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Review

Synthesis, Characterization, and Aqueous Solution Behavior of Electrolyte- and pH-Responsive Carboxybetaine-Containing Cyclocopolymers†

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ABSTRACT: A novel pH- and salt-responsive carboxybetaine monomer, 4-(*N*,*N*-diallyl-*N*-methylammonio)-butanoate (**2**), was prepared and cyclocopolymerized with the cationic monomer *N*,*N*-diallyl-*N*,*N*-dimethylammonium chloride (**3**) in 0.5 M NaCl aqueous solution (pH = 7.0) using 2-hydroxy-1-[4-(hydroxyethoxy)phenyl]-2-methyl-1-propanone (Irgacure 2959) as the free-radical photoinitiator. The molar feed ratio of **2**:**3** was varied from 100:0 to 0:100 with the total monomer concentration held constant at 2.5 M. Cyclopolymerization to five-membered ring structures common to diallylammonium salts was confirmed by ^{13}C NMR spectroscopy. Reactivity ratio studies indicate that **2** and **3** copolymerize in a nearly ideal fashion ($r_1 = 0.86$, $r_2 = 0.99$). Weight-average molecular weights and second virial coefficients vary from (6.0 to 12.8) $\times 10^4$ g mol^{-1} and (1.62 to 5.36) $\times 10^{-4}$ mL mol g^{-2}, respectively. Dilute solution viscosity behavior depends on copolymer composition, ionic strength, and pH. Copolymers with a large excess charge exhibit typical polyelectrolyte behavior, while those with balanced charge exhibit “anti-polyelectrolyte” behavior reported for zwitterionic (co)polymers. The polymers studied here are closely analogous cyclocopolymers we prevoiusly reported containing sulfobetaine mer units.[25] Unlike solutions of sulfobetaine-containing polymers, soltuions of poly(**2**-*co*-**3**) remain soluble at very low ionic strength even up to 100% incorporation of **2**. Additionally, while the sulfobetaine systems are insensitive to pH, solutions of poly(**2**-*co*-**3**) exhibit a pH-dependent viscosity. All the copolymers have an apparent pK_a of ~3.6. Copolymers with **2** incorporations of 28 mol % and above have viscosity responsiveness between pH values of 2.5 and 4.5. The maximum pH response was achieved for solutions of poly(**2**-*co*-**3**) containing 37 and 56 mol % of the carboxybetaine monomer **2**.

Introduction

Ion-containing water-soluble polymers are a diverse class of polymers, ranging from biopolymers such as nucleic acids and proteins that mediate life processes to commercial polymers with applications in water remediation, drag reduction, and formulation of pharmaceutics, cosmetics, and coatings. Charged polymers can be arbitrarily divided into two classes: polyelectrolytes and polyampholytes. The former have ionizable functional groups that are *either* anionic or cationic. The charges may be along or pendent to the macromolecular backbone, and charges are balanced by small gegenions or counterions. Zwitterionic polymers have *both* cationic and anionic charges along or pendant to the backbone. Polymers containing cationic and anionic functionality on different mer units are termed polyampholytes while those having both charges on a single mer unit are called polybetaines.

Charge−charge repulsions along the polyion backbone and osmotic effects, resulting from counterion mobility, are responsible for chain extension and the large hydrodynamic volume of polyelectrolytes in water at low ionic strength. The degree of extension depends greatly on copolymer composition, flexibility, and the effective charge density.[1−3] The solution behavior of polyampholytes is also governed by the charge balance on the polymer chain. A sufficient excess of either charge can cause the polymer to exhibit typical polyelectrolyte behavior.[4−12] Polymers with charge balance, on the other hand, typically exhibit “anti-polyelectrolyte” behavior, characterized by a collapsed conformation in deionized water and an expanded conformation in the presence of small electrolytes.[5,9,13]

Charge density and the type of ions are also important factors affecting the solution properties of polyampholytes near their isoelectric points. Higher charge density polymers consisting of sulfonate and ammonium ions are largely insoluble in pure water and require a critical concentration of added electrolyte for solubilization.[5,14−25] Low charge density polyampholytes can be solubilized in water provided comonomers are sufficiently hydrophilic.[7] Carboxylate/ammonium polyampholytes, on the other hand, tend to be soluble even in deionized water.[26−32]

