA content from 10 to 90 mol% and molecular weights from 5,000 to 50,000 g mol^{-1} and no micellization was observed [33]. Instead of micellization, the copolymers gave aggregation with the cloud points lying between the cloud points of the DMA and MEMA blocks. Similar aggregation with the diameter of around 650 nm was reported by Lowe but no micellization was observed [29]. Thus, it is difficult to get DMA–MEMA block copolymer micelles with DMA block forming the micelle core due to the small temperature difference (5–10 °C) between the cloud points of these two blocks [33]. In contrast, partial protonation of the DMA residues at pH 7.5 allows us to obtain stable micelles by increasing the solution temperature or by adding salt at room temperature, with the MEMA block forming the micelle core [33]. However, in both cases while the salt-induced micelles are stable, the micelles obtained at pH 7.5 in the absence of salt by increasing temperature above the cloud point of the MEMA residues are stable only over a rather narrow temperature range (65–68°C) for a 40:60 DMA:MEMA block copolymer.

In order to produce much greater solubility differences between the DMA block and the MEMA block, selective betainization or quaternization can be used. Thus stable micelles are formed with the more soluble betainized DMA block forming the solvated corona and the MEMA block forming the micelle core, both at higher temperatures and also at room temperature in the presence of high salt concentrations (see Fig. 8).

Therefore, selective betainization of the DMA residues of the DMA–MEMA block copolymers was carried out by reacting with 1,3-propane sultone (10% excess based on DMA residues) in THF at room temperature within 24 h. Fig. 9 shows the spectra of a 46:54 DMA–MEMA precursor copolymer (spectrum a) and after its selective betainization (spectrum b: in the absence of salt, spectrum c: in the presence of 0.5 M K_2CO_3). The degrees of betainization (see Table 3) were determined using ^{1}H NMR spectroscopy (see Fig. 9(a)). The peak integral of the six dimethylamino protons of betainized DMA residues at δ 3.2–3.3 was compared to that of the six protons of the $-CH_2-$ groups (at δ 2.5–2.7) bound to the nitrogen of the MEMA residues (see Fig. 9(b)). After salt addition, all peaks due to the MEMA residues completely disappeared (see Fig. 9(c)), thus the MEMA block is no longer solvated. Presumably, it forms the non-solvated micelle core, while the betainized DMA block forms the solvated micelle corona. As salt is removed by dialysis, the MEMA residues become rehydrated again. Thus, the micellization is completely reversible. In addition, when the solution temperature (without salt and at $pH > 8$) is increased above the cloud point of the MEMA block, the MEMA block became partially dehydrated and formed the micelle cores while the betainized DMA remained still solvated and formed the micelle corona.

DLS studies confirmed that the diameters of micelles obtained in the presence of salt at 20 °C increased from 10 to 46 nm with increasing copolymer molecular weight (see VB114, VB113 and VB125 in Table 3: Note that the copolymer compositions are similar). In addition, the micelle diameters were between 13–38 nm at high pH, depending on both solution pH and the salt concentration (see VB197 in Table 3). All micelles had very low polydispersities (except VB197, at 65 °C at pH 7 without salt addition). Under similar conditions, in the presence of salt and at room temperature, the micelle diameters of betainized DMA–MEMA diblock copolymer (see VB121, 123, 197 in Table 3) are 10–20% higher than that of the selectively quaternized DMA–MEMA diblock copolymers synthesized from the same precursor diblock copolymer by reacting with either benzyl chloride or methyl iodide [34].

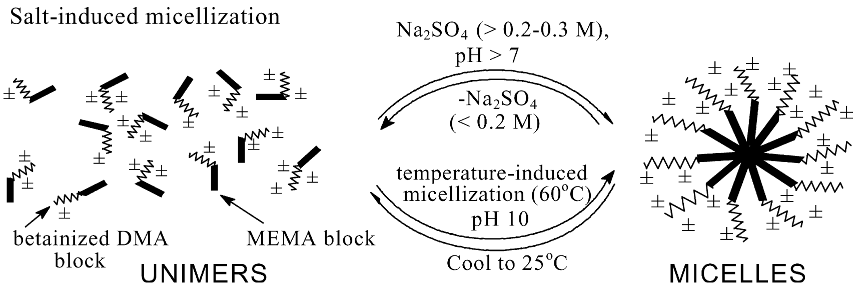

Fig. 8. Schematic representation of the formation of micelles for selectively betainized DMA–MEMA block copolymers.

Dialysis of salt at room temperature, lowering the temperature below the cloud point of the MEMA block in the absence of salt and/or addition of acid caused complete dissociation of the betainized DMA–MEMA diblock copolymer micelles. These micellization are completely reversible.

