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Computer Simulations of Interpolyelectrolyte Complexes Formed by Star-like Polymers and Linear Polyelectrolytes

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Summary: Complexes formed by star-like polymers of various topology and oppositely charged linear polyelectrolytes were simulated using Brownian dynamics technique. Structural properties and their dependence on the polyelectrotyte charge were investigated and compared with similar data for complexes with dendrimers. Remarkable overcharging was observed for all stars in complexes.

Keywords: computer modeling; molecular dynamics; polyelectrolytes; polyelectrolyte complexes; star polymers

Introduction

Interpolymer complexes on the base of linear polyelectrolytes (PE) as a guest and macroions as a host attract the attention of researchers due to their possible use for gene and drag delivery. Such complexes can change their structure and stability by minor changes of the external conditions such as the salt concentration or pH. One of the most interesting features of these complexes is the overcharging effect: for complexes where the absolute value of the charge of the linear PE exceeds that of the macroion the adsorbed charge is remarkably larger than the value necessary for neutralization of the host charge.

Branched polymers such as regular dendrimers or randomly hyperbranched polymers containing charged groups were widely used as macroins because they allow to concentrate a large charge in the small volume. There are several publications devoted to the experimental[1,2] as well as theoretical[3–5] study of such complexes.

Star polymers can be also used as macroions in complexes with linear polyelectrolytes. For example, T. K. Georgiou et. al.[1] has studied complexes formed by DNA and star polymers with charged arms. These complexes were used for the transfection of DNA into cell. Star polymers mimic dendrimers in terms of their dense architecture and flexibility but they are easier to synthesize and less expensive.

In our previous works[6–8] we have simulated complexes of linear PE chains with dendrimers where terminal groups or all monomers were charged. In present work complexes formed by star-shaped polyelectrolytes and oppositely charged flexible linear chain were simulated. Results were compared with those obtained for complexes with dendrimers.

Model

In our previous work complexes with dendrimers of the 3-th generation and 4-th generation were considered. To compare with results for these dendrimers we have chosen stars with the same number of charges. Several stars were considered

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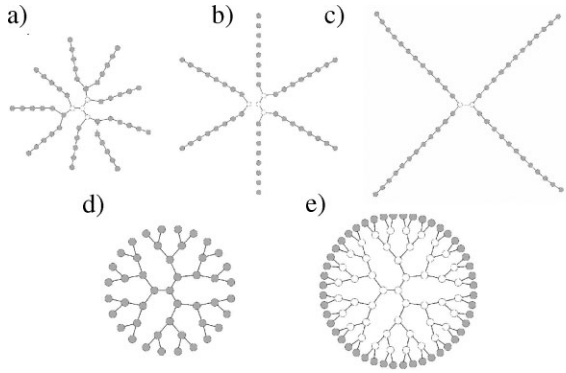

Figure 1.
Schematic representation of structure of the studied star-shaped polyelectrolites: a) asymmetric 9-arm star with arm length $N_{arm} = 5$ (star 9×5); b) 6-arm star with $N_{arm} = 8$ (star 6×8); c) 4-arm star with $N_{arm} = 12$ (star 4×12); d) dendrimer of 3rd generation with all charged groups (dendrimer 3f); e) dendrimer of 4th generation with charged terminal groups (dendrimer 4t). Shaded circles represent charged monomers.

(Figure 1). Both polymers in complexes studied consisted of spherical monomers – ''beads'' connected by rigid bonds – ''rods''. The bond length was taken to be equal l.

Every charged monomer of star possesses a positive charge equal to $+e$ and monomers of linear chain possess an opposite charge $-e$. All stars in complexes studied possess the overall charge close to $+48\,e$. Chain length N_{ch} in complexes varied from 48 (neutral case) up to 90. Of course the systems should contain counterions both from the star and from the chain. However the effective charge of complexes considered is relatively small and we suppose that counterions go away from the complex and don't influence its properties. It corresponds to the case of the dilute solution of complexes. Our simulation with explicit counterions (not shown) confirms the correctness of such an approximation. The simulation results were compared with data for complexes with a dendrimer of 3rd generation where all groups are charged (dendrimer 3f) and with a dendrimer of 4th generation with charged terminal groups (dendrimer 4t). The charge of both dendrimers is equal to $+48\,e$.

