§5. DNA in Nanopores: Strong Electrostatic Interactions in Cellular Dynamics Processes

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DNA that carries genetic information in living cells is a charged polymer with a unit charge in every 3~4 Angstroms along its thread. When this DNA migrates from cellular liquid of the dielectric constant ε_w= 80 into a nano-size pore embedded in the cell membrane, the pore both geometrically and electrostatically affect the DNA. The membrane has the low dielectric constant ε_m=2-3, and roughly speaking, the electrostatic energy is enhanced by $\varepsilon_w /\varepsilon_m$ times. In this respect, the electrostatic interactions are very important in the life processes [1].

In order to study the DNA and ion distributions in the nano-size pore, we perform molecular dynamics simulations. We take a rectangular box which is separated to upper and lower compartments by the membrane in the middle. The membrane is pierced by a cylindrical pore extending along the vertical axis, and the pore and compartments are filled with cellular liquid of large dielectric constant ε_w. Salt ions and neutral solvent particles that emulate water are put in these space. As mentioned, the electrostatic inter-actions are important due to large inhomogeneity of the dielectric constant, thus the Poisson equation must be solved for charges $\rho(r)$ and dielectric constant $\varepsilon(r)$.

$$\nabla \bullet \left(\varepsilon \nabla \varphi \right) = -4\pi\rho$$

This equation is solved in real space using the conjugate gradient method (this takes up more than 90% of all the computation times). The DNA is modeled by connected charged and neutral beads of different sizes that correspond to the phosphate group, neutral sugar ring and base. These particles move under the Coulombic and Lennard-Jones forces [1].

Fig.1 shows the time histories of the number of (positive) counterions, (negative) coions, and the net charge in the pore for the empty pore (a) and DNA-stuffed pore (b). When the DNA is absent from the pore, a few pairs of counterions and coions reside in the pore, but isolate ions are not present because of the electrostatic repulsion from the membrane.
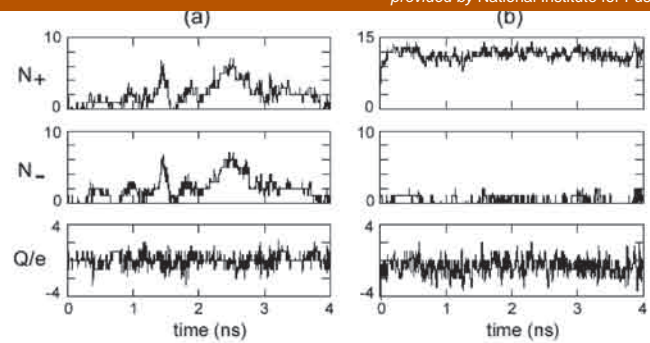

Fig.1 Time histories of the number of counterions and coions and net charge in the pore for (a) the empty pore and (b) DNA-stuffed pore.

With the DNA in the pore, counterions condense on the DNA to reduce the electrostatic energy as depicted in Fig.1(b). On the other hand, coions are repelled from the negatively charged DNA and are depleted from the pore. The DNA is elongated in the pore due to electrostatic repulsion from the membrane.

The effects of the electrostatic interactions are best shown in Fig.2 where the dielectric constant of the membrane is set to the normal value ε_m=2 in (a), and is ε_m=80 in (b). In the figure only charged phosphate beads are plotted for the DNA (for clarity). Coions (red sphere) are depleted by repulsion from the pore in (a), but there are a few of them in (b). This clearly proves the importance of the electrostatic effects in the life process.
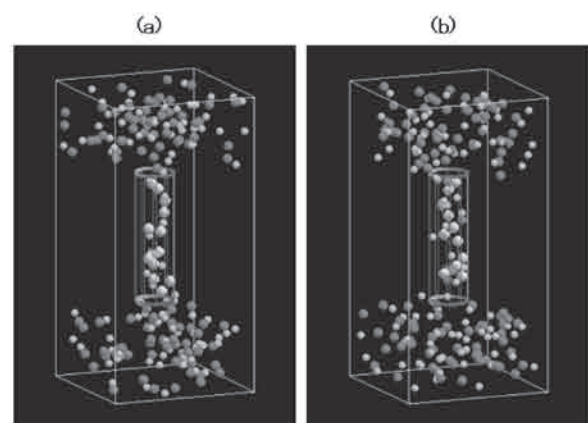

Fig.2 Snapshots of DNA (only charged phosphate groups are plotted), counterions [green spheres] and coions [red spheres] for (a) ε_m=2 and (b) ε_m=80 cases.

Reference
[1] Y.Rabin and M.Tanaka, Phys.Rev.Lett., 94, 148103 (2005)