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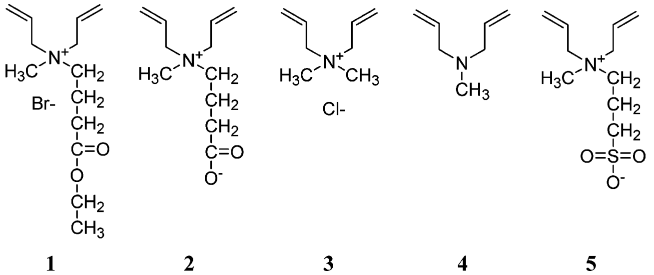


Figure 1. Chemical structures of the diallyl monomers *N*,*N*-diallyl-*N*-(3-ethoxycarbonylpropyl)-*N*-methylammonium chloride (**1**), 4-(*N*,*N*-diallyl-*N*-methylammonio)butanoate (DAMAB) (**2**), *N*,*N*,-diallyl-*N*,*N*-dimethylammonium chloride (DADMAC) (**3**), *N*,*N*-diallyl-*N*-methylamine (DAMA) (**4**), and 3-(*N*,*N*-diallyl-*N*-methylammonio)propanesulfonate (DAMAPS) (**5**).

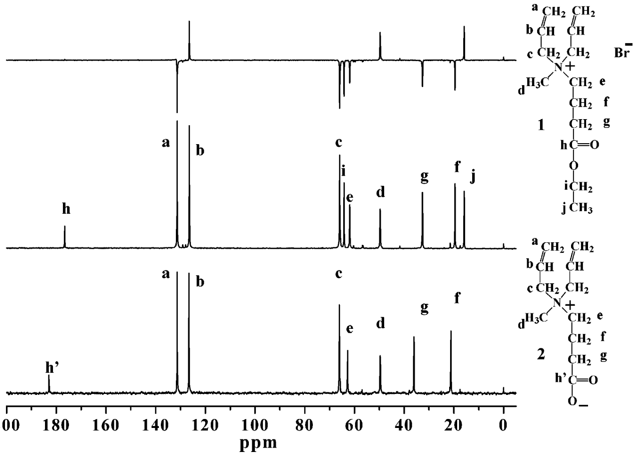


Figure 2. NMR data confirming the structure of **2** and the precursor ethyl ester (**1**). Top to bottom: DEPT135 spectrum of **1**, ^{13}C NMR spectrum of **1**, and the ^{13}C NMR spectrum of **2**.

Polybetaines synthesized from zwitterionic monomers represent a special class of polymers that provide a well-controlled balance of charge distribution along the polymer. Most studies of polybetaines have focused on (meth)acrylamide,[14,21,22,28,29,33] (meth)acrylate,[16,18,21,24,34−38] or vinylpyridine[18,33,37,39−41] based polymer backbones. These molecular architectures can be controlled to yield flexible backbones with short persistence lengths.

Recently, our group[25,42−46] and others[23,26,32,47] have reported various zwitterion-containing polymers derived from diallylammonium monomers (Figure 1). A series of cyclocopolymers based on the copolymerization of *N*,*N*-diallyl-*N*,*N*-dimethylammonium chloride (**3**) or *N*,*N*-diallyl-*N*-methylamine (**4**) with 3-(*N*,*N*-diallyl-*N*-methylammonio)propanesulfonate (**5**) have been synthesized and extensively characterized.[25,42−46] These monomers undergo photochemically induced cyclopolymerization, yielding the five-membered rings common to diallylammonium salts.[48] In earlier communications, we reported preliminary studies of copolymers based on **3** and the pH responsive monomer 4-(*N*,*N*-diallyl-*N*-methylammonio)butanoate (**2**).[46,49] Herein we present the full synthetic details and polymer characterization as well as the electrolyte and pH-responsive solution behavior of the resulting copolymers. The viscosity response is compared to analogous polymers containing sulfobetaine mer units (**5**).

Experimental Section

Materials. All reagents were purchased from Aldrich Chemical Co. and used as received unless otherwise noted. *N*,*N*-Diallyl-*N*-methylamine was synthesized as previously described.[50]

4-(*N*,*N*-Diallyl-*N*-methylammonio)butanoate (2). *N*,*N*-Diallyl-*N*-methylamine (**4**) (0.9 mol), ethyl 4-bromobutyrate (0.99 mol), and acetonitrile (500 mL) were deaerated by multiple freeze−pump−thaw cycles, combined, and allowed to react under reflux with stirring for 60 h. Acetonitrile was removed under vacuum, and the resulting oil was washed continuously with ether for 5 days utilizing a liquid−liquid extractor. The oil was then lyophilized to remove any associated water. The ammonium bromide solid, **1** (mp 47−49 °C), was obtained in 85% yield. Elemental microanalysis for $C_{12}H_{24}NO_2Br$. Calculated: C, 50.99%; H, 7.90%; N, 4.57%; Br, 26.09%. Found: C, 50.85%; H, 7.97%; N, 4.58%; Br, 26.33%.