Excluded volume interactions of i-th and j-th beads were described using a modified Lennard-Jones potential without the attractive term:

$$\widetilde{U}_{LJ}(r_{ij}) = \begin{cases} 4\epsilon_{LJ}\left[\left(\frac{\sigma}{r_{ij}}\right)^6 - \left(\frac{\sigma}{r_{cut}}\right)^6\right], & r_{ij} \le r_{cut} \\ 0, & r_{ij} > r_{cut} \end{cases} \quad (1)$$

There r is a distance between beads, r_{cut} is a cut radius of the potential that was equal to $r_{cut} = 2.5\sigma$. Potential parameters were chosen as $\sigma = l/0.8$ and $\epsilon_{LJ} = 0.3k_BT$. Potential (1) corresponds to the case of athermal solvent. This potential with the same parameters was used in our previous works.[6–10]

Electrostatic interactions were described using a Debye-Hückell approach. Interactions of j-th charged bead with all other charged beads in the system are described by the following potential:

$$\frac{U_{ij}^C}{k_BT} = \lambda_B \sum_i \frac{\exp(-r_{ij}/r_D)}{r_{ij}},$$

where r_{ij} is a distance between charged beads; λ_B is a Bierrum length and r_D is a Debye radius. The Bierrum length

$$\lambda_B = \frac{e^2}{4\pi\tilde{\epsilon}k_BT}$$

characterizes the strength of electrostatic interactions in the medium with the

dielectric permittivity $\tilde{\epsilon}$. In aqueous solutions at room temperature the Bierrum length is approximately equal to 7.14 Å. This is almost equal to the segment length of a flexible polymer chain. So, the Bierrum length was taken to be equal l as in our previous works.[6–10]

The Debye radius

$$r_D = \left(4\pi\lambda_B \sum_i z_i^2 c_i\right)^{-1/2} \quad (2)$$

describes a screening of electrostatic interactions caused by the presence of the salt in the solution. In the equation (2) c_i is a concentration of ions of the i-th type and z_i is their charge. As in our previous works[6–10] we choose the value of $r_D = 8.96l$ which corresponds to the salt concentration 2.2 mmol/l.

The simulation of the systems considered was performed using the Brownian dynamics method. Motions of particles in the system are described by Langevin equations. In this method interactions between monomers are taken into account explicitly and interactions of monomers with the solvent are described by the friction and random Brownian collisions.

As in our previous works[6–10] the algorithm based on the Ermak-McCommon equation[11,12] was used. The equation for the total force $\mathbf{F}_j^0$ acting on the j-th monomer is written as follows:

$$\mathbf{F}_j^0 = -\sum_{k=1}^{N} \mu_k \left(\frac{\partial \nu_k}{\partial \mathbf{r}_j}\right)_{r^0} - \partial \tilde{U}_{\mathrm{LJ}} \Big/ \partial \mathbf{r}_j^0 - \partial U_j^C \Big/ \partial \mathbf{r}_j^0$$

There $\nu_k = \frac{1}{2}(\mathbf{r}_{k+1} - \mathbf{r}_k)^2 - l^2 = 0$ is an equation of the k-th rigid bond; μ_k is a corresponded Lagrangian coefficient and $\mathbf{r}_j^0$ is a radius-vector of the j-th monomer before the immediate time step Δt. The value of l was taken to be equal to 1.25σ.

To preserve bond lengths fixed the SHAKE algorithm[13] with tolerance 2×10^{-6} was used.

