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Repulsion between oppositely charged rod-shaped macromolecules: role of overcharging and ionic confinement

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The interaction between two oppositely charged rod-shaped macro ions in a micro ion solution is investigated via Monte Carlo simulation of the primitive model. The focus is on asymmetry in rod and/or ion charge, i.e. conditions where oppositely charged objects can repel one another. For equally and oppositely charged rods with asymmetric z : 1 micro ions, repulsion may be induced by overcharging one of the rods with the z valent ions. For asymmetrically charged rods in a symmetric z : z micro ion solution, a repulsive interaction — at separation of the order of one ion diameter – can arise via an unbalanced osmotic pressure contribution from the ionic atmosphere in the inter rod space, and an attractive interaction – at smaller separation – may occur due to a "squeezing out" of the micro ions from the space between the rods (with a consequent gain in entropy). The thermodynamics of each mechanism is investigated in terms of rod charge and size, and micro ion valance, size, and concentration. Our findings contribute to an understanding of the complex role of charge asymmetry on the interaction of, for example, oppositely charged polyelectrolytes, functionalized nanotubes, and rod-like biomolecules, e.g. viruses.

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I. INTRODUCTION

Interactions among charged macromolecules or particles in aqueous solution are the basis of many biological and industrial processes. Very often, the charged objects have rod- or filament-like form, e.g. biomolecules^{1–3}, charged polymers (polyelectrolytes) such as DNA⁴, viruses⁵, coated and functionalized nanotubes^{6,7}, functionalized cellulose fibrils⁸, and liquid crystals^{9,10}. Therefore, applications of rod shaped macromolecules range from synthetic biology and drug transport to flocculation, hydrogels, bio-contact materials, and chemical sensors in aqueous environments^{11,12}.

Studies on the interactions of oppositely charged objects^{13–21} tend to be more rare than their like-charge counterparts^{22–30}, possibly because of the intuitive preconception that oppositely charged objects always attract one another, and thus do not present interesting phase behavior. Indeed, many mean field theoretical approaches, like Debye-Hückel³¹ or Derjaquin, Landau, Verwey, and Overbeek (DLVO)^{32,33} theory, along with the common superposition approximation, predict an electrostatic attraction between oppositely charged objects, and screening by added electrolyte^{34,35}.

Interestingly, certain theoretical treatments do predict the possibility of repulsion between oppositely charged objects. For example, the full Poisson-Boltzmann (PB) equation can predict a short range repulsion which originates from the osmotic pressure associated with the micro ion atmosphere around the charged macro ion, for two spherical^{13,14}, planar^{13,15,20}, or cylindrical³⁶ objects that are non-equally (asymmetrically) charged. Beyond the PB equation, the so called weak and strong coupling approaches^{28,37,38} account for non-mean field effects, and thus offer improved accuracy over a greater range of conditions. Kanduč *et al.*³⁹ have extensively mapped the interactions between asymmetrically charged plates, under both strong and weak coupling conditions, and as function of the plate charge asymmetry. Both pure attraction and attraction followed by short range repulsion were observed. In the case of oppositely charged plates, the strong coupling approach led to onset of repulsion at closer separation than did the mean field and weak coupling approaches.

Repulsion between oppositely charged macro ions has been observed via experiment by, e.g., Besteman *et al.*⁴⁰ in their study of interactions between a negatively charged mica plate and a surface terminated with positive amine groups. Furthermore, oppositely charged polymer complexes are known to dissociate upon addition of high concentrations of salt⁴¹⁻⁴³.

To better understand the interaction of rod-like, oppositely charged objects in the presence of electrolyte, including the occurrence of repulsion, we present here a primitive model Monte Carlo simulation study. Macro ions are modelled as rigid cylinders and micro ions, i.e. counter-ions or salt, by charged hard spheres. The solvent is implicit. We investigate the influence of the size and charge of both the macro and micro ions, and the micro ion concentration, and focus in particular on cases where the rods or ions comprising the electrolyte carry non-equal (asymmetric) charge. Our parameter space is chosen to represent biological environments, which invariably contain mixtures of multi and monovalent ions. The focus on charge asymmetry is particularly poignant because of its known influence on the composition and properties of polyelectrolyte complexes and multilayer films^{44,45}.

