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Electrostatic Layer-by-Layer Self-Assembly of Poly(carboxybetaine)s: Role of Zwitterions in Film Growth

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ABSTRACT: We report on self-assembly of a weak zwitterionic polymer—poly(carboxybetaine), PCB5—within a polyelectrolyte multilayer film. Multilayer growth and ionization of carboxylic groups are monitored in situ using ATR-FTIR. Deposition of PCB5 within the film is contrasted for two pH regimes: (1) at slightly acidic pH values where PCB5 carries overall cationic charge, but a significant number of dipoles provided by ionized carboxylic groups also exists within the polymer chain, and (2) at neutral and basic pH values where these polymers become zwitterionic. In the latter case, no multilayers could be produced with either polyanions or polycations. In the former case, PCB5 can be deposited within the polymer film via alternating adsorption with a variety of polyanions, such as heparin, DNA, poly(carboxylic acid)s, or poly(styrenesulfonate). The produced films can be erased from the solid surface by exposure to solutions with higher pH values, when the fraction of charged carboxylic groups in PCB5 is increased. The presence of zwitterions in PCB5 chains allowed building hybrid layers which contained PCB5 bound with both a polyanion and a polycation. In contrast to PCB5/polyanion films, hybrid films showed a stability region extended to neutral pH values and dissolved at both $pH > 7$ and $pH < 4$. The PCB5-containing films show promise for bioseparation and biotechnology applications when used as sacrificial layers or for controlled release of incorporated small molecules.

Introduction

Polyampholytes are ubiquitous in nature where they are represented by lipids or a wide variety of proteins. Synthetic counterparts of proteins in the polyampholyte family are copolymers that contain both negatively and positively charged units. In conditions when attraction between charged units is relatively weak, a polyampholyte chain adopts a coil conformation and remains soluble in water. The adsorption behavior of polyampholyte coils is drastically distinct from polyelectrolytes which contain all positive or all negative charges.[1] Polarization of dipoles contained within polyampholyte chains can be induced in the vicinity of a charged surface, leading to adsorption of polyampholytes even at surfaces with a net charge of the same sign.[1,2]

Polyzwitterions represent a type of polyampholyte with positive and negative charges located in the same unit. One abundant class of zwitterions is polybetaines (PBs) which contain a quaternary ammonium group as a source of positive charge. The literature comprehensively describes synthesis of polybetaines of two types: polysulfobetaines (PSB),[3−8] which are zwitterionic independent of solution pH, and polycarboxybetaines (PCB),[9−18] which are zwitterionic at neutral to basic pH values, but become cationic at low pH when carboxylic groups are protonated. Synthesis, characterization, and solution properties of various classes of PBs are comprehensively described in a recent review.[19] Because of inter- and intramolecular association of positive and negative charges within polymer chains, PBs exhibit structural ordering in blends,[20] as well as unusual properties in solution, such as (1) poor solubility at low salt concentrations;[14,18] (2) "antipolyelectrolyte" behavior, i.e., polymer chain expansion in high salt solutions as indicated by an increase of solution viscosity[11,14,16] or dynamic light scattering measurements;[12] and (3) strong dependence of polymer properties on the distance between the quaternary ammonium and the anionic groups[15,21] as well as on the type of substitution at the quaternary nitrogen atom.[21,22] The presence of inter- and intramolecular association is reflected in poor solubility of PBs[17] and reduced apparent viscosity[11] of PB solutions. In the case of PCBs, low values for electrophoretic mobility[21] and dissociation constants ($pK_0 < 2$) were reported for PCB1, which contains only one methylene group between positive and negative charges ($n = 1$).[22,23] Higher pK_0 values of 2.4[23,24] or 3.6[18] were found for PCBs with $n \geq 2$.

Significant interest in PBs stems from the known properties and wide use of their long-alkyl-chain monomeric analogues as low-toxicity biodegradable surfactants and wetting agents. Polymeric zwitterions, specifically those containing phosphorylcholine—a headgroup commonly found in cell membranes—showed improved biocompatibility[25] and antibacterial properties.[26,27] Such polymers were suggested for medical usage for gene delivery[28] and medical device coatings.[26] PSBs have also been considered as potential antibioadherent (bioinert) coatings,[29] and recently PSBs were shown to demonstrate cell-resistant properties.[30] Incorporation of PBs into polymer films via a layer-by-layer technique presents a significant advance as it affords producing thin-film materials or supermonolayer surface coatings which contain these macromolecules.

