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Morphologies of charged diblock copolymers simulated with a neutral Coarse-Grained model

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Abstract

We present the results of coarse grained molecular dynamics simulation using a charge free model that is able to capture different regions of the morphological phase diagram of charged diblock copolymers. Specifically, we were able to reproduce many phases of the poly(acrylic acid)-(1,4)-poly-butadiene (PAA-PBA) diblock copolymer, Ca^{+2} and water systems as a function of pH and calcium concentration with short range LJ type potentials. The morphologies observed range from bilayers to cylinders to spherical micelles. Such polyanionic/cationic amphiphiles in water typically present multiple challenges for molecular simulations, particularly due to the many charge interactions which are long ranged and computationally costly. Further, it is precisely these interactions that are thought to modulate large amphiphile assemblies of interest such as lipid rafts. However, our model is able to reproduce different morphologies due to pH and with or without the addition of Ca^{2+} as well as the lateral phase segregation and the domain registration observed in neutral and charged diblock copolymer mixtures. The results suggest that the overall effect of charges is a local structural rearrangement that renormalizes the steric repulsion between the headgroups. This simple model which is devoid of charges is able to reproduce the complex phase diagram and can be used to investigate collective phenomena in these charged systems such as domain formation and registration or co-localization of lipid rafts across bilayer leaflets.

Introduction

Current progress in the development of soft materials often relates to the control of curvature and topology.¹ Amphiphilic block copolymers which self-assemble into various ordered mesophases^{2–7} offer critical advantages over much smaller natural amphiphiles including phospholipids, such as robustness and a broad the range of properties achievable through amphiphilic chemistry.^{4,8,9} Compared to typical phospholipid bilayers, copolymer vesicles have thicker and tougher membranes which can still be fluid and deformable.^{10,11} Diblock copolymers which form micron-size vesicles and worm-like micelles can survive cross-linking into monoliths without structural disruption, leading to dramatic modifications of mechanochemical properties^{12–16} which can be useful in medical and industrial applications.^{4,9} The different morphological structures are a product of the interfacial balance between solvated and solvophobic components.¹⁷ With charged diblock copolymers, diverse strategies have been employed to tune this balance; including (but not

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limited to) modification of the hydrophilic headgroup in polystyrene-poly-(acrylic acid) block copolymers,⁶ mixing in poly(1,2-butadiene-*b*-ethylene oxide) diblock copolymers,¹⁸ and changing the pH and concentration of cation with poly(acrylic acid)-(1,4)-poly-butadiene (PAA-PBD) diblock copolymer.¹⁹ As a general rule, any process that decreases intra-coronal repulsion drives transitions from higher curvature (*e.g.* spherical micelles) to flatter structures (*e.g.* vesicles).²⁰ These features of diblock copolymers make them potentially useful in applications ranging from drug delivery and transport to rheological additives and embedded encapsulators¹³ and raise questions about the physical nature of the morphologies and the transitions between them.

In this study we focused on reproducing observed structures for PAA-PBD at different pH concentrations and in the presence or absence of Ca²⁺ counterion. Exploiting the fact that a relationship exists between the headgroup corona size and the morphology of the aggregate,¹⁹ we modify our model headgroup potential parameters (size and interaction strength) to obtain the desired structures. Our model is devoid of charges and consists of short polymers (13 beads) plus water (3 water molecules per bead) and linker (L-type) particles to represent Ca²⁺. MD simulations with an absence of charges have the advantage of being far cheaper in terms of CPU-cycles, since demanding long-range forces treatments can be avoided. Further, the short polymers we modeled do not entangle which allows for reasonable sampling of the dynamical processes, while still being surface active.

