Quantitative Study of Linker-Mediated Binding Between DNA-Coated Colloids

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ABSTRACT

DNA provides a useful tool to control self-assembly of microparticles; not only does it induce self-assembly but it allows the user to specify the way particles interact and bind to each other. Here we study a DNA-coated colloidal system where two non-complementary sequences (A and B) are grafted to polystyrene spheres. A single stranded DNA (ssDNA) linker in solution is used to induce self-assembly. We measure the melting temperatures for a variety of linker lengths (17, 19, 21, and 23 bases in total length) and a range of linker concentrations (1nM~0.8mM). We show that the melting temperature of the material depends on both the length of the linker and the concentration within the sample. A mathematical model is built, assuming local chemical equilibrium and using principles of mass-action, that predicts the yield of aggregation of the system, allowing us to calculate the melting temperature. The use of linkers brings along multiple advantages that direct-hybridization based micromaterials lack, and new characteristics such as a fluid phase re-entry when increasing the concentration of linkers past a threshold concentration. Linker-mediated systems provide a useful tool for the research of biological and synthetic self-assembly processes, as well as having important potential engineering applications.

MOTIVATION

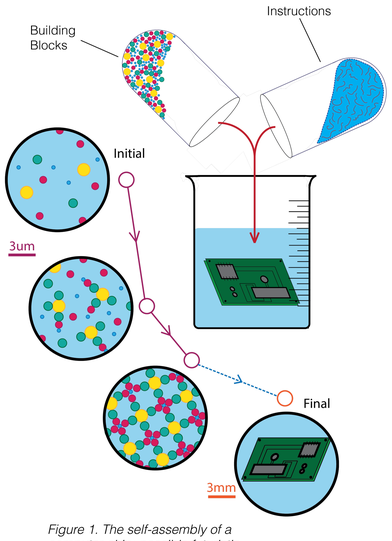

Figure 1. The self-assembly of a computer chip: possible futuristic application of linker based DNA-coated colloidal systems

EXPERIMENTAL SYSTEM

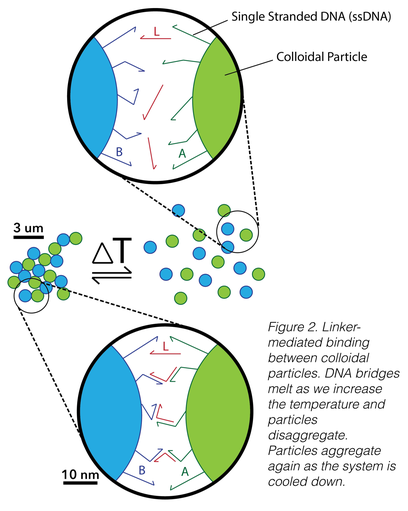

Figure 2. Linker-mediated binding between colloidal particles. DNA bridges melt as we increase the temperature and particles disaggregate. Particles aggregate again as the system is cooled down.

WHY LINKERS?

Why not design the sequences grafted to the microspheres so they bind directly with each other? Linker-based systems allow us to change the interaction strength, the specificity of binding, and the kinetics, for any particular desired temperature or range of temperatures, simply by adjusting the linker length and concentration.

HYPOTHESIS

The melting temperature will increase with increasing linker concentration or linker length. However, there may exist a critical linker concentration at which particles become saturated, preventing interparticle binding.

