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Phase Behavior and Selectivity of DNA-Linked Nanoparticle Assemblies

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We propose a model that can account for the experimentally observed phase behavior of DNA-nanoparticle assemblies [R. Jin et al., J. Am. Chem. Soc. 125, 1643 (2003); T. A. Taton et al., Science 289, 1757 (2000)]. The binding of DNA-coated nanoparticles by dissolved DNA linkers can be described by exploiting an analogy with quantum particles obeying fractional statistics. In accordance with experimental findings, we predict that the phase-separation temperature of the nanocolloids increases with the DNA coverage of the colloidal surface. Upon the addition of salt, the demixing temperature increases logarithmically with the salt concentration. Our analysis suggests an experimental strategy to map microscopic DNA sequences onto the macroscopic phase behavior of the DNA-nanoparticle solutions. Such an approach should enhance the efficiency of methods to detect (single) mutations in specific DNA sequences.

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Colloidal particles that can be selectively linked by specific sequence single-stranded DNA represent an entirely novel class of complex liquids. With these particles, it becomes feasible to “design” multicomponent mixtures, where the attractive interaction between every pair of species can be controlled independently.

During the past few years, the unique molecular recognition properties of DNA have been exploited to create self-assembled nanostructures and nanodevices with a remarkable degree of control (see, e.g., Ref. [1]). Self-assembled nanostructures based on DNA have also been utilized to detect specific DNA sequences [2–5]. In nanoparticle-based DNA detection systems, single-stranded DNA (ssDNA) “probe” molecules are chemisorbed onto the surface of gold nanoparticles (Fig. 1). These probe ssDNA can specifically bind to a dissolved “target” ssDNA and thus detect its presence with high sensitivity and selectivity: At high enough concentration, the target ssDNA strands induce a sharp demixing transition [6] that leads to aggregation of the nanoparticles coated with the complementary probe strands. These aggregates can be easily detected by optical means.

The sensitivity of the nanoparticle-based DNA detection method is some 2 orders of magnitude higher than that of the corresponding fluorophore-based DNA-array scheme [3]. In addition, the method can be used to distinguish different DNA sequences that differ from each other by only a single base. The reason is that a single mismatch in the DNA sequence results in a significant change in the DNA-colloid demixing temperature. The fluorophore-based systems lack this level of selectivity [3].

In a recent paper, Jin et al. [4] have analyzed the dependence of the dissolution temperature (see [6]) of DNA-linked nanoparticles on the DNA coverage density, the particle size, and the salt concentration. In the experiments [3,4], short DNA molecules (∼20-20 base oligonucleotides) and small gold colloids (∼10–50 nm) were used. The principal experimental findings are the following: (i) The higher the ssDNA coverage density on the surface of colloids, the sharper the dissolution profiles, and the higher the dissolution temperature. (ii) The addition of salt stabilizes the aggregates. The dissolution temperature increases logarithmically with salt

FIG. 1 (color online). Computed temperature dependence of the fraction of the ssDNA-coated colloids in the fluid (dilute) phase of a binary colloidal mixture (species A and B) and added ssDNA linkers. Above the demixing temperature, the volume fractions of both the A and B colloids are equal to 20%. The target ssDNA can form links between A and B colloids, but not between A and A, or B and B. At low temperatures, virtually all colloids end up in the dense “gel” phase. The two curves illustrate the effect of a mutation in the target DNA. The solid and dashed curves were obtained with μ = μAB = 3.5, s = 10, q = 6, and M = 5. All temperatures are relative to the melting temperature of the perfectly complementary linker (solid curve). The dsDNA melting temperature for the dashed curve (corresponding to a base-pair mismatch) is 10% lower than $T_m$ for the perfectly matched linker. The arrow indicates the optimal stringency temperature.
concentration. The higher the salt concentration, the larger the total fraction of DNA-nanoparticle aggregates.

Below, we propose an explanation for these experimental findings. We argue that the origin of the sharp phase-transition profiles is the entropic cooperativity of the DNA-nanoparticle network. Upon cooling, the system undergoes liquid-liquid phase separation. The dense “liquid” phase is strongly cross-linked and behaves as a solid gel.

