Optical properties of DNA-hosted silver clusters

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CHAPTER 6

Strings of colloidal particles glued by DNA tubes

We investigate the formation of strings of colloidal particles in a magnetic field and their stabilization by DNA tubes. Colloidal particles can form strings in an external magnetic field. However, as soon as the magnetic field is turned off, the strings fall apart due to the thermal motion of the particles. Here we show that DNA tubes can be used as a nano-contact glue which keeps colloidal particles functionalized with short DNA strands into stable strings. These strings remain flexible, which is a desirable characteristics for the examination of the colloids interaction or network formation.

6.1 Introduction

Self-assembly of colloidal particles into desired configurations is one of the most important goals in colloidal physics and material science [106–108]. Since their sizes are typically on the micrometer scale, these microscopic mechanisms can be directly observed and followed with optical microscope.

Over the years, different assembly schemes have been suggested, including the microwave-assisted self-organization of colloidal particles [109], a field-assisted assembly of oppositely charged particles [107], and using patching particles [110]. Also DNA linkers appear as a very good nanocontact glue between the colloids [106, 108].

Colloids aligned in a string represent one of the important configurations, whose realization is not very demanding. In principle, particles with dielectric or magnetic susceptibilities align in an electric or magnetic field, respectively, and form the strings of colloids [111]. However, the main issue is that after the field is switched off, strings fall apart due to the lack of interactions which would hold the colloidal particles together. There are several approaches how to keep the strings stable that include an annealing process [111], electrostatic interactions [107] or using the self-protected DNA strands [108].

In the previous years, it has been shown that the DNA scaffolds [23] can stabilize organic dyes [25, 26], plasmonic particles [26, 78, 97], and colloidal particles into desirable configurations. It has also been shown that the DNA origami structures can be driven by short DNA strands to change reversibly from one configuration to the other [28]. The particle size in these cases is typically much smaller than a micrometer.

Here we demonstrate a new approach to glue the colloidal particles together using DNA nanotubes. DNA nanotubes with programmable circumference have been developed in the group of John Reiff [34]. In this chapter, we use a slightly modified procedure [35, 36] for 6-helix tubes in order to allow the attachment of the DNA functionalized colloidal particles to the DNA tubes. The modified tubes have dockers which are single-stranded protrusions from the DNA tubes that can bind to the complementary DNA strands on the colloids.

	Name	DNA sequence (5′-3′)
1	linker 1	biotin-GTA-GAA-GTA-GG-organic dye
2	linker 2	biotin-TTT-AAT-ATT-A-organic dye
3	U1mod	CCT-ACT-TCT-ACT-TGG-CGA-TTA-GGA-CGC-TAA-GCC-ACC-TTT-AGA-TCC-TGT-ATC-TGG-T
4	U2	GGA-TCT-AAA-GGA-CCA-GAT-ACA-CCA-CTC-TTC-CTG-ACA-TCT-TGT
5	U3	GGA-AGA-GTG-GAC-AAG-ATG-TCA-CCG-TGA-GAA-CCT-GCA-ATG-CGT
6	U4	GGT-TCT-CAC-GGA-CGC-ATT-GCA-CCG-CAC-GAC-CTG-TTC-GAC-AGT
7	U5	GGT-CGT-GCG-GAC-TGT-CGA-ACA-CCA-ACG-ATG-CCT-GAT-AGA-AGT
8	T6	GGC-ATC-GTT-GGA-CTT-CTA-TCA-CCT-AAT-CGC-CTG-GCT-TAG-CGT

Table 6.1: DNA sequences. DNA oligomers used for functionalization of colloids (1-2), creation of 6-helix DNA tubes (3-8). Strand 2 is complementary with the docker of strand 3, which enables the connection of the tubes and the functionalized colloidal particles. Strand U1mod is a modified strand U1 from the reference [34] (a docker and two thymines are added at the 5′ end of the strand).