The ammonium bromide intermediate, **1**, was then dissolved in deionized water and passed over an Amberlite IRA-400-(OH-) ion-exchange resin to yield the carboxybetaine monomer, **2**, in quantitative yield. The structure was confirmed by ^{13}C NMR spectroscopy (Figure 2).

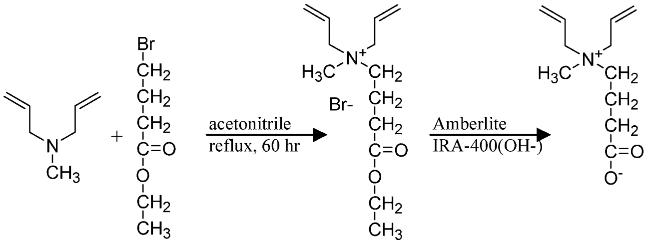
Cyclocopolymers 2-*co*-3. The homopolymers poly(**2**-*co*-**3**)-(100/0) and poly(**2**-*co*-**3**)(0/100) and the copolymers poly(**2**-*co*-**3**)(8/92) through poly(**2**-*co*-**3**)(80/20) were synthesized by free radical photopolymerization in a 0.5 M aqueous NaCl solution under a nitrogen atmosphere at 35 °C using 0.3 mol % 2-hydroxy-1-[4-(hydroxyethoxy)phenyl]-2-methyl-1-propanone (Irgacure 2959) (Ciba) as the photoinitiator. The feed ratio of **2**/**3** was varied from 0/100 to 100/0 mol % with the total monomer concentration held constant at 2.5 M. The pH of the reaction medium was maintained at 7.0. The polymerizations were carried out in a Rayonet photoreactor (Southern New England Ultraviolet Co.) operating at 300 nm. A low-conversion sample was obtained for reactivity ratio studies. The reaction was terminated at <50% conversion to minimize copolymer drift and photodegradation of the resulting (co)-polymers. The polymers were purified by dialysis against deionized water with 6000−8000 MWCO dialysis tubing (Spectrapor). The dialysis was carried out for 2 weeks with frequent changing of the permeate before recovery by lyophilization.[25,45] Conversions were determined gravimetrically. Isolated yields were as follows: poly(**2**-*co*-**3**)(0/100), 37.2%; poly(**2**-*co*-**3**)(8/92), 32.5%; poly(**2**-*co*-**3**)(28/72), 42.4%; poly(**2**-*co*-**3**)(37/63), 46.3%; poly(**2**-*co*-**3**)(56/44), 39.1%; poly(**2**-*co*-**3**)(80/20), 36.4%; poly(**2**-*co*-**3**)(100/0), 28.8%.

Instrumental Methods. ^{1}H and ^{13}C NMR spectra were recorded with a Bruker AC-200. ^{13}C NMR spectra of the cyclocopolymers were obtained at 50.3 MHz using 15−20 wt % 1.0 M NaCl aqueous (D_2O) polymer solutions with DSS as an internal reference. DEPT135 experiments confirmed peak assignments for both monomer and polymer samples. A recycle delay of 10 s, 90° pulse length, and inverse gated decoupling to remove all NOE were used for quantitative spectral analysis. Elemental microanalyses were performed by MHW Laboratories, Phoenix, AZ. Molecular weight studies were performed with a Brookhaven Instruments 128-channel BI-2030 AT digital correlator using a Spectra Physics He−Ne laser operating at 632.8 nm in 1.0 M NaCl in water at 25 °C. Weight-average molecular weights were determined via Berry plot analyses. Polydispersities were determined by aqueous size exclusion chromatography (ASEC) using CATSEC columns (Eichrom Technologies Inc.) with 1 wt % acetic acid, 0.1 M Na_2SO_4 as the eluent, and refractive index and UV detectors. Dispersion corrections were made using poly(ethylene oxide) standards. Refractive index measurements were carried out using a Chromatix KMX-16 differential refractometer. Solution pH values were measured using an Orion 900A potentiometric titrator.