However, interaction of PB chains with other polyelectrolytes is not yet well understood even in solution. Unlike much better studied association between polycations and polyanions, where entropic gain due to counterion release is considered to be a major driving force of complex formation, binding of zwitterionic polymers is not accompanied by counterion release. On the other hand, significant contribution to intermolecular interactions comes from dipole interactions. Earlier studies of association of PSBs in solution by Knoesel et al. were based on

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viscometry and fluorescence and indicated association of PSB with polycations which resulted in formation of water-soluble complexes.[31] Miyazawa et al.[32] and McCormick and co-workers[33] studied interactions of PBs with surfactants, using phosphorylcholine-based PBs or PCBs and PSBs, respectively. Evidence of strong binding of PBs with anionic surfactants was found, and possible interactions of PBs with cationic surfactants were also suggested.[33] Later reports described association of PSBs with either polyanions or polycations and indicated different effects of the latter polymers on the upper critical solution temperature (UCST) of PSBs.[34] An intriguing self-association of PSBs in solution triggered by a cationic polymer was also described by Osada et al.[35] Studies of interpolymeric association of weak PBs such as PCBs are still in their infancy and focused on interactions of PCBs with polyanions.[23,36] At surfaces incorporation of polybetaine moieties within films has been shown with PSBs. Specifically, PSB-containing films were produced as a result of chemical activation of adsorbed polyelectrolytes, as reported by Laschewsky et al.,[37,38] or as result of layer-by-layer self-assembly described by Schlenoff and co-workers.[30]

In this paper, we explore layer-by-layer self-assembly of PCBs within a film and show that PCB-containing films of two types can be constructed. The first type is obtained by alternating adsorption with a variety of polyanions. The produced films can be erased from a solid surface by exposure to solutions with higher pH values. The second novel type of PCB-containing films presents hybrid layers in which PCB molecules are bound with both polyanions and polycations. The possibility of construction of the latter hybrid films is a direct consequence of the presence of zwitterions in the PCB units. The hybrid multilayers have an unusual pH stability range from 4 to 7, which is useful for biotechnology applications, and at present, to our knowledge, the first example of incorporation of a weak zwitterionic polymer within a multilayer film.

Experimental Section

Materials. Polycarboxybetaine with five methylene groups separating N^+ and COO^- (poly(4-vinylpyridiniopentanecarboxylate), PCB5, was synthesized by reaction of poly(4-vinylpyridine) (Aldrich), M_w 200 000, with ω-bromocarboxylic acid (Aldrich).[23] 20% and 98% quaternized poly(4-vinylpyridine) (Q20 and Q98) were obtained by reaction of poly(4-vinylpyridine) (M_w 200 000; Aldrich) with ethyl bromide (Aldrich) in ethanol solution.[39] Poly(methacrylic acid) (PMAA, M_w 150 000), heparin, and DNA were obtained from Aldrich. Poly(styrenesulfonate) (PSS, M_w 500 000) was purchased from Scientific Polymer Products, Inc. To control pH, 0.01 M Na_2HPO_4 buffer (General Storage, pure grade) was used, whose pH was adjusted to a required value. Millipore (Milli-Q system) filtered water with a resistivity 18.2 MΩ was used in all experiments. D_2O with 99.9% isotope content was purchased from Cambridge Isotope Laboratories and was used as received.

Deposition of Multilayers. For ellipsometry studies, deposition of multilayers was performed by sequential adsorption of polymers from aqueous buffered solutions onto flat silica wafers.[40] In a typical experiment, the substrates were alternately exposed to 0.1 mg/mL polymer buffered solutions for 15 min followed by two intermediate rinsing steps with 0.01 M phosphate buffer at a certain pH for 30 s each. Before the measurements, films were dried with dry nitrogen.