6.2 Microscopy

To follow the formation of the strings of colloids, we used a Nikon eclipse Ti-E microscope system with a Nikon 100x/1.45 NA Oil immersion DIC H objective, Nikon FITC (Excitation: 465-495 nm, Dichoric mirror 505 nm, Emission: 515-555 nm) and TRITC (Excitation: 540/25 nm, Dichroic mirror 565 nm, Emission: 605/55 nm) filters and a Nikon Intensilight C-HGFIE lamp. For the detection, we used a Nikon Digital Sight DSQi1Mc camera in combination with Nikon NIS Elements 4 software. DNA strands used to functionalize the colloids are also appended with the organic dye molecules in order to improve the visualization process: 6-FAM (FITC filters) and Cy3 (TRITC filters).

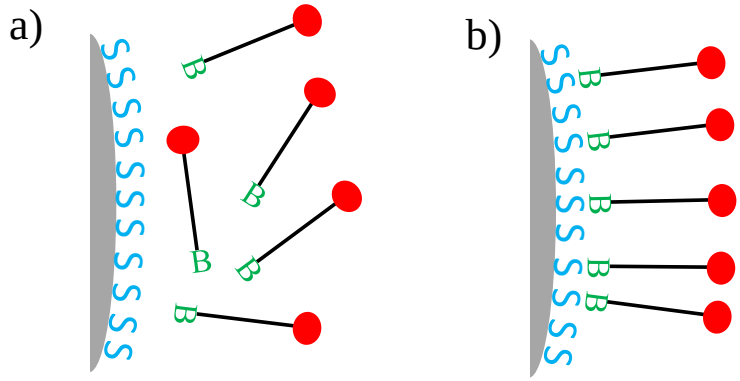

Figure 6.1: Functionalization of the colloidal particles with single-stranded DNA. a) The surface of the colloidal particle (gray) is covered with Streptavidin (S). Biotinylated (B) DNA strands with organic dye (red circle) at the 3′ are mixed with streptavidin-coated particles. The fluorescent dye is appended to the DNA in order to facilitate the visualization of colloids. b) The attachment of the biotin (B) and streptavidin (S) enables functionalization of the particles with DNA strands.

6.3 Functionalization of colloidal particles

We purchased the streptavidin-coated superparamagnetic particles (Dynabeads MyOne Streptavidin C1) from Life Technologies. In order to functionalized them with single stranded DNA oligonucleotides (Integrated DNA Technologies), we followed the procedure published by Dreyfus et al. [112]. Biotinylated oligonucleotides attach to the streptavidin-coated colloids (Figure 6.1) by suspending 5 μL of 10 mg/mL Dynabeads and 5 μL of 6 μM DNA in 65 μL phosphate buffered saline (PBS; 10 mM phosphate, 47 mM NaCl, 0.5 % w/w Pluronic surfactant F127 and 3 mM NaN_3, pH 7.5) and placing this suspension in an oven for 30 minutes at 55°C. The excess and unbound DNA was washed out by centrifuging the particles for 45 seconds at 3000 rpm and pipetting out the liquid above the sedimented colloids. After adding 100 μL PBS, the washing procedure was repeated 3 times.