Related simulations have been previously conducted on ions around a single charged rod^{46-48} , and on two rigid cylinders carrying the same charge (motivated largely by the counterintuitive DNA-DNA condensation^{24,25,28} and bundle formation^{26,29,30}). To our knowledge, prior studies on oppositely charged rod-like objects consist only of the PB study by Harries³⁶ and our recent work on asymmetrically charged rods at moderate concentrations of 1 : 1 micro ion electrolyte²¹. Here we extend our previous study to cover a wider range of parameters: we investigate asymmetrically charged rods in a z : z micro ion solution along with symmetrically charged rods in a z : 1 micro ion solution, and decipher the effects of finite rod and ion size.

II. METHODS

Our model consists of two parallel, cylindrical rods, each with a continuous line charge along its center, and hard sphere micro ions, in a periodic cubic simulation box with edge length 20 l_B , where $l_B = e^2/4\pi\varepsilon k_B T$ denotes the Bjerrum length, e is the elementary charge, ε the dielectric constant of the medium, k_B the Boltzmann constant, and T the absolute temperature. The rods span the simulation box in the z-direction. The macro (rods) and micro ions interact via hard core and Coulombic interactions.

Canonical ensemble Monte Carlo (MC) simulation is performed at a constant rod-rod separation through random displacements of the hard sphere micro ions. The average total force on rod i, $F_{tot}^i = F_{el}^i + F_{hs}^i$, is determined by calculating the electrostatic force, $F_{el,i}$, using a modified Ewald summation method⁴⁹, and integrating the hard sphere collision force $F_{hs,i}$

between the micro ions and the rods based on the contact density, as specified in Ref. 25. Our Ewald summation is based on a uniform line charge, rather than discretized point charges⁴⁹. The continuous line charge description enhances the computational efficiency of the simulation and ensures that the choice of rod charge discretization does not affect the outcome.

The components of the force F_{el}^1 , F_{el}^2 , F_{hs}^1 , and F_{hs}^2 can differ for each rod due to system asymmetries, but Newton's third law $\sum_i \vec{F}_{tot,i} = 0$ and the translational invariance of the system assure that the total force on each rod is equal and opposite, i.e. $(F_{tot}^1 = -F_{tot}^2)$. The numerical accuracy and convergence are evaluated by checking Newton's third law. In the figures that follow, the symbol size reflects the magnitude of error.

Simulations consist of ca. 10^5 MC steps for equilibration, followed by ca. 10^8 steps for data collection. As the collision force generally converges more slowly than the electrostatic force⁵⁰, equilibration is based on convergence of the collision force. A positive force corresponds to repulsion.

Rod and micro ion diameters are $d_c = 2.2 \ l_B$ and $d_{ion} = 0.6 \ l_B$, respectively, unless otherwise stated. The reported micro ion concentrations are those of the cations, and include counter-ions and added salt. This convention is chosen owing to counter-ion release upon macro ion approach. Micro ion concentrations are calculated assuming $l_B = 0.714$ nm. All systems are charge neutral, overall.

III. RESULTS

A. Symmetric rod charge in asymmetric salt: repulsion via asymmetric overcharging

In Figure 1, we present the force between two rods of equal but opposite charge per length ($\tau_1=4 \ e/l_B$ and $\tau_2=-4 \ e/l_B$), as a function of dimensionless rod-rod separation $D^* = (D - d_c)/d_{ion}$, at different concentrations of a 3 : 1 micro ion. As expected, at low micro ion concentration, the rods attract one another at all separations. However, when the concentration reaches c = 0.05 M, repulsion occurs at larger separation. The maximum repulsive force increases, and the separation at maximum repulsion decreases, with micro ion concentration. At the same time, increased micro ion concentration yields a more rapid



Figure 1: At left, the force per length between two equally but oppositely charged rods, of charge density $\tau_1 = 4e/l_B$ and $\tau_2 = -4e/l_B$, as a function of scaled rod separation, at different 3 : 1 micro ion concentrations. At right, the cumulative charge distribution around rod 1 (bottom) and rod 2 (top), as functions of scaled distance to the rod surface, at selected scaled rod separations D^* .

decay of the repulsive force through screening.

We also present in Figure 1 the cumulative charge distribution around each rod. We observe overcharging of rod 1 (but not rod 2) due to the presence of trivalent ions. This asymmetric overcharging leads to the observed repulsion between the oppositely charged rods. We further note that no overcharging occurs beneath a threshold separation, where interactions with rod 2 lead to the release of some of the trivalent ions.