For in-situ ATR-FTIR (Fourier transform infrared spectroscopy in attenuated total reflection mode) studies, multilayers were prepared using the procedure similar to that described above, except that multilayers were constructed on the surface of an oxidized ATR Si or Ge crystals installed within a flow-through ATR-FTIR stainless steel cell. The deposition was performed in situ using D_2O polymer solutions.[39]

For zeta-potential determination, multilayers were deposited onto 4 μm silica particles from 0.1 mg/mL polymer aqueous solutions in 0.01 M phosphate buffer at pH 4.5. Each deposition cycle was followed by centrifugation of suspensions for 1 min, removal of supernatant, and redispersing particles in pure buffer solution. The washing procedure was repeated three times to ensure complete removal of excess polymer. Prior to zeta-potential measurements, particles were additionally washed and redispersed in Milli-Q water adjusted to pH 4.5. Deposition, washing, and redispersion steps were performed in a shaker (Fisher Scientific) at 1600 rpm.

Ellipsometry Measurements. Dry sample ellipsometry measurements were performed using a home-built single wavelength phase-modulated ellipsometer at 65° angle of incidence. The setup description and data analysis can be found in our earlier publication.[41] Ellipsometry substrates were low dopant Si wafers (resistivity 5 kΩ•cm) with naturally grown SiO_2 layer. Optical properties of the substrates and oxide layer thicknesses were determined prior to polymer deposition. Deposited films were blow-dried by ultrapure nitrogen before measurements. For the purpose of analysis the refractive index of all polymer films was fixed at the value of 1.5.

ATR-FTIR Measurements. In-situ ATR-FTIR experiments were done with a Bruker Equinox-55 Fourier transform infrared spectrometer equipped with a narrow-band mercury cadmium telluride detector. The experiments were performed using a home-built flow-through cell. The ATR surface was a rectangular Si or Ge crystals of dimension 50 mm × 20 mm × 2 mm (Harrick Scientific) whose beam entrances and exit surfaces were cut at 45°. The fractions of film retained on the surface and the degree of ionization of the PCB carboxylic groups were quantified using experimental protocols described earlier.[40] In particular, the ionization degrees were calculated from the integrated intensities of the vibrational bands which correspond to asymmetric stretching vibrations of protonated carboxylic groups ($-COOH$) and ionized carboxylic groups ($-COO^-$) of PCB5 centered at 1700 and 1550 cm^{-1}, respectively (see Supporting Information), assuming earlier confirmed equal extinction coefficients for these bands.[42] In all ATR-FTIR measurements, we used films with thicknesses not higher than 100 nm, which was smaller than the penetration depth of the evanescent field of 0.46 μm calculated for D_2O/silicon interface at $\sim$1600 cm^{-1}. Although ATR-FTIR measurements of thin films allow determining the amounts adsorbed after appropriate calibration of the signal intensity using solutions of nonadsorbing polymers,[42] here we did not follow this procedure, and the amounts adsorbed were determined by ellipsometry.

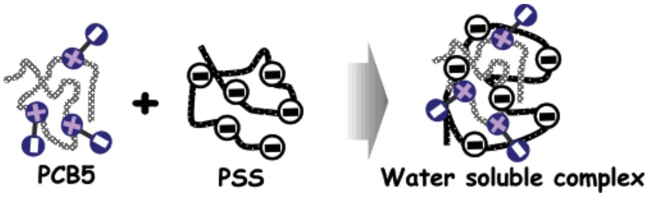
Zeta-Potential Measurements. Zeta-potential was measured by laser Doppler electrophoresis using Zetasizer Nano-ZS equipment (Malvern). The measurements were performed after depositing each successive polymer layer on silica particles. Though the polymer deposition was performed in 0.01 M phosphate buffer at pH 4.5, polymer-coated silica particles were repeatedly washed and redispersed in Milli-Q water at 4.5 prior to zeta-potential measurements. The results were averaged over 30 runs. Each value was obtained by averaging measurements of three samples.