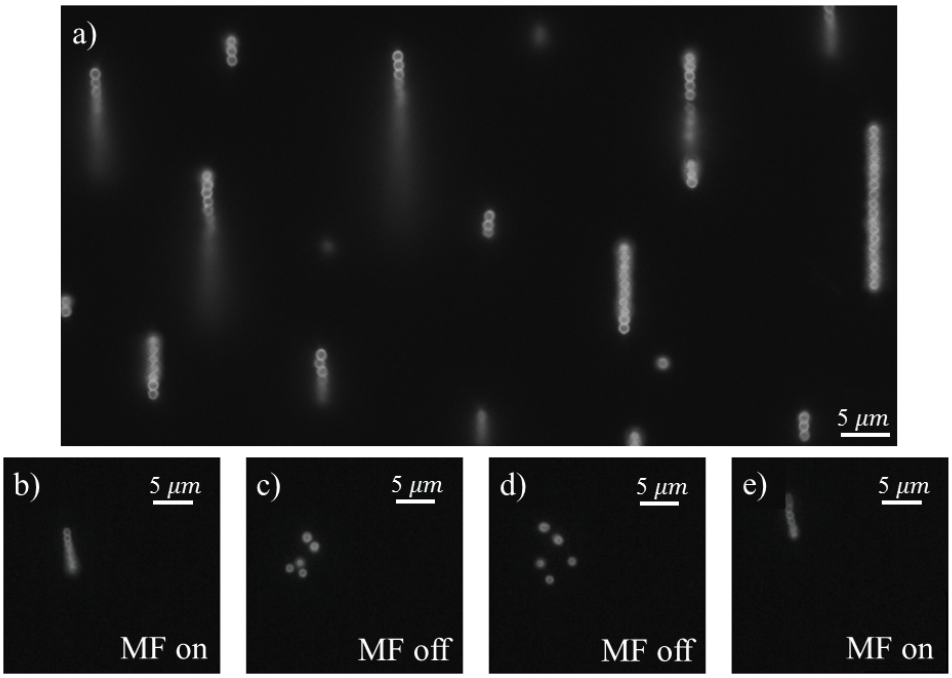

Figure 6.2: Strings of self-organized colloids in a magnetic field. a) Superparamagnetic colloids organize in the magnetic fields (MF) into strings. b) When the MF is on, a string is stable. c)-d) We follow the behavior of the string when the MF is turned off. The attraction between the particles stops and they diffuse apart due to thermal motion. As the time progresses, the particles are further apart due to the diffusion process. e) If we switch on again the MF, the particles reorganize into a string.

6.4 Tube synthesis

Following the procedure given by Yin et al. [34] and including modification suggested by Copp et al. [35], we mixed the DNA oligonucleotides with buffer at the final concentrations: 3 μM U1mod- U5 and T6 (Table 6.1) and 12.5 mM magnesium acetate and 20 mM ammonium acetate. This solution was then heated to 95°C and left to slowly cool down in a thermos flask for two days to let the DNA strands self-assemble into DNA tubes (Figure 6.3).

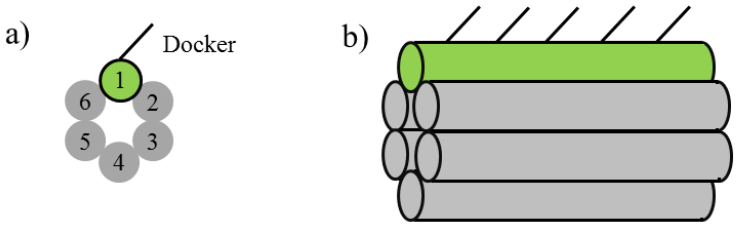

Figure 6.3: Formation of the DNA tubes. a) Strands: docker-TT-U1, U2-U5 and T6 self-assemble into the DNA tubes. b) Schematic representation of the DNA tube with the docker protruding out of the tube. The dockers are single strands of the DNA responsible for the attachment to the colloids functionalized with the complementary strands.

6.5 Results

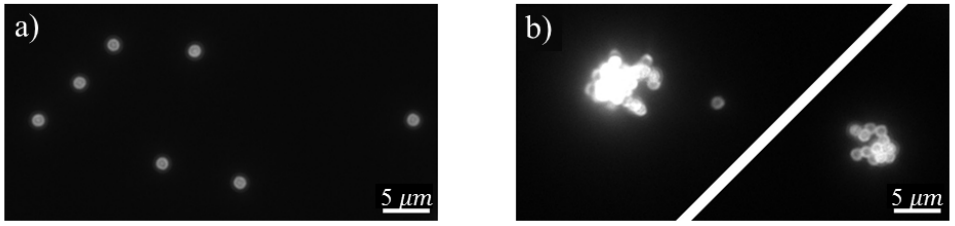

Figure 6.4: Colloids functionalized with non-complementary (a), and self-complementary (b) single stranded DNA. a) Colloids with non-complementary strands do not attach to each other. Even if the collision occurs, they diffuse away without permanent attachment. b) The self-complementary DNA strands tend to bunch together into clumps of particles without possibility to control the process. This is why the organization of the colloidal particles with complementary strands is not a good approach.

