S6-1 Structure Formation by Electrostatic Forces in Biological Systems
生体高分子の強い静電気力による構造形成

Motohiko Tanaka
田中基彦

Institute for Fusion Science, Toki 509-5292, Japan
Email: mtanaka@nifs.ac.jp, URL http://dphysique.nifs.ac.jp/
土岐市下石町 322-6　核融合科学研究所 連携研究推進センター

Electrostatics plays an important role in making structures of soft condensed matters (polymers, gels, colloids) when the Coulombic (electrostatic) energy $e^2/\varepsilon a$ dominates over thermal energy kT. This happens in liquids of normal pressure and room temperature, including hydration of molecules and DNA stacking under hydrogen bonds. Here, we present the aggregation of like-charged macromolecules in salted liquid, and the translocation of DNA through a nano-sized pore permeated in a low-dielectric constant membrane.

1. Ionic Soft Matters and Biological Systems

It is not well recognized that the Coulombic forces are contributing a great deal in making structures of biological materials. For example, DNA is a strongly charged polymer (one unit charge per 3.4 Angstroms stack) for which hydrogen bonds between oxygen, nitrogen and hydrogen atoms stabilize the double helix of DNA. Cell membrane is again an assembly of polymers having ionic (hydrophilic) heads and hydrophobic tails. Bare charges, if present, are usually dressed by salt ions such as sodium, potassium and chloride, and electric fields are almost not visible in some distances away.

Two extremes of ionized "soft" matters are high- temperature ionized gases (plasmas) and ionic soft matters including charged polymers and living cells. The criterion of forming the latter matter is whether the electrostatic energy is greater than thermal (entropic) energy that smears out specific structures,

$$Q^2/\varepsilon R > kT \qquad (1)$$

where Q and R are the charge content and size of an object, ε is dielectric constant of medium (solvent), and T is the temperature.

The length for which the Coulomb and thermal energies become equal, $a= Q^2/\varepsilon kT$, is called *the Bjerrum length*, which is about the size of molecular objects, i.e. 7 Angstroms in water (note ε_w=80). In such circumstances, molecules should be treated as objects of finite sizes and their collisional encounters are important. Peculiar structure formations of charged polymers [1] and over-screening for charged macromolecule [2] take place in this regime. On the other hand, in high-temperature plasmas reversed inequality $Q^2 / \varepsilon R << kT$ holds. Then, the Bjerrum length is extremely shorter than characteristic plasma sizes, and the complete Debye shielding smoothes out specific structures; collective phenomena are the central issue of plasmas.

We use the molecular dynamics simulations to trace the motion of particles (monomers and ions) with the Newton equations of motion. The forces on particles are calculated by $\mathbf{F}_i$= -grad ϕ with the potential given by

$$\phi(\mathbf{r}_i) = \sum_j q_i q_j / \varepsilon r_{ij} + 4\varepsilon_{LJ}\left[(\sigma/r_{ij})^{12} - (\sigma/r_{ij})^{6}\right] \qquad (2)$$

where $r_{ij}=|\mathbf{r}_i - \mathbf{r}_j|$, σ is the sum of radii of two encountering particles; the Lennard-Jones potential of the second term is truncated at the bottom, thus provides only the volume exclusion effects and no attraction forces.

2. Merging of Like-Charged Macromolecules

Oppositely charged objects repel each other and should keep large distances in vacuum. In

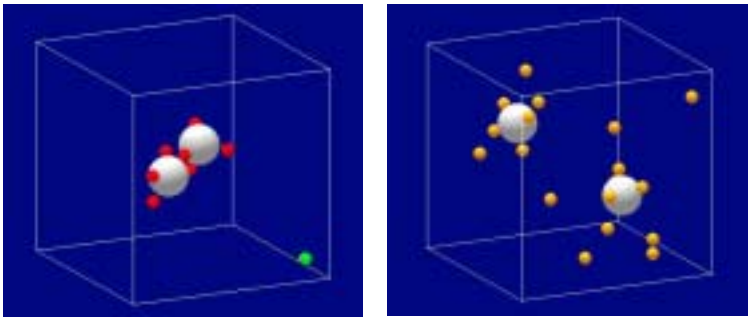

Fig.1: Aggregation of like-charged macromolecules by mediation of multivalent counterions (small spheres), for trivalent (left) and monovalent (right) cases. Solvent particles are not shown.