Overcharging appears to be a necessary but not a sufficient condition for repulsion. For example, at concentration of c = 0.03 M, overcharging occurs when the rods are far apart $(D^*=13)$, but the interaction between the rods remains attractive throughout. As repulsion is favored by both screening and overcharging, our finding here suggests overcharging below a threshold level to be insufficient to cause detectable repulsion, even in a diminished charge screening environment.

In Figure 2, we present a schematic of the force components along with qualitative depictions of ion condensation and depletion. Simulated hard-sphere and total forces on each rod, as a function of rod-rod separation, for various micro ion concentrations, are presented in the Supporting Information. In the absence of overcharging, the rods mutually attract one another. This attraction arises from electrostatic and hard sphere force components F_{el}^1 and



Figure 2: Schematic presenting the forces and ion behavior in a system of two equally but oppositely charged rods in a 3 : 1 micro ion solution. In the top panel, the micro ion concentration is sufficiently low so that condensation of trivalent ions does not lead to overcharging. In the bottom panel, the concentration is sufficiently high so that condensation of trivalent ions leads to overcharging.

 F_{hs}^1 on rod 1, and from the attractive hard-sphere force F_{hs}^2 on rod 2. When overcharging occurs, F_{el}^1 turns repulsive, F_{hs}^1 diminishes or even changes sign to repulsive, F_{hs}^2 becomes less attractive, and F_{el}^2 becomes less repulsive, owing to the shift in positions of the anions toward the region between the rods, and the additional trivalent ions present, associated with the reversal of rod 2 charge.

Additional insight is provided by comparing the internal (Coulombic) energy and the potential of mean force (PMF), as shown in Fig. 3. The PMF is obtained by integrating the total average force and represents the free energy profile, whose entropic contribution includes the hard sphere interactions with the ions. The zero of the PMF is taken at a dimensionless rod-rod separation of $D^* = 13$. At low micro ion concentration, we observe the PMF to be attractive at all separations, but the internal energy profile to exhibit a repulsive barrier, indicating the attractive entropic interactions to more than compensate for repulsive electrostatic interactions. Interestingly, the internal energy barrier decreases,



Figure 3: Internal (Coulombic) energy ΔU_{int} and the potential of mean force (PMF) per rod length for two equally but oppositely charged rods ($\tau_1 = 4e/l_B$ and $\tau_2 = -4e/l_B$), as a function of scaled rod-rod separation, at different concentrations of a 3 : 1 micro ion.

while the PMF barrier increases, with concentration, suggesting macro ions to dampen both the hard sphere entropic and the Coulomb energetic effects. In particular, macro ions reduce the entropic gain associated with the release of ions as the rods approach one another.

In Figure 4, we show that the extent of overcharging and the maximum repulsive force increase with ion diameter. While the attractive interaction between ion and rod is diminished at larger ion diameter, the weakened ion-ion pairing energy and overall crowding in the bulk (as suggested by Messina *et al.*⁵¹ and observed by Deserno *et al.*⁴⁷) leads to enhanced extent of ion condensation, and ultimately to overcharging and inter-rod repulsion. In this sense, ion size and concentration act in a similar way to favor overcharging and enhance repulsion.

In contrast, overcharging and repulsion diminish approximately linearly with rod diameter in the range $d_c = [1.1l_B, 4.4l_B]$ (Supporting Information). The decreasing trend can be explained through a decrease in the electrostatic coupling parameter $\Xi = 2z^3 l_B^2 \tau / d_c^{25,46}$.



Figure 4: The maximum overcharging of the negative rod (squares) and the maximum force per length between the two rods (triangles), as functions of the ion size at 3 : 1 micro ion concentration 0.09 M. Rod charges per length are $\tau_1 = 4e/l_B$ and $\tau_2 = -4e/l_B$.

B. Asymmetric rod charge: repulsion via ion confinement

We next consider cases where the magnitude of rod charge is asymmetric. In the following, a 1 : 1 micro ion concentration of c = 0.13 M is present, the charge per length of the negative rod (rod 2) is kept at $\tau_2 = -4e/l_B$, or roughly that of double stranded DNA, and the charge per length of the positive rod (rod 1), τ_1 , is varied.