Initial system configurations were generated using the procedure proposed by Murat and Grest[14] that was used in our previous works also.[6–10]

As units of length, energy, charge and time $l, k_B T, e$ and $\zeta l^2 / k_B T$ were used. There ζ is a friction coefficient of a bead.

To generate the initial configuration of a star its central bead was considered as the origin of coordinates. Other beads were successively connected to previous ones according to the chosen topology (Figure 1).

For the generation of the initial chain configuration its first bead was placed in the position with coordinates $x_{\max} + 1, y_{\max}$ and $z_{\max}$ where $x_{\max}$, $y_{\max}$ and $z_{\max}$ are maximum values of coordinates of star beads. Then the chain of the desired length was built from the first bead. Generated chain had an extended planar configuration with the valence angle $\theta = 90°$ (Figure 2).

The generated systems consisting of one star and one chain were equilibrated during 7–9 series by 2×10^6 simulation steps. As in our previous works[6–10] equilibration considered to be reached when the mean square gyration radii of the star and of the chain stopped to change. After the equilibrating 7 production runs of 2×10^6 simulation steps each were performed. All characteristics of the systems were averaged over the whole simulation time.

Results

Size

It was shown in our previous work that the size of a dendrimer in a complex doesn't

Figure 2.
The initial configuration of the system.

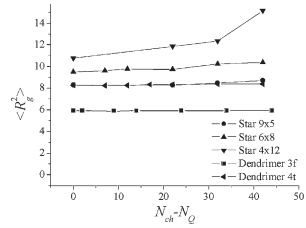

Figure 3.
Mean-square gyration radius of branched polymers in complexes simulated.

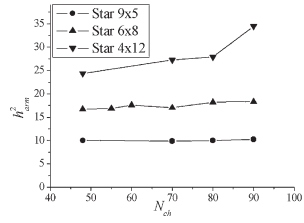

Figure 6.
End-to-end distance for the arms of different star-shaped polymer in complexes studied.

change by the increase of the chain length if its charge exceeds the dendrimer charge. In contrast to dendrimers the size of a star 4×12 with small number of arms and long arms. changes by the increase of the length of a polyelectrolyte chains as can be seen from Figure 3.

The analysis shows that this behavior is connected with the asymmetric deformation of a star. To describe the symmetry of stars in the complexes several characteristics were calculated: principal moments λ_x^2, λ_y^2 and λ_z^2 of the star gyration tensor (Figure 4), the asphericity $b = \lambda_z^2 - 1/2\left(\lambda_x^2 + \lambda_y^2\right)$, the acylindricity $c = \lambda_y^2 - \lambda_x^2$ and the relative shape anisotropy $\kappa^2 = \frac{b^2 + (3/4)c^2}{R_g^4}$ (Figure 5).

It is seen that the shape anisotropy of a star 4×12 in complexes depends on the number of chain monomers. This is due to a flexible structure of this star. Its arms can change their size (Figure 6).

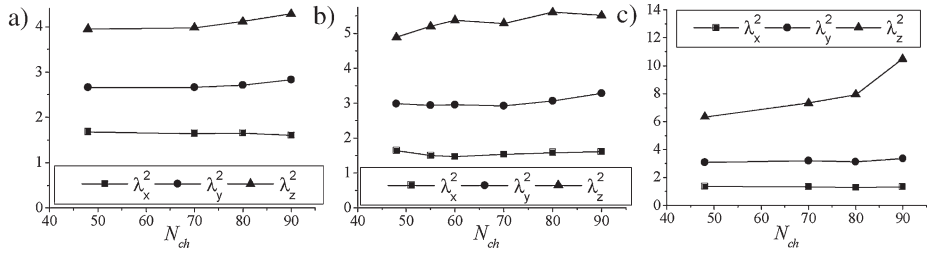

Figure 4.
The dependence of principal axes of star inertia tensor on chain length for complexes of stars 9×5 (a), 6×8 (b) and 4×12 (c).