Results and Discussion

4-(*N*,*N*-Diallyl-*N*-methylammonio)butanoate (2) was synthesized by a two-step reaction as shown in Scheme 1. The reaction of **4** with ethyl 4-bromobutyrate proved to be reasonably facile despite the hindered nature of the amine nucleophile. An initial problem

Scheme 1. Synthetic Pathway for the Preparation of 4-(*N*,*N*-Diallyl-*N*-methylammonio)butanoate (2)



4 **1** **2**

encountered was oxidation of the amine at the long reaction times required. Elimination of oxygen through the freeze–pump–thaw process proved sufficient to prevent oxidation. Conversion of the intermediate ester (**1**) to the carboxybetaine monomer (**2**) was readily achieved with one pass over a column packed with the Amberlite IRA-400(OH-) ion-exchange resin. This method has the additional benefit of eliminating ionic impurities from the sample. Monomer structure **2** was confirmed by ^{13}C NMR spectroscopy (Figure 2).

DADC Cyclocopolymers (2-*co*-3). The photoinitiator 2-hydroxy-1-[4-(hydroxyethoxy)phenyl]-2-methyl-1-propanone (Irgacure 2959) generates a high concentration of radicals and thus more rapid conversion than thermal initiators during the polymerization of diallyl salts. Polymerization reactions proceed as shown in Scheme 2. Feed ratios of monomer **2** were varied from 0 to 100 mol % **2** (poly(**2**-*co*-**3**)(0/100) to poly(**2**-*co*-**3**)(100/0)). Polymerization conditions and the resulting copolymer compositions are listed in Table 1. No phase separation or precipitation occurred during polymer synthesis; therefore, homogeneous reaction conditions throughout the polymerization can be inferred.

Representative inverse gated decoupled ^{13}C NMR spectra are shown in Figure 3 for the homopolymer poly(**2**-*co*-**3**)(0/100) and the cyclocopolymer poly(**2**-*co*-**3**)(37/63). The five-membered ring structure[51] is evident in each copolymer spectrum with the cis conformation predominating as in the DADMAC homopolymer. Copolymer compositions of low-conversion samples were determined utilizing eq 1

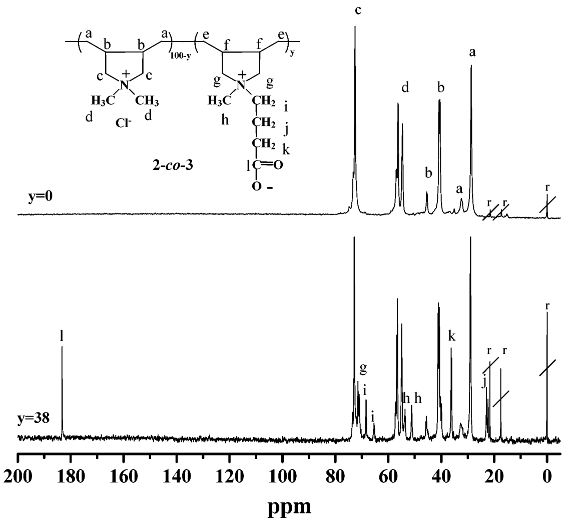


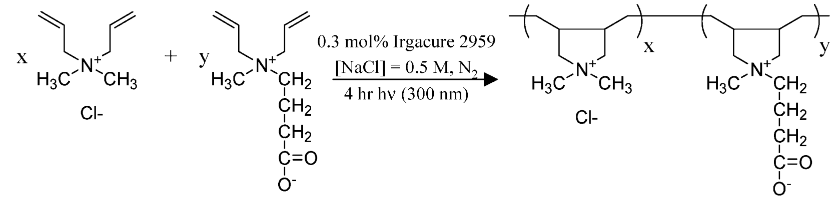
Figure 3. Inverse gated decoupled ^{13}C NMR spectra of the **3**-*co*-**2** cyclocopolymers in D$_2$O (1 M NaCl): (a) $y = 0$; (b) $y = 38$.

$$\text{mol \% } \mathbf{2} = \frac{4}{3}\left(\frac{I_l + I_i + I_k}{I_a + I_b}\right) \quad (1)$$

in which I_l, I_i, I_k, I_a, and I_b represent integrated intensities corresponding to carbons l, i, k, a, and b, respectively. These compositions were then used to determine the reactivity ratios by a nonlinear least-squares method.[52] A plot of copolymer composition vs feed composition is shown in Figure 4. Not surprisingly, the reactivity ratios obtained, $r_1 = 0.86$ and $r_2 = 0.99$, for the **3** (M$_1$)/**2** (M$_2$) monomer pair are close to the ideal values expected for comonomers with the same reactive functionality.