We show in Figure 5 that rod charge asymmetry may induce a repulsive force between the rods. Indeed, at a charge ratio of $|\tau_1/\tau_2| \leq 0.125$, a repulsive force occurs at a separation of about one micro ion diameter. In contrast, the repulsive force observed above for the case of ion charge asymmetry occurs at much larger separations (see Figure 3). Notably, the systems of Fig. 5 do not exhibit overcharging, as the micro ions are monovalent and their concentration is moderate.

In Figure 6, we present a qualitative description of the mechanism of the repulsive interaction (quantitative graphs are given in the Supplementary Information). When the rod charge asymmetry is weak, most of the condensed ions reside on the outer sides of the respective rods, inducing electrostatic and hard sphere forces that are attractive. However, past a threshold asymmetry, a significant fraction of the cations around (the more highly charged) rod 2 reside in the space between the rods, resulting in a repulsive hard sphere force on rod 1 and a repulsive electrostatic force on rod 2, and a diminished attractive hard sphere force on rod 2.



Figure 5: The force per length between two oppositely and asymmetrically charged rods, versus scaled rod separation, for various degrees of charge asymmetry, in the presence of a 1 : 1 micro ion concentration of 0.13 M. At top, the total force between the rods and at bottom, the hard-sphere contribution to the force. The figure is adapted from Ref. 21 and is provided here for clarity and self-consistency.

In fact, a similar mechanism of repulsion for oppositely charged objects has been reported previously for asymmetrically and oppositely charged spherical colloids, and even between charged and neutral colloids⁵². Theoretically, the repulsion between asymmetrically charged objects can be predicted by the non-linear Poisson-Boltzmann equation in planar^{13,20}, spherical^{13,14} and cylindrical geometries³⁶. However, the prediction has been shown to be quantitatively inaccurate in the case of asymmetric cylinders studied here due to, e.g., the assumption of point like ions in the Poisson-Boltzmann equation²¹.

In Figure 7, we show the internal (Coulombic) energy and the potential of mean force (PMF) for oppositely and asymmetrically charged rods of $|\tau_1/\tau_2| = 0.125$ and $|\tau_1/\tau_2| = 0.250$, when only monovalent counterions are present (micro ion concentration 0.02 M) and at 1 : 1 micro ion concentrations 0.13 M or 0.27 M. When $|\tau_1/\tau_2| = 0.250$, each of these concentrations leads to pure attraction, as indicated by the monotonically increasing PMFs. Interestingly, for the cases with added salt, the corresponding internal energy profiles exhibit repulsive maxima, suggesting entropic hard sphere forces to engender the attraction. When $|\tau_1/\tau_2| = 0.125$, we observe repulsive barriers for the two added salt conditions, but note the



Figure 6: Schematic presenting the forces and ion behavior in two systems with different rod charge density ratios. The force magnitudes vary with rod charge density and micro ion concentration. The cartoon corresponds qualitatively to a system of rod charge $\tau = 4e/l_B$ and 1 : 1 micro ion electrolyte at micro ion concentration 0.13 M. In top panel, rod charges

are similar and they mutually compensate. In the bottom panel, rods have dissimilar magnitude of charge and ion reside between the rods leading to repulsive hard-sphere force.

barrier to disappear below a threshold concentration. A certain quantity of micro ions thus appears to be needed to induce repulsion between asymmetrically oppositely charged rods. The micro ions act to 1) suppress the ion release entropy and enhance ion condensation to the more strongly charged rod, resulting in an enhanced repulsive hard sphere collision force due to the condensed ions, and 2) more effectively screen the Coulombic attraction between the rods, i.e. decrease the Debye length. Similar to our findings, ion release entropy has been identified as the driving force of purely attractive interaction between oppositely charged spherical colloids¹⁶ and plates¹⁸.

All systems presented in Fig. 7 exhibit global free energy (i.e. PMF) minima at rod-

rod contact. In cases exhibiting a repulsive maximum, e.g. $|\tau_1/\tau_2| = 0.125$ with added salt, a local DLVO-like secondary free energy minimum appears in the separation range $D^* = [1, 2]$. As the maximum repulsive force corresponds to rod-rod separations of one micro ion diameter, the location of the local free energy minimum is also expected to scale with ion size. The energy differences between the two minima and the (chosen) zero lever at large rod separation can be interpreted as the free energy difference between reversible and irreversible binding.