Model

Coarse-Graining (CG) of polymers and bilayers has a long history, we refer the interested reader to the book edited by Voth²¹ and reviews by Vernik *et al.*²² and Murtola *et al.*²³ For this study, we have chosen to extend the recently developed coarse grained model for polyethylene glycol (PEG) surfactants by Shinoda *et al.*²⁴ The model's description of water density, surface tension and compressibility, allows for accurate structure at the boundary with alkanes and consequently the self-organized surfactant structures at the mesoscale. The non-bonded interaction is given by the following two Lennard-Jones (LJ) functions:

$$U_{LJ_{9-6}}(r_{ij}) = \frac{27}{4} \varepsilon \left\{ \left(\frac{\sigma}{r_{ij}} \right)^9 - \left(\frac{\sigma}{r_{ij}} \right)^6 \right\}$$

$$U_{LJ_{12-4}}(r_{ij}) = \frac{3\sqrt{3}}{2} \varepsilon \left\{ \left(\frac{\sigma}{r_{ij}} \right)^{12} - \left(\frac{\sigma}{r_{ij}} \right)^4 \right\}$$

where, ε is the dissociation energy and σ is the distance where U crosses the 0 energy level (*i.e.* $r_{ij} < \sigma$ causes steric repulsion), r_{ij} is the distance between sites i and j . The LJ_{12-4} function is used for the pairs involving water and linker particles, while the LJ_{9-6} is used for all other pairs. The non-bonded interactions are calculated for all pairs except for those pairs involved in a bond or bend intermolecular interaction. We employed the PEG surfactant description as a template for the charged diblock copolymers (see Figure 1). To obtain the desired aggregate morphologies we added two new beads types, EC and L. Type EC corresponds to the charged moieties (PAA) within the headgroup. Type 'L' (linker) mimics the calcium, when condensed within the charged headgroup produces a reversible cross-linking between polymers.

To mimic the repulsion between the ionized head-groups (EC-EC) without actually using charges, we increased the size of these beads, σ_{EC-EC} , and reduce the depth of potential energy well, ϵ_{EC-EC} obtaining an almost exclusively repulsive potential. L-type particles are single beads with a strong attractive interaction with the EC beads. The strength (ϵ_{EC-L}) and size (σ_{EC-L}) of the potential energy function is such that it generates cross-linking of the polymers. Even though this interaction is strong (~ 3 kcal/mol) it is not irreversible; the system does have free L-particles in solution at equilibrium with bound L particles. For completeness, the parameters ϵ and σ for the entire model are listed in Table 1.

The total potential energy includes terms corresponding to intramolecular interactions: bond stretching and angle bending term are described as harmonic potentials,

$$U_{intra} = \sum^{Bond} k_b (r - r_0)^2 + \sum^{Angle} k_a (\theta - \theta_0)^2$$

where k_b and k_a are spring constants, r_0 and θ_0 are the equilibrium distance and angle. For the new “charged” beads these parameters were the same as for the EO beads in the original model²⁴ as showed in Table 2. Thus the intramolecular interactions are the same for PAA and PEG.

The chemical moiety PAA is a weak polyacid with an apparent dissociation constant of pKa ~ 4.7 ,²⁵ that tends to increase with the degree of dissociation.²⁶ The pKa is also affected by the presence of different counterions, ionic strength, the pH, salt size, and even the polymer conformation.^{27,28} To mimic the effects of acidity of the medium, we impose a degree of “ionization”, α , to the headgroup although it is expected that the relationship between pH and α is non-trivial. Early studies²⁹ proposed to describe the titration curves of these acids by means of a generalized Henderson-Hasselbalch equation:

$$pH = pK_a - n \log \frac{1 - \alpha}{\alpha} \quad (1)$$

with $n=2$ for polyacrylic acid.²⁹ In Table 3 we compared the results obtained from this equation with modern potentiometric measures.^{27,28} There is some disparity with respect to the calculated values, however for the sake of consistency and simplicity we use Eq. (1) realizing that our pH values are approximate. The extremes cases of $\alpha = 0$ and $\alpha = 1$ cannot be related with any pH and therefore are not mentioned in Table 3, however their structures are analogous to those observed at $\alpha = 0.2$ and $\alpha = 0.8$ respectively. Further $\alpha = 0$, which corresponds to zero ionization is identical to the PEG model which has been well characterized by Shinoda et. al.²⁴