Results and Discussion

Multilayers of PCB5 with Polyanions. The presence of cationic charge in a PCB chain results in much stronger dissociation of carboxylic groups when compared with dissociation of nonzwitterionic poly(carboxylic acid)s. For example, while PMAA is a weak polyacid with $pK_a \sim 6.5$,[43] a pK_a of 3.6 was found for PCB3,[18] accounting for a large $\Delta pK_a \sim 3$ difference in $-COOH$ ionization. Similarly, low pK_a values were also found for carboxybetaines of poly(4-vinylpyridinium) family with a charge spacing of 2−8 methylene groups.[23]

Self-assembly of PCB5 was studied in two regions: (1) pH > 6 where PCB5 is zwitterionic and (2) $3.5 < pH < 5.5$ where PCB5 is largely zwitterionic, but also carries weak positive charge arising from a small fraction of protonated polymer units. In the first regime, one of us has recently studied interactions

Scheme 1. Formation of Water-Soluble PCB5/PSS Complex by Solubilization of PCB5 Chains in Excess Negative Charge of PSS



between PCBs and a range of polyanions such as PMAA, PSS, or DNA in solution. Association between PCBs with spacing length from 2 to 8 methylene groups at basic pH values was confirmed using fluorescence quenching and potentiometry techniques.[23] However, our results show that no precipitation of PCB5/polyanion complexes occurred at pH > 6.5−7 regardless of 1:1 ratio of PCB5 to polyanion charged repeat units. The key to this unusual behavior is that binding of zwitterionic and anionic units does not usually produce electrically neutral hydrophobic sequences of bound units, as in the case of interactions of a polycation and a polyanion. Instead, associated PCB5/polyanion chains are solubilized in solution due to the presence of negative charge on the polyanion (Scheme 1). This example shows that binding between polyelectrolyte chains is not sufficient for successful deposition of these macromolecules within a film on a solid substrate. As we have shown earlier, the multilayer growth is largely predicted by solution phase diagrams of associating polyelectrolytes.[44] The formation of insoluble complexes in solution is a good indicator for successful self-assembly of polymer chains at a solid surface, while solubilization of polyelectrolyte chains opposes deposition of the film, as described in our recent review.[45] Multilayers of PCB5 with neither of the polyanions could be produced at basic pH values because of overwhelmingly strong solubilization of polyelectrolyte chains in solution. For the same reason of chain solubilization in excess charge, PCB5 assembly with either polycations (Q20, Q98) was hindered at basic pH, where PCB5 is zwitterionic, despite the intermolecular association between PCB5 and the polycations detected in solution at this pH (data are not shown).

However, multilayers of PCB5 with all polyanions were successfully formed at 3.5 < pH < 5.5 where PCB5 carried weak cationic charge. Note that with strong polyanions, such as PSS and heparin, formation of multilayers could be also accomplished at even lower pH values (pH < 3.5). However, binding between PCB5 and PMAA chains did not occur at pH < 2.5 due to protonation of PMAA units. These differences were revealed in the experiments with PCB5 and polyanions in solution, where we observed formation of water-insoluble PCB5/polyanion complexes. The binding between PCB5 and PSS chains in solution has also been confirmed by potentiometry.[23] The deposition of multilayers at 3.5 < pH < 5.5 occurred due to a charge compensation mechanism between adsorbing PCB5 and polyanion chains. In solution, such interaction resulted in formation of insoluble polyelectrolyte complexes. At surfaces, robust multilayer growth occurred, as followed with in-situ ATR-FTIR, without desorption of previously adsorbed chains during each successive deposition cycle. The representative ATR-FTIR spectra of PCB5/PSS films are given in the Supporting Information. Ellipsometry measurements of dry film thicknesses showed that all PCB5/polyanion systems showed linear increase in film thickness as a function of layer number when the number of deposited layers exceeded five. Average thicknesses deposited within PCB5/polyanion films during linear film growth are presented in Table 1.