Classical light scattering studies (Table 1) conducted in 1.0 M NaCl solution indicate that all copolymers containing **2** have weight-average molecular weights, M_w, ranging from 8.9×10^4 to 21.8×10^4 g mol^{-1}. These moderate molecular weights are in the typical range

Scheme 2. Synthetic Pathway for the Cyclocopolymerization of 3 and 2



3 **2** poly(**2**-*co*-**3**)

Table 1. Monomer Feed Ratios and Polymer Compositions for the Copolymerization of 3 and 2[a]

sample	**2** in feed (mol %)	**2** in copolymer (mol %)[b]	$M_w \times 10^{-4}$ (g mol^{-1})	$A_2 \times 10^4$ (mL mol g^{-2})	PDI[d]	DP$_n$[e]
poly(**2**-*co*-**3**)(0/100)	0	0[c]	6.0	2.56	1.63	228
poly(**2**-*co*-**3**)(8/92)	10	8.0 ± 0.9	10.7	3.84	1.67	389
poly(**2**-*co*-**3**)(28/72)	25	28 ± 2	10.6	2.46	1.52	406
poly(**2**-*co*-**3**)(37/63)	40	37 ± 3	21.8	1.62	1.73	720
poly(**2**-*co*-**3**)(56/44)	60	56 ± 4	8.9	2.67	1.65	297
poly(**2**-*co*-**3**)(80/20)	80	80 ± 3	9.5	5.33	1.37	365
poly(**2**-*co*-**3**)(100/0)	100	100[c]	11.0	5.36	1.45	332

[a] Molecular weights and second virial coefficients, A_2, determined by classical light scattering in 1.0 M NaCl. The polydispersity index (PDI) was determined by aqueous size exclusion chromatography (ASEC) using PEO standards to correct for dispersion. [b] As determined by inverse gated-decoupled ^{13}C NMR spectroscopy (D$_2$O). [c] Theoretical value. [d] As determined by aqueous SEC. [e] Calculated from M_w and PDI.

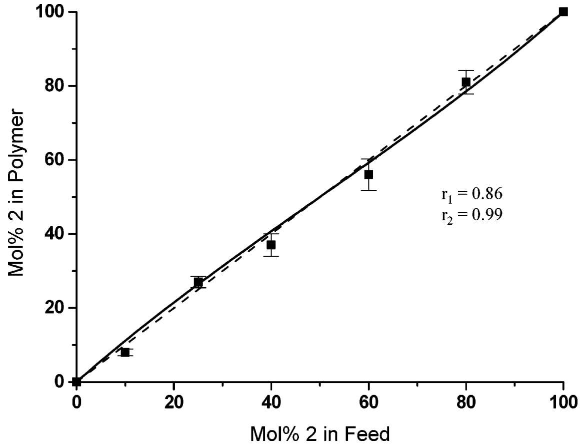


Figure 4. Mole % carboxybetaine incorporation in **3**-*co*-**2** copolymers as a function of mole % carboxybetaine in the feed as determined by inverse gated decoupled ^{13}C NMR spectroscopy. The dashed line represents an ideal copolymerization. The solid line results from fitting experimental data to the model of Tidwell and Mortimer.[52]

for diallylammonium polymers and are likely the result of chain transfer to monomer involving labile allylic hydrogen atoms.[53] Second virial coefficients, A_2, for the copolymers containing **2** range from 1.62×10^{-4} to 5.36×10^{-4} mL mol g^{-2} with a minimum at 37 mol % **2** incorporation. The low values of A_2 observed in 1.0 M NaCl at 25 °C indicate near-Θ conditions.

It is important to note the narrow range of molecular weights (and DP's) obtained under polymerization conditions that differed only in the feed ratio of the comonomers. The kinetic chain length, therefore, appears independent of the monomer feed ratio, in agreement with the measured reactivity ratios $r_1 \approx r_2 \approx 1$. The narrow range of molecular weights also enables the comparison of the solution properties of these polymers. Any observed differences should be due to differences in chemical composition.

Aqueous size exclusion chromatography (ASEC) of polymer samples after purification by dialysis afforded polydispersity indexes between 1.37 and 1.73. The purification process probably narrows the molecular weight distribution somewhat from that found in the polymerization solution due to elimination of lower molecular weight oligomers. Combining the weight-average molecular weights determined by light scattering with the polydispersity indexes determined by aqueous SEC allows the calculation of number-average molecular weights, M_n, and degrees of polymerization, DP$_n$.

