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Soft Matter

Cite this: *Soft Matter*, 2012, **8**, 9265

www.rsc.org/softmatter

EDITORIAL

Polyelectrolytes in biology and soft matter

DOI: 10.1039/c2sm90104h

Many important biological macromolecules, such as DNA, RNA, polypeptides, and polysaccharides, as well as large number of artificial macromolecules, such as poly(styrene sulfonate) (PSS) and polyacrylic acid (PAA), are highly charged polyelectrolytes. Commercial applications of polyelectrolytes range from colloidal stabilization, flocculation and flow modification to superabsorbent gels (diapers being a prominent example). Electrostatic interactions, mediated by mobile ions and water, play crucial role in these systems, influencing a molecule's structure, physical properties and function. These macromolecules often self-organize by electrostatic forces into large-scale superstructures. This is exemplified by DNA compaction into chromatin fiber in the nuclei of eukaryotic cells. Viral self-assembly, including proteins, DNA or RNA provides another salient example. The reason polyelectrolytes are so prevalent in life and their properties are so difficult to understand is related to long-range electrostatic interactions between charged groups on the chains as well as their interactions with mobile counterions and salt.

Given the importance and ubiquity of polyelectrolytes both in artificial and biological systems, a growing number of theoretical and experimental investigations have been addressing various aspects of polymer physics and biophysics in these systems. Among the major open problems is the question of how the ionic atmosphere around the polyelectrolyte couples to its internal modes. This, in turn, may explain how electrostatic effects contribute to determining the persistence length of polyelectrolytes. In the pioneering work of Odijk,[1] Skolnick and Fixman[2] (OSF), a Debye–Hückel based approach to modeling electrostatic interactions was used to define an electrostatic persistence length of semiflexible polyelectrolytes proportional to the square of the Debye screening length. This approach was extended to flexible polyelectrolytes by Khokhlov and Khachaturian[3] with predictions similar to the OSF theory. Barrat and Joanny[4] and Dobrynin[5] (BJD) introduced alternative models in which the electrostatic persistence length of flexible polyelectrolytes is on the order of the Debye screening length, and is much shorter than the OSF prediction.[6] Experimental data on flexible polyelectrolytes seems to be more consistent with BJD predictions.[7,8] Manning recently suggested that the interplay between the electrostatic self-repulsion and the polymer chain buckling is important in determining the polyelectrolyte persistence length.[9] Atomistic and coarse-grained simulations by Papoian and coworkers showed that the electrostatic contribution to DNA's large persistence length is significantly higher than OSF predictions at physiological salt concentrations.[10] Thus the effect of many-body interactions between ions in solutions and polyelectrolyte ions on overall chain rigidity is still poorly understood, and much more work is needed to achieve a quantitative agreement between theory and experiments.

A number of major challenges remain in the field of biological polyelectrolytes. Hydration-mediated interactions are not well described at distances at and below 1 nm from the polyelectrolyte surfaces, which leads to significant difficulties in applying continuum electrostatics-based models. It has been known for over hundred years that different small counter- and co-ions may result in dramatically different overall behaviors of polyelectrolytes, even when their charges are the same.[11] Although many aspects of ion-specific interactions have been recently understood,[12] we are still far from a satisfactory simple conceptual model explaining the large amounts of experimental data. Interestingly, it was recently discovered from atomistic simulations that major biological polyelectrolytes, such as DNA and proteins preferentially interact with Na^+ compared with K^+, which coincides with the prevalence of K^+ in the interior of cells, while Na^+ is prevalent in extracellular media.[13,14] Collins speculated that such a preference may be needed for keeping the cells' interior from precipitating.[15] This possibility, along with role of the multitude of small ions in the cell interior needs to be further investigated.

Open problems in the polymer physics of polyelectrolytes include the question of DNA translocation through nanopores and DNA and RNA packing in viral capsids and the nuclei of eukaryotic cells. Electrophoretic mobility is a particularly difficult problem, because it involves coupling between polymer chain dynamics and many-body interactions among mobile ions and the polyelectrolyte chain.[16] All these processes are also coupled to hydrodynamic flow induced by the electrophoretic process. Near a nanopore, polymer confinement and interactions with nanopore walls make it difficult to quantitatively model translocation phenomenon.[17] Packing of DNA and RNA in viral capsids requires large-scale spatial organization of polyelectrolyte chains, often involving complexation with oppositely charged polypeptides protruding in from the capsid walls. In the nuclei of eukaryotic organisms, genomic DNA is carefully folded into superstructures with the help of positively charged histone proteins.[18,19] Most of the physical chemistry behind the corresponding processes is not well understood. In particular, the role of flexible positively charged histone tails is very intriguing.[20] Recent works indicate that histone tails are not featureless coils, but are significantly organized.[21] An important open question is how histone tails mediate chromatin compaction.