In our representation, every headgroup bead would represent a ionizable moiety that could be charged (EC) or neutral (EO) (see Figure 3 in violet (EC) and green (EO) respectively.) By definition:

$$\alpha = \frac{N_{EC}}{N_{EO} + N_{EC}}$$

where N_{EO} and N_{EC} are the total number of neutral and charged beads respectively. For simplicity, we made the approximation that all of the different polymers in a simulation have

an identical degree of ionization. Therefore, by specifying the ratio between “charged” and neutral beads we can estimate the equivalent pH of the medium. We simulated all degrees of ionization shown in Table 3 and display some of them in Figure 2. To test the hypothesis that the particular choice of EC position does not effect the results at every degree of ionization at least 4 different systems were simulated in which the position of the “charged” beads within the headgroup were altered. We found no significant difference in the placement of the EC group with respect to all measured parameters providing strong support for our hypothesis. Thus we use one of the permutation tested (the one where we have the most data) for each pH reported in Table 3.

Simulations

The model has been used in all simulations as is implemented in the LAMMPS package³⁰ using an NPT ensemble (Nose-Hoover thermostat and barostat), with $T = 298\text{K}$ and $P = 1\text{bar}$. The time step was 10fs. Once we have adjusted the “pH” (EC to EO ratio) of the system as explained above, we prepared the initial conditions by randomly placing molecules within the box. Since these are surfactant systems we need an appropriate surfactant/water ratio to see the appropriate phases. We have tested different system sizes using 5000 to 10000 water beads, 512 to 1024 surfactant molecules and 100 to 1000 L-type particles. The final sizes of these systems vary between $100\text{ Å} \times 100\text{ Å} \times 100\text{ Å}$ and $200\text{ Å} \times 200\text{ Å} \times 100\text{ Å}$. To obtain the stable morphology the following procedure was used. At every condition the initial configuration was equilibrated for 100ns. Following this period, a given morphology was considered stable when its structure did not visibly change for at least 200ns. Along with the pH, we investigated different systems in the presence of a cross-linker. The addition of the L-particles was done by taking a previously equilibrated snapshot and randomly switching some water sites to cross-linker particles. The number of added L-type beads was half of the amount of EC beads. This ratio is equivalent to the acidic moieties and counterion ratio in a neutral mixture of PAA and calcium. Again, the equilibrated structures were obtained after 200ns of a constant morphology.

The total concentration of L-type particles is known within the simulation box, however it is difficult to relate this value to the concentration reported in experiments¹⁹ due to the different ratio of the system volume to the surface of the water-polymer interface. Given the finite size of the simulated system, it is appropriate to consider that our values represent the local concentration around the aggregates, which are expected to be larger than the total concentration as reported experimentally. Therefore we parametrized and evaluated the action of the cross-linker only in terms of its presence or absence.

Figure 2 shows five different structures obtained at different points in the pH scale, in the presence or absence of L-type particles. The polymers employed, represented in Figure 1, are composed of a headgroup with five ionizable groups and a tail containing 21 CH_n groups (7 beads), which are in agreement with the observed experimental morphologies. We start our analysis with no cross-linker (L) in the system, followed with discussions of linker addition and then a discussion of observed collective phenomena in mixed PEG-PAA systems.