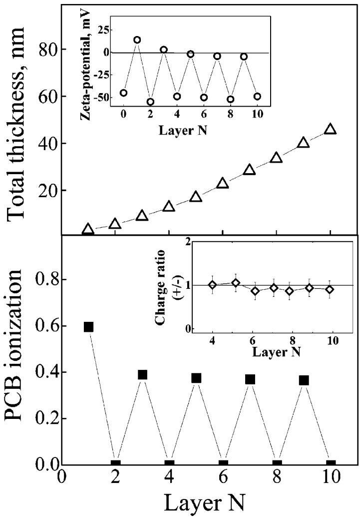


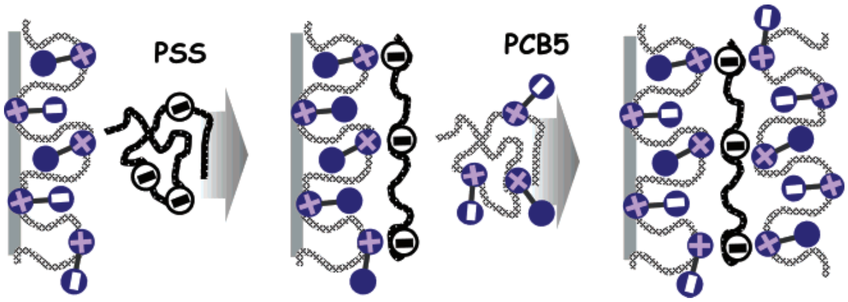
Figure 1. Top panel: ellipsometric thicknesses during deposition of a 10-layer PCB5/PSS film onto a Si wafer plotted against the number of layers. Inset shows evolution of zeta-potential during deposition of a 10-layer PCB5/PSS film onto 4 μm silica particles. Bottom panel: average ionization of PCB5 carboxylic groups during the buildup of a PCB5/PSS film at the surface of an ATR Si crystal as monitored by in-situ ATR-FTIR. Inset shows the ratio of positive to negative charges within the PCB5/PSS film as a function of layer number. The first layer deposited was PCB5. Film depositions were done from 0.1 mg/mL polymer solutions at pH 4.5 supported by 0.01 M phosphate buffer. Representative ATR-FTIR spectra of PCB5/PSS films are presented in the Supporting Information.

Table 1. Bilayer Thickness and Critical Dissolution pH (pH_{crit}) for PCB/Polyanion Films Deposited at pH 4.5

polymer system	bilayer thickness (PCB5/polyanion), nm	pH_{crit}
PCB5/heparin	25 (13/12)	5.8
PCB5/PMAA	12 (6/6)	6.1
PCB5/DNA	12 (7/5)	6.4
PCB5/PSS	10.9 (5.4/5.5)	7.2

When exposed to increasing pH values, all films dissolved above a critical pH value. The critical pH values were defined as the maximum values at which more than 90% of film did not dissolve for 1 h. Table 1 shows that the critical pH value was dependent on the system. The pH stability region extended to higher pH values in the series PCB5/heparin ≈ PCB5/PMAA < PCB5/DNA < PCB5/PSS. Correlation between film dissolution and changes in ionization of self-assembled PCB5 were clearly shown for PCB5/PSS systems which allowed observation of ionized and nonionized forms of carboxylic groups without spectral overlap with other vibrational bands. We found that $(PCB5/PSS)_5$ films deposited at pH 4.5 dissolved at pH higher than 7, when ionization of carboxylic groups exceeded 60%. The dissolution sequence of PCB5 films formed with different polyanions reflects the role of chain hydrophobicity and polyanion charge density on extension of the pH stability region of films. We have reported earlier a similar instability at higher pH values for films which are self-assembled through hydrogen bonding.[40,46,47] In the latter case, pH-triggered film dissolution occurred due to disruption of intermolecular hydrogen bonds between self-assembled chains. For PCB-containing films, film disintegration was most likely a consequence of solubilization of associated polyelectrolyte chains in solution, which was facilitated by increased ionization of carboxylic groups in PCB5

Scheme 2. Formation of PCB5/PSS Multilayer at pH 4.5[a]



[a] Oscillations of ionization are shown by transition from a zwitterionic structure of PCB5 units with ionized carboxylic groups to cationic PCB5 units with protonated carboxylic groups.

chains. Indeed, intermolecular association between PCB5 and polyanions was detected in solution at high pH values.[23]

The top panel in Figure 1 shows variation of ellipsometric thickness of PCB5/PSS film during film deposition at pH 4.5. The inset in the top panel in Figure 1 shows equilibrated values of zeta-potential of PCB5/PSS multilayers deposited onto 4 μm silica particles. An interesting feature is that, in contrast to nonzwitterionic polycations, adsorption of overall cationic (at pH 4.5) PCB5 on a negatively charged, polyanion-topped surface does not result in surface overcharging, with zeta-potential values close to 0 mV. The absence of the charge reversal is explained by the predominant presence of zwitterionic, overall neutral PCB5 units in the loops of adsorbed PCB5 chains.