Colloidal particles functionalized with DNA do not attach to each other if the strands are not complementary (linker 1 in Table 6.1) as presented in Figure 6.4 a. If the strands are self-complementary (linker 2 in Table 6.1), they form clumps as presented in Figure 6.4 b. The colloids labeled with

complementary strands bunch together and cannot form the strings.

The superparamagnetic particles in MF form strings such that the free colloids are attracted by the growing magnetic field of the string, so they attach onto the ends of the string. In the Figure 6.2 a, one can see the strings of different lengths formed in the solution when the MF is on. These strings can exist only when the MF is on. One of these strings is shown in the Figure 6.2 b. Some of the colloids appear blurry, because they are out-of-focus. However, it the MF is off, the emitters start diffusing away (Figure 6.2 c, d). If we switch on the MF again, and if the colloids are sufficiently close together, they will form the strings again. But, as it can be seen, the strings deteriorate as soon as the MF is off.

In order to keep them together, some kind of 'glue' is necessary to form the stable structure. Our approach is to use DNA tubes and try to organize the colloidal particles. The schematic representation of the tubes is given in Figure 6.3. These tubes have dockers, strands complementary to the ones used for functionalization of the colloidal particles. The Watson-Crick pairing will enable the binding of the tubes and colloidal particles.

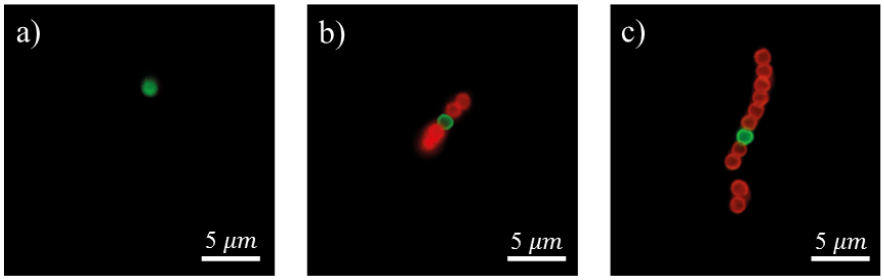

Figure 6.5: Formation of the strings of colloids connected with DNA tubes. a) Single colloidal particle attached to the DNA tubes (tubes are not visible). b) In the magnetic field, the colloids form string. c) The colloids stay in the string even after switching off the magnetic field. The DNA tubes are responsible for this stability, because they act as a 'glue' which holds the colloids together.

The most efficient procedure that we found for forming strings consists of several steps. First, we mix small concentration of the colloids with DNA tubes (labeled with FAM). Then we add this solution on the cover slip and image the colloid (Figure 6.5 a). In order to track the procedure, the colloids which we add subsequently are labeled with the different organic dye (Cy3).

If the MF is on, they will form a string (Figure 6.5 b). The longer the MF is on, the more colloids will attach to the string, which is now stable, due to the fact that the dockers on DNA tubes mediate between the string and the colloids which attach (Figure 6.5 c).

It is also possible to connect two or more strings together. The underlying mechanism is that the tubes in the magnetic field attract each other strongly. On the other hand, as we have already seen, only the magnetic field is not sufficient to keep the colloids together. The 'unused' dockers of the DNA tubes at the ending part of the strings must connect efficiently to the colloids of the adjacent string. In Figure 6.6 a, we see the two strings approaching each other. At the beginning, the collided strings in Figure 6.6 b are kept together due to the MF. The two strings stay together even if the MF is off (6.6 c); the DNA tubes glue the two strings together.