Results

No Crosslinker

The PEG surfactants aggregates have different morphologies depending on the surfactant/water ratio³¹ and the Shinoda model is able to capture this feature.³² In our simulations we worked at surfactant/water ratios that showed stable bilayers for $\alpha=0$. Figure 2 shows that the structures obtained at pH 4.5 ($\alpha=0.2$) were bilayers. At these conditions, experiments

show vesicles¹⁹ which are in agreement with the bilayers observed in the simulated box given the finite size and periodic boundary conditions of our systems. The aggregates observed in experiments have characteristic length scales in the order of μm ¹⁹ which are well beyond the length scales we simulate (10 nm). The aggregates obtained by simulations were stable (over 500 ns) bilayers when the initial distribution of the molecules was already close to a bilayer structure (see Figure 2). However, sometimes when starting from a random distribution the final stable structure was a bilayer with water-filled holes was observed. The stability of both types of structures was not affected by changes in the system size (bilayer area). Therefore we hypothesize that there exist a large interconversion barrier between the two morphologies which would lock the system into a local free energy basin depending on the initial configuration. Further, finite size effects might contribute to the barrier for interconversion by stabilizing structures on the length scale of the simulation box. Thus much larger and longer simulations would be required to observe configurational fluctuations which would allow the interconversion between pierced and flat bilayers.

The stable structures at pH 5.5 ($\alpha=0.4$) were cylinders or worm micelles which is in agreement with the experimental result at these conditions. Also at pH ~ 6.5 ($\alpha=0.6$) worm-like micelles are observed both in our simulations and in experiments. In fact, the experiments show a mixture of cylinders with spheres (see Figure 2), and in our simulations we also observe the presence of cylinders, which are extended across the periodic boundary conditions, as well as elongated spheres (or short cylinders). Finally at higher pHs ~ 7.5 ($\alpha=0.8$) the structures observed are spherical micelles in agreement with experiments as well.

As mentioned previously, at low and moderate pH if the initial configuration was close to a bilayer, this structure were stable even when the simulated area was increased. This is indicative of the surfactive nature of the diblock copolymers. However, this stability was gradually lost as the pH was increased (6.5 and higher). In these cases, larger undulations and peristaltic motions were observed particularly in the largest systems simulated and finally in the simulations at the highest pH the bilayer broke up yielding higher curvature structures such as cylinders. These observations are consistent with metastable bilayer structures and/or finite size effects and is expected that the enlargement of the simulation box would not favor a bilayer morphology.

We see that increasing the pH transforms flatter structures (bilayers) into higher curvature structures (micelles). From the point of view of the individual molecules that compose these structures, elevating the pH augments the number of ionized group, *i.e.* the amount of EC groups has increased. These “charged” beads (EC) are larger than the neutral beads (EO) and increase the overall size of the polymer headgroup. By geometric packing considerations, the enlargement of the area per headgroup, while keeping the hydrocarbon volume and chain length constant, tends to decrease the shape factor:¹⁷ the shape of individual polymers are more conical, and the thermodynamically favored aggregate thus has a larger curvature. A lower pH which results in an increase in the positive charged moieties which repel one another. This repulsion can be modeled by a local LJ interaction which increasing the size of the headgroup. This increase in size can be captured by a judicious choice of σ for the EC particle (Table 1).

Addition of crosslinker

In experiments, the addition of calcium shows to have a similar effect as the neutralization of the headgroup achieved by decreasing the pH,¹⁹ the larger the concentration of counterion –or the lower the pH– the flatter the morphology obtained. In simulations the presence of crosslinker particles shows a similar effect and the addition of 1 L-type bead for every 2 EC beads generates flatter structures. In Figure 2, the presence of L-type particles convert the

cylinders (pH~ 6.5) or spheres (pH~7.5) into flatter cylinders as can be depicted by the different transverse sections: the circular profile flattens into an oval shape. These structures are stable within our simulations for more than 500ns, however they have not been seen in experiments. This fact, added to the different curvatures observed in the structures and the expected slow interconversion dynamics between morphologies for surfactant systems³³ suggests that these structures are metastability. As mentioned previously, the different ratio of the system volume to the surface of the water-polymer interface leaves a very small amount of non-condensed L-type particles (less than 1%) in solutions. Therefore it is difficult to relate the linker concentration observed in the simulation box with the bulk salt concentration reported experimentally.