Further clues on the mechanism of interaction of PCB5 with polyanions were obtained by in-situ ATR-FTIR measurements, which provided ionization of carboxylic groups of PCB5 during self-assembly. Quantification of ionization of carboxylic groups from IR intensities of $-$COOH and $-$COO$^-$ peaks in this region has been described in our earlier papers.[39,42] The PCB5/PSS system was an ideal choice for these measurements because of the absence of spectral overlap in the 1500$-$1700 cm^{-1} region, which prevented measurements of PCB5 ionization in the PCB5/PMAA system. Ionization of carboxylic groups of PCB5 during the deposition of PCB5/PSS multilayers at pH 4.5 is shown in the bottom panel in Figure 1 (see also Figures 1S and 2S in the Supporting Information). The interaction of PCB5 and PSS chains at a surface at pH 4.5 is also illustrated in Scheme 2. After the deposition of the first layer of PCB5 to a bare, oxidized silicon crystal, PCB5 remained ~60% zwitterionic due to a significant fraction of ionized carboxylic groups. This value is in good agreement with the reported solution pK_a value of ~3.6 found for PCBs with $n > 2$.[18] Apparently, binding of PCB5 at the surface did not result in significant adjustment of PCB5 ionization because of the low ionization of surface silanol groups at pH 4.5 (a pK_a of 9$-$9.5 for surface silanol groups was reported[48]). Deposition of the second PSS layer caused a dramatic change in ionization of PCB5 whose carboxylic groups became completely protonated. Ionic pairing between PSS units and positive charges of zwitterionic PCB5 units results in neutralization of positive charge in the PCB5 units and therefore in cancellation of its effect on ionization of PCB5 carboxylic groups. Excess charge supplied by the adsorbed PSS chains is manifested by strongly negative values of surface zeta-potential measured after PSS deposition steps (inset in top panel in Figure 1). Further adsorption of slightly cationic PCB5 leads to neutralization of surface negative charge, and the average ionization of PCB5 carboxylic groups reverts to ~40%. Despite the neutral surface charge of the PCB5-topped film (inset in top panel in Figure 1), the next PSS layer could be successfully deposited to the surface as a result of locally induced cationic charge in the predeposited PCB5 layer. Oscillations of ionization of carboxylic groups as a function of layer number were observed earlier,[39,49] where a weak poly(carboxylic acid) was deposited with a polycation. However, unlike these other cases, carboxylic groups of PCBs *are not involved* in inter-polyelectrolyte binding, as binding in the PCB5/PSS system occurs through association of cationic groups of PCB5 units. The difference explains the larger magnitude of the oscillations in the PCB5/PSS system. Drastic changes in PCB5 ionization were in contrast with the maintenance of a charge balance within the film shown in the inset in the bottom panel of Figure 1. For the films consisting of more than four layers, the charge ratio was kept around unity, with a slight excess of positive or negative charges for PCB5- and PSS-terminated films, respectively. For thinner films, the data (not shown here) deviated from unity due to significant contribution of the surface charge of a Si substrate which was not taken into account while calculating the charge ratio within the film. The charge ratio was found as a molar ratio of total positive to negative charge within the film as calculated from ellipsometry data on individual layer thicknesses (assuming a density of 1 g·cm^{-3}) and from ATR-FTIR data on ionization of PCB5 carboxylic groups.

This study presented a first example of incorporation of weak PBs, such as PCBs, with variable charge within a multilayer film. In particular, PCB5 chains were rendered partially cationic to promote self-assembly with polyanions. Similar self-assembly was previously reported by Schlenoff and co-workers[50] for PSBs, when deposition pH needed to be adjusted to an extremely low value of 1 to cause protonation of the sulfonate groups. Another example of incorporation of PB units into multilayers is by producing copolymers of sulfobetaines with charged monomers.[30] In both of these examples, including our work described above, the role of zwitterions in self-assembly was not strongly manifested. In the next section, we present an example of construction of a hybrid mutilayer in which the zwitterions play a distinct role in self-assembly.