THE MELTING PROCESS

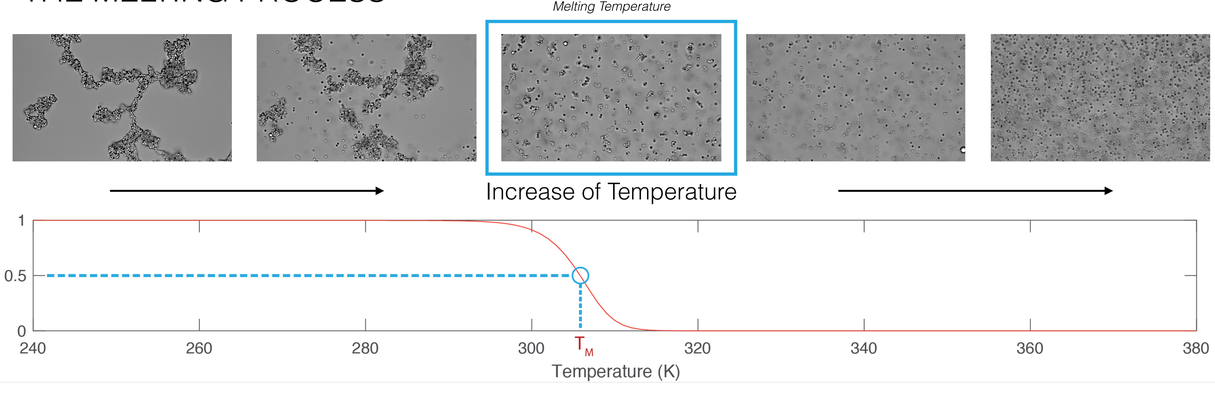

Figure 3. DNA-coated colloidal particles aggregate at low temperatures and disaggregate when heated. Sample is shown at its equilibrium state for different temperatures. The melting temperature is the temperature at which half of the colloidal particles are bound to at least another particle and the other half are not bound to any other particle.