We have shown that the change in the number of beads representing ionized groups as well as the presence of L-type particles changed the morphologies of the aggregates. At the molecular level the effect is related with a change in the overall size of the headgroups cross section relative to the tails. In the case of Ca^{2+} the cross-linking binds the headgroups together such that the resulting diblock copolymer headgroup cross section size is similar to the tail size. This is achieved by a judicious choice of interactions between L and EC. The change in size is quantified in Figure 3. The radial distribution function (RDF) of the center of mass of the headgroups shows a dramatic difference between linker (L-type) and no L-type linker (Figure 3, top). The RDF also shows a shrinkage in their effective volume when the pH is reduced or when L-type particles are added as evidenced by the position of the first peak. This reduction in size ($\sim 10\text{\AA}$ to $\sim 6.5\text{\AA}$) promotes the formation of flatter structures. Further, the phase changes from liquid like (one diffuse peak) to solid like (multiple peaks with the second neighbor peak split into two) with the addition of the L-type particle. The headgroups form an interlaced hexagonal close packed morphology although the packing is not observed in the hydrophobic tails as seen in Figure 4. Thus the tails are liquid like while the headgroups are solid like. Gelation of PAA by calcium is well documented in experiments^{18,19} although there have been no experimental studies of RDFs. The RDF also shows a shrinkage in their effective volume when the pH is reduced (Figure 3, bottom) or when L-type particles are added (Figure 3, top) as evidenced by the position of the first peak. This reduction in size, which in turn is associated with the diminution of the repulsion between headgroups, promotes the formation of flatter structures.

Collective Phenomena

Up to this point, we have tuned the parameters to fit the experimental observables and shown that some regions of the phase diagram can be reproduced by local effect on the headgroup size. We now show that the model is not only useful in investigating the molecular origins of different phase and can be used to observe collective phenomena based on the physics of the model.

We have employed this model to simulate the recent experiments¹⁸ involving lateral phase segregation in mixture of neutral and charged diblock copolymers in the presence of calcium. Similar to what is observed for signaling lipid phosphatidylinositol (PIP2),^{34,35} divalent cations cross-bridge the polyanionic amphiphiles, induce demixing. These systems generate domains within bilayer vesicles as well as stripes within cylindrical micelles.¹⁸ Imaging made clear that the cation-induced gel domains in one leaflet of a bilayer register with domains of the same size in the other leaflet. Specifically, only two intensities (I_{gel} and $I_{fluid} = 0$) are measurable on vesicles, whereas any mis-registration would have produced three intensities ($2I_{gel}$, I_{gel} and $I_{fluid} = 0$). The origin of the transmembrane coupling is not well understood and several mechanisms have been proposed.³⁶

To investigate this collective phenomena a 50:50 mixture of neutral diblock copolymers containing PEG headgroups (Shinoda model^{24,32}) and those described by the model

presented in this work were used. These mixed systems yield stable bilayers with the appropriate surfactant/water ratio with a homogeneous mixture of headgroups *i.e.* no lateral phase segregation. However, the addition of L-type particles induces lateral phase segregation as seen along the different snapshots in Figure 4. In our flat bilayers with the linker particles the stable morphology is total separation with one single domain per leaflet. In agreement with experiments these domains are reverted to the original mixed state if the linker particles are removed.

The registration (co-localization) of the domains across the bilayer, observed in experiments,¹⁸ was captured by our simulations. As can be seen in the lateral view of the membrane in Figure 4, the domain in one side of the membrane corresponds to a similar domain in the other leaflet. In all of our simulations we observed the same trend and all domains were co-localized across the bilayer. We observed that a minimum of 50 amphiphiles were required before the domain registration was observed. Domains containing less than 50 amphiphiles were not able to register while those containing more than 50 showed strong co-localization in terms of fluctuations of the mismatching area between domains. These observations suggest a correlation between the size, order, and level of registration of the domains.