We first consider a simple model for a binary mixture of DNA-coated colloids. Each colloidal species is covered with specific ssDNA molecules, in such a way that all possible pairs of colloids can be bound by three types of complementary ssDNA linkers: viz. $AA$, $BB$, and $AB$.

For the sake of simplicity, we use a lattice model to analyze the phase behavior of this system. Colloids of type $A$ and $B$ can occupy the nodes of a three-dimensional lattice with coordination number $q$. The system is grand canonical with respect to all the components: $\mu_A$ and $\mu_B$ are the chemical potentials of colloids of species $A$ and $B$, respectively; and $\mu_{AA}$, $\mu_{BB}$, and $\mu_{AB}$ are the corresponding chemical potentials of linkers. First, we consider the situation where only type $AB$ are present (this corresponds to the experimental conditions of Refs. [3,4]). For this system, the grand canonical partition function is

$$Z = \sum_{N_A, N_B, n} g(N_A, N_B, n) Q_{AB}^n e^{(\mu_A N_A + \mu_B N_B)/T},$$

where $N_A$ and $N_B$ are the number of colloids $A$ and $B$, respectively, $n$ is the number of nearest neighbor $AB$ colloidal pairs for a given realization of the grand canonical ensemble, and $g(N_A, N_B, n)$ is the total number of possible configurations with $n$ nearest neighbor $AB$ pairs for a given values of $N_A$ and $N_B$. The sum with respect to $n$ extends over all values of $n$ consistent with the fact that there are $N_A$ and $N_B$ colloids $A$ and $B$ present. The number of links between a given pair of colloids depends on the surface density of probe strands on the $A$ and $B$ colloids. If there is only one pair of probe strands per contact, then this pair can accommodate at most one linker and the bound linkers obey Fermi-Dirac statistics. In contrast, there are (infinitely) many probe strands per contact, then the binding of linkers is determined by Bose-Einstein statistics [7]. In general, the maximum number of linkers per contact is a number $M \geq 0$. For $\infty > M > 1$, the bound linkers obey fractional statistics. In practice, the local coverage of probe molecules fluctuates [4]. We assume that the maximum number of linkers per bond, obeys Poisson statistics. Moreover, we assume that the values of $M$ for different colloidal pairs are uncorrelated. If we average over all possible values of $M$, we obtain the following expression for the grand partition function of linkers (for a given $AB$ colloidal pair):

$$Q_{AB} = \sum_{M=0}^{\infty} p(M) \sum_{0}^{M} e^{L(\mu_{AB} - \epsilon_{AB})/T} = \frac{1 - ze^{-\bar{M}(z-1)}}{1 - z},$$

where $\bar{M}$ is the average value of $M$, and $z \equiv e^{(\mu_{AB} - \epsilon_{AB})/T}$.

It is straightforward to generalize the model [Eq. (1)], to the case where all three possible types of linkers are present. This results in multiplicative factors in Eq. (1) that account for all possible configurations of all linkers: $Q_{AA} Q_{BB} Q_{AB}$, where $Q_{AA}$ and $Q_{BB}$ are defined analogously to $Q_{AB}$, Eq. (2).

The expression given by Eqs. (1) and (2) can be interpreted as the partition function of a three-state spin model with Hamiltonian

$$H = \frac{1}{2} \sum_{(ij)} \hat{\sigma}_i J^{ij} \hat{\sigma}_j - \sum_i \hat{\eta} \hat{\sigma}_i,$$

$$\hat{\sigma}_i = (1, 0), (0, 1), \text{or } (0, 0) \text{ if } A, B, \text{ or a vacancy (solvent) occupies site } i; \text{ and } \hat{\eta} = (\mu_A^c, \mu_B^c).$$