liquid with salt ions, oppositely charged macro molecules can aggregate! This counter-intuitive behavior is made possible if (i) the Coulombic energy prevails over thermal energy (inequality (1)), and (ii) counterions of multi-valency are present in the liquid. Figure 1 shows the result of the molecular dynamics simulations for two macromolecules (Q=-10e on each) and small ions under $e^2/\varepsilon RkT=10$; small ions are multivalent counterions Ze (Z=1 or 3) and monovalent coions (–e). These ions are immersed in the solvent which is modeled by large number of neutral particles and dielectric constant $\varepsilon = 80$. The figure shows that the macroions aggregate when the valency of counterions are multivalent $Z > 1$ for monovalent salt ions.

3. DNA in a Nanopore

The RNA string goes through a nano-size pore of the nuclear membrane after being transcripted from DNA in nuclei. Also a synthetic pore-membrane can be used as the DNA sensor by measuring the pore current.

We are studying translocation of a single-stranded DNA through the pore by molecular dynamics simulations [3]. Our model consists of upper and lower compartments and the pore of a nanometer radius, which are filled with solvent (water, dielectric constant $\varepsilon = 80$) and monovalent salt of 1M/l concentration. The central part of the system is a membrane of low dielectric constant $\varepsilon_m = 2$.

Figure 2 shows the ssDNA and ions in the pore (denoted by a cylinder) at steady phase. Large spheres represent DNA monomers of

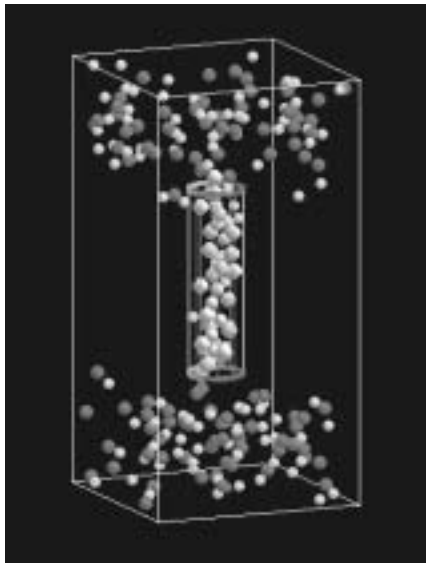

Fig.2: ssDNA in a nano-size radius pore. Counterions condense on charges of DNA for electroneutrality while coions are depleted from the pore to reduce ion energy which is enhanced by low dielectric membrane..

neutral sugar rings, bases and charged phosphate groups. Due to enhancement of electrostatic energy by low dielectric membrane surrounding the pore, charged groups of DNA are repelled from the pore wall. (Free) coions are depleted from the pore for which both electrostatics and volume exclusion of bulky DNA monomers play their roles. Counterions condense on the DNA without penalty of electrostatic energy increase and the pore is kept charge neutral.

Finally, we mention quite high efficiency of a PC cluster machine equipped with low-latency communication software GAMMA combined with commercial Fortran/C compilers [4].

Acknowledgments: This work was supported by Grant in Aid No.16032217 from Japan Ministry of Education, Science and Culture.

References:

[1] M.Tanaka, Toyoichi Tanaka et al., *Phys.Rev. E56,* 5798 (1997); ibid. *E62,* 3803 (2000).
[2] M.Tanaka and A.Grosberg, *J.Chem.Phys. 115,* 567 (2001); *Europhys.J.E7,* 371 (2002); *Phys.Rev. E68,* 061501 (2003).
[3] Y.Rabin and M.Tanaka, submitted.
[4] M.Tanaka, LANL, *physics* /0407152 (2004); Japan Physical Soc. *Butsuri 59,* 898 (2004).