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Complexity in a Molecular String

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Abstract

It is shown that a single molecular string, or a linear macromolecule, exhibits rich variety of morphologies in its folded compact structure. Experimental evidence on nanometer-size ordered structure is given as the folding products from giant DNAs. Numerical simulation has been carried out, together with theoretical analysis, and phase diagram is proposed for the morphological variation in a molecular string.

Keywords:
folding transition, coil-globule transition, giant DNA, polyelectrolyte

1. Physics of a Giant DNA

In living cells both for prokaryote and eukaryote, individual double-stranded DNA chains usually exist in a highly packed state [1]. For example, in mammalian cells, individual DNA chains have a contour length or full-stretch length, L, on the order of a centimeter, and they are stored within the space on the order of micrometer. The persistence length, λ, of DNA is usually on the order of 50nm in aqueous environment. Thus, a DNA chain with L = 1 cm corresponds to a linear, freely jointed polymer chain with $N \approx 10^5$ segments, where $N = L/(2\lambda)$. If DNA chains act as ideal linear chains, the average end-to-end distance is $\langle R \rangle \sim 2\lambda N^{1/2} \approx 30\mu$m. This means that DNAs in natural origins behave as flexible molecular string with the course graining of the order of micrometer, whereas they look stiff rod on the length scale of nanometer. In spite of the recent development of molecular biology, the problem how the long DNAs are folded in a compact space without entanglement has not been solved yet.

In the present paper, we describe such a problem from both points of view; experimental features with long DNA chains and generalized theoretical discussion for a molecular string.

(1) Through the observation on the conformation of individual long DNA chains, it has become clear that the DNAs undergo large discrete transition between elongated coiled state and collapsed compact state on the level of the individual chains, i.e., the transition is first-order phase transition [2,3]. On the contrary, the physico-chemical parameters on the ensemble average of the chains are always continuous with the transition, i.e., the transition on large number of molecular chains does not belong to any kind of phase transition.

(2) The process of nucleation & growth has been observed on the level of the single DNA chain [4,5]. As the product of the crystallization on the single DNAs, various kinds of morphologies, such as toroid, rod, and spherical structures, are formed [6-10]. (See Fig.1)

(3) On the mechanism of the phase transition in giant DNAs, it is shown that the change in the translational entropy of the counter ions exhibits the significant contribution to the free energy [3,11].

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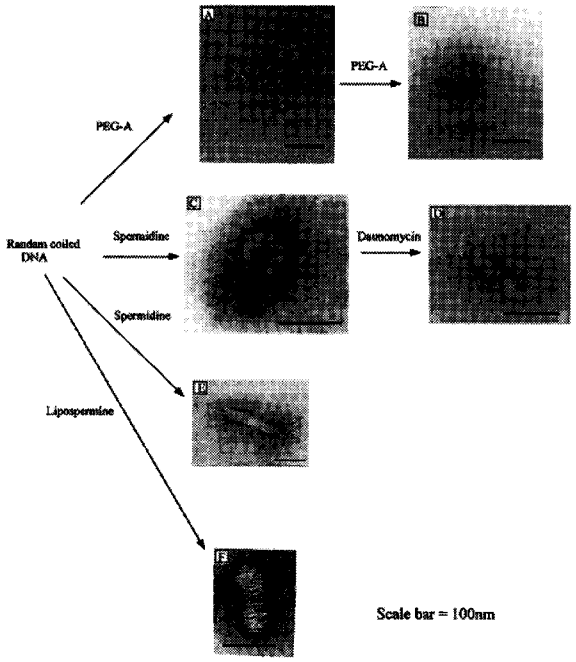

Fig. 1 Morphologies of T4DNAs (contour length: 57 μm) as were observed with transmission electron microscopy. (Modified from Refs. 6, 8, 9, 11, 12) A) With aminated polyethyleneglycol (PEG-A) at intermediated concentrations, the DNA chain exhibits intrachain segregated state, and B) with the increase of PEG-A concentration, nearly spherical product is generated. C) With a trivalent cation, spermidine, toroidal form is observed, and D) an anticancer drug, daunomycine, changes the toroidal morphology into fragmented barrel structure. E) With spermidine, rod structure is also obtained in addition to the toroid. F) With lipospermine, the DNA takes spool-like structure.

2. Phase Diagram in a Molecular String

As has been described in the above section, we have confirmed that individual isolated giant DNAs undergo large discrete transition between a disperse and a condensed state, i.e., the coil-globule transition.

In order to obtain general characteristics on the transition of molecular strings, we have performed Monte Carlo calculations by adopting so-called multi-canonical method. With this methodology, we can attain the global minimum in the free energy. The results of the numerical simulation is summarized schematically in Fig.2 [9]. At high temperatures, elongated coil state is generated, corresponding to a gas state. As is shown by a thick line in the figure, condensed phases exist at lower temperatures. It is noted that liquid-like state is found for the region of flexible chain. Thus, for flexible

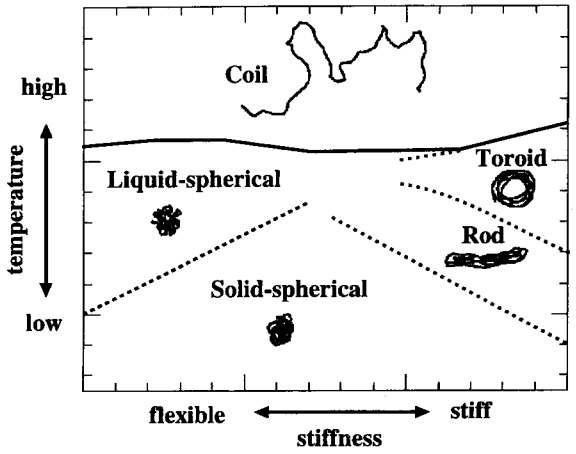

Fig. 2 Schematic representation of the phase diagram in the morphological change of a single polymer chain with the parameters of chain stiffness and temperature. (Partly modified from Ref.9) The temperature axis can be translated into the manner of pairwise interaction between the segments, where high and low temperatures correspond to repulsive and attractive interactions, respectively.

chains, the transition has the nature similar to gas-liquid phase transition. On the other hand, for stiff chains several kinds of solid-like states are generated. From the experiments on the giant DNA chains, we have actually observed the morphologies such as toroid, rod and spherical.

3. Future Problem

The next research target would be the experimental studies to make sure such kinds of phase diagram for various polymer chains beside DNAs.

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