The Hamiltonian for a three-component lattice gas model [Eq. (3)] has been studied extensively [12]. The mean-field expression for the free energy is

$$f = T \phi_A \ln \phi_A + T \phi_B \ln \phi_B + T(1 - \phi_A - \phi_B) \ln(1 - \phi_A - \phi_B) + \frac{q J^{AA}}{2} \phi_A^2 + \frac{q J^{BB}}{2} \phi_B^2 + q J^{AB} \phi_A \phi_B.$$

where $\phi_A$ and $\phi_B$ are the average volume fractions of $A$ and $B$ colloids. The equilibrium phase behavior of the system in the mean-field approximation follows from the analysis of this free energy [12]: Depending on the strength of the interaction between the colloidal species, the system can be in a homogeneous state, or separate into two, or even three, coexisting phases. It is straightforward to generalize the model to any number of colloidal species and corresponding linkers.
We first apply the above model to analyze the experiments of Refs. [3,4]. In those experiments, only AB linkers were present in solution and, hence, $J^{AA} = J^{BB} = 0$. The free-energy difference between the helix and coil states of a dsDNA molecule, $\epsilon(T) = \epsilon(T)$ constitutes an input to the interaction potential. We adopt the simple form $\epsilon(T) = s (T - T_m)$, where $T_m$ is the melting temperature of a dsDNA molecule and $s \approx 10$ [13]. The dissolution curves of the DNA-linked colloidal aggregates are shown in Fig. 1. The fraction of colloids in solution is plotted as a function of temperature. Above a critical temperature $T_c$, all colloids are in solution. Consistent with the measurements of Ref. [4], the dissolution temperature of the aggregates increases with increasing surface coverage of ssDNA molecules (represented by the linker occupation number $\overline{M}$) on the colloids. In the "Bose-Einstein" limit ($\overline{M} \gg 1$), $T_c$ saturates at a value $T_c = \frac{1}{8}[\ln(1 - \exp(-8/\lambda))]^{-1}T_m$, as follows from Eq. (4) in the case of equal initial volume fraction of colloids A and B ($\phi_A = \phi_B$).

The fact that the dissolution of the DNA-linked colloidal aggregates occurs in a narrow temperature range makes it possible to distinguish DNA strands that differ in only a single-base pair [3]. This is achieved by selecting a temperature ("optimum stringency temperature") where a perfectly matched target results in the aggregation of a high proportion of the nanoparticles, while the same amount of ssDNA with a single mismatch causes only a small fraction of the nanoparticles to aggregate. As can be seen from Fig. 1, our model reproduces the observed behavior: For the model calculations shown in Fig. 1, the optimum stringency temperature (indicated by the arrow) is the dissolution temperature ($T$ on the binodal) for the mismatched-DNA-linked colloids, $T = 1.273$ (dashed curve) (in the units of $T_m$ for the perfectly complementary dsDNA), and we assumed that $T_m$ for the mismatched DNA is 10% lower compared with $T_m$ of the perfectly complementary DNA. At this temperature, 100% of the mismatched and only 0.1% of the perfectly complementary DNA-linked colloids are dissolved. The selectivity is thus extremely high.

Next, we consider the effect of the varying of salt concentration on the melting of the DNA-linked colloids. Added salt has two effects: It changes the DNA melting temperature and it modifies the electrostatic colloid-colloid and DNA-colloid interactions. For the salt concentrations used in the experiments of Ref. [4], all electrostatic interactions are strongly screened [15] and hardly depend on the salt concentration. However, the salt concentration does affect the melting temperature of the DNA. To estimate this effect, we make use of the known properties of polyelectrolytes, in particular, the theoretical prediction [17] that the melting temperature of the DNA helix-coil transition is proportional to the logarithm of the salt concentration. This result has been verified experimentally (see, e.g., Ref. [18]). A more detailed analysis of this result in the context of the present work will be presented in Ref. [16]. Here we simply use the fact that, for the experimentally used salt concentrations, the DNA melting temperature varies with salt concentration as $[14,18] T_m = T_m^0[1 + \alpha \log c]$, where $T_m^0$ is the DNA melting temperature at a reference state (with a salt concentration $I_0 = 0.1$ M), $\alpha = 0.05$, and $c = I/I_0$. We then obtain the following expression for $T$: $T = \exp\left[(\log(c) + 1 + \alpha \log c)/\alpha\right]$, where $\mu$ and $T$ are expressed in the units of $T_m^0$. This expression reproduces the experimentally observed dependence of $T_c$ on $\log c$ [4].