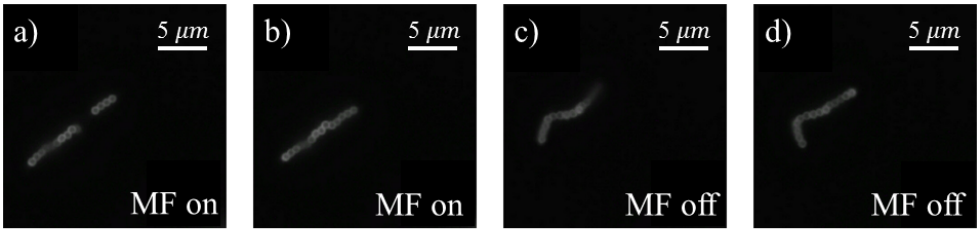

Figure 6.6: The attachment of two strings. a) If the MF is on two strings attract each other with their induced magnetic fields. b) These two strings collide and form a larger string. c) Even if we switch off the magnetic field, the strings stay together, due to the fact that free dockers on DNA tubes which are at the end points of the string connect to the colloids of the neighboring string making a strong bond. d) The string is not rigid and it changes its shape in time. DNA tubes enable somewhat flexible connections between the colloids.

This system is flexibile, as we can see that the shape of the string has changed in 6.6 d with respect to the shape of the string in Figure 6.6 c. This means that DNA tubes behave as the flexible bonds between the colloids. It is also important to mention that the solution with the strings still contains 'unused' DNA tubes which can be picked up by the moving strings of colloids. This is also one of the possible explanations why there are still some active dockers on the ending points of the strings. The lengths of the strings

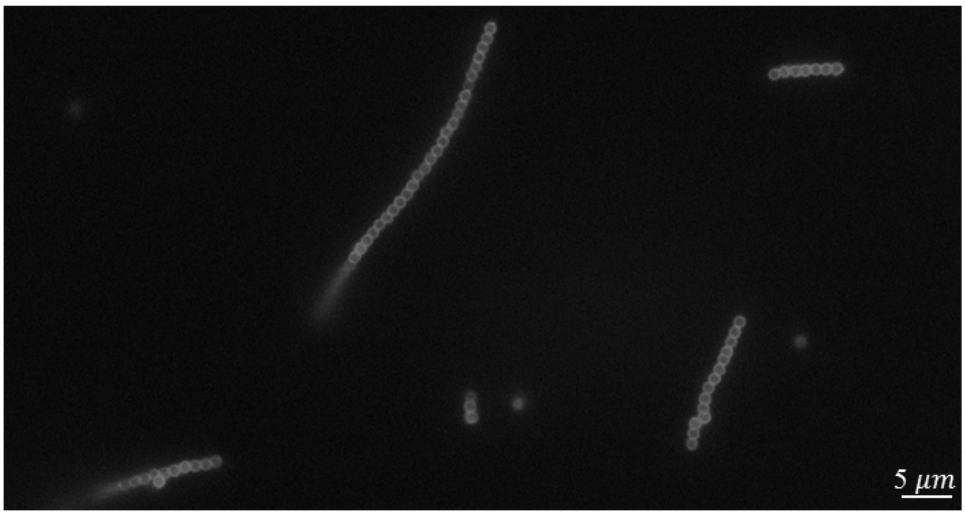

Figure 6.7: Strings of colloids formed in magnetic field and connected with DNA tubes. The length of the strings is arbitrary and is related to the length of the interval when the magnetic field was switched on.

can have arbitrary lengths. In principle, the longer the MF is on, the longer strings can be formed. In Figure 6.7, one can observe that the string length ranges from a few to few dozens of colloids. Typically the smaller strings append to each other and form 'superstrings'.

6.6 Conclusion

We have shown that DNA is a promising material for organization of the colloidal particles. When the particles were functionalized with complementary DNA strands, they simply bunched together and formed irregular shapes. However, DNA tubes with dockers represent an excellent nano-contact glue between the DNA functionalized colloids aligned in magnetic field. In the approach we took, stable strings of arbitrary lengths were formed. The DNA tubes form a type of 'glue' that allows flexibility of the strings of colloids which is an important property for the formation of larger self-assembled structures.