In our latest paper [44], we also reported an interesting behaviour of the betainized DMA–MEMA diblock copolymers in aqueous solution. Such diblock copolymers defined as thermo-responsive schizophrenic diblock copolymer forms the MEMA core micelles above an upper critical micelle temperature of about 50 °C and the betainized-DMA core micelles below a lower critical micelle temperature of approximately 20 °C.

4. Conclusions

We described for the first time that the selective betainization of the DMA residues in the tertiary amine methacrylate based dibasic block copolymers can be achieved using 1,3-propane sultone under mild conditions. Preliminary experiments on the DMA, MEMA, DEA and DPA homopolymers confirmed that only DMA homopolymer was quantitatively betainized at room temperature in THF within 24 h. The DEA and MEMA homopolymers required significantly longer reaction times and refluxing THF. The sterically hindered DPA homopolymer remained completely unbetainized even after 4 days in refluxing THF. This reactivity differences due to steric hindrance allowed us to study selective betainization of the DMA residues in the tertiary amine methacrylate copolymers. We have shown that selective betainization of the DMA residues in the DMA–DEA, DMA–DPA and DMA–MEMA block copolymers can be achieved by reacting with near-stoichiometric amount of 1,3-propane sultone in THF at room temperature. These selectively betainized tertiary amine methacrylate (co)polymers were water-soluble at room temperature both in acidic media and also at neutral pH. Both betainized DMA–DEA and DMA–DPA block copolymers behave as hydrophilic–hydrophilic blocks in acidic media but as hydrophilic–hydrophobic blocks in neutral/alkali media. DLS and ^1H NMR studies confirmed reversible pH-induced micellization up to pH 13 without any precipitation; with the hydrophobic block (DEA or

Table 3
A summary of copolymer compositions, molecular weights, polydispersities (PD) and the hydrodynamic diameters, PD and solution conditions for selectively betainized DMA–MEMA block copolymers

Sample code	DMA content[a] (mol%)	Precursor M_n[b] (g mol^{-1})	Precursor PD[b] (M_w/M_n)	Calculated M_n[c] (g mol^{-1})	Temp. (°C)	pH and salt conc. (mol dm^{-3})	Micelle diameter[d] (nm)	Micelle PD[d]
VB109	65	19,200	1.10	29,000	21	1.0 M Na_2SO_4	29	0.038
VB122	59	31,150	1.08	44,000	21	0.7 M Na_2SO_4	37	0.033
VB112	48	15,000	1.10	19,850	21	0.9 M Na_2SO_4	26	0.031
VB121	46	25,500	1.10	33,450	21	0.7 M Na_2SO_4	35	0.033
VB197	40	27,600	1.09	35,000	23	No salt/pH 7	Unimer	–
VB197	40	27,600	1.09	35,000	65	No salt/pH 7	13	0.256
VB197	40	27,600	1.09	35,000	25	NaOH/pH > 11	Unimer	–
VB197	40	27,600	1.09	35,000	65	NaOH/pH > 11	37	0.026
VB197	40	27,600	1.09	35,000	25	0.1 M Na_2SO_4	Unimer	–
VB197	40	27,600	1.09	35,000	65	0.1 M Na_2SO_4	38	0.024
VB197	40	27,600	1.09	35,000	24	0.4 M Na_2SO_4	37	0.068
VB113	37	18,850	1.07	23,500	22	0.6 M K_2CO_3	33	0.065
VB113	37	18,850	1.07	23,500	21	0.7 M Na_2SO_4	30	0.051
VB114	36	5,200	1.11	6,450	20	0.8 M Na_2SO_4	10	0.536
VB123	35	36,000	1.10	44,000	21	0.5 M Na_2SO_4	46	0.056

[a] As determined by ^1H NMR spectroscopy.

[b] As determined by GPC (calibrated with poly(methyl methacrylate) standards).

[c] As calculated from GPC analyses of precursor polymers.

[d] As determined by DLS on 1.0% copolymer solutions.