Consistent with our observations here, our prior all-atom molecular dynamics simulations on DNA complexation with polyethylenimine (PEI) at different protonation states showed polyelectrolyte charge asymmetry to enhance the number of ions within the polyelectrolyte complex⁵³. Furthermore, theoretical considerations based on electrostatic free energy have suggested that both polyelectrolyte charge asymmetry and added salt can lead to a decrease in the free energy of complexation⁵⁴. Additionally, recent experimental work has provided evidence of a secondary free energy minimum in the complexation between DNA and polyethylenimine: intermediate binding states and loose association between the polymers have been reported⁵⁵. These intermediate binding states have been suggested to be behind the efficiency of polyethylenimine-DNA complexes as DNA delivery vectors in gene therapy^{55,56}, with the hypothesis being that intermediate binding can lead to more efficient and controllable release of genetic material in the cell.

In Figure 8, we illustrate the dependence of the inter-rod force on the rod diameter ratio d_{c1}/d_{c2} . We find that the interaction of two oppositely charged rods can be driven from purely attractive to short-range repulsive (around $D^* = 1$) by increasing the relative size of the more weakly charged rod (rod 1). A larger rod 1 more weakly compensates the charge of rod 2, causing more cations to remain condensed to the negative rod during approach, and thus acting to increase the repulsive hard sphere force. Furthermore, increasing the diameter of rod 1 provides more contact surface for the cations which further enhances the hard sphere force. The influence of rod size asymmetry on the cation distributions around the two rods is presented in the Supporting information.



Figure 7: Internal (Coulombic) energy ΔU_{int} and potential of mean force (PMF) per rod length, versus scaled rod separation, for two oppositely charged rods with different charge ratios $|\tau_1/\tau_2|$ and different 1 : 1 micro ion concentrations. The PMF figures are adapted from Ref. 21. This previously published data is provided here for clarity and self-consistency.



Figure 8: The force per length between two oppositely and asymmetrically charged rods versus scaled rod separation for various degrees of rod diameter asymmetry in the presence

of a 1 : 1 micro ion concentration of 0.13 M. Throughout, the diameter of the rod 2 is

$$d_{c2} = 1.1 \ l_B.$$

C. Interplay of the two mechanisms

The two mechanisms presented above – describing repulsion between oppositely charged rods due to asymmetric rod charge and asymmetric ion charge – are not mutually exclusive.



Figure 9: The force per length between two oppositely and asymmetrically charged rods, versus scaled rod separation, for different micro ion concentration and valence.
Throughout, the rod charge ratio is |τ₁/τ₂|=0.063. The inset shows a comparison of the resulting cumulative charge distributions, around the more strongly charged rod, for symmetric 3 : 3 and asymmetric 3 : 1 multivalent micro ions at D* = 6.5.

Indeed, Trulsson *et al.*¹⁷ observed that an asymmetric z : 1 micro ion can induce repulsion between asymmetrically charged planar plates at close separation, even when no charge inversion was detected. The close range repulsion is caused by the presence of a large amount of ions between the plates, due to both the charge asymmetry of the plates and the highly correlated structure of the multivalent and the monovalent ions between the plates. At larger plate separations, repulsion was accompanied by asymmetric overcharging¹⁷.

In Fig. 9, we show the influence of micro ion valence on the force between two asymmetrically and oppositely charged rods. We find a 1:1 micro ion to result in a stronger repulsive peak than either a 3:3 multivalent micro ion either of the same concentration (0.13 M) or at an equivalent ionic strength (0.01 M micro ion concentration). Since there are fewer multivalent ions present and they are less likely to reside between the rods, they exert a weaker hard sphere repulsion. This finding is in contrast to the observations of Trulsson *et al.*¹⁷ in the planar geometry, where ions are forced to reside between the plates and the presence of multivalent ions enhances the concentration of monovalent ions in the interplanar space.

While either rod or ion charge asymmetry can induce a repulsion between oppositely charged rods, the two effects together are far from additive. We show in the inset of Fig. 9 how the degree of overcharging of the more highly charged rod is greater in the case of the asymmetric multivalent micro ions (at the same concentration). Multivalent co-ions are able to themselves condense somewhat to the counterion layer which originally caused the charge reversal, and thus suppress overcharging and lessen repulsion.