Some of the proposed mechanisms to account for registration are: mediation by transmembrane proteins,³⁷ electrostatic coupling, cholesterol flip-flop, dynamic chain interdigitation,^{36,38,39} and composition-curvature coupling.⁴⁰ The absence of transmembrane proteins automatically discard them as possible driving forces. Cholesterol flip-flop is dropped given the lack of this molecule. Even more the surrogating L-type particles do not show any flip-flop. The neutrality of the model indicates that no electrostatic coupling between headgroups is present. Further, the headgroups of the “charged” domains do not interact at all since the employed cutoff is one third of the minimum headgroup distance. From the remaining group we analyze chain interdigitation. We have observed that, interdigitation of the hydrophobic tails does not change during registration therefore it is unlikely to be a possible driving force. In Figure 5 the RDF of the terminal hydrophobic bead with the hydrophobic beads of amphiphiles belonging to the other leaflet is reported. This function does not show significant differences between the registered and non registered systems as would be expected in case of strong interdigitation.

Overall the interaction of the domains seems to be of a collective and cooperative nature, nonetheless the precise origin of the driving force for domain registration in the reported model is a subject of current research. It should be noted that even if in our MD simulations the systems seem to be stable and the methods employed are standard in the study of membranes it is important to consider the methodological limitations. It should be also noted that while the model is proficient in describing the morphological phase diagram of charged polymers its simplicity and phenomenological nature could be regarded as *ad-hoc*. The transferability and ability to describe other phases is also an area of ongoing research. Further, Our MD trajectories spanned over 500 ns that might not be enough to observe the interconversion between different morphologies.

Conclusions

We have shown that it is possible to reproduce key phases found in the morphological phase diagram of the PAA-PBD diblock copolymer by modifying a few interaction parameters of PEG surfactant headgroups with no need of charges. The change of pH was achieved by changing the ratio between “ionized” and not-ionized beads in the hydrophilic headgroup. In this way we were able to obtain different morphologies analogous to those observed experimentally. Only two new particles were needed in order to produce the cross-linking of

the head-group, analogous to the effect of calcium in experiments. In molecular terms, it was showed that both a decrease in pH as well as the presence of linker modified the effective headgroup radius inducing the transition of the aggregates to flatter morphologies. One of the most important features of the model is that it seems to capture the essential physics of the system without making use of “expensive” charges. Thus, it seems possible to achieve the description of part of the polymers morphological complexity by modifying the steric interaction between the headgroups and not considering any long range attraction or repulsion inherent in charged systems. This suggests that the overall effect of charges is a local structural rearrangement that renormalizes the steric repulsion between the headgroups.

Mixtures of neutral and “charged” surfactant, crosslinker and water showed demixing of both amphiphiles yielding two phase spotted bilayers. Our model is able to describe collective phenomena such as co-localization or registration of the obtained domains. The complete absence of charges in the model suggests that the electrostatic coupling does not contribute to the co-localization process. Further, the lack of change in the degree of interpenetration of the hydrophobic tails in different leaflets during the registration diminishes the chances of interdigitation as a possible driving force.

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Figure 1. Snapshot illustrating the CG model of the polymers. The different beads are represented in different colors: OA (red), EO (green), EC (violet), CM and CT (cyan) and L-type particles (yellow). The neutral polymer (right) have the same parameters defined by Shinoda *et al.*²⁴ The “charged” polymer (left) shows a molecule with degree of ionization $\alpha = 0.4$.

Figure 2.