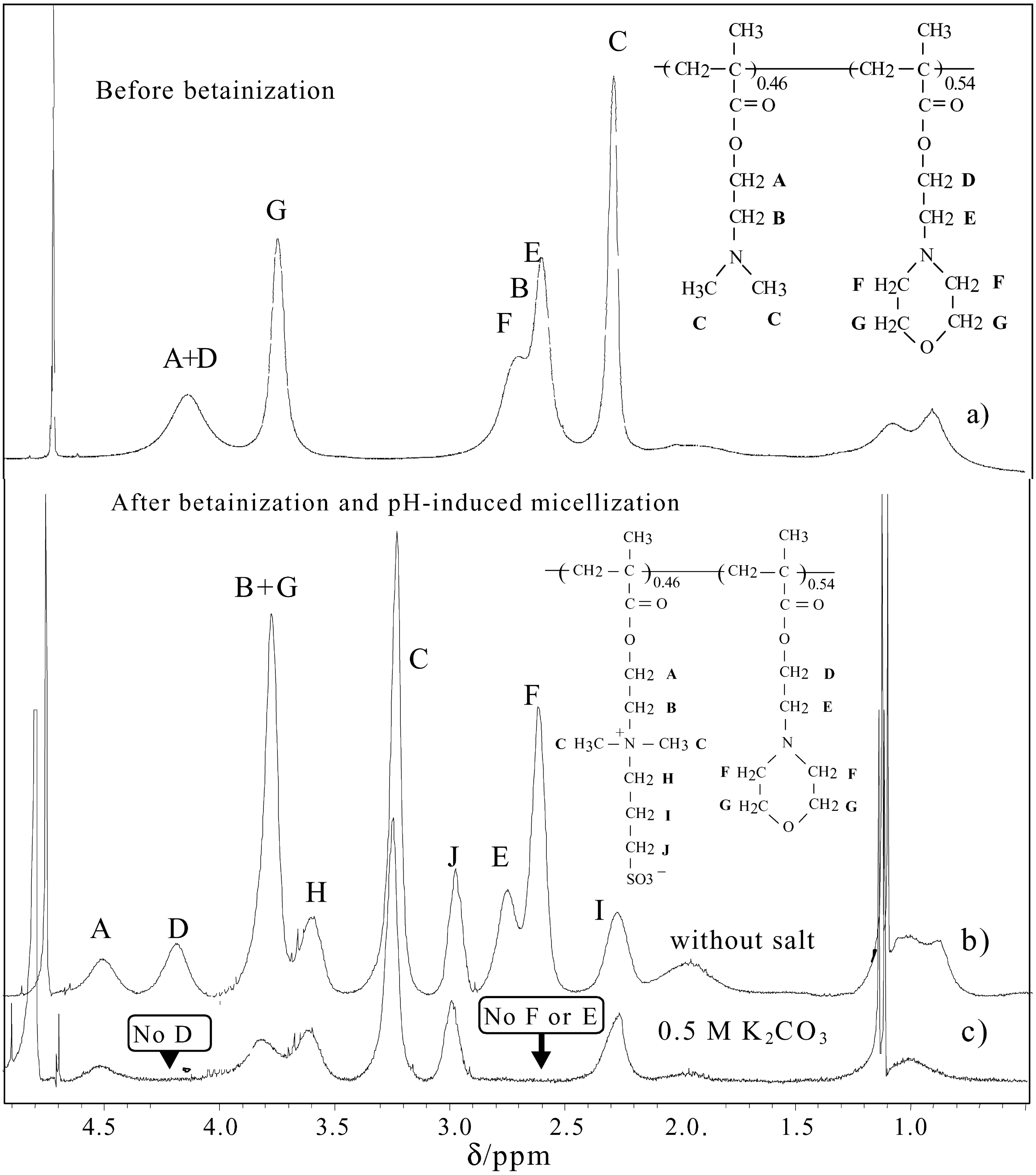

Fig. 9. ^{1}H NMR spectra of a 46:54 DMA–MEMA block copolymer (VB33B) in D_2O: (a) before selective betainization; (b) after selective betainization (VB121); (c) after selective betainization and in the presence of 0.5 M K_2CO_3. Note the disappearance of the MEMA signals due to micellization in the latter case.

DPA) forming the micelle core and the hydrophilic block (betainized DMA) forming the solvated corona. The micelle diameters were in the range of 20–40 nm depending on M_n's and block compositions. In contrast, the precursor blocks precipitate above pH 10 due to deprotonation of the DMA block. In addition, betainization of the DMA residues in DMA–DEA copolymer significantly reduces the surface activity of the DMA–DEA copolymer due to the high charge density on the betaine block, which presents efficient packing at the air–water interface.

Selective betainization of the DMA residues of the DMA–MEMA block copolymers enhanced the solubility difference between these two hydrophilic blocks. Thus stable micelles were obtained; with the MEMA block forming dehydrated micelle cores either at high temperature in alkaline media (pH 7–13) or in the presence of salt at room temperature. In both cases, micellization was reversible and micelle diameters were in the range of 10–46 nm depending on the solution pH, electrolyte concentration, temperature, block composition and copolymer M_n.

In summary, selectively betainized block copolymers exhibited reversible pH-, salt- and temperature-induced micellization under various conditions with the micelle diameters of 10–46 nm. In some cases near-monodisperse micelles were obtained. Betainization significantly reduced the surface activities of the DMA-DEA precursor block copolymers.

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