IV. DISCUSSION

In this paper, we investigate the role of asymmetry – in macro and micro ion charge – on the interaction between two oppositely charged, rod-shaped macro ions. We employ a simple model of charged cylinders and spheres, with implicit solvent, and evaluate force and energy profiles via Monte Carlo simulation. While intuition would suggest attraction between the oppositely charged objects, we demonstrate two mechanisms through which repulsion may occur, one due to asymmetric overcharging in the case of micro ion charge asymmetry, and one due to the osmotic pressure exerted by the ions between the rods in the case of macro ion charge asymmetry. To our knowledge, this is the first study in which the interactions of oppositely charged, rod-shaped macromolecules have been extensively mapped out by simulation as functions of micro ion concentration and the size and charge of the macro and micro ions. Due to the simplicity of the model system, the findings generalize to many different molecular, particle, and colloidal systems, including polyelectrolytes, rodlike viruses, membrane proteins, and various charged nanorods and filaments.

For oppositely charged rods of similar charge density, a repulsion can be induced via asymmetric overcharging in the presence of an asymmetric z : 1 micro ion. At a certain micro ion concentration, the multivalent (but not monovalent) micro ions condense to one of the rods to an extent sufficient to reverse its charge, and lead to long range attraction. The interaction becomes attractive at closer rod-rod separation, where the two rods compensate each others charge and ions are released for entropic gain. The findings of our earlier allatom simulations of salt-induced decomplexation of polyelectrolyte systems^{53,57} are in line with our results here. In this earlier study, destabilization of DNA-polycation complexes occurred at high 2 : 1 micro ion concentration via overcharging of the DNA by divalent cations⁵⁷.

For oppositely charged rods of asymmetric charge density, a repulsion can be induced via the osmotic pressure of hard sphere ions confined in the inter-rod space. A repulsive peak in the force profile occurs at a rod-rod separation of about one micro ion diameter. At smaller separation, the interaction can become attractive again as these ions are "squeezed out" of the intra-rod space, resulting in a DLVO-like free energy double minimum, as we reported previously²¹.

The overcharging of a cylindrically shaped macro ion by solution micro ions is critical to the first mechanism. Overcharging cannot be described by most mean field, e.g. Poisson-Boltzmann, treatments of colloidal and macro ion systems, as it arises from strong electrostatic coupling. Applicable theoretical treatments include 1) integral equation theories^{47,58,59} and 2) one component plasma (OCP)^{60,61} or strong coupling approaches^{38,46} (for reviews, see Refs. 38,62. The former are based on correlation functions related by Orstein-Zernike equations and approximate closures⁶²). The latter emphasize the extent of electrostatic coupling between a macro ion and its micro ionic atmosphere, assumed to form a strongly correlated fluid^{38,60}. Predictions from these approaches vary, e.g. some predict a monotonous increase in overcharging with micro ion concentration, whereas others predict a maximum to occur^{62,63}.

In particular, for the system studied here the OCP model by Shklovskii⁶⁰ predicts overcharging to saturate at a 3 : 1 electrolyte concentration $c \approx 0.02$ M, beyond which co-ion condensation occurs. In contrast, we observe increases in overcharging and repulsion with micro ion concentration over all conditions studied, up to 0.27 M (see Figure 1). This disagreement may be partly explained by the OCP theory's neglect of ion size and mean field treatment of the bulk solution. Indeed, ion size in the bulk^{22,47} and the interplay of counter- and co-ion excluded volumes near the charged surface^{51,64} have been shown to significantly influence overcharging. Simultaneously, a steric upper limit for condensation into the first micro ion layer is set by the finite ion size, as investigated previously using a modified Poisson-Boltzmann approach⁶⁵. Accurate theoretical prediction of the repulsion between oppositely and asymmetrically charged objects would require further theoretical development accounting for ion size and non-mean field effects.

Ion release entropy plays an important role in both of our postulated repulsion mechanisms, by reducing the osmotic pressure exerted by the condensed ions (through hard sphere interactions). Indeed, the internal (Coulombic) energy profiles exhibit higher repulsive barriers than do the free energy profiles. Elsewhere, the entropic gain of ion release, more so than Coulombic attraction, has been shown to be behind the attraction of oppositely charged surfaces^{18,20} and spheres¹⁶. From early on, the entropy of ion release has been seen as a major driver toward the condensation of small ions to a charged polymer⁶⁶, and to the complexation of oppositely charged polymers⁶⁷. The idea has been the subject of some debate, perhaps due to possible differences⁶⁸ between weakly and strongly charged polyelectrolytes: the gain of counterion release entropy is proportional to the number of counterions and hence to the macromolecule charge. Further theoretical development related to the phenomena reported here should take careful account of ion release entropy.