Hybrid Multilayers of PCB5 with Polyanions and Polycations. Our next intention was to take advantage of the presence of dipoles within PCB5 chains and to attempt deposition of PCB5 within a film when PCBs are “sandwiched” between a polycation and a polyanion. Specifically, after PCB5 binds with the polyanion sublayer, the negative charge of bound zwitterionic units of PCB5 can be available for further binding with polycations (Scheme 3). In this case, the success of self-assembly was dependent on the relative binding strengths of PCB5 with arriving polycations and the underlying polyanion. In particular, we found that a polycation with high charge density, Q98, did not result in construction of hybrid layers,

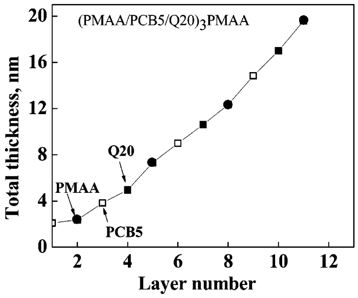
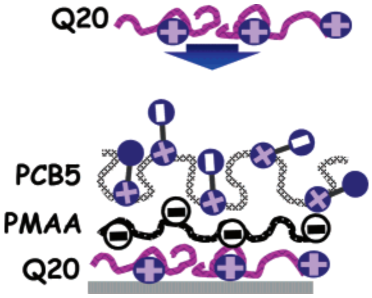


Figure 2. Ellipsometric monitoring of successive layer-by-layer deposition of a (PMAA/PCB5/Q20)$_3$PMAA film at pH 4.5. Film thickness is plotted against layer number. First layer was PCB5 followed by PMAA (filled circles), PCB5 (open squares), and Q20 (filled squares) deposition.

Scheme 3. Schematic Presentation of Hybrid Multilayer Formation at pH 4.5



but instead replaced PCB5 chains when added to a three-layer Q98/PMAA/PCB5 film. Complete release of PCB5 occurred after several minutes as detected by in-situ ATR-FTIR. Seeking to understand the reason for the displacement, it is important to contrast the density of positive charge on the PCB5 and Q98 chains. As directly measured by in-situ ATR-FTIR, ~30% of carboxylic groups in PCB5 chains were protonated and provided excess positive charge at pH 4.5. Arriving Q98 chains carried higher charge density and were able to form a large number of Q98-polyanion electrostatic pairs per Q98 chain. Note that polymerization degrees for PCB5 and Q98 were the same, as these two polymers were prepared from the same P4VP precursor. The binding of Q98 with a polyanion-topped film provided a larger entropic advantage, compared to binding of PCB, by a larger number of counterions released in solution.

To promote adsorption of a polycation on top of the polyanion/PCB5 layers, it was important to avoid chain displacement by keeping the charge density of the polycation equal or lower than that of PCB chains, i.e., ~30% at pH 4.5. A polycation with 20% of quaternized units, Q20, was chosen for this purpose. Figure 2 shows the film thickness as a function of layer number during construction of a hybrid (PMAA/PCB5/Q20)$_3$PMAA multilayer. Systematic increase in film thickness occurred at each deposition step. Hybrid multilayer growth was also monitored using in-situ ATR-FTIR, which shows that no competitive displacement of deposited macromolecules occurred during successive depositions, and all three components were included within the film.

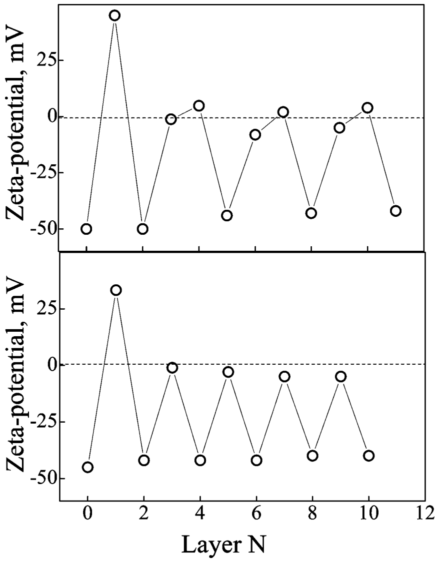


Figure 3. Zeta-potential evolution during deposition of (PMAA/PCB5/Q20)$_3$PMAA (top panel) or PCB5/PMAA (bottom panel) layers onto 4 *μ*m silica particles at pH 4.5. First layer was PCB5. Conditions for deposition of the hybrid film (top panel) are the same as in Figure 2.