Electrolyte Responsive Dilute Solution Behavior. To study the effect of environmental stimuli on the individual polymer coils, studies were performed in dilute solution. The critical overlap concentration, c^*, of the highest molecular weight polymer, poly(**2**-*co*-**3**)(37/63), was determined to be 7 g/dL from the plot of log apparent viscosity vs log concentration. Subsequently, the polymers were dissolved at concentrations of 1.25 g/dL, well below the critical overlap concentration of poly(**2**-*co*-**3**)(37/63), so that the solution behavior in the dilute regime could be probed. In the absence of any externally added acid or base, the pH of all polymer solutions fell in the range 6.9−7.1, indicating all mers from **2** were in the zwitterionic form.

The solution behavior of polyampholytes with excess charge has been described mathematically[13,54−56] as an electrostatic excluded volume:

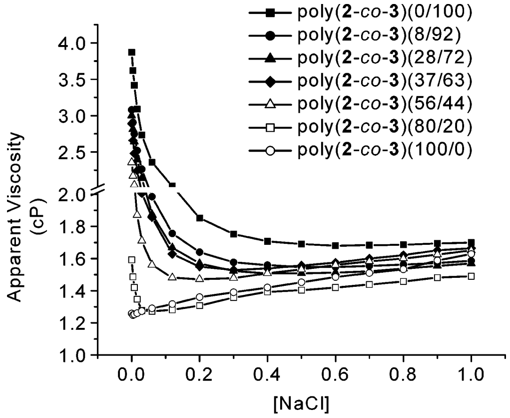


Figure 5. Apparent viscosity of poly(**3**-*co*-**2**) solutions as a function of sodium chloride concentration. All polymers containing **3** exhibit a sharp initial decrease in apparent viscosity with increasing ionic strength. Poly(**3**-*co*-**2**)(37/63) through poly(**2**-*co*-**3**)(80/20) exhibit minima in the apparent viscosity at intermediate sodium chloride concentration.

$$v^* = -\frac{\pi(f l_B)^2}{\kappa_s} + \frac{4\pi l_B \Delta f^2}{\kappa_s^{\,2}} \qquad (2)$$

where l_B is the Bjerrum length, f is the total fraction of charged monomers, Δf is the charge imbalance, and κ_s is the usual Debye−Huckel screening parameter. The screening of the attractive polyampholyte interactions is described by the first term of eq 2, and the screening of the repulsive effects is described by the second term. When charges are perfectly balanced, $\Delta f = 0$ and only the attractive term need be considered. When $\Delta f \neq 0$, the behavior of the polymer coil in solution depends on the relative magnitude of the two terms. At low ionic strength the second term dominates, and the resulting positive electrostatic excluded volume causes the stretching of the polymer chain. At intermediate ionic strength, the second term diminishes rapidly and the first term dominates, resulting in a negative electrostatic excluded volume and a collapsed polymer chain. At high ionic strength, both terms become unimportant, and the electrostatic contribution to the coil size becomes unimportant.

The general behavior predicted by eq 2 was observed experimentally by measuring the viscosity of poly(**2**-*co*-**3**) solutions as a function of sodium chloride concentration (Figure 5). The importance of the second term in equation two was demonstrated by monitoring the solution behavior at low ionic strength. All polymers except poly(**2**-*co*-**3**)(100/0) exhibit sharp decreases in solution viscosity with increasing ionic strength in this regime. Further, the viscosities of the polymer solutions at [NaCl] = 0 increase with decreasing incorporation of **2** (increasing Δf). For [NaCl] concentration between 0.03 and 0.50 M, minima in the respective solution viscosities were observed for poly(**2**-*co*-**3**)(37/63), poly(**2**-*co*-**3**)(56/44), and poly(**2**-*co*-**3**)(80/20). Solutions of copolymers poly(**2**-*co*-**3**)(0/100), poly(**2**-*co*-**3**)(8/92), and poly(**2**-*co*-**3**)(28/72), on the other hand, exhibit no minima since Δf is sufficiently large to cause the repulsive term to dominate. At high ionic strength, all the polymer solutions demonstrate constant viscosity with increasing [NaCl], consistent with predictions utilizing eq 2.