The model described above suggests a novel approach to DNA screening (mutation analysis). As mentioned above, colloids functionalized with oligonucleotides have been used as probes to differentiate perfectly complementary targets from those with single-base mismatches (see Ref. [3]). The drawback of the existing method is that the thermodynamic properties of DNA-linked nanoparticle assemblies are sensitive to the parameters of the system, such as the grafting DNA density, the concentrations of DNA linkers and colloids, the monodispersity of colloids, and the pH and ionic strength of the solvent. As it is essential to maintain precisely the same experimental conditions when performing the measurements on different target DNA strands, mutation-screening experiments are rather demanding.

Here we propose a method that should be relatively insensitive to unavoidable variations in the experimental conditions. To illustrate our approach, consider a system consisting of three colloidal species A, B, and C (see Fig. 2). Species B and C are grafted with ssDNA molecules that have similar sequences and only different by a mismatch (either a single base or multiple base). We assume that the target ssDNA is either perfectly complementary to the AB sequence, or mutated, and thus perfectly complementary to the AC sequence (the method is easily generalized to a larger possible number of mutations).

The addition of the target ssDNA induces a two-phase separation in the system. Importantly, the composition of the dense aggregate (and, by implication, the composition of the remaining solution) depends on the nature of the target ssDNA. The characteristic mean-field phase dia-

gram for this case is shown in Fig. 2 in terms of the concentration differences (selectivity plot) between B and C colloids. The target is perfectly complementary to AB. The melting temperature of the target DNA is assumed to be some 5% higher for a perfectly matched sequence than for a mismatched sequence. The initial concentrations of A, B, and C colloids are chosen to be equal. Our main prediction is that the sequence of the target can be determined simply by monitoring the concentration differences of the species B and C in either a dense (solid curve) or dilute (dashed curve) phase. In the case shown in Fig. 2, at the optimal stringency temperature $T = 1.165$ (in the units of $T_m$ of the AB linker), the difference...
the surface coverage density selectivity of the DNA screening can be tuned by varying concentrations can be easily detected. In this way, a single discrimination between a larger number of possible mutations. It is straightforward to generalize the technique to discriminate between different linkers.

In the experiments of Ref. [4], the salt concentration varied in the range ~0.1–1 M. This corresponds to a Debye screening length of ~1–0.3 nm, i.e., at least 1 order of magnitude smaller than the size of colloids and length of DNA linkers. The direct electrostatic interaction between the colloids in solution is thus effectively screened. However, at lower salt concentrations, direct electrostatic effects may become significant. This phenomenon will be discussed in Ref. [16].

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[6] In Refs. [3,4], the word “melting” is used to describe the process of dissolution of the DNA-linked colloidal aggregates. In the present work, we avoid the use of terms “melting” and “freezing” for this transition and use instead “dissolution” and “demixing,” as we argue that it is, in fact, more closely related to a liquid-liquid phase separation. This phase transition should also be distinguished from the melting of ssDNA linker molecules bound to complementary ssDNA grafted to colloids.
[7] At this level of description, we ignore the interaction between different linkers.
[13] The expression for the free-energy difference that we employ [ε(T) = s(T − Tm), where s ~ N[ΔS]] represents the first term in the expansion of the exact free energy, ε(T) ∼ N(ΔH − T ΔS), where N is the number of base pairs in a DNA molecule, and ΔH and ΔS are, respectively, the enthalpy and entropy difference between the helix and coil states at a given temperature per base pair (see, e.g., Ref. [14]).
[15] In the experiments of Ref. [4], the salt concentration varied in the range ~0.1–1 M. This corresponds to a Debye screening length of ~1–0.3 nm, i.e., at least 1 order of magnitude smaller than the size of colloids and length of DNA linkers. The direct electrostatic interaction between the colloids in solution is thus effectively screened. However, at lower salt concentrations, direct electrostatic effects may become significant. This phenomenon will be discussed in Ref. [16].