Since research on polyelectrolytes is interdisciplinary and at the interface of polymer physics and biological physics, a themed issue on this topic brings the work of researchers from many fields of science into a single venue, providing a snapshot of the current state of the art in the field. Some of the questions outlined above are either reviewed or otherwise addressed in the following contributions.

Counterions

The interactions between polyions and counterions and the resulting counterion distribution, including counterions condensed on the chain and counterions located within couple solvation shells from the chain, significantly modify electrostatic fields and resulting properties of polyelectrolytes. These questions have been studied for a number of years and are the focus of active research in a number of groups. Several papers in the current issue directly address this topic of ion–polymer interaction: The interactions between nucleic acids and counterions, as modeled by atomistic and coarse-grained molecular dynamics simulations, are extensively reviewed in an article by Mocci and Laaksonen (DOI: 10.1039/c2sm25690h). On a closely related topic, the association of ions with single-stranded and double-stranded DNA oligomers of different lengths was reported by I. A. Shkel and M. T. Record (DOI: 10.1039/c2sm25607j). The ion-specific condensation of counterions on charged peptides was investigated by atomistic molecular dynamics simulations and accounted for by an additional empirical potential in Poisson–Boltzmann equation in the paper by Heyda and Dzubiella (DOI: 10.1039/c2sm25599e). The effect of the strong interaction of positive salt ions, such as Li, and the polyethylene oxide (PEO) block of PEO-polystyrene diblock copolymers on the effective interaction parameter between the two blocks and the resulting change of domain spacing is analyzed in the paper by Nakamura and Wang (DOI: 10.1039/c2sm25606a).

Polyelectrolyte stiffness and ions

Fundamental questions such as the condensation of counterions onto a polyelectrolyte backbone and its effect on the resulting chain stiffness are still controversial in spite of more than 35 years of intensive theoretical and experimental studies, as discussed above. One aspect of this phenomenon, the effect of condensed counterions on Poisson's ratio of a polyelectrolyte is addressed in the communication by Gerald Manning (DOI: 10.1039/c2sm25185j). The unexpected effects of mobile ion entropy on the force-extension behavior of polyelectrolytes are reported in the paper by Landy *et al.* (DOI: 10.1039/c2sm25608h). Another aspect, the effect of electrostatically induced tension in the chains on the salt dependence of the thickness of a polyelectrolyte brush is analyzed in the paper by Zhulina and Rubinstein (DOI: 10.1039/c2sm25863c).

Complexation

The complexation of polyelectrolytes with oppositely charged objects such as colloids, other polyelectrolytes, or surfactants has been at the center of charged polymer research. The ability to understand and control these complexation phenomena will undoubtedly lead to improvements in drug delivery, printing, and other applications. Several papers of the current issue address the following related problems: The phase diagram of oppositely charged polyelectrolytes and colloids is systematically studied in the paper of Sennato *et al.*, accounting for the surface charge inhomogeneities of polyelectrolyte-decorated particles (DOI: 10.1039/c2sm25576f). The effect of polymer molecular weight, concentration, stoichiometry, ionic strength, pH, and temperature on complexation and coacervation of polypeptides is described in the work of Priftis and Tirrell (DOI: 10.1039/c2sm25604e). The theory of complexation between double-stranded DNA and cationic micelles induced by counterion release and resulting in large micelles is presented in the paper by Schiessel *et al.* (DOI: 10.1039/c2sm25603g). The formation of core–shell cylindrical micelles upon the complexation of anionic double-hydrophobic block polyelectrolytes with cationic fluorosurfactants in a narrow stoichiometric range is reported by Stepanek *et al.* (DOI: 10.1039/c2sm25588j). The layer-by-layer assembly of nanocapsules with PEGylated polyelectrolytes and their potential drug delivery applications are presented in a paper by Shutava *et al.* (DOI: 10.1039/c2sm25683e). A different type of complexation—electrostatically induced aggregation between neutral semipermeable shells in asymmetric electrolyte solution is proposed in the paper of Lobaskin *et al.* (DOI: 10.1039/c2sm25605c).

Stimuli-responsive polyelectrolytes

One of the most active areas for the development and industrial applications of charged polymers is in the field of stimuli-responsive materials. Three papers in the present issue address this topic. The synthesis and stimuli-responsive properties of amphoteric nano-, micro-, and macrogels, membranes, and thin films are reviewed by Kudaibergenov *et al.* (DOI: 10.1039/c2sm25766a). Schmaltz *et al.* presents the effects of block length and arm number on the properties of dual stimuli responsive star-block copolymers (DOI: 10.1039/c2sm25686j), and the collapse of a weak polyelectrolyte star in poor solvent is described theoretically by A. Polotsky *et al.* (DOI: 10.1039/c2sm25593f).