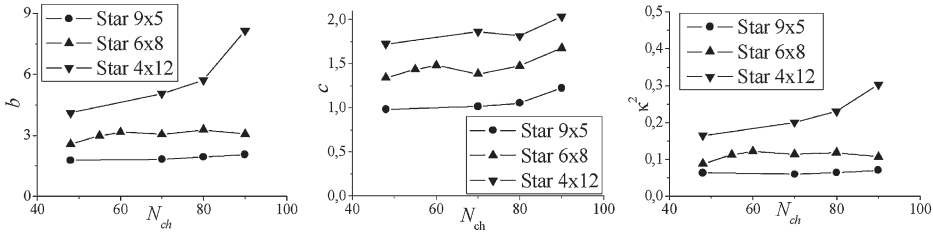

Figure 5.
Dependence of the asphericity *b*, acilindricity *c* and relative shape asymmetry κ^2 of stars studied in complexes with chains of various lengths.

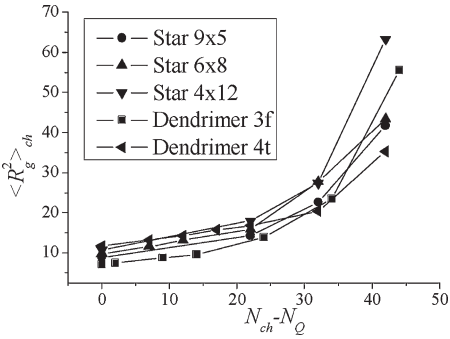

Figure 7.
Mean-squared radius of gyration of chains in the complexes with different branched polymers.

Figure 7 shows how the size of the polyelectrolyte chain in a complex changes by the increase of its length. All curves have two regions with the different slope. If the chain is relatively short almost all its monomers are adsorbed on a star and $\left\langle R_g^2 \right\rangle$ of the chain increases slowly. When the chain length reaches some critical value the "tail" appears (Figure 8) and the gyration radius grows more rapidly.

Structure of Complexes

The internal structure of complexes can be characterized by a radial density distribution function $\rho(r)$

$$\rho(r) = \frac{\langle n(r) \rangle}{V(r)}.$$

There $\langle n(r) \rangle$ is the average number of beads in a thin spherical layer with a volume $V(r)$ at the distance r from the center of mass of the complex.

These functions for beads of different type are presented in the Figure 9.

The density of star monomers has a maximum near the center of mass of complex and decreases monotonously with increase of the distance from it. The chain monomers penetrate into the star. The

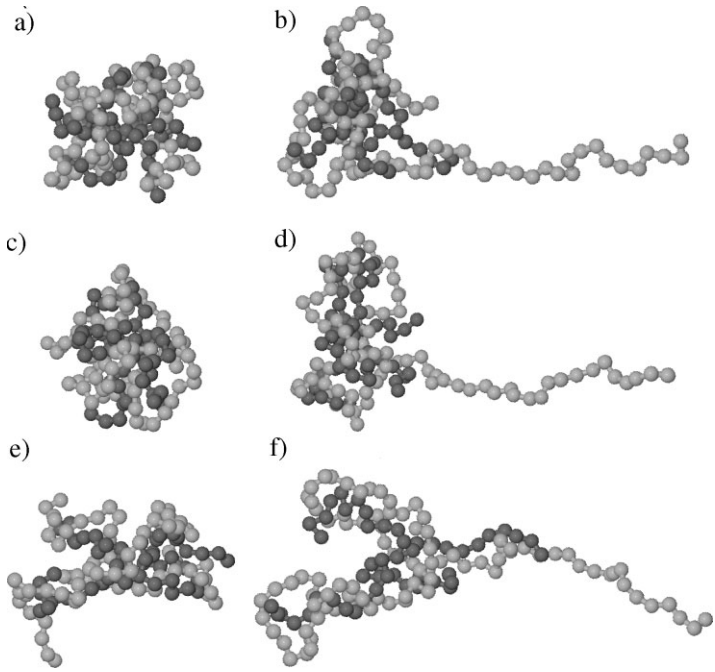

Figure 8.
Typical snapshots of the complexes of stars 9×5 (a and b), 6×8 (c and d) and 4×12 (e and f) with chains $N_{ch} = 70$ (a, c and e) and 90 (b, d and f). Dark and light spheres represent star and chain beads respectively.