It is instructive to compare the poly(**2**-*co*-**3**) carboxybetaine solutions studied here with analogous poly(**5**-

co-**3**) sulfobetaine solutions reported in previous studies.[25] The behavior observed for poly(**2**-*co*-**3**) solutions is generally consistent with that of poly(**5**-*co*-**3**) solutions; however, the dipole−dipole interactions in poly(**5**-*co*-**3**) appear to induce stronger collapse of the polymer coil. Thus, in the latter, in the absence of salt, a decrease in viscosity is also observed with increasing zwitterionic mer incorporation. However, while poly(**2**-*co*-**3**) solutions remains homogeneous over the entire range of copolymer composition in deionized water, solutions of poly(**5**-*co*-**3**) become insoluble when over 55 mol % **5** is incorporated. Likewise, the viscosity minima observed at intermediate salt concentrations are more pronounced for poly(**5**-*co*-**3**) solutions than for poly(**2**-*co*-**3**) solutions. For the polymer containing 55 mol % **5**, the minimum in viscosity is accompanied by macroscopic phase separation. All solutions of poly(**2**-*co*-**3**), however, remain homogeneous at all added salt concentrations. Both poly(**5**-*co*-**3**) solutions and poly(**2**-*co*-**3**) solutions exhibit similar behavior at high salt concentrations where all electrostatic effects are shielded.

pH Responsive Dilute Solution Behavior. Another property of carboxybetaines that differentiates them from sulfobetaines is the pH-responsive solution behavior attributed to the weak acidity of the carboxylic acid group. Titration with 5.5 M HCl revealed that all the copolymers have pK_a values of ∼3.6. These values of are consistent with those observed for acrylamido polymers containing carboxybetaine moieties previously investigated by our group, specifically those having three methylene groups between charges.[28] Although most carboxylic acids possess pK_a values significantly higher than those observed here, the presence of the nearby quaternary ammonium strongly influences the basicity of the carboxylate group.[28,57−61]

The solution viscosity of each polymer was determined at pH values ranging from 1.5 to 7.5 (Figure 6). In these viscometric experiments, the ionic strength was kept constant at the selected pH levels via addition of sodium chloride. The final electrolyte concentration for all polymers was below 0.09 M.

Poly(**2**-*co*-**3**)(8/92) had little viscosity response to pH, probably due to insufficient incorporation of the carboxybetaine monomer species. Polymers incorporating 28 mol % and greater of **2**, however, exhibited viscosity responses at pH values between 2.5 and 4.5. According to the Henderson−Hasselbalch equation,[62] these values reflect 93% and 11% protonation, respectively, so it is not surprising that all of the changes in viscosity were observed within this range.

Kantor and Kardor[10−12] have developed a model for charge imbalanced polyampholytes in which the polymer chain undergoes a transition from a “globular coil” in a charge balanced state to an “extended chain” with a large excess of charge on the polymer. At intermediate charge imbalances, the polymer adopts a “beaded-necklace” morphology (Figure 7). Although the specific interactions of this system may be better described by a polyelectrolyte modified by dipolar interactions, the qualitative picture should still hold and thus provide an explanation of the observed viscosity changes.[63] Changes in pH produce changes in the charge imbalance of the copolymers. At high pH, excess charge is reduced and intramolecular associations are stronger, resulting in more “beads” and lower viscosity (Figure 7A,B). At low pH, charge imbalance increases, and the polymers adopt a more extended conformation in solution (Figure 7A).