DNA compaction

The most dramatic example of the importance of electrostatics in biological systems is in the compaction of DNA. Two reviews address this complex topic in the present issue. The electrostatics of DNA and the interplay of various compaction strategies in different biological systems from viruses and bacteria to archaea and eukaryotes are reviewed by Carrivain *et al.* (DOI: 10.1039/c2sm25789k). The systematic review of the polyelectrolyte properties of chromatin, illustrated by experimental results of the folding and self-association of the well-defined model chromatin, and the relation between these experiments and computer modeling, emphasizing the influence of histone tails on nucleosome interactions, is presented by Korolev *et al.* (DOI: 10.1039/c2sm25662b). A somewhat different, but related topic of conformational collapse of surface-bound helical filaments is addressed in the paper by Quint *et al.* (DOI: 10.1039/c2sm25798j).

Electrophoresis and translocation

Another feature distinguishing polyelectrolytes from neutral polymers is their mobility under the action of electric fields. Electrophoresis is one of the standard techniques used to characterized charged polymers, but in spite of its wide utilization in many fields, it is still not completely understood in detail. The influence of the shape of a polyelectrolyte on its electrophoretic mobility is described in the paper by Hsu *et al.* (DOI: 10.1039/c2sm25741f). The electric field also forces polyelectrolytes to translocate through nanopores. This process is one of the stringent tests of our understanding and accurate modeling of single chain dynamics and is necessary for the efficient use of DNA translocation in the new generation of DNA sequencing technologies. The effects of dielectric mismatch and chain flexibility on the translocation barrier is addressed in a paper by Kesselheim (DOI: 10.1039/c2sm25615k).

Conclusions

The physics and physical chemistry of polyelectrolytes in biological and soft matter systems are among the most challenging and most exciting problems currently facing polymer and biological physics. The papers in this thematic issue provide a glimpse of the state of the art in the field. We anticipate and hope that in the foreseeable future, significant advances in both theory and experiment will lead to a much deeper understanding of polyelectrolyte physics, chemistry and biology.

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References

1 T. Odijk, *J. Polym. Sci., Polym. Phys. Ed.*, 1977, **15**, 477.
2 J. Skolnick and M. Fixman, *Macromolecules*, 1977, **10**, 944–948.
3 A. R. Khokhlov and K. A. Khachaturian, *Polymer*, 1982, **23**, 1742–1750.
4 J.-L. Barrat and J.-F. Joanny, *Europhys. Lett.*, 1993, **24**, 333.
5 A. V. Dobrynin, *Macromolecules*, 2005, **38**, 9304–9314.
6 A. V. Dobrynin and M. Rubinstein, *Prog. Polym. Sci.*, 2005, **30**, 1049–1118.
7 M. Beer, M. Schmidt and M. Muthukumar, *Macromolecules*, 1997, **30**, 8375–8385.
8 K. Nishida, H. Urakawa, K. Kaji, B. Gabrys and J. Higgins, *Polymer*, 1997, **38**, 6083.
9 G. S. Manning, *Biophys. J.*, 2006, **91**, 3607–3616.
10 A. Savelyev, C. K. Materese and G. A. Papoian, *J. Am. Chem. Soc.*, 2011, **133**, 19290–19293.
11 W. Kunz, J. Henle and B. Ninham, *Curr. Opin. Colloid Interface Sci.*, 2004, **9**, 19–37.
12 W. Kunz, *Specific Ion Effects*, World Scientific Publishing Company, 1st edn, 2009.
13 A. Savelyev and G. A. Papoian, *J. Am. Chem. Soc.*, 2006, **128**, 14506–14518.
14 L. Vrbka, J. Vondrsek, B. Jagoda-Cwiklik, R. Vcha and P. Jungwirth, *Proc. Natl. Acad. Sci. U. S. A.*, 2006, **103**, 15440–15444.
15 K. D. Collins, *Biophys. J.*, 1997, **72**, 65–76.
16 G. Slater, C. Desrulsseaux, S. Hubert, J. Mercier, J. Labrie, J. Boileau, F. Tessier and M. Pepin, *Electrophoresis*, 2000, **21**, 3873–3887.
17 M. Muthukumar, *Polymer Translocation*, Taylor & Francis Group, 2011.
18 B. Alberts, A. Johnson, J. Lewis, M. Raff, K. Roberts and P. Walter, *Molecular Biology of the Cell*, Garland Science, 5th edn, 2007.
19 H. Schiessel, *J. Phys.: Condens. Matter*, 2003, **15**, R699–R774.
20 B. Strahl and C. Allis, *Nature*, 2000, **403**, 41–45.
21 D. A. Potoyan and G. A. Papoian, *J. Am. Chem. Soc.*, 2011, **133**, 7405–7415.