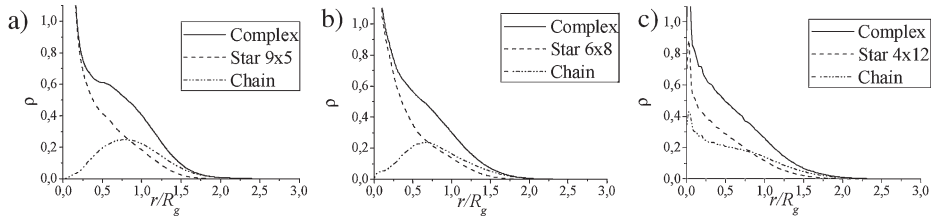

Figure 9.
Radial density distribution functions of monomers in complexes with star-shaped polymers: star 9×5 (a); star 6×8 (b) and star 4×12 (c). The data presented is for the complexes with chain $N_{ch} = 70$.

maximum penetration is observed for the most flexible star 4×12. The penetration of chain monomers into a star is higher than in complexes with dendrimers.

The distribution of a charge inside the complex can be characterized by the dependence of the integral charge $Q_{tot}(r)$ which contains in the sphere of radius r with the center of mass of a complex. (Figure 10).

It is seen that there is some irregularity in the distribution of charges inside the complexes. Near the center of mass the $Q_{tot}(r)$is positive and goes through the maximum. It means that the density of star monomers in this region is larger than that of chain monomers. Than $Q_{tot}(r)$ decreases, goes through zero at some distance r and became negative at larger distances. An exception is a neutral complex where $Q_{tot}(r)$ goes through the negative minimum before it reaches 0. It shows that there is the region in a neutral complex with the star where the chain monomers density is larger than that of star monomers. It is not the case for neutral complexes with dendrimers where $Q_{tot}(r)$ has a positive maximum only.[6–8]

Overcharging

Our previous simulation of complexes formed by a dendrimer with charged groups and an oppositely charged linear polyelectrolyte has revealed a remarkable overcharging.[6–8] Now we consider this effect for complexes with charged stars. The value of the overcharging is characterized by the excess charge adsorbed on a star. For the estimation of adsorbed charge it is necessary to determine a criterion of the adsorption. We use two criteria similar to those in the previous works.[6–8]

1. ''Local'' criterion: the chain monomer is considered as adsorbed when the distance between it and closest monomer of a star is less than some critical distance r_c. As in the works [6–8] we choose $r_c = \sigma + l = 1.8l$. This value corresponds to the radius of the first coordination sphere for the monomers in the star and the chain. The overcharging is given by a difference between the number of adsorbed chain monomers and the number of charged monomer units in a star $(N_{ads} - N_Q)$. Its dependence on the

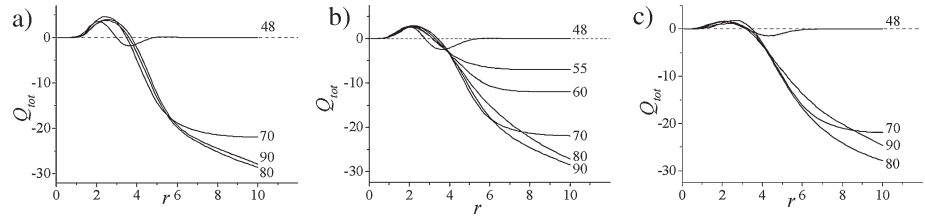

Figure 10.
Integral charge distribution functions for complexes of stars 9×5 (a), 6×8 (b) and 4×12 (c).