We find steric considerations to play an important role in the behavior observed here. In particular, the repulsion between two oppositely and asymmetrically charged rods can be enhanced by increasing the size of the more weakly charged rod. Experimental evidence of the influence of charged rod-like object diameter also exists: Akinc et al. have observed that quaternizing the PEI charged nitrogens with methyl and ethyl side chains made PEI-DNA complexes less tolerant to salt, i.e. more prone to decomplex⁴². In addition, an increase in ion size can lead to an increase in the extent of overcharging, and hence also repulsion between the macro ions. This observation is in line with previous simulations in spherical⁵¹ and cylindrical⁴⁷ geometries. When the macro ion charge is asymmetric, the observed DLVOlike free energy minimum occurs at a rod surface separation equivalent to one ion diameter, and hence is also sensitive to ion size. Interestingly, rather mixed experimental reports have appeared^{45,69,70} on the influence of differences other than salt valency, such as ion size, on the behavior of salt-polyelectrolyte systems. An explanation to the discrepancy has been suggested by Pozar and Davor⁷⁰, who note that polyelectrolyte interactions become ion specific only at high salt concentration. In these elevated concentrations overcharging could occur with extent regulated by ions size.

It is important to note that ion size likely plays an important role in experimentally relevant systems also through its effect on ion hydration. For example, we have recently connected the polyelectrolyte complexation thermal^{71,72} and plasticization responses with hydration effects⁷³. These studies highlight the importance of hydration – including entropic effects related to water binding to ions – and suggest the ion size effects of simplified continuum solvent models, like those described here, to be insufficient to describe the full range of observed behavior.

It is interesting to consider combining the effects of the two repulsion mechanisms, i.e. due to macro and micro ion charge asymmetry. Adjusting either the concentration or type of micro ions allows for significant tuning of the force profile between asymmetrically charged rods, in particular where only the more strongly charged rod becomes overcharged. As the length scale of repulsion differs between the two mechanisms, the possibility of multiple repulsive free energy maxima emerges. On the other hand, increased micro ion charge and concentration, while favoring overcharging and condensed ion osmotic effects, also enhances electrostatic screening, tending to suppress electrostatic interactions. This leads to a delicate balance of different contributions. Predicting these subtle behaviors within a simple model framework could greatly assist technological developments involving highly charged macro ions. Full investigation of the emergence of multiple repulsive maxima is, however, beyond the scope of this work.

V. CONCLUSION

We present here a study of the interaction between oppositely charged, rod-like macro ions in a solution of micro ions (salt), with specific focus on how asymmetry in the rod charge content or ion valences may induce repulsion. We find the key variables – macro and micro ion size and charge, and micro ion concentration – to provide robust control over the resulting force and free energy profiles. Two mechanism of inter-rod repulsion are proposed. For oppositely (and symmetrically) charged rods with an (asymmetric) z : 1micro ion, repulsion at intermediate rod-rod separations is induced by overcharging of one of the rods by the multivalent micro ions. For oppositely (and asymmetrically) charged rods with a (symmetric) z : z micro ion, repulsion at close rod-rod separations is induced by the osmotic pressure of the ions in the inter-rod space. The two mechanisms are not mutually exclusive, and occur over different rod-rod separation ranges. By capturing electrostatic and excluded volume effects within a simple model framework, our findings serve as an important starting point toward molecularly detailed models incorporating explicit solvent and macro ion heterogeneity and flexibility.

VI. SUPPLEMENTARY MATERIAL

The Supplementary Material consists of the following figures: 1. The emergence of repulsion between oppositely charged rods of equal charge magnitude and the hard sphere contribution to the total force between the rods as the concentration of 3:1 micro ion increases. 2. The emergence of repulsion between oppositely charged rods of non-equal charge magnitude and the hard sphere contribution to the total force as the asymmetry between the charge magnitudes of the rods increases. 3. Overcharging and repulsion force between oppositely charged rod as the function of rod radius. 4. Influence of rod diameter on the cation distribution around the oppositely charged rods.

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