Characteristic snapshots of the morphologies obtained for C-type polymers and its location within the morphological phase diagram for diblock copolymer PAA₇₅-PDB₁₀₃ (HOV: Higher-Order Vesicle, V: vesicle, C: cylinder, S: spheres. Reproduced from Geng *et al*¹⁹). In all snapshots only C-type polymers (hydrophobic core in gray, hydrophilic corona in white) and L-type particles (yellow) are shown in space filling representation. Legends describe the condition from where the morphologies were obtained: membrane bilayer (pH~ 4.5), a mixture of short and long cylinders (pH~6.5), spheres at pH~ 7.5, flat cylinders at pH 6.5 and 7.5 in the presence of L-type particles.

Figure 3. Radial distribution function for the center of mass of the polymers headgroups. Bottom: system with absence of L-type particles and at pHs 5.5 (red), 6.5 (green) and 7.5 (blue). Top: systems at pH 7.5 with (magenta) and without (blue) the addition of L-type particles.

Figure 4.

Snapshots of the patches formation time evolution (top: topview where water and L-type particles were removed, bottom: lateral view). In space filling representation the neutral (red) and “charged” (gray) polymers as well as the L-type particles (yellow). Water is represented in light blue. From left to right: the small C-type particles patches converge to one patch per leaflet as long as the L-type particles condense. The final patches are in register or co-localized.

Figure 5.

Radial distribution function for the hydrophobic tail terminal bead with the hydrophobic beads of amphiphiles belonging to the other leaflet, before (red) and after (green) registration is produced. The slight difference between both suggest that the chain do not change the level of interpenetration during if the domains are or are not co-localized.

Table 1
Non-bonded interaction parameters

Atoms ^a		Function	ϵ (kcal/mol)	σ (Å)
W / L	W	LJ12-4	0.8950	4.3710
W / L	CT	LJ12-4	0.3600	4.4780
W / L	CM	LJ12-4	0.3400	4.4385
W / L	OA	LJ12-4	0.7000	3.9500
W	E*	LJ12-4	0.5700	4.3100
L	EO	LJ12-4	0.5700	3.7650
L	EC	LJ12-4	2.7500	3.7650 Attraction
L	L	LJ12-4	0.0040	6.5300 Repulsion
CT	CT	LJ9-6	0.4690	4.5850
CT	CM	LJ9-6	0.4440	4.5455
CM	CM	LJ9-6	0.4200	4.5060
OA	OA	LJ9-6	0.4491	3.7130
EC	EC	LJ9-6	0.0040	6.8000 Repulsion
EO	EC	LJ9-6	0.4050	4.2500
EO	EO	LJ9-6	0.4050	4.2500
E*	OA	LJ9-6	0.4400	3.8900
E*	CT	LJ9-6	0.4100	4.3400
E*	CM	LJ9-6	0.3770	4.2740
CT	OA	LJ9-6	0.4372	4.0330
CM	OA	LJ9-6	0.3650	3.9870

^aW: water, L: linker particle, CT: -CH₂CH₂CH₃, CM: -CH₂CH₂CH₂, EO: neutral headgroup moiety, EC: ionized headgroup moiety, E* = EC or EO, the cutoff used is 15Å;

Table 2

Intra molecular potentials

Bonded Params			Angle Parameters		
Atoms	k_b (kcal/mol/Å ²)	r_0 (Å)	Atoms	k_a (kcal/mol/rad ²)	θ_0 (°)
CT	6.16	3.65	CT	1.190	173.0
CM	6.16	3.64	CM	1.190	175.0
CM	7.10	3.61	CM	1.500	172.0
CM	7.10	3.61	E*	3.200	146.0
E*	4.90	3.28	E*	3.400	132.0
E*	15.00	2.79	E*	3.000	131.0

Table 3
Relationship between degree of ionization and pH

n_{EC}	α	pH ^a	pH ^b	pH ^c
1	0.2	4.7	5.5	4.5-5.5
2	0.4	5.7	6.5	5.5-6.4
3	0.6	6.6	7.5	6.4-7.2
4	0.8	7.4	8.5	7.5-8.1

^a See Katchalsky and Spitnik²⁹

^b See Benegas et al.²⁷

^c See Laguecir et al.²⁸