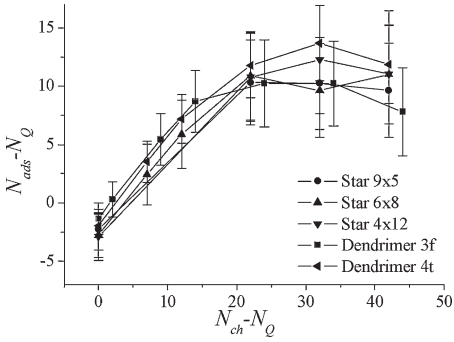

Figure 11.
Dependence of the overcharging value (estimated by using the local criterion) on the excess chain length in the complexes studied.

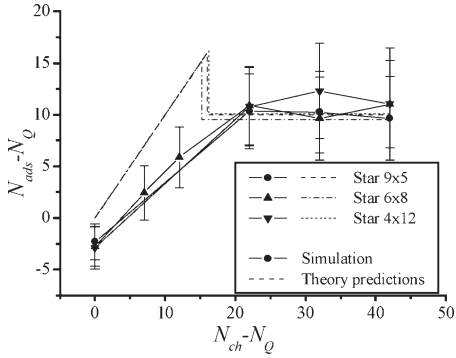

Figure 13.
Comparison of the number of adsorbed chain monomers with theoretical[3] predictions.

excess chain length (N_{ch} –N_Q) is shown in Figure 11.

2. Integral criterion: an excess charge is estimated by the value Q^0_{tot} of the integral charge $Q_{tot}(r)$ at the distance r where this charge is equal to zero for a neutral complex. (Figure 12)

It is seen that regardless of the adsorption criterion in all cases there is a remarkable excess charge adsorbed on a star. Its value is close to that for a dendrimer 3f where all monomer units were charged. From another side the maximum overcharging for stars is less than that for a dendrimer 4t where only terminal units are charged. This dendrimer has a larger size and therefore its charges are distributed over the larger surface than both for stars considered and the dendrimer 3f.

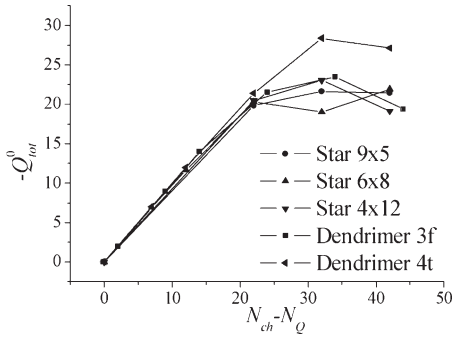

Figure 12.
Dependence of Q^0_{tot} on the excess chain length $N_{ch} - N_Q$ for complexes of stars and dendrimers.

As in[6–8] we have compared our results with predictions of the correlation theory developed by Nguyen and Shklovskii[3] for complexes formed by a hard impenetrable charged sphere and a flexible oppositely charged polyelectrolyte chain (Figure 13).

The radius of the sphere R corresponding to a given star with gyration radius Rg was estimated by using the relation $R^2 = {}^5/_3 R_g^2$ valid for a solid sphere.

Theory predicts a sharp maximum of the overcharging value at some critical value of the polylectrolyte length and a plato at larger values of N_{ch}. The position of the maximum corresponds to the appearance of a tail. It is seen that for stars the maximum of the overcharging corresponds also to the tail formation. However instead of the sharp maximum the broad non-monotonous dependence is observed for stars in complexes. The value of the maximum is less that the theory predicts. The position of the maximum is shifted to larger values of the chain length. Such a behavior is qualitatively similar to that observed for complexes with dendrimers[6–8] and reflects the flexibility and penetrability of these systems. Therefore we can conclude that the overcharging for stars in complexes with flexible polyelectrolyte chains is similar to that for the dendrimer 3f (all units are

charged) with the same charge. The star topology has only small effect on it.

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