EXPERIMENTAL RESULTS

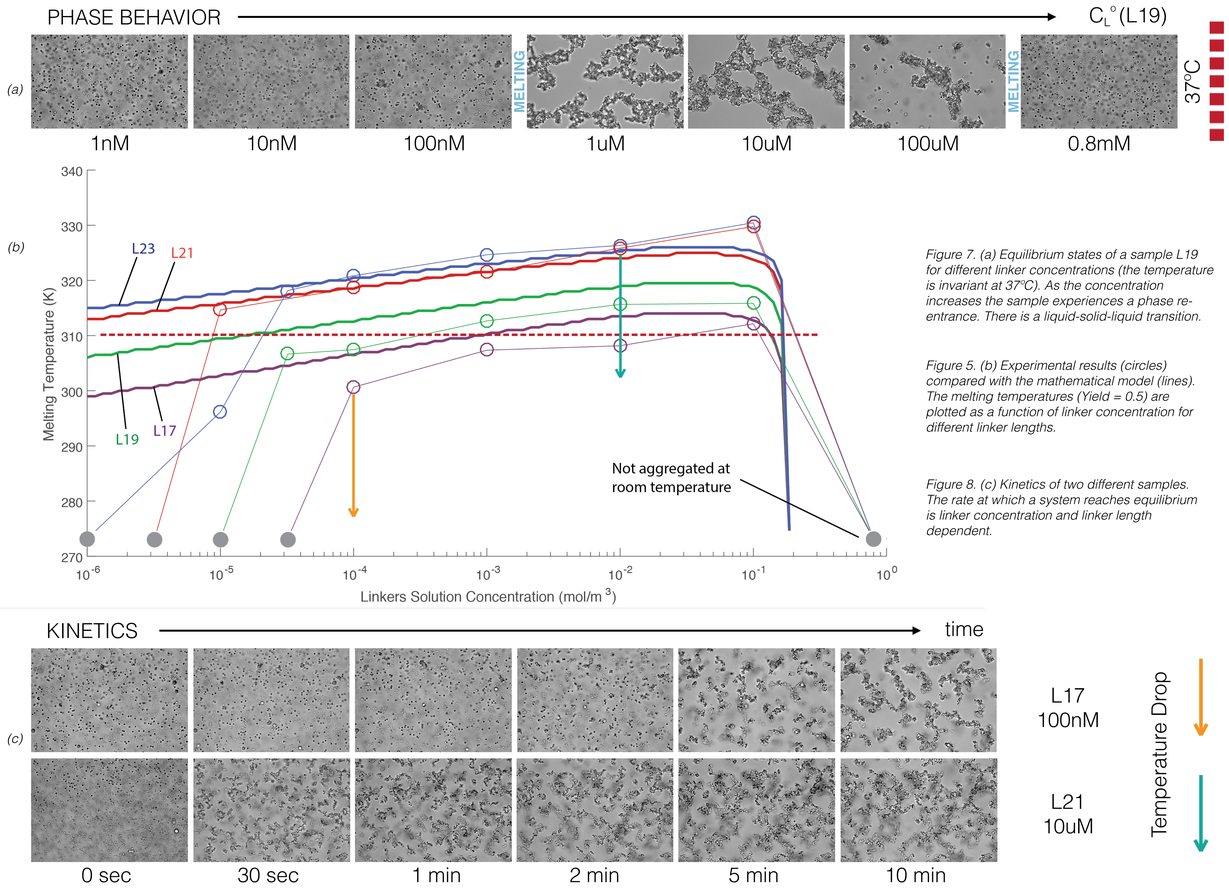

Figure 7. (a) Equilibrium states of a sample L19 for different linker concentrations (the temperature is invariant at 37°C). As the concentration increases the sample experiences a phase re-entrance. There is a liquid-solid-liquid transition.

Figure 5. (b) Experimental results (circles) compared with the mathematical model (lines). The melting temperatures (Yield = 0.5) are plotted as a function of linker concentration for different linker lengths.

Figure 8. (c) Kinetics of two different samples. The rate at which a system reaches equilibrium is linker concentration and linker length dependent.

MODEL

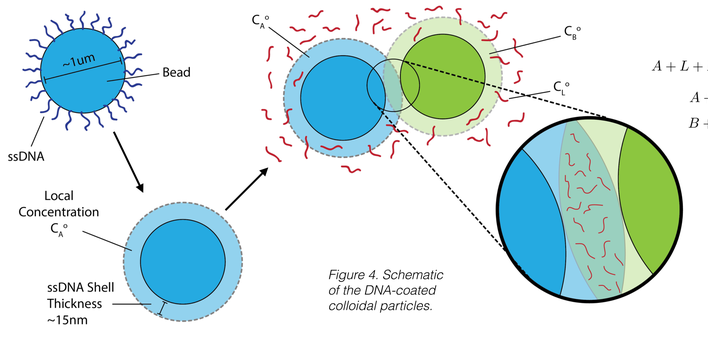

Figure 4. Schematic of the DNA-coated colloidal particles.

In the overlapping region we assume chemical equilibrium is established locally:

$$A + L + B \rightleftharpoons ALB \longrightarrow K_1 = C_{ALB}C_o^2/(C_A C_B C_L) = e^{-\Delta G_1/RT}$$

$$A + L \rightleftharpoons AL \longrightarrow K_2 = C_{AL}C_o/(C_A C_L) = e^{-\Delta G_2/RT}$$

$$B + L \rightleftharpoons BL \longrightarrow K_3 = C_{BL}C_o/(C_B C_L) = e^{-\Delta G_3/RT}$$

where

$$C_A^o = C_A + C_{AL} + C_{ALB}$$

$$C_B^o = C_B + C_{BL} + C_{ALB}$$

$$C_L^o = C_L + C_{AL} + C_{BL} + C_{ALB}$$

$$C_L^o \simeq C_L$$

CONCLUSIONS

We can predict with notable precision the melting temperature of a sample for any linker sequence, length, and concentration. We were able to adjust the melting temperature of a sample by a couple of degrees by changing the linker concentration by an order of magnitude. This means that we can predict and adjust very precisely the melting temperature and, potentially, other thermodynamic parameters. We also show that a material can be neutralized at extreme linker concentrations (~1 nM and ~1 mM), preventing any particle aggregation. Taken together, our findings highlight the tunable nature of linker-mediated interactions, which we anticipate will be essential to encoding the large number of mutual interactions needed to program self-assembly in multicomponent mixtures.

ACKNOWLEDGMENTS

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