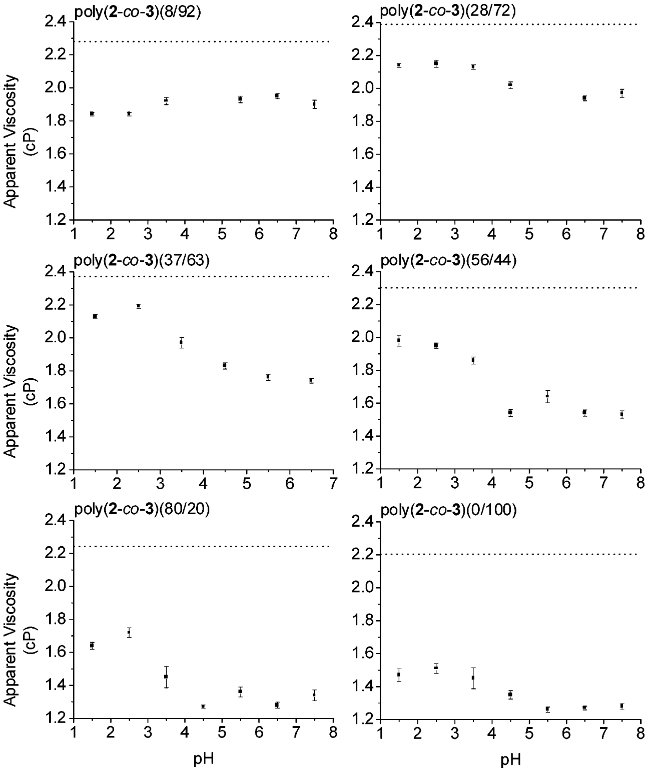


Figure 6. Apparent viscosity of the poly(**2**-*co*-**3**) solutions plotted as a function of pH at a concentration of 1.25 g/dL. Ionic strengths of the solutions were as follows: poly(**2**-*co*-**3**)(8/92) = 0.074, poly(**2**-*co*-**3**)(28/72) = 0.054, poly(**2**-*co*-**3**)(37/63) = 0.057, poly(**2**-*co*-**3**)(56/44) = 0.070, poly(**2**-*co*-**3**)(80/20) = 0.081, and poly(**2**-*co*-**3**)(100/0) = 0.088. The dashed lines represent the viscosity of poly(**2**-*co*-**3**)(0/100) at the same ionic strength. Error bars represent two standard deviations from the mean.

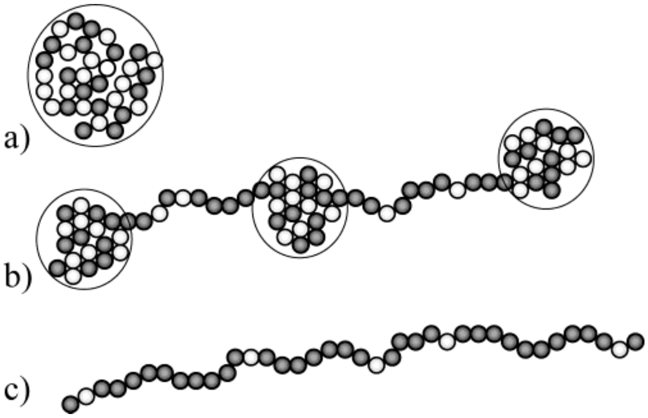


Figure 7. Conceptual model of pH-responsive polymer behavior. Highly charge balanced polymers (high **2** incorporation at high pH) exist in a collapsed globular state (A). At intermediate charge imbalances a beaded necklace morphology predominates (B). At high charge imbalances the polymer exists in an extended conformation (C).

It is important to note that none of the poly(**2**-*co*-**3**) solutions have apparent viscosities approaching that of the poly(**2**-*co*-**3**)(0/100) homopolymer, even when fully protonated. Apparently, the protonated form of **2** retains significant associative properties due to a combination of hydrophobic and hydrogen-bonding interactions. Increasing the incorporation of **2** initially increases the responsiveness of the copolymers by increasing the intramolecular associations at high pH. After a critical degree of monomer incorporation is reached, however, the responsiveness begins to decrease due to increasing intramolecular association at low pH. Thus, the greatest response to pH is observed for poly(**2**-*co*-**3**)(37/63) and poly(**2**-*co*-**3**)(56/44) solutions.

Conclusions

A novel carboxybetaine monomer, 4-(*N*,*N*-diallyl-*N*-methylammonio)butanoate (**2**), has been synthesized and copolymerized with *N*,*N*-diallyl-*N*,*N*-dimethylammonium chloride in a nearly ideal copolymerization. The resulting copolymers maintain the five-membered ring structure common to diallylammonium salts as determined by ^{13}C NMR spectroscopic analysis. Solutions of poly(**2**-*co*-**3**) exhibit polyelectrolyte character at low electrolyte concentrations but, in contrast to the previously studied solutions of sulfobetaine polymers, remain soluble up to 100% incorporation of **2**. Copolymers with at least 37 mol % **2** exhibit viscosity minima at intermediate electrolyte concentrations. Unlike polymers containing sulfobetaine mer units, solutions of poly(**2**-*co*-**3**) also exhibit a pH-dependent viscosity. All copolymers have an apparent pK_a of ~3.6. Copolymers with **2** incorporations of 28 mol % and above have viscosity responsiveness between pH values of 2.5 and 4.5. The maximum pH response was achieved for solutions of poly(**2**-*co*-**3**)(37/63) and poly(**2**-*co*-**3**)(56/44).

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