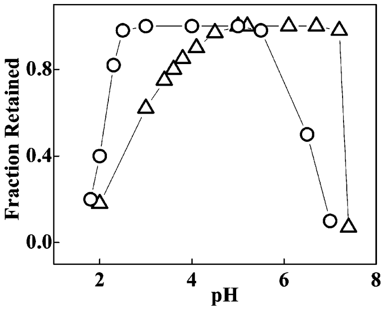


Figure 4. Relative thickness loss of (PMAA/PCB5/Q20)$_3$PMAA (triangles) and a 10-layer PCB5/PMAA (circles) films deposited at pH 4.5 and exposed to lower or higher pH values. The pH-triggered film disintegration was monitored by ellipsometry of dry films and by in-situ ATR-FTIR (see Supporting Information for representative ATR-FTIR spectra and more details).

Top panel in Figure 3 shows equilibrated values of surface zeta-potential after completion of each adsorption cycle during deposition of hybrid PMAA/PCB5/Q20 multilayers, when multilayers were deposited onto 4 *μ*m silica particles. For comparison, deposition in nonhybrid PCB5/PMAA films is shown in the bottom panel of Figure 3. Similar to results for PCB5/PSS systems in Figure 1, adsorption of PCB5 on a negatively charged, PMAA-topped surface does not result in surface overcharging. Subsequent adsorption of Q20 in the hybrid PMAA/PCB5/Q20 system (top panel) is not driven by the overall opposite charge of the surface, but instead interaction with negative charges of zwitterionic groups occurs. The slightly positively charged surface, after adsorption of Q20, is able to accommodate the next layer of a polyanion through a conventional charge compensation mechanism usually found in polyelectrolyte multilayers. Scheme 3 also illustrates the suggested mechanism of self-assembly of a weak polyzwitterion within a hybrid polyelectrolyte layer.

Finally, we report an unusual pH stability profile for constructed PCB5-containing multilayers which could be controllably destroyed by variation of the external pH. Figure 4 shows that a hybrid film constructed at pH 4.5 could be dissolved by either increase or decrease of external pH which resulted from ionization changes in carboxylic groups of PMAA and PCB5 and nonquaternized pyridine units of Q20. For comparison, the pH stability profile of binary PCB5/PMAA systems built under the same conditions is also shown in Figure 4. One can see that inclusion of Q20 into the film significantly alters the film deconstruction profile. At higher pH values, inclusion of positively charged Q20 within the multilayer caused stabilization of the film upon an increase in pH because of the presence of a strongly bound Q20/PMAA pair. In a control experiment, we have shown that two-component Q20/PMAA films do not dissolve upon an increase in pH. In contrast, when pH was lowered below 4.5, hybrid films gradually dissolved at $\text{pH} < 4.2$, while two-component PCB5/PMAA (Figure 4) and Q20/PMAA[39] films showed significantly greater stability and did not disintegrate until pH was lowered to 2 or 1.8, respectively. In all systems, disintegration occurred due to protonation of carboxylic groups and accumulation of excess positive charge in the film. In the hybrid films, however, the presence of the PCB5/Q20 bilayer created a “weak link”, as both PCB5 and Q20 chains became cationic at acidic pH. The ability to control the pH range of multilayer decomposition might be useful for drug delivery, biotechnology, and membrane separation applications. One example includes the use of hybrid layers as release sublayers that could be dissolved in aqueous environment in response to pH variations for preparing free-standing polyelectrolyte membranes. Compared to earlier reported hydrogen-bonded and electrostatically assembled sacrificial films that can be selectively decomposed in response to pH[51] or ionic-strength variations,[52] hybrid layers based on PCBs have a unique pH decomposition profile because they (1) provide a film stability range close to neutral and slightly acidic conditions relevant for biotechnology and (2) afford dual pH response.

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Supporting Information Available: Representative in-situ ATR-FTIR spectra of deposition and destruction of PCB5-containing multilayers. This material is available free of charge via the Internet at http://pubs.acs.org.

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